

**REHABILITATION OF SINKHOLES AND  
SUBSIDENCES ON DOLOMITIC LAND,  
EKURHULENI METROPOLITAN MUNICIPAL AREA  
OF JURISDICTION, GAUTENG, SOUTH AFRICA**

**By**

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## ABSTRACT

*Extensive research has been done on the investigation, evaluation, development and management of land underlain by dolomite to prevent the formation of sinkholes and subsidences. Little emphasis is, however, given to the various processes and methodologies with respect to the investigation and rehabilitation of sinkholes or subsidences.*

*In South Africa most sinkholes and subsidences have been recorded on dolomite of the Malmani Subgroup of the Chuniespoort Group on the Far West Rand and in an area south of Pretoria within the City of Tshwane, with numerous studies done on the occurrence of sinkholes and subsidences in these two areas. However, a large number of sinkholes and subsidences have also been recorded on the East Rand in the Ekurhuleni Metropolitan Municipal area, which is the focus of this research.*

*Very little is published on the occurrence of sinkholes and subsidences, the related geological models, investigations and rehabilitation work done in the Ekurhuleni Metropolitan Municipal area. It has been attempted with this thesis to document the various processes and methodologies applicable to the investigation and rehabilitation of dolomite-related sinkholes and subsidences within a non-dewatering environment. This is based on experience gained during the investigation and rehabilitation of various sinkholes and subsidences within the Ekurhuleni Metropolitan Municipal area on the East Rand, over the past ten years.*

*Various methods of investigation, including non-intrusive and intrusive methods have been tried and tested to determine the extent of subsurface erosion within an affected sinkhole or subsidence area. The gravity geophysical method in association with the drilling of percussion boreholes; exposure of the affected area by means of excavation and the use of the Dynamic Probe Super Heavy (DPSH) method, in areas not accessible for a drilling rig where gravel, cobbles and boulders are absent in the subsurface profile; is the most appropriate methods for sinkhole or subsidence investigations on the East Rand. The gravity method is, however, not always successful in delineating narrow grykes in a shallow dolomite environment. The use of a specific method or methods of investigation is prescribed by the accessibility of a site. Accessibility constraints within a build-up area, may lead to the use of an investigation method other than what is generally preferred.*

*The specific method or combination of methods used to rehabilitate a sinkhole or subsidence will depend on the available funds, current and proposed land use, subsurface conditions, accessibility constraints caused by existing infrastructure for equipment and the impact of the rehabilitation procedure on existing infrastructure.*

*The various sinkhole and subsidence rehabilitation methods used on dolomite in South Africa and their applications are discussed, including: the Inverted Filter Method, Dynamic Compaction Method, combination of the Inverted Filter and Dynamic Compaction Methods, Compaction (backfill) Grouting Method, Combination of the Inverted Filter and Compaction Grouting Methods,*

*Combination of the Dynamic Compaction and Compaction Grouting Methods and the use of Self-Compacting Concrete or Soil-cement Mix.*

*Nearly half of the Ekurhuleni Metropolitan Municipal area is classified as dolomite land. A total of 241 ground movement incidents had been recorded, since 2005 to mid-2013. The Ekurhuleni Metropolitan Municipal area of jurisdiction is divided into three regional areas, namely:*

- *Southern Regional area: More than 50% of the region is directly underlain by dolomite and chert of the Monte Christo Formation of the Malmani Subgroup of the Chuniespoort Group. A total of 141 ground movement incidents had been recorded, with all dolomite-related sinkholes and subsidences caused by ingress of water. Approximately 85% were caused by sewer lines, 7% by leaking water lines and valves, 4% by surface water ponding and 3% by concrete stormwater lines.*
- *Northern Regional area: The northern portion of the region is directly underlain by dolomite of the Malmani Subgroup; from west to east by, chert-poor dolomite of the Oaktree Formation, chert-rich dolomite of the Monte Christo Formation, chert-poor dolomite of the Lyttelton Formation and chert-rich dolomite of the Eccles Formation. Dolomite of the Monte Christo Formation is also encountered in the south-eastern portion of the region. A total of 83 ground movement incidents had been recorded. Ground movement incidents are related to both ingress of water and dewatering of dolomite groundwater compartments including the Bapsfontein, Elandsfontein and Sterkfontein-East Dolomite Groundwater Compartments and Sub-Compartment.*
- *Eastern Regional area: More than 50% of the region is regarded as dolomite land, with large portions of dolomite of the Monte Christo Formation and the Oaktree Formation of the Malmani Subgroup covered by the Karoo Supergroup. Dolomite of the Monte Christo Formation also occurs in the south-western portion of the regional area. A total of 17 ground movement incidents had been recorded. None of the recorded ground movement incidents are, however, related to dolomite. Incidents are related to poorly backfilled old wet services, natural erosion of subsurface soils, collapse of shallow coal workings and collapse of mine shafts and ventilation shafts.*

*The sinkhole and subsidence rehabilitation method mostly used in the Ekurhuleni Metropolitan Municipal area is the Inverted Filter Method accounting for 85% of rehabilitation work, 10% for compaction grouting and 5% for the use of the Dynamic Compaction Method.*

*The sinkhole and subsidence rehabilitation method should not be prescriptive, given the vast number of variables involved. A comprehensive understanding of the affected area is essential although for cost effective and practical rehabilitation measures.*

*A site specific set of criteria for the rehabilitation of the features and affected infrastructure must be developed to ensure proper stabilisation and safe future use of the area. Basic principles can however be applied to each sinkhole or subsidence, such as: Ensuring the trigger of the sinkhole or subsidence has been identified and removed; the position and extent of the receptacles have been determined as best as possible and erosion paths sealed; the known eroded area, possible*

*voids and cavities properly backfilled and densified; a proper impervious or engineer designed earth mattress created; ensuring that all affected subsurface wet services are replaced and comply with industry standards; and that proper surface drainage exists.*

*From the seventeen generic geological models presented and ten case studies recorded it is evident that each sinkhole or subsidence is unique, affected by a large number of influencing factors considered in the selection of the most appropriate rehabilitation method. These influencing factors including, the depth and lateral extent of the instability feature and triggering mechanism, complexity of the geological model and external influencing factors such as available funding, socio-economic factors, impact by third parties, the impact on existing infrastructure and proposed land use after rehabilitation.*

*The sinkhole or subsidence evaluation process, selection of the rehabilitation method and related standardised flow chart, developed during this research study, are illustrated by the seventeen generic geological models and recommended rehabilitation methods developed for the East Rand. Even though each sinkhole or subsidence is unique, the evaluation of the various influencing factors considered to determine the most appropriate rehabilitation method are the same, as illustrated by the various flow charts for the different models. The same approach is therefore suggested in other regions affected by sinkholes and subsidences. Similar or near similar geological scenarios may exist in other dolomite or limestone regions and the various generic geological models and rehabilitation methods developed for the East Rand may serve as a guideline to determine the most appropriate rehabilitation method in similar geological scenarios.*

*The seventeen generic sinkhole-and-subsidence-geological models, related flow charts and recommended rehabilitation methods, for the East Rand provide a broad base understanding of different dolomite environments, their susceptibility to sinkhole or subsidence formation and best practice rehabilitation, as seen by the author.*

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## DECLARATION

I, ILSE KLEINHANS declare that the thesis / dissertation, which I hereby submit for the degree Doctor of Philosophy in Engineering Geology at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: .....

DATE: .....

---

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# 1. INTRODUCTION

## 1.1 Background

Engineering problems related to karst features, including sinkholes and subsidences, on carbonate (limestone and dolomite) and evaporate (gypsum and salt) rocks is common all over the world, including the United States of America, United Kingdom, Europe, Asia and Africa and have been documented by various authors (Buttrick *et al.*, 2001 and 2011; Waltham *et al.*, 2005; Ford and Williams, 2007; Zhou and Beck, 2011; Galve *et al.*, 2012; Gutierrez *et al.*, 2014; Parise *et al.*, 2015 and Kleinhans and Van Rooy, 2016).

Dolomite karst features are phenomena that have been reported and published on as early as 1884 in South Africa by Penning (in Jennings, 1966). Initially these events occurred naturally, caused by periods (100's to 1000's of years) of drought followed by wetter periods. Since the 1950's, the causes of sinkholes and subsidences are mainly anthropogenic (related to mining and urbanisation). Dolomite groundwater compartments located above the gold bearing Witwatersrand Supergroup were dewatered and development of townships on dolomite land took place (including the installation of subsurface wet services), especially in the Gauteng Province previously known as the Pretoria-Witwatersrand-Vereeniging (PWV) area of the Transvaal Province.

Although dolomite land (land underlain by dolomite or limestone within 100 m from natural ground surface) (SANS 1936, 2012) occurs in the Northern Cape, North West, Limpopo and Mpumalanga, it is the dolomite of the Malmani Subgroup of the Chuniespoort Group in the Gauteng Province and the West Rand District that is notorious for sinkhole and subsidence formation. The Gauteng Province is regarded as the capital province of South Africa with a very high population density of people in this province and a high percentage residing on dolomite. This includes formal and informal housing, with an increase in overpopulated informal settlements due to the demand for housing on dolomite land generally regarded as not suitable for residential use.

Gold was discovered on the Witwatersrand in the late 1800's and the first mine shaft on the West Rand, at the Venterspost mine, could only be sunk in June 1934. Previous attempts were halted by excessive groundwater within the dolomites of the Malmani Subgroup of the Chuniespoort Group, located above the goldbearing Witwatersrand Supergroup formations (Wolmarans, 1984). Dewatering of the dolomite compartments, in order to mine the underlying goldbearing reefs, commenced in various areas between the late 1950's to 1980's, resulting in a dramatic increase in sinkhole and subsidence formation (50 events per year were recorded in the early 1960's (Brink, 1979)).

More than 3000 events, including sinkholes, subsidences and ground cracks are recorded within Gauteng and the West Rand District in the database of the Council for Geoscience (Constantinou and Oosthuizen, 2014). Some of these events have resulted in major damage to infrastructure and loss of life (Brink, 1979, Buttrick and Roux, 1993 and Buttrick, 1995).

Most of the sinkholes and subsidences have been recorded in the West Rand District and in an area south of Pretoria within the City of Tshwane. Numerous research studies have been done on the occurrence of sinkholes and subsidences in these two target areas.

However, a large number of sinkholes and subsidences have also been recorded in the Ekurhuleni Metropolitan Municipal (EMM) area on the East Rand, which is the focus of this study. As the rate of sinkhole and subsidence formation on the East Rand is lower than in the West Rand District and Tshwane Metropolitan Municipal areas, very little is published on the occurrence of sinkholes and subsidences, the related geological models and rehabilitation work done in the Ekurhuleni Metropolitan Municipality.

## 1.2 Study Objectives

The primary objective of this study is to document the various processes and methodologies applicable to the investigation and rehabilitation of dolomite-related sinkholes and subsidences within a non-dewatering environment. This is based on existing best practice and experience gained over the past ten years during the rehabilitation of sinkholes and subsidences within the Ekurhuleni Metropolitan Municipal area.

Extensive research has been undertaken on the investigation, evaluation, development and management of land underlain by dolomite to prevent the formation of sinkholes and subsidences in South Africa. The investigation, evaluation and management of dolomite areas are well documented by various authors (Buttrick *et al*, 2001 and 2011) and a number of industry standards exist, namely: Department of Public Works - PW 344 (2010); Council for Geoscience (2003) and South African National Standards - SANS 1936: Part 1 to 4 (2012).

Little emphasis is, however, given to the various processes and methodologies available and used specifically with respect to sinkhole or subsidence investigation and rehabilitation. The only standardized document available on the rehabilitation of sinkholes and subsidences on dolomite land in South Africa is SANS 2001 Part BE 3 (2012).

This research has the following main objectives:

- Present a literature review on the mechanism and influencing factors of sinkhole and subsidence formation on dolomite land; the impact of sinkholes and subsidences on existing infrastructure and record of sinkholes and subsidences.
- Document the methods of investigation and the information required to assess the extent and nature of a sinkhole or subsidence and related sub-surface impact, in order to determine the best practical and economical rehabilitation methodology.
- Document the various rehabilitation processes currently used in practise and their application to various subsurface conditions.



- Provide an overview on the occurrence of sinkholes and subsidences within the Ekurhuleni Metropolitan Municipal area, based on experience gained during the rehabilitation of these events over the past ten years.
- Document the formation of sinkholes and subsidences related to specific geological conditions within a dolomite environment, based on case studies and experience gained during the investigation and rehabilitation of sinkholes and subsidences within the Ekurhuleni Metropolitan Municipality area of jurisdiction on the East Rand of Gauteng, South Africa.
- Development of a guideline document: Proposed procedures and methods of sinkhole and subsidence rehabilitation, based on the specific geological environment in which they formed.

### 1.3 Study Area

The Ekurhuleni Metropolitan Municipal (EMM) area of jurisdiction covers a surface area of approximately 1971.58 km<sup>2</sup>, of which approximately 989 km<sup>2</sup> (98900 ha) is classified as dolomite land. The EMM area of jurisdiction is divided into three regions, namely:

- Southern Region: Including the towns of Germiston, Alberton, Vosloorus, Katlehong, Tokoza and western half of Tsakane. The Southern Region covers a surface area of approximately 476.63 km<sup>2</sup>.
- Northern Region: Including the towns of Tembisa, Bapsfontein, Kempton Park, Boksburg and the northern portion of Benoni. The Northern Region covers a surface area of approximately 795.64 km<sup>2</sup>.
- Eastern Region: Including the towns of Daveyton, southern portion of Benoni, Brakpan, Springs, Kwa-Thema, eastern portion of Tsakane and Nigel. The Eastern Region covers a surface area of approximately 699.31 km<sup>2</sup>.

The Ekurhuleni Metropolitan Municipal area of jurisdiction, regions and dolomite land map is presented in Figure 1.

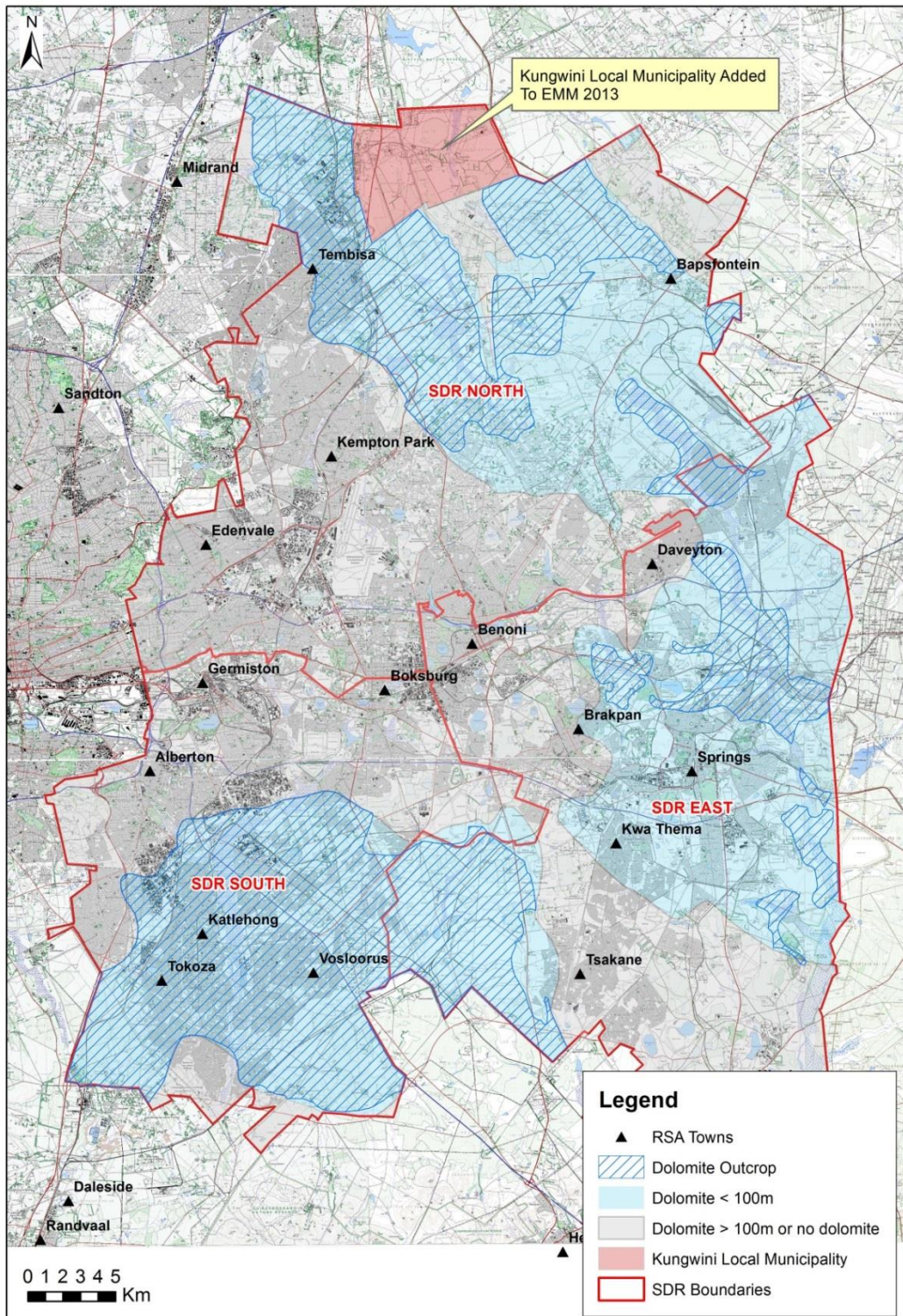


Figure 1: Ekurhuleni Metropolitan Municipal area of jurisdiction, service delivery regions and dolomite land map (VGIconsult Projects Dolomite Database, 2014).

## 2. FORMATION OF SINKHOLES AND SUBSIDENCES ON DOLOMITE

### 2.1 Introduction

Based on experience gained during the investigation and rehabilitation of sinkholes and subsidences within various dolomite regions in South Africa, but mainly on the East Rand during the period of 2005 to 2015 and as documented by various authors such as Buttrick and Van Schalkwyk (1995), sinkholes and subsidences in South Africa have largely been attributed to human activities relating to development on dolomite land. These activities include the use of inappropriate subsurface wet services in dolomitic areas, poor maintenance of wet services leading to the deterioration and leaking of existing engineering infrastructure over time, poor management of surface water run-off, poorly backfilled service trenches, lack of monitoring and control of the original groundwater level allowing artificial drawdown by excessive abstraction and dewatering of dolomite compartments and ground vibrations (e.g. heavy machinery, passing trains or blasting). These activities act as triggers causing the mobilising of overlying in situ materials into voids located within or above dolomite bedrock and the subsequent development of sinkholes or subsidences and damage to infrastructure. Natural and human-induced static and dynamic loadings (e.g. load imposed by heavy vehicles, drilling rigs, dumped material and engineering structures) may trigger the collapse of pre-existing cavities under marginal conditions (Gutierrez *et al.*, 2014).

Thousands of dolomite-related sinkhole, subsidence and crack events have occurred over the past 50 years within the Gauteng Province (Richardson, 2013). The damage to structures due to the occurrence of these instability features totals billions of rands and lead to 38 deaths (Brink, 1979, Buttrick, 1995 and Buttrick *et al.*, 2014).

### 2.2 Composition and Weathering of Dolomite

Both dolomite and limestone are regarded as sedimentary carbonates (in Wilson and Anhaeusser, 1998).

Ancient carbonate rocks are predominantly composed of two minerals; calcite ( $\text{CaCO}_3$ ) or dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ). When a carbonate rock is dominated by calcite (more than 95% with less than 5% dolomite), it is called limestone. When it is dominated by dolomite (the mineral) it is called dolomite rock (Warren, 2000).

Limestone is classified as a chemical or biochemical sediment consisting essentially of calcium carbonate ( $\text{CaCO}_3$ ), primarily in the form of calcite, and minor constituents such as silica, feldspar, pyrite and siderite (Warren, 2000).

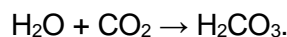
The origin of dolomite creates a problem since the mineral is not excreted by organisms as shell material. Direct precipitation from solution is not considered adequate to explain the great thicknesses of dolomite rock that are developed in the geological record. The most widely held explanation of the formation of dolomite is by the process of dolomitization, be it penecontemporaneous or post depositional dolomitization. Limestone is considered to have been the original precipitate and dolomite represents secondary replacement (Buttrick, 1986).

Dolomite as a rock, contains more than 90% dolomite and less than 10% calcite as well as detrital minerals and secondary silica (chert). Very few, if any, sedimentary dolomites are truly stoichiometric, i.e.  $\text{CaMg}(\text{CO}_3)_2$ , and are better represented as:  $\text{Ca}_{(1+x)}\text{Mg}_{(1-x)}(\text{CO}_3)_2$ , encompassing the spectrum from calcian to magnesian dolomites (Warren, 2000).

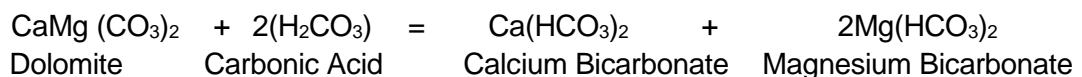
The structure of the dolomite may be presented as layers of calcite ( $\text{CaCO}_3$ ) and magnesite ( $\text{MgCO}_3$ ) (Warren, 2000). In ordinary dolomite, the proportion of  $\text{CaCO}_3$  to  $\text{MgCO}_3$  is 1:1. Calcium may, however, be substituted for magnesium up to a Ca:Mg ratio of 1:5.

Dolomite is therefore as defined above theoretically a simple carbonate of magnesium and calcium. A considerable content of iron and manganese may be present. Iron, manganese and magnesium are diadochic in the structure of dolomite. These elements have, therefore, the ability to occupy the same lattice position in the crystal structure. Consequently iron and manganese may be substituted for magnesium in the dolomite lattice. Eriksson *et al.* (1974) has suggested that iron and / or manganese may have been present in the initial  $\text{CaCO}_3$  precipitate.

Rainwater and percolating groundwater is enriched with carbon dioxide to form a weak carbonic acid as follows:



Thus weakly acidic groundwater circulating through the network of existing joints, fractures and faults, acting as preferential pathways, in the dolomitic succession, that causes the leaching of the carbonate minerals. This weak acid acts on the dolomite resulting in the rock going into solution in the form of bicarbonates. Even though dolomite rock is a particularly compact and impervious rock with a porosity of less than 0,3%, the solubility of dolomite is high in comparison to other rocks (Brink, 1979). The process may be presented as follows:



The process of dissolution progresses slowly in the slightly acidic groundwater (above and at groundwater level). Most solution takes place below the level of the water table, where the water is more acidic than deeper down, causing large horizontal caverns being corroded into the rock and at depth within the phreatic zone, where widening of fissures by corrosion continues to take place (Brink, 1979). Water in the phreatic zone is not static, dissolved bicarbonates are continuously being removed by the slow migration along joints. The flow of  $\text{CO}_2$ -charged water results in the development of a network of interconnected caverns in the zone immediately below a water table which has been static for any appreciable period of geological time (Jennings, 1966).

The weathering of the rock has given rise to cave systems, voids and other solution features, which make it a unique rock on the South African landscape (Buttrick, 1986).

Cycles of erosion and planation resulting in such long periods of static water table lead to the concentration of solution-cavities at particular subsurface elevations. Subsequent lowering of groundwater level through the incision of streams in a new cycle of erosion leads to the exposure of such cavities in the vadose zone above the groundwater level and to the solution of new cavities below the new static level of the groundwater level (Brink, 1979). Solution thus results in the formation of vertical slots in the rock both above and below the groundwater level, and the formation of horizontal chambers at the level of a static groundwater level (Brink, 1979).

As solution of dolomite, both in the vadose and phreatic zones, is dependent on the number and the spacing of discontinuities (bedding planes, joints, tension fractures and faults) and, to a lesser extent, on the composition of the rock, the resulting dolomite bedrock surface is frequently highly irregular and characterized by the presence of pinnacles, giving rise to a karst landscape (Brink, 1979).

The process of dolomite dissolution as specified by Jennings *et al.* (1965), Brink and Partridge (1965) and Brink (1979) has been well summarised in the *Guideline for engineering geological characterization and development of dolomite land*, by the Council for Geoscience (2003) as follows:

The process of dissolution has resulted in a vertically zoned succession of residual products, which, in turn, are generally overlain by geologically younger formations or soils. Hard, unweathered dolomitic rock is overlain by slightly weathered jointed bedrock and thereafter, through a sudden, dramatic transition, to totally weathered and low-strength, insoluble residual material consisting mainly of manganese oxides (wad), chert and iron oxides that reflect the original insoluble matrix structure. Depending upon the local subsurface structure, this very low strength, porous and permeable horizon may, in certain locations, be up to several tens of meters thick but is generally less than 10 m thick. With the passage of geological time, concurrently with the downward progression of the intense weathering of the dolomitic rock, compaction by the mass of the overlying materials has resulted in a progressive densification of these low-strength materials. Consequently, the vertical succession of the residual products of weathering reflects an upward increase in strength and a decrease in porosity and permeability. This process results in a decrease in overburden quality with depth.

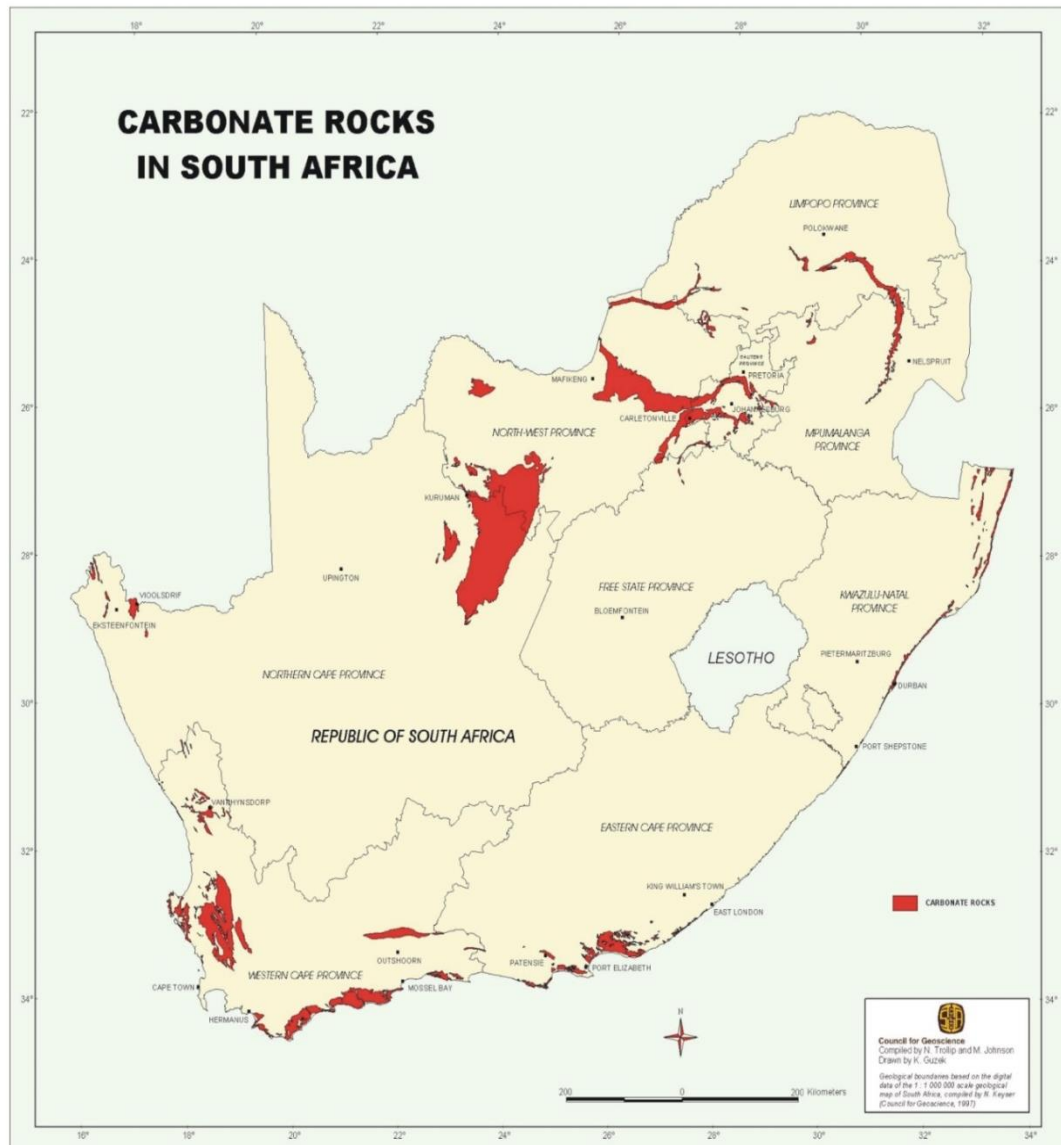
Infiltrating water from leaking wet services or surface water accumulation acting on this low-density material, results in a loss of support. Materials can either collapse or be transported into these voids and cave systems resulting in surface ground movement; sometimes with catastrophic results. The manifestation of this ground movement on the surface is either as a sinkhole or a subsidence.

### **2.3 Definition of dolomite land in South Africa**

SANS 1936 (2012) defines dolomite land as land underlain by dolomite or limestone residuum or bedrock (or both), within the Malmani Subgroup and Campbell Rand Subgroup, typically at depths of no more than:

- 60 m in areas where no de-watering has taken place and the local authority has jurisdiction, is monitoring and has control over the groundwater levels; or
- 100 m in areas where de-watering has taken place or where the local authority has no jurisdiction or control over groundwater levels.

The distribution of carbonate rocks in South Africa is illustrated in Figure 2.



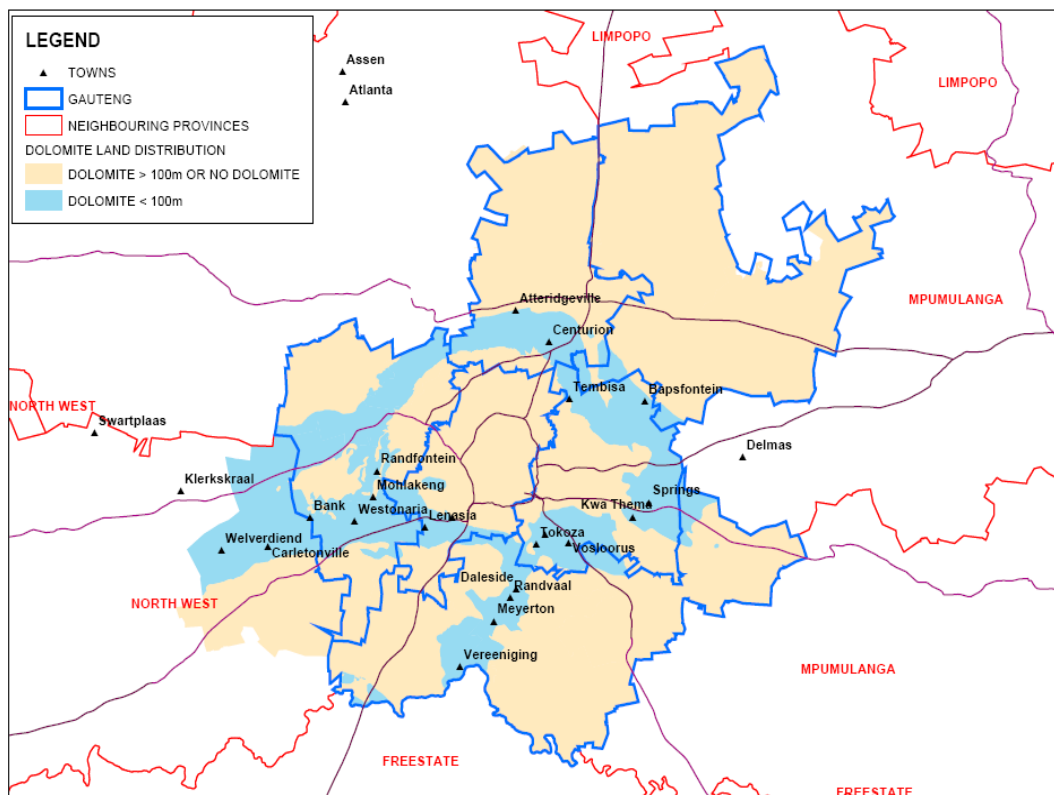
**Figure 2: Distribution of carbonate rocks in South Africa (after Council for Geoscience, 1997).**

Areas classified as dolomite land and the various Municipal areas in Gauteng are illustrated in Figure 3 (Bosch, 2003).

Apart from the Malmani Subgroup and the Campbell Rand Subgroup carbonate-related (therefore also dolomite-related) instability can also take place in any karstic terrain (SANS 1936, 2012).

SANS 1936 further specifies that any reference to dolomite applies equally to limestone.

The focus of this study is, however, on the dolomite conditions and sinkhole and subsidence formation and rehabilitation on the East Rand covering the Ekurhuleni Metropolitan Municipal area, where more than 50% of the surface area is classified as dolomite land underlain by the Malmani Subgroup of the Chuniespoort Group. The remaining area of jurisdiction is underlain by rock formations other than that of the Malmani Subgroup.



**Figure 3: Gauteng Dolomite Land Map (after Bosch, 2003)**

The distribution of the different dolomite formations of the Malmani Subgroup and the dolomite land within the Ekurhuleni Metropolitan Municipality is illustrated in Figure 4.

## 2.4 Environment of Deposition and Stratigraphy of the Chuniespoort Group

According to Beukes (1987), Altermann and Wotherspoon (1995), the Transvaal Supergroup encompasses one of the world's earliest carbonate platform successions. The late Archaean to early Proterozoic Transvaal Supergroup is preserved in a 500 000 km<sup>2</sup> intracratonic basin on the Kaapvaal Craton (Eriksson *et al.*, in Johnson *et al.*, 2006).

This basin developed during a major period of erosion in Post-Ventersdorp times. The erosional surface underlying the Black Reef Formation is representing widespread removal of pre-existing lithologies and deposition of a sheet of sandstone as a new base level was established under gentle, northward-directed tectonic compression (Clendenin, 1989).

The Black Reef quartzite covers a regional unconformity over the Archaean basement granites, the Witwatersrand and the Ventersdorp Supergroups (Eriksson *et al.*, in Johnson *et al.*, 2006). Initial fluvial sedimentation followed by shallow marine conditions as an epeiric sea is discernible in the Black Reef Formation (Button, 1973).

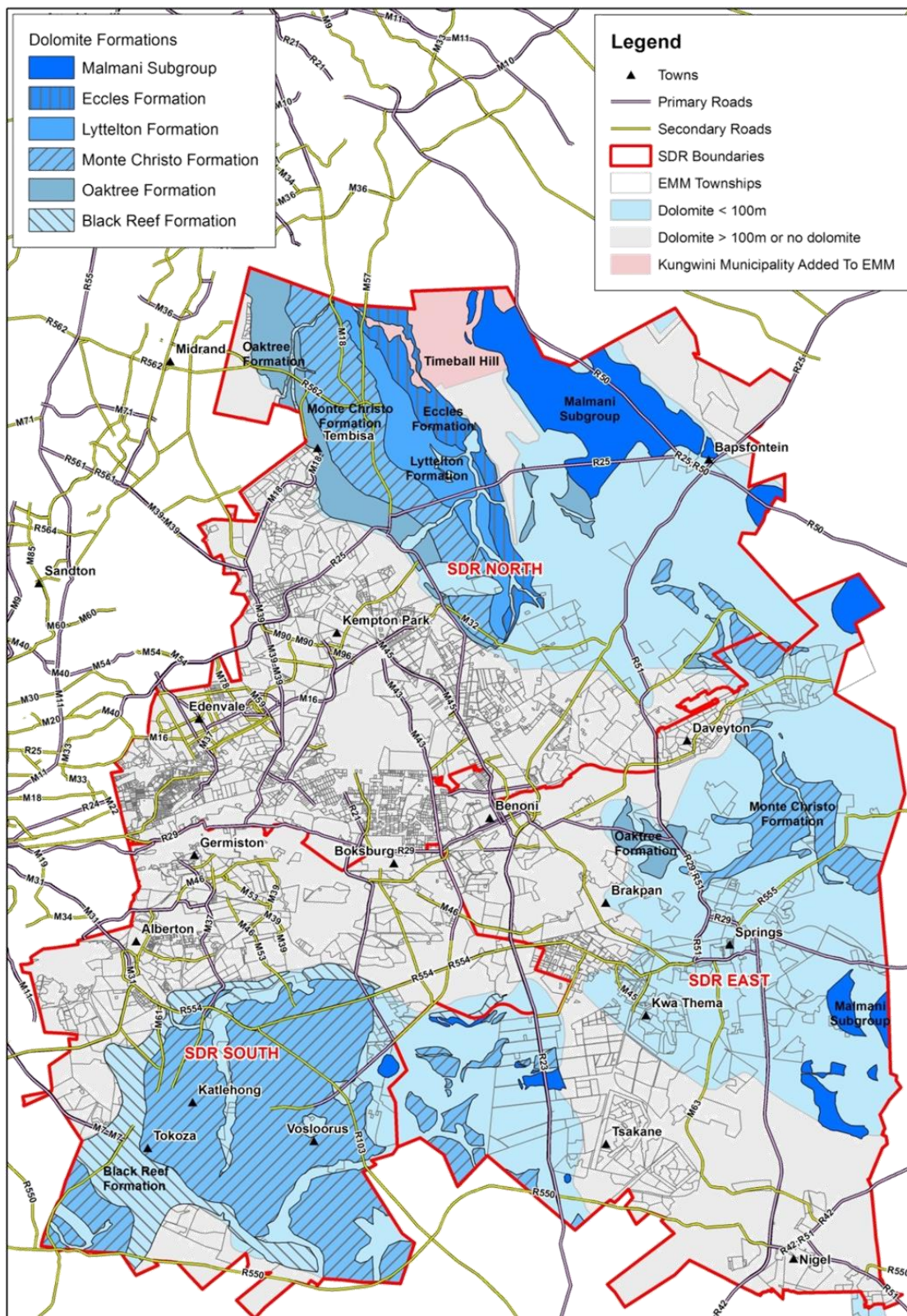


Figure 4: Formations of the Malmmani Subgroup in the Ekurhuleni Metropolitan area (after Council for Geoscience, 2013).



The distribution of the Malmani Subgroup and the Black Reef Formation in the Gauteng Province is illustrated in Figure 5.

The deposition of limestone has been estimated at 2 550 Ma (Walraven and Martini, 1995). The limestone precipitated in favourable environmental conditions by algal photosynthesis and inorganic precipitation. The dolomitisation of limestone took place in an environment where meteoric and marine water mixed and the saline brine became supersaturated with respect to magnesium and silica and undersaturated with respect to calcite, thereby increasing the dolomitisation and chertification potential.

The Malmani Subgroup of the Chuniespoort Group in the Transvaal basin is underlain by the Black Reef Formation and overlain by the Pretoria Group sediments or the Karoo Supergroup sediments. Intrusive dykes and sills have intruded the dolomite in sub-regions.

The approximately 30 m thick Black Reef Formation represents a laterally continuous unit of relatively mature quartz arenites with lesser conglomerates and subordinate mudrocks, forms a thin veneer of arenaceous rocks unconformably overlying older successions. An impersistent basal conglomerate is succeeded by thicker sandstones and thin mudrocks, the whole forming an upward-fining sequence (Henry *et al.*, 1990).

According to SANS 1936 (2012) the Black Reef Formation comprises conglomerate-quartz arenite-shale with a gradual transition from carbonaceous shale to carbonate, which can be found throughout the Transvaal Supergroup basin. Arising as a weathering product from carbonate, residual dolomite (wad) can thus be present in the Black Reef Formation (Brink, 1979). According to Brink (1979) the Black Reef Formation comprises basal conglomerate, wad, quartzite and carbonaceous shale.

According to Button (1973) and Eriksson and Truswell (1974), the Malmani Subgroup is up to 2000 m thick and the dolomite rocks are approximately 2200 to 2300 Ma years old. The Malmani Subgroup is subdivided into five formations of which only the first four are present in the central area of the country, based on chert content, stromatolite morphology, intercalated shales and erosion surfaces of which some are chert-poor and some are chert-rich: The Eccles and Monte Christo Formations are chert-rich and the Oaktree and Lyttelton Formations are chert-poor.

Three depositional environments have been recorded for the formations of the Malmani Subgroup by Eriksson (1972), and Eriksson and Truswell (1974). The environments represented in the epeiric sea are the subtidal, supratidal and intertidal zones:

- The chert-poor Oaktree and Lyttelton Formations were deposited in the deep sea subtidal zone, supersaturated with respect to iron and manganese and not influenced by meteoric waters.
- The chert-rich Monte Christo Formation was deposited in the intertidal zone situated between the tidal flats and the subtidal zone.

The dolomite in this zone is recrystallized, reflecting a meteoric influence causing slightly acidic water that presents the ideal environment for the development of silica precipitates such as chert.

- The chert-rich Eccles Formation was deposited in the supratidal zone (or Sabkha) constituting an area which is only flooded during exceptionally high tides and storms.

Deposits is in the form of evaporates and carbonates such as anhydrite, gypsum and halite. The influence of slightly acidic meteoric water results in an acidic environment with a chert-rich dolomite being deposited.

#### 2.4.1 Oaktree Formation

This chert-poor formation represents the basal unit of the Malmani Subgroup. The Oaktree Formation is transitional from siliciclastic sedimentation to platformal carbonates and consists of 10 m to 200 m thick carbonaceous shales, stromatolitic dolomites and locally developed quartzites.

The Oaktree Formation according to Brink (1979) comprises dark-coloured chert-poor dolomite, sometimes with wad and with carbonaceous shale towards the base.

The Oaktree Formation comprises a higher percentage (> 1%) of manganese in the dolomite therefore the presence of large quantities of wad and manganocrete in this formation (Brink, 1979).

#### 2.4.2 Monte Christo Formation

Tyler and Tyler (Eriksson *et al.*, in Johnson *et al.*, 2006) specifies a 300 m to 500 m thickness for the chert-rich Monte Christo Formation resting concordantly on the Oaktree Formation, beginning with an erosive breccia and continues with stromatolitic and oolitic platformal dolomites.

Brink (1979) specifies that the Monte Christo Formation comprises light-coloured chert-rich recrystallized dolomite with stromatolites and basal oolitic bands.

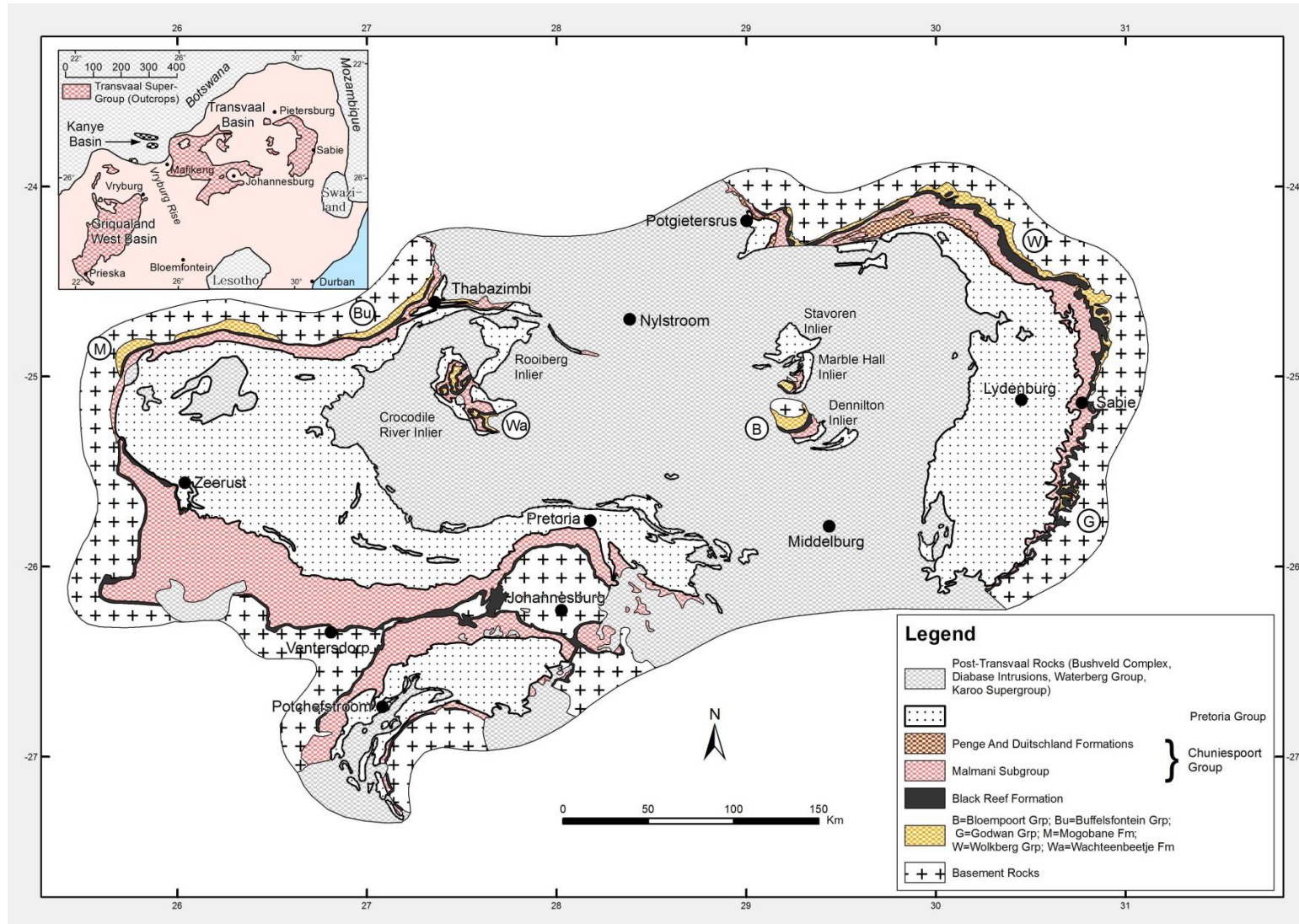


Figure 5: Distribution of the Malmani Subgroup and the Black Reef Formation in the Gauteng Province (after Eriksson *et al.*, 2006)

### 2.4.3 Lyttelton Formation

The shales, quartzite and stromatolitic dolomites of the 100 m to 200 m thick Lyttelton Formation overlies the Monte Christo Formation (Eriksson *et al.*, in Johnson *et al.*, 2006). Thus chert-poor formation like the Oaktree Formation, has a higher concentration of iron and manganese (1,5%) which gives rise to wad formation (Brink, 1979).

The dolomite tends to weather into sharp pinnacles (Buttrick, 1986).

According to Brink (1979) the Lyttelton Formation comprises dark-coloured chert-free dolomite with large stromatolitic mounds; residual dolomite (wad) sometimes present.

### 2.4.4 Eccles Formation

The up to 600 m thick chert-rich dolomites of the Eccles Formation is overlaying the Lyttelton Formation and includes a series of erosion breccias (Eriksson *et al.*, in Johnson *et al.*, 2006).

According to Brink (1979) the Eccles Formation comprises chert-rich dolomite with stromatolites and oolite bands with the chert content increasing upward in the succession.

### 2.4.5 Frisco Formation

An erosion breccia separates the Eccles Formation from the overlying Frisco Formation (up to 400 m thick). Tyler and Tyler (Eriksson *et al.*, in Johnson *et al.*, 2006) specifies that the Frisco Formation comprises mainly of stromatolitic dolomites.

According to Brink (1979) the Frisco Formation comprises chert-free dolomite with some primary limestone and with carbonaceous shale at the base.

The Frisco Formation is, however, not present in the central area of the country or in the study area.

### 2.4.6 Penge and Duitschland Formations of the Chuniespoort Group

The above mentioned upper two formations of the Chuniespoort Group does not form part of the Malmani Subgroup and is not present in the central area of the country or in the study area.

## 2.5 Definition of a sinkhole and a subsidence

SANS 1936 (2012) defines a sinkhole as a feature that occurs suddenly and manifests as a hole in the ground that is typically circular in plan.

A subsidence is defined as a shallow enclosed depression that occurs slowly over time and may typically be circular, oval or linear in plan. In past South African literature, a subsidence as defined above was synonymous with the term doline.

In terms of size, sinkholes and subsidences are defined as: small (<2 m diameter), medium (2 m to 5 m diameter), large (5 m to 15 m diameter) and very large (>15 m diameter) (Buttrick *et al.*, 2001 and 2011).

## 2.6 Mechanism of Sinkhole and Subsidence Formation

The mechanism of sinkhole and subsidence formation is described in detail by Jennings *et al.*, (1965) and Brink (1979). The formation of sinkholes and subsidences are evaluated from ingress of water (i.e. leaking wet services or poor surface water run-off) or dewatering perspective.

### 2.6.1 Mechanism of Sinkhole Formation

In a paper on the formation of sinkholes in dolomite, presented by Enslin and Smit in 1955 at the First Regional Conference on Soil Mechanics and Foundation Engineering, sinkhole formation was ascribed to the collapse of the roofs of caverns in the dolomite causing the overlying soil to slump into the cavern (Donaldson, 1963). Furthermore Enslin (1951) specifies that sinkholes occur most frequently in the upper 100 to 200 feet (or 30 m to 60 m) of the dolomite series, immediately below the giant chert breccia of the Transvaal dolomites and that sinkholes are very often aligned along major fault planes in the dolomite.

According to Donaldson (1963) the following conditions are required for the formation of a sinkhole:

- Cavities or voids must exist into which the eroded material can be washed, including open fissures and cavities in the dolomite.
- There must be a sufficient flow of water from a source to erode the material and the soil must be of such permeability as to allow enough flow to cause erosion.
- The material must be erodible by the flow of water through the soil.
- The soil should have enough inherent strength to arch over the eroded area, forming a roof.

The mechanism of sinkhole formation as described by Jennings *et al.* (1965) and Brink (1979) is illustrated in Figure 6 and may be summarised as follows (Council for Geoscience, 2003):

- Diagram 1: Cavities, which may be in a metastable state, exist within bedrock or the overburden.

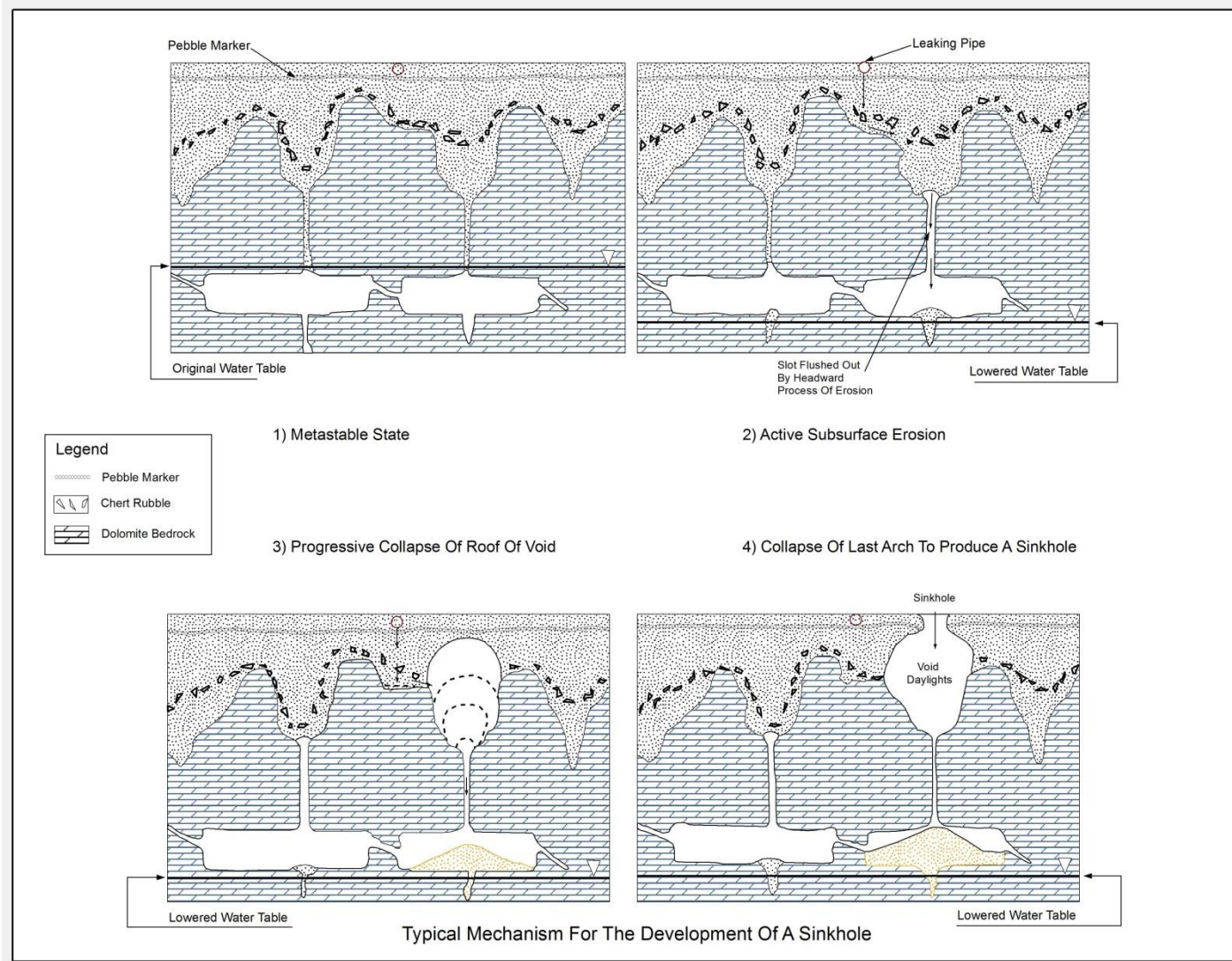


Figure 6: Mechanism of Sinkhole Formation (modified after Jennings *et. al.*, 1965)

- Diagram 2: Active subsurface erosion caused by concentrated ingress water will result in transportation (mobilization) of materials downwards into the nearest underlying cavity or cavities (receptacles) in or above the dolomite bedrock.
- Diagram 3: Headward erosion leads to successive arch collapse. The last final arch might be stable for a considerable length of time and is sometimes supported by a near-surface stable layer of chert, hardpan ferricrete or intrusive material.
- Diagram 4: A triggering mechanism leads to the breaching of the last final arch, causing the void to break through to surface. Particularly in the case of small sinkholes, the cross-section resembles a bottleneck (narrow opening at surface), a shape that may be maintained for some time.
- Lowering of the groundwater level (triggering mechanism) may exacerbate these conditions by increasing the potential development space as a result of lowering the base level for subterranean erosion and by exposing receptacles that were previously below the groundwater level (SANS 1936, 2012). The groundwater level presents the base level of subsurface erosion. Bezuidenhout and Enslin (1969) and Kleywegt and Enslin (1973) consider dolomitic land to be most sensitive to water level drawdown when the water level is within 30 metres of the ground surface. The opposite is also true, when a dewatered dolomite area is recharged, sinkholes can also be triggered by this mechanism.

Reference is made of four independent triggering mechanisms by Jennings (1966), namely:

- Over wetting of the soil profile that weakens the arch material.
- Earth tremors.
- Mining related soil movement.
- Large and continuous vibrations.

A number of independent conditions are necessary before a sinkhole can form (Jennings *et al.* 1965):

- Adjacent stable or rigid material (for example dolomite rock or pinnacles) to form abutments for the roof of the void. The span has to be appropriate to the strength of the bridging material, since with a span which is too large, the arch cannot form.
- A condition of arching develops in the overburden residuum i.e. a portion or all of the vertically acting selfweight must be carried by arching thrusts to the abutments. Complete arching will have occurred when the vertical stress along the intrados is zero.
- A void develops below the arch in the residuum.

- A receptacle (cavity or void) exists below the arch to accept mobilized material to enlarge the void described in the above bullet to a substantial size. Some form of transportation of the material, such as flowing water is essential.
- When a void of appropriate size has been established in the residuum, some triggering agency (water from a leaking wet service causing a loss of strength or washing out of material) is applied to cause the final roof to collapse, the void will move progressively upwards and `daylighting` of the void as a sinkhole at natural ground surface.

Buttrick (1987 and 1992), however, states that only two of the above mentioned interdependent conditions for sinkhole formation as specified by Jennings *et al.* (1965) are acceptable, namely adjacent stable abutments and a receptacle must be present. Buttrick stipulates that if the water table is below the receptacle depth, the nature of the blanketing layer above dolomite bedrock and located between abutments plays a critical role in determining the susceptibility of these materials to sinkhole formation due to ingress of water. Ingress water from a leaking wet service as a process of internal erosion may cause the formation of a subsurface void which will eventually collapse forming a sinkhole. This process deviates from the order of events as specified by Jennings *et al.* (1965), where it is stipulated that the final contributing factor is ingress water.

Buttrick (1987 and 1992) also describes the nature and role of wad and ferroan soils and gap graded materials (i.e. chert rubble and fines) within the blanketing layer, their position and permeability and their high susceptibility to subsurface erosion resulting in the formation of a sinkhole due to a triggering mechanism such as ingress of water. Furthermore he has a theory that the drawdown of a shallow water table through a profile of wad may lead to the formation of a sinkhole due to a process of liquefaction. The wad must, however, be positioned in the critical position of the profile, namely the throat. The wad would transmit a dynamic load causing the pore pressure momentarily to surpass the stabilising forces, resulting in a change in state and mobilization. The mobilized material would rush into the gryke or throat and into the receptacle. The overlying material would also be destabilised and mobilized, being drawn down into the throat. The energy source for the dynamic load could be induced earth tremors related to mining or vibrations related to heavy traffic or a passing train.

## 2.6.2 Mechanism of Subsidence Formation

According to Donaldson (1963) a subsidence will occur instead of a sinkhole where the soil is too weak to form an arch.

A subsidence is an enclosed depression, which forms as a result of the compression at depth of low-density dolomite residuum. Two main types of subsidences can be identified based on the mechanism of formation, namely dewatering type and surface saturation-type subsidences (Council for Geoscience, 2003). A third type, which can be referred to as incompletely developed sinkhole, has a similar surface appearance as the former two types but is caused by the erosion of subsurface materials (Council for Geoscience, 2003).



### 2.6.2.1. *Dewatering-type Subsidence*

A dewatering-type subsidence occurs gradually and typically manifests itself as a large, enclosed depression. The mechanism of this type of subsidence formation is illustrated in Figure 7 and summarised as follows (SANS 1936, 2012):

- Diagram 1: An area is underlain by compressible dolomite residuum (wad) at a relatively shallow depth with the groundwater level within or above the compressible material. As the groundwater recedes, pore pressures in the residual dolomite soils, typically characterised by high void ratios, gradually dissipate and the effective stress on the soil increase causing consolidation of the compressible material.
- Diagram 2: A surface depression occurs gradually at surface due to the load of the near-surface materials on the deeper lower density materials that settle into a denser state. Surface tension cracks occur in the peripheral areas of differential movement.
- Diagram 3 and 4: The size of the feature depends on the subsurface profile, i.e. the thickness, nature and depth of the low density materials below the OWL (original groundwater level), the configuration and depth of the dolomite bedrock. Compression may be excessive and the rate of surface settlement is rapid if a thick succession of wad is exposed by this drawdown.

### 2.6.2.2. *Surface Saturation-type Subsidence*

This type of subsidence is typically relatively small (i.e. less than 5 m in diameter). The mechanism of subsidence formation in this instance is as follows:

- An area underlain by compressible dolomitic residuum material at relatively shallow depth with the groundwater level within or below the compressible material. The movement of the groundwater level does not play a role in ground-surface movement.
- The surface materials are saturated owing to poor water management, i.e. poor drainage or a leaking wet-service.
- The wetting front penetrates the surface material and reaches the low-density material.
- A surface depression occurs gradually due to the mobilisation of the deeper low density materials which then settle into a dense state (saturation driven), causing the overlying soils to migrate downwards in the subsurface profile to take up the gap left by the material that has settled to the denser state. The movement will generally decrease rapidly when the cause of wetting is stopped.

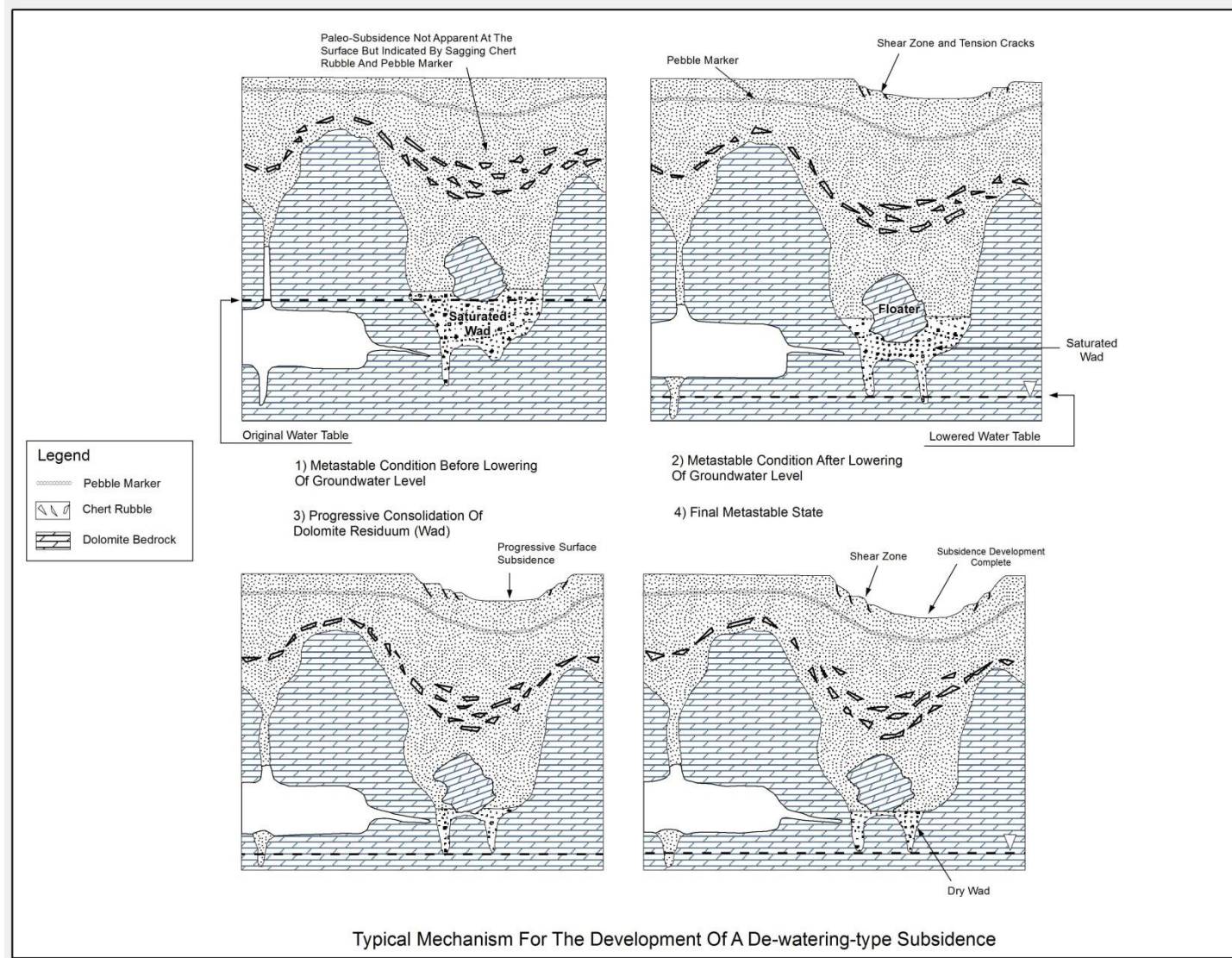


Figure 7: Mechanism of dewatering-type subsidence formation (modified after Jennings *et. al.*, 1965).

- The size of the feature depends on the profile underlying the saturated area, i.e. the thickness, nature and depth of the near surface and deeper low-density materials, the configuration and depth of the bedrock dolomite and the extent of the saturation (e.g. the extent of the area covered by water, the volume of the water and the length of the period during which saturation occurs).

The above mentioned phenomena has also been described as hydrocompaction in the United States (Zisman and West, 2015). Hydrocompaction also referred to as hydro-collapse is a process of settlement and resulting volume change that occurs in fine sand with minor amounts of silt and clay, driven primarily by the infiltration of water into the soil fabric (Zisman and West, 2015). During wet periods, the continuing infiltration of water into the soil fabric produces a redistribution of soil particles causing the soil to settle while during dry periods settlement occurs (although to a lesser extent in west central Florida) because of an increase in effective stress (Zisman and West, 2015). Soils susceptible to hydrocompaction are typically geologically immature soils that have high void ratios and low densities with weak structural and chemical bonds between particles. Water infiltrating the soil fabric causes a loss in these bonds. This causes the soil particles to compress in the soil column to more stable positions. As this process continues over time, soil supporting portions of a structure is lost and a net decrease in soil strength occurs in soil support (Zisman and West, 2015). The repeated saturation and drying of these soils subjects the soil to repeated cycles of tensile and compressive forces that exacerbates settlement (Zisman and West, 2015). Also the movement of water through the soil causes soil particles to move downward due to erosion as the water percolates into the ground surface (Shlemon, 2004).

### 2.6.2.3. *Partially Developed Sinkhole*

The premature termination of subsurface erosion by ingress of water may also result in a settlement feature at surface, which appears to be similar to a subsidence (Council for Geoscience, 2003). According to De Bruyn and Bell (2001) the process of sinkhole formation is prematurely terminated due to inadequate receptacle space, choking of the throat, or inadequate energy in the mobilising agency to continue moving the soil downwards.

## 2.7 Karst Terrain Susceptibility and Hazard Mapping

Karst terrain susceptibility and hazard mapping is one of the mitigating measures that has evolved in countries such as the USA, England, Spain, Italy, Belgium and South Africa (Waltham *et al.*, 2005; Gutierrez *et al.*, 2014). The most important step in sinkhole hazard analysis, once the sinkholes and areas affected have been mapped and characterised by means of surface and subsurface investigation methods, is the construction of a comprehensive **catographic** sinkhole inventory, to predict the spatial and temporal distribution of future sinkholes and their characteristics (Gutierrez *et al.*, 2014). Sinkhole databases should include information on: precise location of the limits of the sinkholes and underlying subsidence structures, morphometric parameters,

genetic type (sinkhole or subsidence mechanisms and material affected), chronology, activity and relationship with conditioning and triggering factors (Gutierrez *et al.*, 2014).

Depending on the information available, two types of models can be produced to predict the occurrence of future sinkholes: susceptibility models and hazard models (Gutierrez *et al.*, 2014). The susceptibility models represent the likelihood of a sinkhole occurring in any specific place in terms of relative probability. These models do not provide quantitative probability values and consequently cannot be used as the basis for quantitative risk analyses. The hazard models provide an estimation of the spatial-temporal probability values of future sinkholes, that is, the probability for a given zone and time interval of being affected by a sinkhole event.

Galve *et al.* (2009) for example, presents susceptibility models based on the statistical relationships between the sinkholes and groups of highly diverse controlling factors applying different mathematical frameworks, favorability functions, logistic regression and frequency ratios. This evaluation process allowed them to identify the model with the highest prognostic capability. The best model predicts 51% of the sinkholes in the evaluation sample within 20% of the area with the highest susceptibility in a sector of the Ebro Valley evaporite karst, North-East Spain, Italy (Galve *et al.*, 2011 and 2012).

Parise and Lollino (2011) and Parise (2015) for example, developed numerical analyses for the implementation of 2- and 3-Dimensional stability models using the finite element method for geological settings represented by continuous soft rock mass, and the distinct element method for jointed rock masses (highly stratified limestone) to evaluate the susceptibility to sinkhole development related to cave systems, anthropogenic features (underground quarries) and natural occurrences, in southern Italy.

### 2.7.1 Method of Scenario Supposition dolomite land classification system

Various classification systems have been developed for the evaluation on dolomite land after Jennings *et al.* (1965), namely: Stephan (1975), Weaver (1979), Venter (1981), De Beer (1981), Wagener (1982), Van Rooy (1984) and Buttrick (1992).

All the above mentioned classification systems are describing the influencing factors taken into consideration for the potential formation of sinkholes or subsidences in order to group geological environments into areas of a specific development potential and risk of sinkhole and subsidence formation.

However, it is the Method of Scenario Supposition developed by Buttrick (1992) and Buttrick *et al.* (2001 and 2011), characterising the potential stability of dolomitic land that was adopted by the geopractitioner industry. The Method of Scenario Supposition is currently used as the prescribed method of dolomite hazard assessment of sites and incorporated into the SANS 1936 (2012) standards.

The evaluation factors as specified by Buttrick (1992) are used to review those conditions in a dolomitic soil profile that are indicative of the potential susceptibility to sinkhole and subsidence formation and to obtain an estimation of the potential maximum size sinkhole or subsidence.

### 2.7.1.1. *Factors characterising the risk of sinkhole formation as defined by Buttrick (1992)*

#### a. **Blanketing layer**

Overburden refers to any loose, unconsolidated soil material that rests upon solid rock (Whitten and Brooks, 1972). The overburden is composed of dolomite residuum and other materials overlying the dolomite bedrock. The term blanketing layer, however, denotes that component of the overburden which overlies the potential receptacles (Figure 8). The nature of the blanketing layer is crucial to the advancement, retardation or prevention of the process of sinkhole or subsidence formation. Particular attention should be given to the grading and internal drainage characteristics (permeability).

#### b. **Receptacles**

Receptacles may occur, either as small disseminated and interconnected openings in the overburden, or as substantial openings (caves) in the bedrock. These openings may be able to receive mobilized (transported) materials from overlying horizons.

#### c. **Mobilizing agencies**

Mobilizing agencies include ingress water, ground vibrations, water level drawdown or any activity or process that can induce mobilization of the material within the blanketing layer.

#### d. **Maximum potential development space**

The `maximum potential development space` is a simplified estimation of the maximum size sinkhole that can be expected to develop in a particular profile, provided that the available space is fully exploited by a mobilizing agency (Figure 9).

The potential development space is associated with either a receptacle or disseminated receptacle and depends on the following:

- i. Estimated depth below ground surface to the potential throat of either the receptacle or disseminated receptacle (i.e. the thickness of the blanketing layer).
- ii. Estimated `angle of draw` in the various horizons in the blanketing layer. The `angle of draw` in a material describes a cone and defines the angle of a metastable slope to which a particular mobilizing agency will become operative in that material. The material within the cone can potentially be mobilized by being moved or drawn into the conduit at the base of the cone. Typical angles of draw may be as follows:
  - Chert (90 degrees);

- Alternating chert and silty clay (wad) (80-90 degrees);
  - Shale (90 degrees);
  - Clayey silt (wad) (45-60 degrees);
  - Silty clay (wad) (45-75 degrees);
  - Chert rubble with clayey silt (45-90 degrees).
- iii. Thickness of the various horizons constituting the blanketing layer.

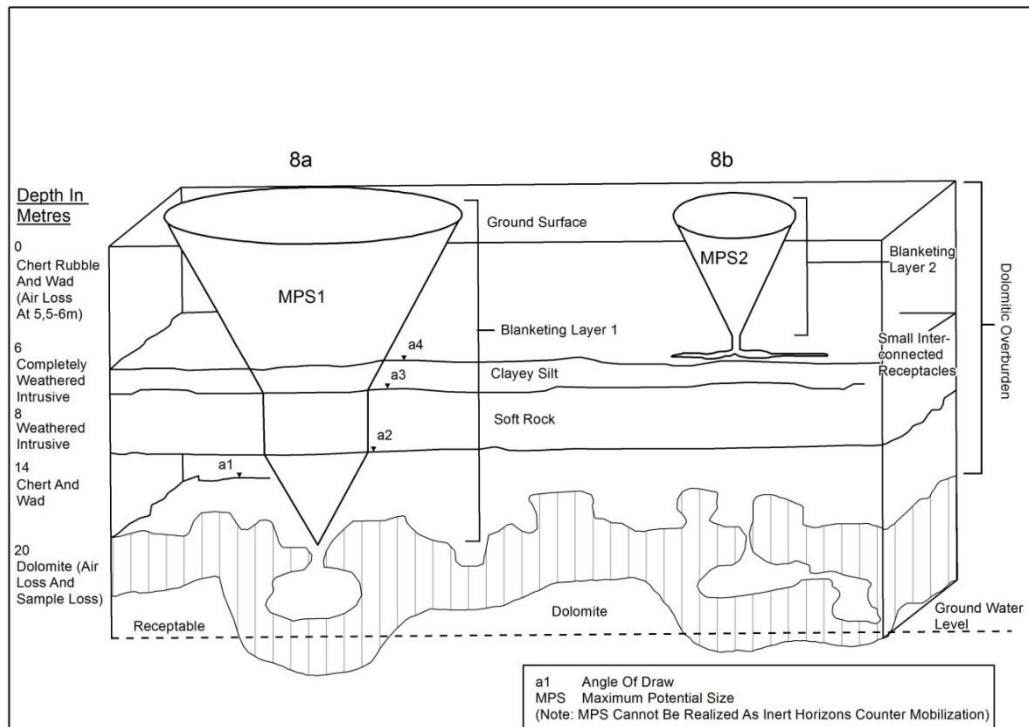


Figure 8: Schematic Three-dimensional Model Showing Various Components Of Dolomite Land (after Buttrick, 1992)

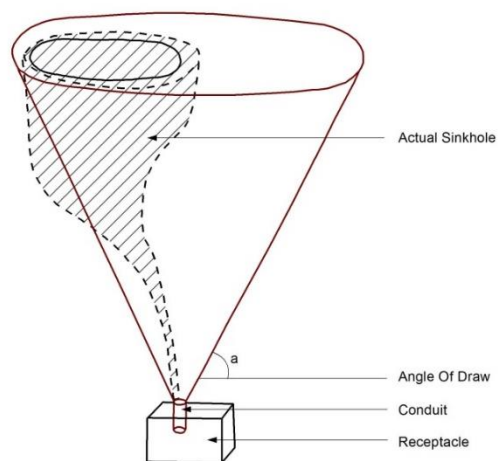


Figure 9: Maximum Potential Development Space Is Not Fully Utilized (after Buttrick, 1992)

Figure 8 displays this concept schematically. The depth to the potential receptacle is obtained from borehole information and the radius of the potential development space on surface is obtained by a simplified diagrammatic construction. The 'angle of draw' of the various materials and the depth of the receptacle, are used to project and estimate the radius.

Realization of the full sinkhole may occur in stages, including an initial catastrophic event when it 'daylights', followed by the growth of the feature owing to slip failures and raveling along the side walls. This process will continue until a metastable state is achieved. The sinkhole could potentially grow until it fully utilizes the limits defined by the potential development space (Figure 9).

Thus, for each receptacle there is a 'potential development space' that may be fully realized or exploited, creating the maximum size sinkhole, provided that:

- The receptacle is large enough to accommodate all mobilized material from within the 'development space'.
- The materials constituting the blanketing layer can be mobilized.
- An adequate and sustained mobilizing agency is presented to mobilize all the material.

In reality, the receptacle may be too small to accommodate the mobilized and hence potential development space may not be fully utilized (Figure 8). In such an instance, where a profile is characterised by receptacles of an inadequate volume, the maximum size sinkhole will be smaller than the potential development space. As there is no efficient technique available at present to ascertain the volume of receptacles, it must be assumed that receptacles of adequate volume are present. It must be emphasized that the potential development space represents the maximum space available in the profile for a sinkhole.

#### e. **Mobilization potential of materials in the blanketing layer**

Under the influence of a mobilizing agency, it is the materials within the blanketing layer that determine the potential susceptibility of the development space to exploitation and mobilization. The susceptibility to consolidation and subsurface erosion, including piping erosion, should be carefully argued, considering aspects such as the grading, density and permeability of materials. The different mobilization susceptibility categories of the blanketing layer are characterised as follows:

- i. **Low susceptibility to mobilization:** The profile displays no voids. No air loss or sample loss is recorded during drilling. Either a very shallow water table or a substantial horizon of materials with a low potential susceptibility to mobilisation may be present within the blanketing layer (e.g. continuous intrusive features or shale material).

- ii. Medium susceptibility to mobilization: This type of profile is characterised by an absence of a substantial 'protective' horizon and has a blanketing layer of materials potentially susceptible to mobilization by extraneous mobilization agencies. The water table is below the blanketing layer.
- iii. High susceptibility to mobilization: The blanketing layer reflects a great susceptibility to mobilization. A void may be present within the potential development space, indicating that the process of sinkhole formation has already been affected. Boreholes may register large cavities, sample loss, air loss, etc. The water table is below the blanketing layer. In a dewatering situation, the lowering of a shallow groundwater level would increase the susceptibility to mobilization.

Figure 8(a) depicts a profile with a deep groundwater level situated within the bedrock. The blanketing layer and hence the potential 'development space' are fully exposed to the potential activities of extraneous mobilizing agencies. This figure also depicts a significant layer of intrusive material with a low mobilization potential. This horizon acts as either an aquitard or an aquiclude that prevents mobilization and movement of material into the receptacle. The material within the 'development space' is thus protected from the mobilization agency.

Figure 8(b) reveals the presence of potential disseminated receptacles above the intrusive horizon displaying the low mobilization potential, a smaller potential development space is thus available for exploitation by a mobilizing agency.

#### 2.7.1.2. Factors characterising the risk of subsidence formation as defined by Buttrick (1992)

##### a. Mobilizing agency

Mobilizing agencies include ingress water and groundwater level drawdown. If dewatering of the local dolomite aquifer may occur, during the lifetime of the development, then the dewatering scenario must be reviewed. In a non-dewatering situation, where subsurface erosion is caused by ingress water, the premature termination of the process may result in a subsidence rather than a sinkhole.

##### b. Receptacles

Inadequate receptacle size may also result in the premature termination of the process of sinkhole development, resulting in a subsidence.

##### c. Nature of the blanketing layer

The following properties of the blanketing layer must be considered:

- Thickness of the soil material (depth to bedrock).
- Depth of the original water table.



- Nature of the soil material above the water table (i.e. type of soil and geotechnical characteristics).
- Nature of the soil material below the water table (i.e. type of soil and geotechnical characteristics).

**d. Mobilization potential**

The influence of the mobilization agency on the profile material is determined by the following:

- Thickness of the overburden.
- Depth of the original water table.
- Thickness and nature of the soil material above the water table.
- Thickness and nature of the soil material below the water table.

The susceptibility of the soil material to mobilization, i.e. consolidation settlement under the influence of the mobilizing agency (water table drawdown or surface water ingress), may be characterised as follows:

- i. Low susceptibility to subsidence formation: In this type of profile, the water table can be above the bedrock and at shallow depth (ingress water), in the bedrock (water table drawdown) or in soil material with geotechnical characteristics reflecting a low susceptibility to consolidation settlement, i.e. material with a high density, low void ratio and low compression index (e.g. Karoo shale).
- ii. Medium susceptibility to subsidence formation: This type of profile is characterised by an absence of a substantial 'protective' horizon and has a blanketing layer of materials potentially susceptible to mobilization by ingress water. The water table is within the bedrock or at depth within the blanketing layer. Voids and disseminated voids may be present above the bedrock, indicating the susceptibility to subsidence formation.
- iii. High susceptibility to subsidence formation: The blanketing layer reflects a great susceptibility to mobilization. The water table is above the bedrock in soil material with low dry density, high void ratio and high compression index. Residual dolomite soils, namely wad and ferroan soils, have a high potential for dramatic ground settlement.

## **2.8 Impact of Sinkholes and Subsidences**

The formation of sinkholes or subsidences have negative social and financial implications in the affected and immediately surrounding areas, resulting in the

relocation of entire communities to safer ground, severe damage to infrastructure or even loss of human life (Waltham *et al.*, 2005; Buttrick *et al.*, 2011).

Thousands of dolomite-related sinkhole, subsidence and crack events have occurred in the past 60 years on the West Rand and in the Gauteng Province (Richardson, 2013). The damage to structures due to the occurrence of these instability features totals billions of rands and has led to 38 deaths (Van Schalkwyk, 1981; Buttrick, 1995; De Bruyn and Bell, 2001).

A community of approximately 30 000 households was relocated to safer ground in a dolomite area west of Johannesburg, South Africa, at a cost exceeding US \$600 million (Buttrick *et al.*, 2011). In Calatayud (Spain), underlain by evaporates, and Allentown (Pennsylvania, USA), underlain by cavernous limestone, sinkhole events have caused the demolition of multi-storey buildings with direct economic losses in excess of US \$6.3 million and US \$8 million, respectively (Dougherty, 2005; Gutierrez *et al.*, 2008). Parise and Lollino (2011) reports on the impact of natural and man-made limestone caves on infrastructure in the Apulia region, southern Italy. The impact of subsidences in the city of Tuzla (Bosnia and Herzegovina) related to the extraction of salt deposits by solution mining is reported by Mancini *et al.* (2009). Guerrero *et al.* (2008) present a review on detrimental effects caused by sinkholes on railways and Galve *et al.* (2012) and Villard *et al.* (2000) reports on the impact of sinkholes on roads in Spain and France. Li and Zhou (2015) reports on the impact of karst paleo-collapses and their impacts on mining and the environment in Northern China. Weary (2015) states that the average cost of karst-related damages in the United States over the last 15 years is estimated to be at least \$ 300 million per year and the actual total is probably much higher, as information from insurance organizations are not available and not all sinkholes are always reported.

The rehabilitation of these sinkholes and subsidences is affected by a large number of aspects, particularly available funding, existing and future land use, geological factors such as the nature and geotechnical characteristics of the material above the dolomite bedrock, depth to dolomite bedrock, presence of voids or cavities above or within bedrock, dyke and sill intrusions and the depth to the groundwater level (Kleinhaus, 2014).

Buttrick and Roux (1993) found that there is an increasing number of ground movement events as development density increases, related to the following:

- An increasing density and greater meterage of waterbearing services in association with an increasing urban-density resulting in a greater frequency of service failures.
- There is a greater volume of water in the sewage system. Should blockages occur in the system greater volumes of water gain access to the subsurface profile, permitting more sustained and serious damage to the subsurface profile.
- There is also a greater negative environmental impact particularly to the soil profile due to trenching and blasting.

Buttrick *et al.* (2001 and 2011) studied the frequency of sinkholes in a well-developed area south of Pretoria, Gauteng on dolomite land with respect to inherent hazard classes over a period of twenty years, during 1984 to 2004. This study formed part of the development and modification of the Scenario Supposition method of dolomite hazard assessment.

Of significance is the occurrence of sinkholes and subsidences with respect to various water bearing infrastructure over the twenty year period: 99% of the recorded events, i.e. 643 of 650, were found to be caused by leaking services and 7 events fell in open land and could not be ascribed to any particular triggering agency. 98% of sinkhole events linked to water bearing infrastructure, occur in areas designated as an area of high inherent susceptibility for sinkhole and subsidence formation (Buttrick *et al.*, 2014).

A total of 245 of the 650 events coincide with buildings, mainly in areas designated a high inherent susceptibility for sinkhole and subsidence formation (Buttrick *et al.*, 2014).

Based on the research done by Buttrick *et al.* (2011), the following conclusions were made:

- Approximately 94% of damaged buildings occurred in areas of high susceptibility, 6% in medium and 0% in low.
- 38% of all events recorded coincide with structures and impact negatively on the stability and integrity of the buildings.
- Typically damage is sustained from sinkholes that are larger than 5 m in diameter.
- 246 sinkholes resulted in the loss of 220 331 m<sup>2</sup> of buildings.
- Losses amount to approximately R1,5 billion, based on average cost of construction of R8 000/m<sup>2</sup>.
- Damage to structures per ground movement event averaged approximately R640 000.00. This figure excludes the stabilisation/rehabilitation of sinkholes or subsidences which may typically vary from R 500 000.00 to in excess of R6 million.

The development potential for sinkholes and subsidences caused by human activities is high, especially within the following environment (Buttrick *et al.*, 2001):

- Highly susceptible conditions comprising poor subsurface conditions e.g. presence of weathered dolomite in the form of residual dolomite (manganiferous soils or wad) regarded as highly compressible and insoluble material; voids or cavernous conditions and sample and/or air loss recorded during drilling of percussion boreholes.
- Areas of previous sinkhole or subsidence formation.
- Areas where palaeo-sinkhole or palaeo-subsidence structures are present.

- Areas of geological contacts and fault zones.
- The presence of a shallow dolomite groundwater level, above dolomite bedrock, that may be subjected to drawdown exposing deeper lying voids.
- Poor management and maintenance of water bearing infrastructure.

## 2.9 Record of Sinkholes and Subsidence in the Gauteng Province

Richardson (2013) did a study on the occurrence of sinkholes and subsidence on dolomitic land areas prior to December 2011, within four municipal areas of jurisdiction within the Gauteng Province, namely: Far West Rand, area south of Pretoria (Centurion located in the City of Tshwane), City of Johannesburg and the Ekurhuleni Metropolitan Municipality.

In Gauteng the dolomites cover a surface area of approximately 2576 km<sup>2</sup> (14% of Gauteng's surface area). However the area considered as dolomitic land covers an area of approximately 4005 km<sup>2</sup> (24% of Gauteng). The dolomitic land on the West Rand area covers a surface area of approximately 493 km<sup>2</sup>. The dolomitic land for the City of Tshwane covers a surface area of approximately 203 km<sup>2</sup>. The dolomitic land for the Ekurhuleni Metropolitan Municipality covers a surface area of approximately 161 km<sup>2</sup>.

Data was sourced from various sources including records, reports and maps held at the Council for Geoscience, research thesis, papers, articles, databases compiled by the CGS and supplied to the CGS by various consultants, companies and state authorities. Richardson (2013), however, states that the data compiled is only an estimation of the number of events that have occurred in Gauteng as sinkhole statistics have not been available since the work by Wolmarans (1984) on the Far West Rand and Schoning (1990) on the area south of Pretoria. In excess of 2400 instability events in a preliminary overview of the sinkhole record for South Africa is indicated by Heath and Oosthuizen (2008). Other data sources evaluated, where reference is made to reported number of events, are Roux (1984 and 1996), De Bruyn and Trollip (2000), De Bruyn *et al.* (2001) and Buttrick *et al.* (2001 and 2011). The CGS database includes recorded events from 1962 to mid-2014.

The data collected was used to do a statistical analysis to investigate the relationship between the formation of sinkholes and subsidence and underlying geology, size distributions, density of events and external influences on dolomitic land areas in the Gauteng Province. The findings of the study by Richardson (2013) indicate that:

- Approximately 3098 instability events (including sinkholes, subsidence and ground cracks) have been recorded within the Gauteng area over the past nearly 60 years (Constantinou and Oosthuizen, 2014).

- More events occur in high rainfall periods (months or years) due to increased ingress water in the ground profile, especially in the Tshwane region. This is, however, true for all dolomite regions.
- Approximately 60% of instability events were recorded as sinkholes, 30% as subsidences and 10% as ground surface cracks (Richardson, 2013). It is, however, stipulated by Constantinou and Oosthuizen (2014) that the dominant type of event recorded is sinkholes (70%).
- The largest percentage of instability features (36%) occurred on the chert-rich Monte Christo Formation, followed by the chert-rich Eccles Formation (31%) and then the chert-poor Lyttelton Formation (17%). The Oaktree Formation has only a record of 7% of instability events, while `Other` formations underlain by dolomite at depth have 9%. In the City of Tshwane nearly 40% of instability events occurred on the Eccles Formation, while the Monte Christo and Lyttelton Formations showed a similar percentage of events. Most of the sinkholes in the West Rand and Ekurhuleni Metropolitan Municipality occurred on the Monte Christo Formation (Constantinou and Oosthuizen, 2014).
- Triggering mechanism of instability events:
  - West Rand: Prior 1984 due to dewatering related to mining and post 1984 most are attributed to ingress water (Wolmarans, 1984). Overall on the West Rand, 47% of events can be attributed to ingress water, 53% of events as a result of dewatering. The largest percentage of instability events has occurred in the Oberholzer Groundwater Compartment.
  - City of Tshwane: 98% of instability events can be attributed to ingress water (11% to a leaking water pipe or sewer, 15% to poor stormwater management or ponding, 72% is likely caused by human induced ingress) and only 2% to natural causes without any evident man-made trigger.
  - Ekurhuleni Metropolitan Municipality: 78% can be attributed to ingress water (26% leaking water pipe or sewer, 15% poor stormwater management or ponding and the remaining 37% were due to human induces ingress) and 22% were identified as due to dewatering.
- Sinkhole and subsidence size (according to Schoning (1990) and Buttrick *et al.* (2001)) and depth distributions:
  - West Rand: More than 60% of the sinkholes and subsidences are sized large (5 m to 15 m diameter) to very large (>15 m diameter).
  - City of Tshwane: More than 60% of sinkholes and subsidences are sized medium (2 m to 5 m diameter) to large (5 m to 15 m diameter).
  - Ekurhuleni: The largest percentage of sinkholes and subsidences recorded are sized small (<2 m diameter) to medium (2 m to 5 m diameter).

- In general, most of the sinkholes and subsidences in Gauteng are considered to be large in size (i.e. 5 m to 15 m diameter). The majority of data evaluated (90%), however, comes from the West Rand and City of Tshwane.
- In general, more than 70% of sinkholes are less than or equal to 5m deep and subsidences are less than or equal to 1m deep, indicating that the capacity of receptacles are generally small to medium or that sinkholes generally form due to cavities or voids migrating upwards like a bubble rising in fluid.
- Difficulties were experienced with the size (and depth) distribution on the different geological formations as a large portion of the data (50% to 80%) does not mention sinkhole diameter and depth (61%). It was not possible to determine if certain size sinkholes were more prevalent on specific formations. However sinkholes and subsidences falling through non-dolomitic cover tended to be very large.
- Based on limited size and depth data, the overall average sinkhole size is 9,8 m diameter and the average subsidence size is 16,5 m diameter. The average sinkhole depth is 4,9 m and subsidence depth 1 m. For the different areas the average size and depth are as follows:
  - West Rand: Average sinkholes size is 11,5 m and depth is 5,3 m with the average subsidence size as 16,9 m and depth of 1 m.
  - City of Tshwane: Average sinkhole size is 8,8 m and depth is 4,7 m with the average subsidence size as 18,9 m and depth of 1,4 m.
  - Ekurhuleni Metropolitan Municipality: Average sinkhole size is 6,9 m and depth is 3,6 m with the average subsidence size as 8,9 m and depth of 0,6 m.
  - City of Johannesburg: Average sinkhole size is 8,8 m and depth is 3,7 m.
- Event density and rate of new sinkhole formation:

Event density: The density of events for dewatered and non-dewatered areas was calculated. According to Waltham and Fookes (2003) the mean sinkhole density is equated to sinkholes per unit area. The event density is calculated by totalling all events within a specific area prior to end of 2011.

Table 1 below shows the event density for the dewatered and non-dewatered areas in Gauteng. City of Tshwane (CoT) has the highest event density, which can be ascribed to the high density of development within this smaller portion of dolomite land.

**Table 1: Sinkhole event densities for the dewatered and non-dewatered areas in Gauteng (after Richardson, 2013).**

		Surface area (km <sup>2</sup> )	No. of events	Event density per km <sup>2</sup> (ha)
West Rand	Dewatered area	520	1130	2.2 (0.02)
	Non-dewatered area	1307	341	0.3 (0.003)
CoT	Non-dewatered area	497	1393	2.8 (0.028)
Ekurhuleni	Dewatered area	141	36	0.3 (0.003)
	Non-dewatered area	847	130	0.1 (0.001)

Rate of new sinkhole formation (NSH): Waltham and Fookes (2003) indicates that the rate at which new sinkholes occur (NSH) equals the events per unit area per year. This was considered for events due to dewatering and ingress separately as depicted in Table 2. Calculating NSH is dependent on the time period, therefore it is essential to have an accurate record. Events due to dewatering can only be considered within the time period during which dewatering occurred for the West Rand and Ekurhuleni, while events due to ingress have been considered over the entire time period prior to end of 2011.

Table 2 shows the rate of new sinkhole formation due to dewatering to be higher compared to the rate due to ingress within the same municipality. This calculation takes area and time into consideration and the area and time periods and history differ for each scenario. Overall the NSH for Gauteng during the last 10 years is 0.01 per km<sup>2</sup> per year.

- Sinkholes and subsidences are still regularly occurring in areas underlain by dolomite in Gauteng. However, the rate of occurrence in the West Rand and Tshwane appear to be decreasing annually.

**Table 2: Rate of new sinkhole formation within Gauteng (after Richardson, 2013).**

		Surface area (km <sup>2</sup> )	No. of events	NSH (per km <sup>2</sup> per year)
West Rand	Due to dewatering	520	726	0.03
	Due to ingress	1307	704	0.01
CoT	Due to ingress	497	1393	0.05
Ekurhuleni	Due to dewatering	141	36	0.03
	Due to ingress	847	130	0.005

### **3. DOLOMITE-RELATED SINKHOLE AND SUBSIDENCE INVESTIGATION METHODS**

The main objective of the investigation of sinkholes and subsidences is to determine the cause and more specifically the extent of the subsurface erosion, the related impact on existing infrastructure within the affected area and the most appropriate rehabilitation methodology to follow to improve subsurface conditions.

The use of a specific method or methods of investigation is, however, prescribed by the accessibility of a site. Accessibility constraints within a build-up area, including existing infrastructure, such as buildings, may lead to the use of an investigation method other than what is generally preferred. The goal is to obtain as much subsurface information as possible to develop a three dimensional perspective of the subsurface conditions.

The investigation methods of sinkholes and subsidences can be divided into two groups, namely:

- Non-intrusive: Geophysical methods and aerial or satellite remote sensing. The use of most remote sensing imagery and aerial photography is restricted where a sinkhole or subsidence is only a few metres in diameter.
- Intrusive: Probing, augering, boring, drilling, pitting, trenching, sampling and testing.

#### **3.1 Wet services**

The first priority when dealing with a sinkhole or a subsidence is to reduce or remove the triggering mechanism that caused the formation of the sinkhole or subsidence and to reduce the likelihood of aggravating the problem (i.e. increase in sinkhole or subsidence size).

In a built-up environment, the triggering mechanism is typically related to ingress water leaking subsurface wet services or due to poor surface water run-off (i.e. ponding). The locality or position and depth of subsurface wet services should therefore be known or determined before considering any investigation methods.

##### **3.1.1 Sewer and Stormwater**

The first step to determine whether a sewer line is broken or disconnected is to undertake a visual inspection at each manhole located on both sides of the sinkhole or subsidence. If the line is malfunctioning (broken or disconnected) flow will be observed in the manhole on one side and no flow in the manhole lower down (natural gradient flow).

CCTV camera inspections to locate the exact position of leaking or ruptured sewer or stormwater pipelines are very useful.

The disadvantage of this method is that in the case of especially sewer lines, where a blockage occurs (will be visible from overflowing sewer manholes higher up along the



line) the sewer line needs to be flushed out first with water under pressure before the CCTV-camera inspection can be carried out. Where a sewer or stormwater line is broken and a part of the pipeline already collapsed into the sinkhole, the CCTV-camera inspection needs to be executed from both sides.

### 3.1.2 Potable Water Mains

As water is transported under pressure, most water lines are located close to surface, typically at 1 m or 1,5 m below ground surface in the case of bulk water lines. Internal water lines to houses are typically at a depth of 0,6 m below ground surface.

As water is under pressure, when a water pipe is broken or cracked, considerable and rapid subsurface erosion can take place. In some sinkhole and subsidence case studies on the East Rand, the impact of subsurface erosion may extend up to nearly 20 m from where the water line was broken.

The only measure that can be taken is to close the water valves on both sides of the sinkhole or subsidence and to temporarily repair the leak in the period until rehabilitation to reduce additional subsurface erosion which may lead to an increase in sinkhole or subsidence size.

However, in some townships there are inadequate cut off valves and an entire township can be without water when closing the nearest water valve to the sinkhole or subsidence. Internal water lines to houses can be tested for leaks by ensuring all taps in and around the house is closed. If the water metre is then still running there is a leak on the internal water line.

### 3.1.3 Surface Water Run-off

A 0,5m high soil berm of clayey material is typically placed around the sinkhole or subsidence area to prevent run-off surface water entering the sinkhole and causing additional subsurface erosion and which may lead to an increase in sinkhole or subsidence size.

## 3.2 Geophysical Methods

No reliable geophysical technique exists that can accurately determine the presence and size of voids in the blanketing layer or caves in dolomite bedrock. However, geophysical investigations are a useful tool that can assist in targeting those areas potentially presenting subsurface structures (for example cavity, void, bedrock, dyke, fault zone, geological contact), typically presented as anomalies on a contour map or a graph. All geophysical anomalies require verification by drilling.

Anomalies are created when there are spatial changes in physical properties. These changes may relate to changes in the soil or rock (lithological variations, structure or fracture densities), or to extreme anomalies (including voids wholly or partially filled with air, water or soil), or to changes with time caused by groundwater movement (including the growth of pollution plumes).

Whether or not a particular geophysical method is inherently capable of detecting a change in physical properties is dependent upon a number of factors (Waltham *et al.*, 2005):

- Required depth of ground penetration.
- The vertical and horizontal resolution required for anticipated target or targets.
- Contrast in physical properties between the target and its surroundings.
- Signal-to-noise ratio for the physical property being measured at the site.

In a dolomite environment the gravity method has proven to be the most successful of all geophysical methods (Kleywegt and Pike, 1982). However, other geophysical methods such as seismic refraction, resistivity, electro-magnetic, magnetic and ground penetration radar are sometimes used in conjunction with the gravity method to try and delineate subsurface features.

### 3.2.1 Gravity Survey

The gravity method is regarded as the most successful geophysical method to determine dolomite bedrock topography and thickness and density of overburden material. A variation in the earth's structure and composition give rise to variations in density. The gravity method is measuring that density, allowing the determination of location, form and distribution of causative geological factors.

Measurements are taken with a gravimeter at each station of a grid on a specific spacing or traverse survey. The grid spacing is a function of the type of anomaly expected, the depth to the source of the anomaly and the size of the investigation area. Station positions and elevations are recorded. The field observations are then reduced to relative Bouguer values using an elevation correction typically of 0,189 milliGals per metre for the East Rand region, corresponding to a bedrock density of 2850 kg/m<sup>3</sup> and a normal theoretical sea level variation of the earth's gravity field of 0,65 milliGals per kilometre.

A relative Bouguer gravity anomaly contour map is then produced presenting anomalies of gravity high and low fields and gradient (transition zone between gravity high and low fields).

Once depth of dolomite bedrock on the Bouguer gravity high and low anomalies and gradient are confirmed by drilling, the relative Bouguer field is adjusted by subtracting a regional field so that the map becomes a better representation of depth to dolomite bedrock. Removal of the estimated regional field results in the creation of a residual data set.

A typical gravity Bouguer and Residual contour map with the correlated subsurface geological profile is presented in Figure 10 (after Trollip, 2006).

Gravity high anomalies typically represent shallow dolomite bedrock and gravity low anomalies deep dolomite bedrock. Areas of highly weathered to residual syenite or dolerite intrusions are also represented by gravity low areas. Steep gravity gradients (closely spaced parallel gravity lines) represent steeply sloping bedrock. It is generally the deeply weathered zones represented by gravity low and steep gravity gradients that represent areas that are highly susceptible for sinkhole or subsidence formation. Enslin (1951) specifies that closely spaced gravity contour lines are the most dangerous, since they generally lie along the contact between the massive dolomite, which will form the walls of the sinkholes, and rubble bridges which may fall away into deeper cavities. Where the dolomite is displaced by a fault the same close spacing may be observed in the gravity contours and it is sometimes possible to locate fault planes directly by gravity surveys.

Kleywegt and Enslin (1973) indicates that the interpretation of the residual gravity map should always be undertaken in conjunction with data obtained from boreholes sited on the basis of the gravity map, the depth to the original water table, the water table drawdown, the ground movement recorded and the likelihood of the accumulation of surface water or infiltration due to ingress water. Major water table drawdown occurred on the West Rand and Far West Rand in the past.

One of the disadvantages of the gravity method is that it cannot distinguish between small subsurface features near the surface and large features at depth. A small void near the surface may create a gravitational anomaly of the same magnitude as that created by a larger void at greater depth. Therefore gravity anomalies need to be investigated by means of drilling.

The gravity method can also not determine cavities within dolomite bedrock.

Additionally, it is critical that the typical subsurface dolomite bedrock environment of the area to be investigated is known to ensure the correct grid spacing is used for the best resolution. If the typical grid spacing of 10 m or 15 m is used, grykes of less than 2 m wide extending to considerable depth within a shallow dolomite bedrock environment will not be delineated. For a shallow dolomite environment with the possibility of narrow deeply weathered zones (grykes) the best grid spacing is 2 m to 5 m.

### 3.2.2 Seismic Refraction Method

Seismic surveys, however, do not work well in urban areas and especially close to highways due to the influence of vibrations from the traffic. In a dolomite environment a further disadvantage is that a layer of softer material (for example wad with a low velocity) or a cavity (low velocity) cannot be detected below a competent layer like chert (high velocity).

### 3.2.3 Resistivity Method

The Resistivity Method may not work well in an urban environment where buried metal or electrical cables are present. On karst, they cannot readily distinguish between

individual large dissolution features and zones of ground broken by multiple narrow fissures (Waltham *et al.*, 2005).

#### 3.2.4 Electromagnetic Survey

The Electromagnetic Method does not work well in build-up areas due to the background noise caused by any iron or steel structures (i.e. fences, metal poles, power cables, sheet-iron structures, buried metal pipes, cars and trucks. This method is more applicable in an open field.

#### 3.2.5 Magnetic Survey

The magnetic survey does not work well in build-up areas due to the background noise caused by any iron or steel structures (i.e. fences, metal poles, power cables, sheet-iron structures, buried metal pipes, cars and trucks).

#### 3.2.6 Ground Penetrating Radar Survey

The Ground Penetrating Radar (GPR) method involves the transmission of short pulses of high-frequency electromagnetic energy or radio waves (25 – 1,000 MHz) to penetrate the surface below the ground, or a concrete floor, through an antenna.

The result is a continuous cross-sectional picture or profile of shallow subsurface conditions. These responses are caused by radar wave reflections from interfaces of material with different dielectric properties. Such reflections are often associated with natural geohydrological conditions, such as bedding, sedimentation, moisture, clay content, voids, fractures and intrusions, as well as with man-made objects (Chang and Basnett, 1999).

The radar signal is attenuated more in wetter materials that have higher conductivity, where depth penetration is therefore reduced. Clayey soils have a lower electrical impedance limiting the depth of penetration to 6 m when dry. If saturated, the ground penetration depth of the clay is limited to only 2 m.

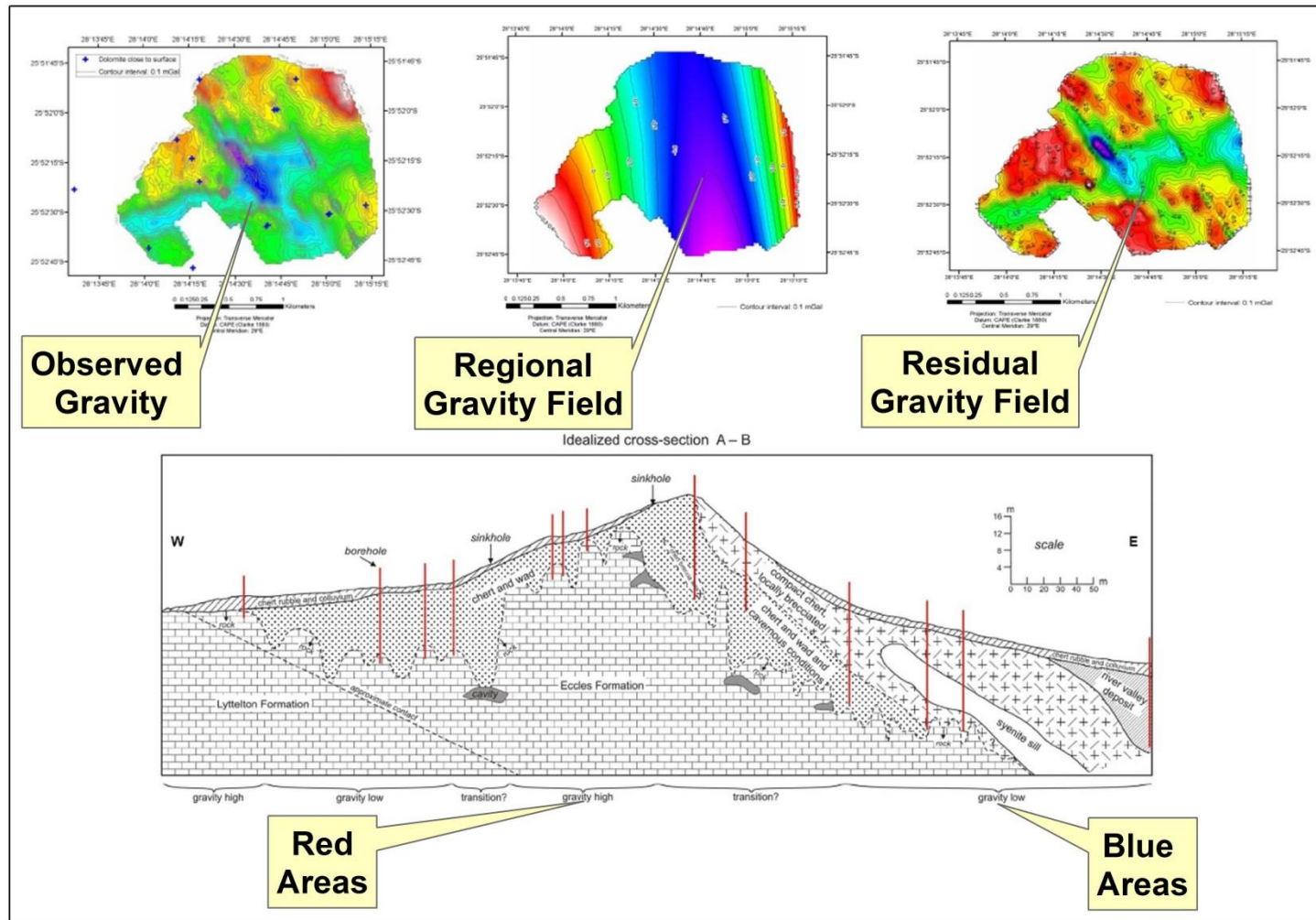


Figure 10: Typical gravity Bouguer and Residual contour map with correlated subsurface geological profile (after Trollip, 2006).

A disadvantage of the GPR Method is that the depth of ground penetration is limited to 15m. However, depending on the specific antenna used, depths of up to 25 m to 30 m has been reported.

The GPR Method has been successfully used in delineating subsurface wet service pipes, tanks and reinforcement in concrete floor slabs of buildings in South Africa. It is obvious that due to the limited penetration depth that dolomite bedrock might in some instances not be reached. However it has the potential to delineate disturbance in the overburden related to arching preceding the development of a sinkhole or a subsidence, typically close to ground surface (<2 m). The GPR method in combination with CPT (Dutch Cone Penetration Test) soundings has been used successfully in central Florida to delineate sinkhole and subsidence boundaries on limestones (Chang and Basnett, 1999).

The GPR method in conjunction with the gravity method was used on a site in Vosloorus Town at a Petrol Station, where a sinkhole occurred due to a leaking bulk water line. The site is characterised by a shallow dolomite bedrock environment (at surface to a maximum depth of 2 m) with narrow (1 m to 2 m width) grykes infilled with residual dolomite (wad). This was to determine if the GPR Method adds any value to the delineation of subsurface cavities or voids, to be investigated and proven by means of drilling. The GPR method successfully delineated the petrol tanks below a reinforced concrete slab at surface, but was not successful in delineating the deeper grykes. In addition, areas delineated as voids by the GPR method proven by drilling to be shallow dolomite bedrock in places. It is therefore felt that this method is currently not suitable but has the potential to be used in future on sinkhole or subsidence sites in a shallow dolomite environment, provided more sinkhole and subsidence investigations are carried out to calibrate the data retrieved from the GPR method.

Not one of the above geophysical methods produces reliable results in the built up environment. Sinkholes and subsidences typically occur in the built up environment.

### **3.3 Direct Indicator Tests**

#### **3.3.1 Dynamic Probe Super Heavy (DPSH) Testing**

Where access for a drilling rig is not possible, the Dynamic Probe Super Heavy Test Method can be used to determine the consistencies of the various soil horizons at depth and to determine if cavities are present at depth.

The Dynamic Probe Super Heavy (DPSH) Test method involves a 60 degree disposable cone, 50 mm in diameter, fitted onto the bottom of an `E` sized rod and driven into the ground by a 63,5 kg hammer falling through 762 mm. The number of blows required to drive the cone through each successive 300 mm of penetration is recorded. This provides an empirical indication of consistency. Once refusal depth is reached (more than 100 blows per 300 mm) the driving rod are withdrawn.

The undrained shear strength correlations to the DPSH test is given by Brink *et al.* (1982) in the table below.

**Table 3: Undrained shear strength correlations with DPSH test (after Brink *et al.* (1982)).**

Soil consistency Description	DPSH (N-value) (blows per 300 mm)
<b>Sandy Materials</b>	
Very loose	<5
Loose	5 – 10
Medium dense	10 -30
Dense	30 – 50
Very dense	>50
<b>Clayey Materials</b>	
Very soft	<2
Soft	2 – 4
Firm	4 – 8
Stiff	8 – 15
Very Stiff	15-30

The disadvantage of using this method is that refusal may be encountered on honeycomb or hardpan pedocretes, cobbles and boulders present within the blanketing layer above dolomite bedrock, giving a false impression that refusal was reached on bedrock. Another problem with the DPSH method is that when a cobble or boulder is struck on the side, the DPSH rods tends to deflect away from that going in a horizontal direction, thus once again, giving a false impression of subsurface conditions, as the cone and rods will still be able to be driven into the ground and can continue for some near horizontal distance without reaching refusal.

The advantage of using this method is that the equipment is small enough to access areas with an opening as small as 1 m. Approximately eight to ten test points can be conducted in one day, thereby a large amount of subsurface information can be gathered in a short period of time at a relatively low cost, provided the subsurface profile lend itself to it. This method will provide good results in a shallow dolomite environment where the blanketing layer above dolomite bedrock comprises mainly of residual dolomite (wad and ferroan) soils or to determine a gryke within a shallow dolomite environment. A height of 2,2 m is generally required for the DPSH test equipment. However, some contractors modified the DPSH test equipment to a 2 m height; thereby DPSH testing can also be conducted within buildings. A borehole needs to be drilled with a concrete drill in the areas where the DPSH tests need to be performed within the concrete slab beforehand.

### 3.3.2 Dynamic Probe Light (DPL) Testing

The Dynamic Probe Light (DPL) testing method involves a 20 mm diameter, 60 degree cone driven into the soil by an 8 kg weight dropped through 575 mm. The results are expressed as millimetres per blow and provide a rough estimate of compaction control and soil consistencies at depth.

The undrained shear strength correlations to the DPL test are given by Brink *et al.* (1982) in the table below.

**Table 4: Undrained shear strength correlations with DPL test (after Brink *et al.* (1982)).**

Soil consistency Description	Dynamic Probe Light DPL (mm per blow)
<b>Sandy Materials</b>	
Very loose	>75
Loose	30 – 75
Medium dense	12.5 - 30
Dense	5 – 12.5
Very dense	2 - 5
<b>Clayey Materials</b>	
Very soft	>110
Soft	55 – 110
Firm	30 – 55
Stiff	15 – 30
Very Stiff	7 - 15

The advantage of using the DPL test is that the equipment can be handled by one person and it can be used to do a quick assessment of subsurface soil conditions. The DPL test is applicable for example in a trench where say residual dolomite (wad) material has been encountered at the base of a trench, the DPL test can then be used to quickly get an estimation on how deep the residual dolomite (wad) horizon extends before more competent material can be anticipated at depth.

The DPL test has similar disadvantages to the DPSH test method, however, refusal with the DPL method can also be encountered on gravels.

### 3.4 Direct Investigation Methods

#### 3.4.1 Rotary Percussion Drilling

The drilling of rotary percussion boreholes (preferably in combination with a micro-gravity survey) is regarded as one of the most reliable in situ point source methods of obtaining subsurface information to examine the extent of subsurface erosion related to sinkholes and subsidences and provide information on the depth to dolomite bedrock, composition of the blanketing layer above dolomite bedrock, presence of voids within the blanketing layer or cavities within dolomite bedrock and the depth of the ground water level.

One of the other advantages of percussion drilling is that boreholes can also be drilled to a maximum angle of 30° from vertical. Therefore subsurface conditions and instability below structures can be investigated to some extent.



A disadvantage is that adequate space is required for the drilling rig and compressor, mounted on a truck, requiring an opening of at least 3 m to 3,5 m for access. Both can be mounted on one truck or the drilling rig and the compressor is each mounted on a truck.

As drilling information is regarded as point source data, a large number of boreholes need to be drilled to examine the subsurface profile and to develop a three dimensional perspective. In the case of a sinkhole or a subsidence, the related subsurface erosion tunnel, void or cavity can be missed. In addition, taking into consideration the vast difference in dolomite bedrock profile (karst landscape), a borehole can encounter dolomite bedrock at 2 m and the next borehole drilled merely 1 m away from the previous borehole can encounter dolomite bedrock at 30 m.

A down-the-hole percussion hammer rig with a typical bit diameter of 165 mm is used applying a drilling air pressure of minimum 16 Bar. During drilling chip samples blown out the hole by means of pressure applied, are retrieved at ground surface for every 1 metre interval and penetration rates are recorded for each metre drilled. The drilling contractor also records the hammer rate (regular or irregular), water usage (foam), sample and air losses, cavities, groundwater strike and volume, and difficult penetration (typically associated with shales of the Karoo Supergroup). The groundwater rest level is measured 24-hours after completion of drilling by the drilling contractor and the borehole backfilled with spoil material recovered from the drilling of the borehole up to 3 m below natural ground surface with a concrete seal of at least 3 m below a surface concrete block.

In areas of Karoo shales the drill hammer is sometimes replaced by a 'cutter' (auger like bit) for easier penetration in and through sticky and stiff clays to retrieve samples. It should although be specified on the drillers logsheet between what depths below ground surface the cutter was used as penetration times of more than 1 min/m can be anticipated sometimes by using a cutter, due to the difficulty experience to get through the clays. This is due to the clays or silty clays that starts to swell (expand) through the section already drilled making it difficult to pull the drilling rods up.

Temporary casings are sometimes required especially in the upper colluvial soil horizons when comprising loose consistency materials to prevent collapse of the sidewalls.

The chip samples retrieved together with the driller's logsheet are used to do an assessment and interpretation of the subsurface profile presented by the borehole. It should, however, be noted that the samples retrieved every 1 m depth interval is disturbed and contaminated with material higher up that could be blown out together. The interpretation of dolomite boreholes is therefore based on experience.

#### Penetration times:

- Penetration times of more than 3 minutes per metre (min/m) are typically associated with hard rock dolomite. Boreholes are typically drilled at least 6 m into bedrock or to 60 m below natural ground level. In dewatered areas, a

representative number of boreholes need to be drilled to 100 m or 6 m into dolomite bedrock whichever occurs first.

- Penetration times of more than 3 min/m and up to 5 min/m are typically associated with hard rock intrusive syenite or dolerite.
- More than 1 min/m is associated with highly weathered soft rock dolomite.
- Variable penetration times are anticipated for material presenting the blanketing material above dolomite bedrock and depends on composition (for example, if the residual chert comprises mostly of chert bands penetration times of over a min/m is anticipated; however if the residual chert comprises primarily of fines (soil) with chert gravel and/or fragments, penetration times of between 15 sec/m to 30 sec/m are rather anticipated). The penetration time for residual chert can typically vary from 15 seconds per metre to more than 1 min/m. Residual dolomite (ferroan soils) may typically vary between 15 sec/m to 50 sec/m. Residual dolomite (wad) may typically vary from 2 sec/m to 30 sec/m. A cavity within dolomite bedrock or a void in the blanketing layer will be recorded as 0 sec/m or up to 5 sec/m depending on the specific drilling contractor. Variable penetration times are also expected within residual shale, residual syenite and residual dolerite and penetration times can also typically vary from 15 sec/m to nearly 1 min/m.

Sample and air losses are typically recorded as a % out of 100. Sample and air losses are typically recorded when a void or cavity has been struck, as all the material is blown into the opening and cannot be retrieved. Most of the times samples can also not be retrieved at depths greater than the cavity or void and penetration times are then used to do an interpretation of the expected material presenting these zones. Sample losses are also anticipated within residual dolomite (wad). Complete sample losses have also been reported below the groundwater level.

### 3.4.2 Excavation

In a shallow to intermediate deep dolomite environment a 22 ton excavator with a maximum reach of 6 m or a TLB with a maximum reach of 3,5 m can be used to evaluate subsurface conditions. An excavation can be carried out to expose the throat of a sinkhole or to determine the position of grykes within a shallow dolomite environment or to determine the depth and extend of problematic soil zones such as residual dolomite (wad). Excavation can be done as trenches or as a point source. A trench excavation with an excavator will, however, provide better information on the typical dolomite profile anticipated.

This is a direct observation of subsurface conditions and in situ parameters such as moisture condition, colour, consistency, structure, soil type and origin can be evaluated in profile. In addition, samples disturbed and undisturbed can be taken of the various soil layers encountered in profile to do laboratory tests to further determine the geotechnical characteristics of material in profile.

The side slopes of the trench in soil need to be cut back to 1:1 vertical to horizontal to prevent collapse of the trench sidewalls.

Stability problems are anticipated in an area with a shallow groundwater table or perched ground water table with the use of an excavator or a TLB. Excavating below the groundwater table or perched ground water table will cause sliding or collapse of the side walls. It is therefore advisable to take great care when working below the groundwater table with an excavator or a TLB. However, in some instances no other alternative method of investigation can be considered and in such cases provision should be made for the temporarily pumping of water in trenches or excavations.

### 3.4.3 Large Diameter Augering

Large diameter auger boreholes (typically 750 mm in diameter) are suitable to be used to investigate deeply weathered soil profiles. This method is mainly used for foundation investigations of heavy structures to be placed on bedrock and not typically used for the investigation of sinkholes or subsidences.

This is also a method of direct observation of subsurface conditions and in situ parameters such as moisture condition, colour, consistency, structure, soil type and origin can be evaluated in profile. In addition, samples disturbed and undisturbed can be taken of the various soil layers encountered in profile to do laboratory tests to further determine the geotechnical characteristics of material in profile. A qualified person is lowered down the hole in a cage by means of a small winch to do profiling and sampling.

Auger trial holes provide reliable geotechnical information down to rock level, however, it is essential that the side walls of the trial hole remain stable during drilling and profiling. This method is therefore not so suitable in a dolomite environment where the subsurface profile comprises hard chert bands, dolomite floaters, thick horizons of residual dolomite (wad) and in an area of sinkhole and subsidence formation the subsurface profile will be unstable due to subsurface erosion that already took place. It is also not suitable to be used in areas with a shallow groundwater or perched water table where collapse of the side walls is anticipated. In addition, another problem in a dolomite environment that make this method not so practical is the presence of dolomite floaters and chert bands in the dolomite subsurface profile on which refusal will be encountered before reaching dolomite bedrock.

### 3.4.4 Borehole Camera

A borehole camera lowered down a predrilled percussion borehole can add some valuable information, such as determining open joints or cavities in dolomite bedrock or voids in the overlying blanketing layer. However, it should be noted that the camera can only be tilted to a maximum of 45° from vertical to evaluate sidewalls. Downhole cameras were successfully used in association with a micro gravity survey to evaluate subsurface conditions in holes drilled for micropiles to support the Skydome structure of the National Corvette Museum in Bowling Green, Kentucky after a sinkhole (measuring 11m diameter) interconnected with a cave system occurred (Polk *et al.*, 2015).

### 3.5 Geohydrological Investigation Methods

#### 3.5.1 Pumping Tests and Dye Tracing

Li and Zhou (2015) refers to the use of pump test results together with dye tracing to confirm findings by well-logs to delineate deeply seated paleo-collapse structures in specific aquifers in a mining area in northern China.

Water inrushes in mine workings along these paleo-collapse structures, causing the formation of sinkholes, fatalities, economic losses and degradation in the environment, needed to be determined and remediated (Li and Zhou, 2015).

Surface geophysical methods were unsuccessful in locating the paleo-collapse structures due to the high depths involved. Four pumping tests were conducted and the piezometric pressures measured. During each pump test a fluorescent dye was introduced into a borehole and collected at all accessible boreholes and discharge points located in the specific aquifer. In all cases, the dye first appeared in two boreholes where electric-magnetic waves was strongly absorbed and associated with a paleo-collapse structure (Li and Zhou, 2015). The straight-line velocities were calculated based on the distances and the dye travel times. The high but contrasting velocities from different traces highlight the rapid flow and strong heterogeneity in the specific limestone aquifer (Li and Zhou, 2015). This in turn assisted in delineation of the possible locations of water-conducting paleo-collapse structures, requiring grouting to prevent (or reduce) the amount of water flowing into the mine and reducing the piezometric pressure (Li and Zhou, 2015).

## 4. METHODS OF SINKHOLE AND SUBSIDENCE REHABILITATION

The various methods of sinkhole and subsidence rehabilitation used in South Africa, as described in Department of Public Works PW344 (2010) and incorporated into the South African National Standards SANS 2001-BE3 (2012) will be discussed.

The specific method, or combination of methods, used to rehabilitate a sinkhole or subsidence will depend on the subsurface conditions, accessibility for equipment and the impact of the rehabilitation procedure on existing infrastructure (Kleinhans, 2013).

All health and safety aspects of work in and around sinkholes and subsidences should be adhered to: All workers executing work in and around sinkholes and subsidences must use harnesses and safety ropes secured away from the sinkhole or suspended from a crane or excavator parked at a safe distance as indicated in the zone specified by the competent person and safe parking distance for equipment (SANS 2001-BE3, 2012).

### 4.1 Inverted Filter Method

The Inverted Filter Method in layman's terms comprises the backfilling of a sinkhole including blocking of the throat of the sinkhole with rockfill and/or boulders or the use of self-compacting concrete. This is followed by layers of progressively finer material, compacted at a specific compaction effort to create an impermeable capping.

#### 4.1.1 Method of Rehabilitation

A schematical presentation of the Inverted Filter Method used to rehabilitate a sinkhole and a subsidence is illustrated in Figure 11.

The rehabilitation of a sinkhole or a subsidence by means of the Inverted Filter Method will typically comprise of the following operations (PW344, 2010):

- Bulk excavation of the sinkhole or subsidence area extending 2 m to 4 m beyond the outer perimeter of the sinkhole or subsidence, with a 1 m deep margin at the surface, extending from the initial excavation outward. The depth of excavation will be based on the subsurface conditions encountered during the dolomite stability investigation. The sidewalls of the excavation should be excavated at 60 Degrees to the horizontal or at 45 Degrees (V:H 1:1) where poor subsurface soils like residual dolomite (wad) is encountered in the subsurface profile during investigations.
- Choking the throat of the sinkhole with:
  - Boulders of 500 mm and larger (no fines allowed) with or without a 3% cement soilcrete mix or,
  - Building rubble (not exceeding 400 mm diameter (excluding tin, wood or other degradable materials) with a mixture of fines not exceeding 30% of mix) or;

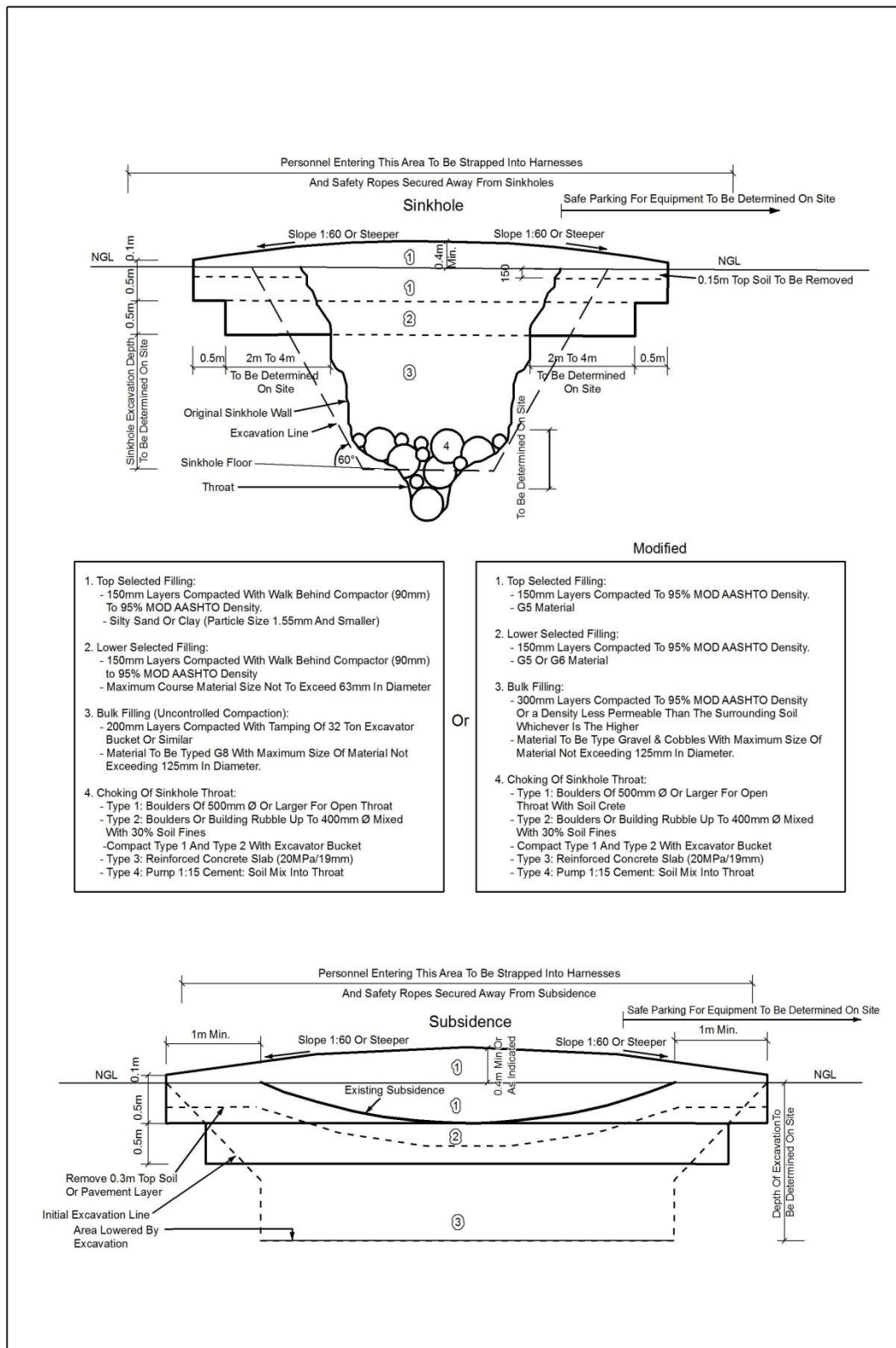


Figure 11: Inverted Filter Method of Rehabilitation (modified after PW344, 2010).

- Mass concrete (Pump 1:15 cement:soil mix) in throat or;
- Reinforced concrete slab (20 MPa/19 mm) or;
- A combination of all these solutions.

Compact in layers of 500 mm thickness by means of tamping with an excavator (minimum 32 ton machine) bucket.

- Backfilling of the excavated sinkhole above the choked sinkhole throat or subsidence area will include Conventional Compaction:
  - Bulk Filling: Backfill to a depth, as specified by the investigator (typically 1 m to 1,5 m below natural ground level), in 200 mm (or 300 mm) thick layers with G8-quality material (COLTO, 1998), including gravel and cobbles not exceeding 125 mm in diameter, each layer compacted to at least 93% (or 95%) of Modified AASHTO Maximum Dry Density at Optimum Moisture Content or to a density less permeable than the surrounding soil, whichever is the higher (PW344, 2010 and SANS 2001-BE3, 2012). The thickness of the layers shall be consistent with the size of compaction equipment used to ensure the specified compaction is achieved throughout the full thickness of the layer (SANS 2001-BE3, 2012). Compacted by means of rammers, walk behind vibrating roller of minimum 900 mm wheel width up to 10 ton vibrating roller, depending on the area to be compacted. The maximum particle size in the backfill shall be limited to two-thirds of the thickness of the compacted layer and is determined by the method of placement and compaction (SANS 2001-BE3, 2012). Material shall comprise of material that is not subject to decomposition, slaking or other degradation (SANS 2001-BE3, 2012). The base of the bulk filling (including 3 layers of 300mm thickness), is sometimes also stabilized with 3% to 5% cement.
  - Lower Selected Filling: From a depth of 1 m or 1,5 m below ground level the compaction density needs to be 95% Modified AASHTO density. Compacted in layers not exceeding 150 mm in thickness and the maximum course size material to be 63 mm in diameter. Selected material shall typically comprise of roads sub-grade (G8) material (or the use of G5 to G6 material, according to COLTO (1998)).
  - Top Selected Filling: The final 500 mm to be filled to specified height above ground level with material generally classified in the range of silty sand to clay (particle size 1,55 mm and smaller or G5-quality material (COLTO, 1998)) and compacted to 95% Modified AASHTO density. This layering shall continue to a height suitable to allow a minimum of 1:60 sloping in all directions, falling away from the centre of the filled area in order to form a positive relief feature. The area is to be finished off in smooth surfaces preventing water ponding. It should, however, be noted that where the land-use after rehabilitation

requires a gradient similar to the original gradient before rehabilitation the Top Selected Filling layer is not constructed to form a positive relief.

Excavation and throat plugging is according to Zhou and Beck (2008) the simplest way to remediate an existing sinkhole. They suggest a plug of rock or stones, concrete blocks or grout of 1.5 times the width of the throat. If the sinkhole does not have an obvious throat, but consists of many discrete fractures, these fractures can be blocked by dental infill grout, where the pockets are filled with high/low slump flowable fill to plug and cap the fractures (Zhou and Beck, 2008).

Use of Geotextiles (also called geosynthetic reinforcement or geogrid) or mesh reinforcement (geogrids or weldmesh) may be considered to temporarily retain the material above the throat of the sinkhole or as support layers within the lower and top selected fill layers or to line the base and walls of the sinkhole (Zhou and Beck, 2008).

Geosynthetics refer to manmade materials used in geotechnical and related engineering applications, due to their high tensile strengths and moduli compared to other polymere materials, the two types of geosynthetics mostly used in reinforced soil structures are geogrids and woven geotextiles (Bonaparte and Berg, In: Beck and Wilson, 1987): Geogrids are reinforcing products consisting of discrete longitudinal ribs that are connected to transverse bars. The spacings of the ribs and bars are large enough to allow earth fill to penetrate the grid aperture. The penetration of soil particles into the plane of the reinforcement results in compaction-induced and load-induced soil-reinforcement 'interlocking'. Woven geotextiles are composed of two sets of filaments or yarns systematically interlaced to form a planar structure. The two sets of filaments or yarns are typically perpendicular.

It should however be noted that the use of geotextiles do not constitute a complete repair of a new or existing sinkhole (Villard *et al.*, 2000). Within long-term repair of a large sinkhole in thick soil, geogrid can only serve as a temporary warning mechanism (Waltham *et al.*, 2005). Geogrids may be used beneficially to improve load distribution on softer overburden material left in place on shallow overburden strata (Zhou and Beck, 2008). Geosynthetics are generally cheaper than other measures (e.g. reinforced concrete slabs) when used as a prevention measure in roads and railways in areas prone to sinkhole formation, they are able to span small cavities, maintaining the serviceability of the road during the lifetime of the project and for large cavities they temporarily prevent the formation of catastrophic sinkholes and accidents, serving as a warning system (Galve *et al.*, 2012). Galve *et al.* (2012) and Gutierrez *et al.* (2014) report on the development and evaluation of sinkhole susceptibility models to optimize the application of geosynthetics to roads. The most cost-effective geosynthetic design solution identified by means of the cost-benefit analyses involves the installation of geogrids able to span cavities 3 m to 4 m in diameter distributed along 55% of the high risk road sections (Galve *et al.*, 2012).

Villard *et al.*, (2000) recommends the use of geosynthetic reinforcement to reinforce roads and railway lines over areas prone to the formation of cavities. The geosynthetic reinforcement is capable to span a stable arch over a 2 m diameter cavity, but where a cavity of larger than 2 m exists up to 4 m an unstable arch will form with the occurrence



of a subsidence at surface as deformation of the geosynthetic takes place and the imported engineering fill above it (Villard *et al.*, 2000). The use of geosynthetic reinforcement for sinkholes linked to large cavities at depth is not recommended (Villard *et al.*, 2000).

#### 4.1.2 Application of the Inverted Filter Method

The Inverted Filter Method is typically applied to:

- Sinkholes of small (less than 2 m diameter), medium (between 2 m and 5 m diameter), large (between 5 m and 15 m diameter) or very large size (more than 15 m diameter).
- Subsidences of all sizes (less than 2 m to more than 15 m diameter).
- Typically used for sinkholes or subsidences extending to a maximum depth of 6 m or the throat of the sinkhole is visible within 8 m from natural ground surface. Zhou and Beck (2008) specifies shallow sinkholes within 10 m from natural ground surface. This method can however also be applied to depths of up to 12 m to 16 m (with a 2 m wide terrace at 6 m) if adequate space exists for such bulk excavations.
- Existing infrastructure located at a distance, outside the area proposed for bulk excavation.
- The groundwater rest level is at a depth greater than the proposed bulk excavation depth.

The Inverted Filter Method is regarded as a cost effective and practical rehabilitation method for shallow sinkholes and subsidences typically to a depth of 3 m to 6 m (maximum reach of an excavator).

## 4.2 Dynamic Compaction Method

The Dynamic Compaction (DC) Method in layman's terms involves the placing of selected materials typically in lifts or layers of 2 m (can vary between 1 m to 3 m), followed by dynamic compaction on a specific grid spacing, including primary and secondary points carried out for each lift (or layer), where a large weight known as a pounder is dropped from a considerable height onto the soil to be compacted and densified (PW344, 2010).

### 4.2.1 Method of Rehabilitation

The Dynamic Compaction Plant (or Equipment) comprises the following components (personal communication Mr Eben Blom of Makarios Geotechnical Contractors):

- A 60 ton Crawler Crane with 18 m lifting height.
- A 17 ton single line pull capacity.

- A Penetration Pounder of 13,5 ton (1,0m square) and/or a 12 ton ball type pounder (0,9 m diameter).
- Ironing Pounder of 10,5 ton and 2,4 m diameter octagonal and/or 12 ton and 3,0 m in diameter.

The depth of compaction is a function of the weight of the pounder and the height of the drop (Byrne *et al.*, 1995). For the normal energy levels this approximates to the following relationship (Byrne *et al.*, 1995):

$$D = k \times \sqrt{Wh}$$

Where

D	is the depth of compaction in metres.
k	is an influence factor which varies between 0.375 and 0.7.
W	is the weight of the pounder in tonnes.
h	is the drop height in metres.

Experience has shown that the depth of influence and the degree of improvement are also influenced by the shape of the pounder (Byrne *et al.*, 1995). A wide range of pounders has been developed for varying site conditions with different pounders often being used on different phases of the same project (Byrne *et al.*, 1995). In addition, the degree of compaction achievable also depends on the soil characteristics and the spacing of the locations at which the hammer is dropped (personal communication Mr Eben Blom of Makarios Geotechnical Contractors).

Dynamic Compaction is usually carried out in three different phases, namely the primary, secondary and ironing phases (Byrne *et al.*, 1995). However, with sinkhole rehabilitation a fourth phase is included namely Dynamic Compaction Probing. The procedures of the four different phases of the Dynamic Compaction Method are as follows:

- Dynamic Compaction Probing: The sinkhole is excavated to a depth as specified by the investigator. Typically in areas where the DC method is proposed as rehabilitation method, bulk excavation of the affected area is done to a depth of 4 m to 6 m below natural ground level, followed by the over-excavation of the sinkhole or sinkhole throat with an excavator; therefore excavation depths can range between 8 m to 12 m within the area proposed for DC Probing. This method can however be applied to a depth of 15 m.

If a cavity is located at a depth greater than the maximum excavated level, the first attempt with the Dynamic Compaction Probing Method will be to collapse the cavity roof at depth. Rockfill or building rubble is then placed in layers or lifts (varying between 1 m to 3 m) and DC Probing used to drive the material into the throat of the sinkhole with a penetration pounder until visual refusal was reached thereby chocking the sinkhole throat. The next layer of fill is placed and followed by DC Probing. Thus process continues until the sinkhole throat is completely filled and compacted.

The DC Probing Method is also used to densify highly compressible residual dolomite (wad) zones within the bulk excavation area before DC production starts as primary and secondary points.

- Primary and Secondary Phases: Compaction of the deepest layer is achieved with the primary phase (Byrne *et al.*, 1995), also refer to Figure 12. The secondary phase achieves compaction mainly in the intermediate layers (Byrne *et al.*, 1995), also refer to Figure 12.
  - Where structures are located within 50 m from the area proposed for Dynamic Compaction, a crack survey is carried out on all structures before and after Dynamic Compaction.
  - The bulk excavated area is surveyed before the start of production DC.
  - The Primary DC points are set out on a grid spacing (typically 5 m by 5 m or 7,5 m by 7,5 m) and surveyed. In Figure 12 a typical grid of Primary and Secondary positions for Dynamic Compaction is illustrated.
  - The excavated area is backfilled in 1 m (or 2 m or 3 m) lifts or layers.
  - Pounder penetration tests and heave tests are carried out randomly at various places on the specific layer to be compacted to determine the optimum blow count (number of blows until refusal is reached), thus to check if the level of compaction being achieved and the spacing of the primary points is adequate, while the energy input is also determined at this stage according to the results of the tests (Byrne *et al.*, 1995).
  - Pounder penetration tests according to SANS 2001-BE3 (2012) are conducted by measuring the level of the top of the pounder placed on the ground surface before compaction and then after each drop. Level measurements are taken on studs positioned diametrically opposite one another on the perimeter of the pounder. The number of drops used during the test is typically 50% more than the specified number of drops.
 

The penetration of the pounder is plotted against the number of blows and the result is used to assess the optimal number of blows to be applied. Tests are typically carried out on about 1% of the print positions or when the nature of the material being compacted changes.
  - Surface heave tests according to SANS 2001-BE3 (2012) measure the heave of the ground surface around the print position during compaction by determining the levels of two or more lines of pegs radiating outwards from the print position to a distance of at least three pounder diameters from the grid point. Level readings are taken after each blow or each alternate blow.
  - On completion of the test, the volume of any surface heave is determined and compared to the volume of the crater. These tests are typically carried out in conjunction with some or all of the pounder penetration tests and assist in assessing the optimal number of blows to be applied.

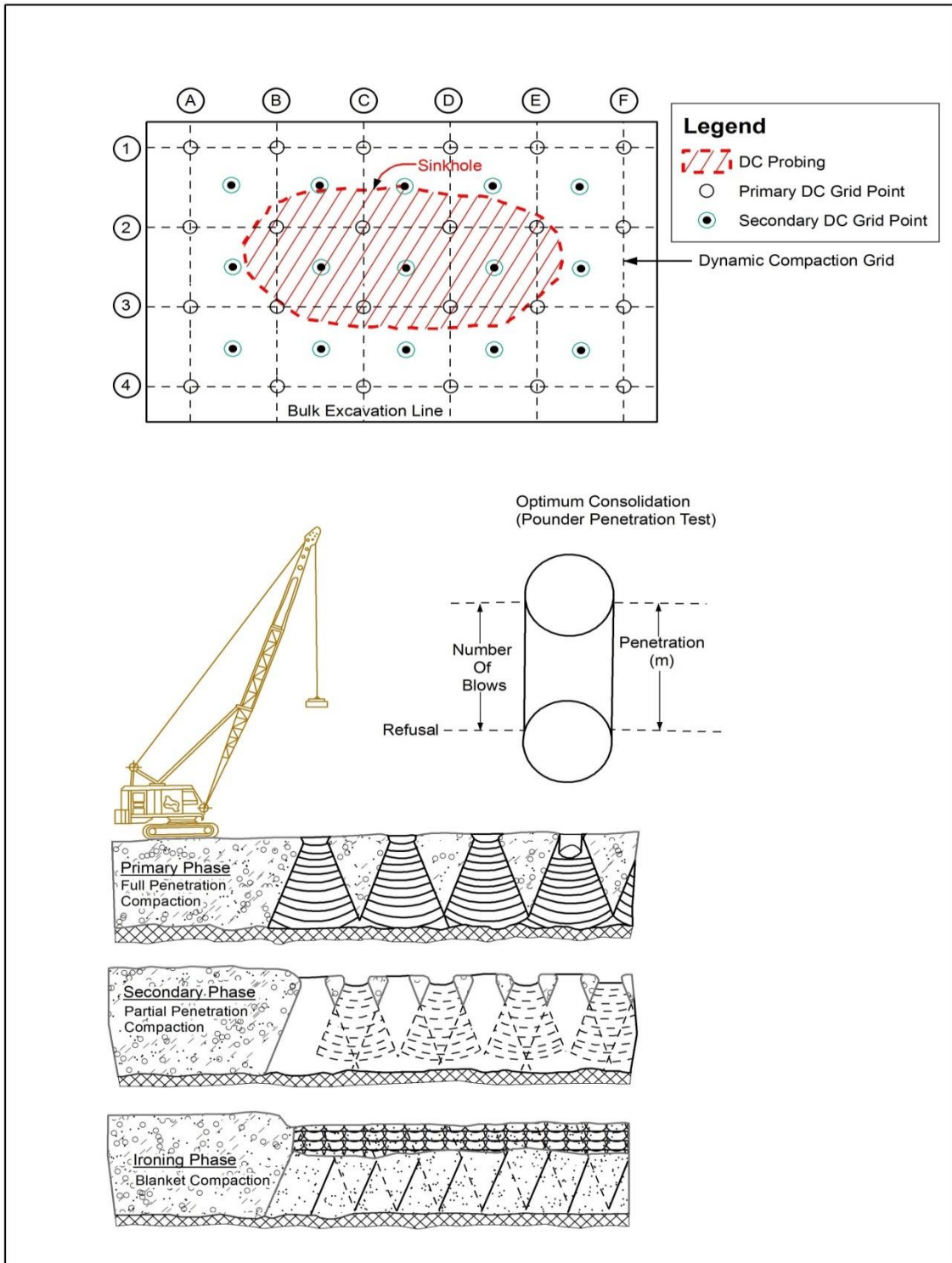


Figure 12: Dynamic Compaction grid layout and compaction patterns for primary, secondary and ironing phases (modified after Byrne *et al.*, 1995).

- Volume and blow counts are recorded for quality purposes for each print position for each layer. The DC imprints are then filled with a suitable material and levelled. The depth of the crater before filling shall not exceed 2,5 m (SANS 2001-BE3, 2012). The volume of bulk fill material imported for backfilling craters shall be recorded (SANS 2001-BE3, 2012).
- The Secondary DC points for each layer are positioned midway between the Primary DC points. The energy input of the secondary phase points is again determined by the results of the field tests before production DC starts. Volume and blow counts are recorded for quality purposes for each print position. The DC imprints are then filled with a suitable material and levelled, before the placing of the next fill layer.
- The following layer of fill is placed and the above mentioned process of Primary and Secondary points repeated.
- Apart from the Pounder Penetration Test and heave tests being used to determine the optimum consolidation for each layer of fill during the early stages of the DC programme; Plate Loading Tests is conducted with large scale plate load equipment (typically 1,0 m diameter) to determine the Soaked Secant Modulus (under a specific load) of the consolidated material during DC on specific layers of fill or after DC. Dynamic Probe Super Heavy (DPSH) Tests can also be done pre and post DC to estimate the degree of improvement achieved.
- Ironing Phase: The ironing phase ensures overlapping of the initial phases by compacting the shallow layers between the initial prints (Byrne *et al.*, 1995). The final ironing phase is aimed at compacting the upper two to four metres.
  - In this phase the entire area is compacted with a single drop 30% to 70% (average 50%) weight overlap to compact the upper 2 m to 4 m (personal communication with Mr Eben Blom of Makarios Geotechnical Contractors). SANS 2001-BE3 (2012) specifies at least two blows of the ironing pounder.
  - The upper 0,3 m of material after the Ironing Phase will be loose and require ripping and re-compaction with a compaction roller.
  - A further set of level readings shall be taken at each grid position on completion of compaction (SANS 2001-BE3, 2012). This information may be used, together with the levels before compaction and the volume of fill material imported, to assess the degree of compaction achieved (SANS 2011-BE3, 2012).

A schematical presentation of the Dynamic Compaction Method used to rehabilitate a sinkhole and a subsidence is illustrated in Figure 13.

#### 4.2.2 Application of the Dynamic Compaction Method

The Dynamic Compaction (DC) Method is applicable for the following conditions:

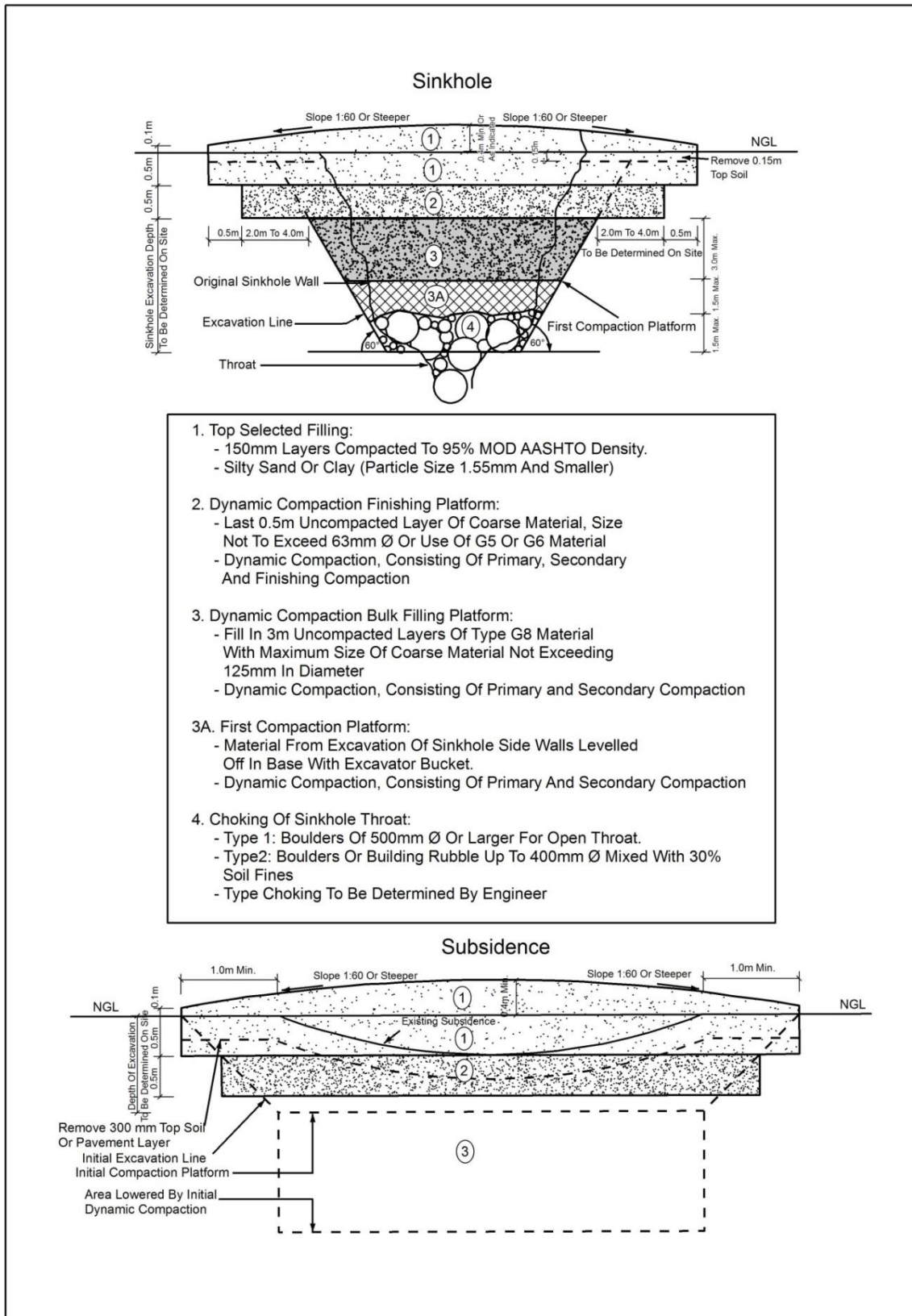


Figure 13: Dynamic Compaction Rehabilitation Method (after PW344, 2010).

- The Dynamic Compaction Method is a method used to increase the density and bearing capacity of the soil when certain subsurface constraints render other methods inappropriate. The impact of the free fall of a heavy weight repeatedly on the ground creates shock waves that help in the densification of the soil. These shock waves can penetrate up to 10 m, all dependent on the energy applied. In saturated cohesionless soils, these waves create liquefaction that is followed by the compaction of the soil, and in cohesive soils, they create an increased amount of pore water pressure that is followed by the compaction of the soil (personal communication with Mr Eben Blom of Makarios Geotechnical Contractors).
- Most soil profiles can be compacted. Compaction and densification of poor subsurface residual dolomite (wad) or soil layers with a loose consistency at depth to a maximum depth of 10 m and / or extending over a large surface area.
- As the impact shock waves can cause damage to surrounding buildings, a safe distance of 50 m is recommended to carry out DC from any structures (personal communication Mr Eben Blom). The Peak Particle Velocity (PPV) created by the shock waves is monitored at all times during DC performance. To reduce the impact of the shock waves on structures a trench can be excavated with a TLB around the area proposed for DC to a depth of between 2,5 m and 3,0 m. Byrne *et al.* (1995) specifies that peak particle velocities of greater than 25 mm/second are only exceeded under unusual circumstances. Using the correct techniques it is therefore possible to carry out dynamic compaction as close as 3 m from underground services and 5 m from sound structures (Byrne *et al.*, 1995).
- Compaction can be achieved both above and below the water table (Byrne *et al.*, 1995).
- Depending on subsurface conditions, the DC Probing Method can successfully be applied to a depth of 10 m to 15 m and in some instances be used to collapse the roof of a cavity or subsurface voids within the overburden, located at a depth greater than the bulk excavated area (typically to a depth of 4 m to 6 m) proposed for production DC (Primary and Secondary Points). The DC method has also been successfully used on limestones in Florida to collapse soil voids, clog bedrock surface openings and collapse cave roofs if the rock is shallow (Fischer and Fischer, 2015).
- The pattern of ground deformation developed during DC often indicates many areas of active and potential sinkhole development or defining the need for site remediation on Florida projects (Zhou and Beck, 2011; Fischer and Fischer, 2015).
- Where the subsurface conditions in the area of the sinkhole presents a safety hazard for workers, the chocking of the sinkhole throat by means of the DC Probing Method can create a safe platform to work on.

The Dynamic Compaction (DC) Method is regarded as a cost effective and practical rehabilitation method to densify material to a maximum depth of approximately between 8 m and 10 m below natural ground level (personal communication with Eben Blom of Makarios Geotechnical Contractors). Byrne *et al.* (1995) specifies a

maximum depth of 12 m. However, under saturated or near saturated conditions, the pore water pressure will increase with each blow of the pounder (Byrne *et al.*, 1995). If it becomes excessive the pounder will have little compacting effect as the blow is being cushioned by the pore water (Byrne *et al.*, 1995). In these circumstances further compaction in these areas may have to be delayed until the pore water pressures have dissipated (Byrne *et al.*, 1995). In coarse grained materials the dissipation of excess pore water pressure takes place immediately (Byrne *et al.*, 1995). With saturated clays on the other hand, dissipation could take weeks and such delays often makes the dynamic compaction method impractical (Byrne *et al.*, 1995).

In addition, where a competent layer of chert, comprising mainly of gravel and cobbles is present near natural ground surface above a compressible layer of residual dolomite (wad), most of the energy expended by the compaction effort is absorbed by the competent chert layer and the material below it is not compacted (De Bruyn and Bell, 2001). To reach the required compaction effort down to a specific depth, it is required to excavate through the competent layer down to the residual dolomite.

Vibro-compaction methods are not suitable to the South African karst due to the high silt and clay content of the overburden soils and the possible initiation or reactivation of subsurface erosion and potential sinkholes.

### 4.3 Combination of Dynamic Compaction and Inverted Filter Method

A combination of the Dynamic Compaction Method and the Inverted Filter Method comprises the collapsing of cavities at depth and / or the chocking of the sinkhole throat by means of the Dynamic Compaction Probing Method described in Section 4.2 up to a specific depth, followed by the conventional Inverted Filter Method described in Section 4.1 including the backfilling of the excavated area by layers of progressively finer material, compacted at a specific compaction effort to create an impermeable capping.

#### 4.3.1 Method of Rehabilitation

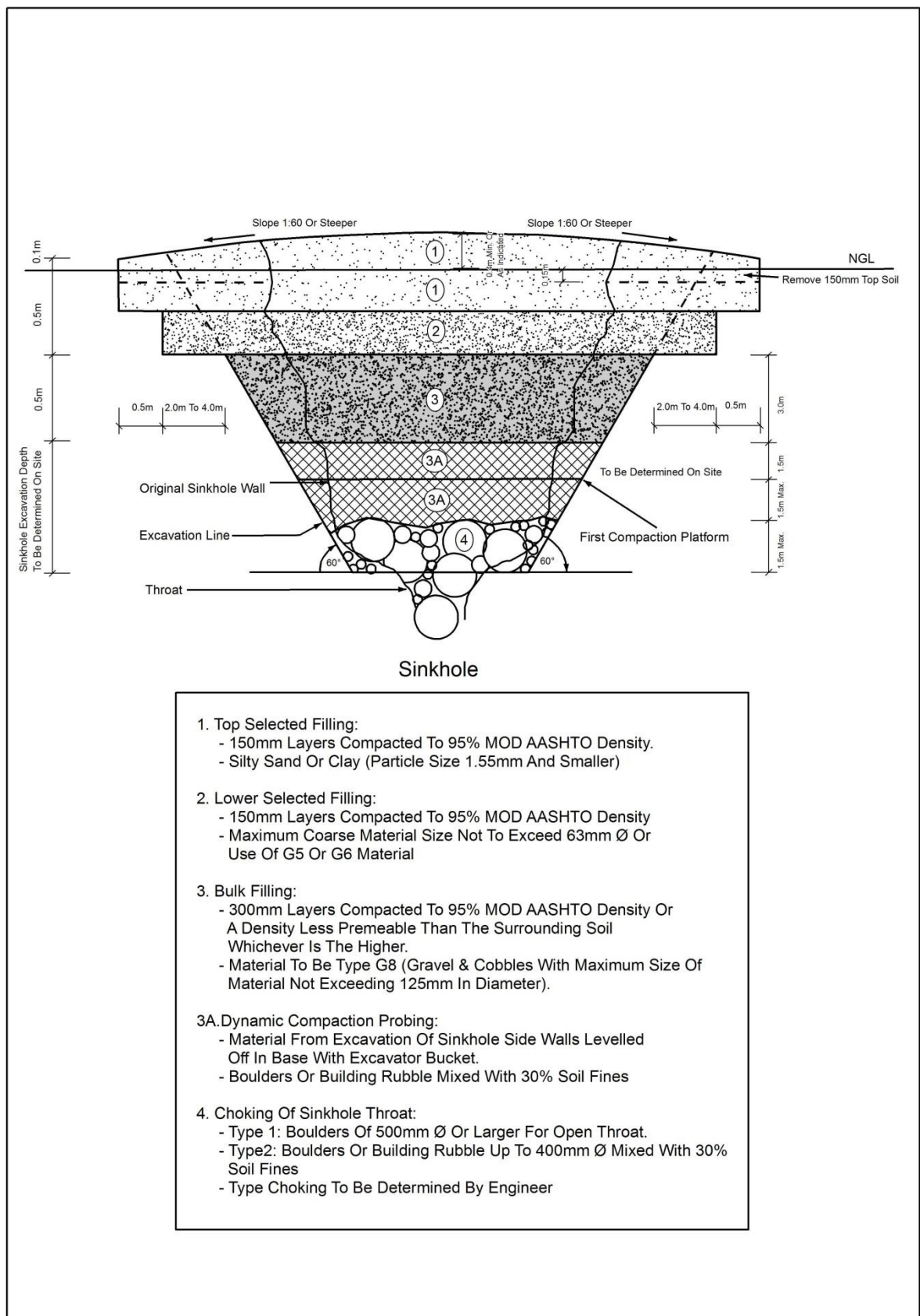
A schematical presentation of a combination of the Dynamic Compaction Method and the Inverted Filter Method used to rehabilitate a sinkhole is illustrated in Figure 14.

The rehabilitation of a sinkhole by means of a combination of the Dynamic Compaction Method and the Inverted Filter Method will typically comprise of the following operations:

- Bulk excavation of the sinkhole or subsidence area extending 2 m to 4 m beyond the outer perimeter of the sinkhole or subsidence, with a 1 m deep margin at the surface, extending from the initial excavation outward.

The depth of excavation will be based on the subsurface conditions encountered during the dolomite stability investigation, but will typically range between 4 m to 6 m below natural ground surface. The sidewalls of the excavation should be excavated at 60 degrees to the horizontal or at 45 Degrees (V:H 1:1) where poor subsurface soils like residual dolomite (wad) is encountered in the subsurface profile.





**Figure 14: Combined Dynamic Compaction and Inverted Filter Method of Rehabilitation (modified after PW344, 2010).**

- In the area of the sinkhole throat over excavate to the maximum reach of the excavator from a depth of the bulk excavated floor area, therefore over-excavated depth of 10 m to 12 m below natural ground surface.
- Dynamic Compaction Probing: If a cavity is located at a depth greater than the maximum excavated level, the first attempt with the Dynamic Compaction Probing Method will be to collapse the cavity roof at depth.
- Rockfill (boulders of 500 mm and larger) or building rubble with a mixture of fines not exceeding 30% of the mix is then placed in layers or lifts (varying between 1 m to 3 m) and DC Probing used to drive the material into the throat of the sinkhole with a penetration pounder until visual refusal is reached thereby choking the sinkhole throat. The next layer of fill is placed and followed by DC Probing. Thus process continues until the sinkhole throat is completely filled and compacted. The DC Probing Method is also used to densify highly compressible residual dolomite (wad) zones within the bulk excavation area.
- Backfilling of the remaining excavated sinkhole area above the choked sinkhole throat by means of the Dynamic Compaction Probing Method will include Conventional Compaction:
  - Controlled Bulk Filling: Backfill to a depth, as specified by the investigator (typically 1 m to 1,5 m below natural ground level), in 200 mm (or 300 mm) thick layers with G8-quality material (COLTO, 1998) or better (including gravel and cobbles not exceeding 125 mm in diameter), each layer compacted to at least 95% of Modified AASHTO Maximum Dry Density at Optimum Moisture Content or to a density less permeable than the surrounding soil, whichever is the higher. Compacted by means of rammers, walk behind vibrating roller of minimum 900 mm wheel width up to 10 ton vibrating roller, depending on the area to be compacted.
  - Lower Selected Filling: From a depth of 1 m or 1,5 m below ground level the compaction density needs to be 95% Modified AASHTO density. Compacted in layers not exceeding 150 mm in thickness and the maximum course size material to be 63 mm in diameter. Selected material shall have typically composition of roads sub-grade (G8) material (or the use of G5 to G6 material according to COLTO, 1998).
  - Top Selected Filling: The final 500 mm to be filled to specified height above ground level with material generally classified in the range of silty sand to clay (particle size 1,55 mm and smaller or G5-quality material according to COLTO 1998) and compacted to 95% Modified AASHTO density. This layering shall continue to a height suitable to allow a minimum of 1:60 sloping in all directions, falling away from the centre of the filled area in order to form a positive relief feature. The area is to be finished off in smooth surfaces preventing water ponding.

It should, however, be noted that where the land-use after rehabilitation requires a gradient similar to the original gradient before rehabilitation the Top Selected Filling layer is not constructed to form a positive relief.

#### 4.3.2 Application of the combined Dynamic Compaction and Inverted Filter Method

- Collapsing of cavities or voids at depth and the chocking of the sinkhole throat by means of the Dynamic Compaction Probing Method up to a specific depth (typically to a depth of 6 m below ground surface), followed by the Inverted Filter Method. A combination of the Inverted Filter Method and the Dynamic Compaction Method can be considered where an area proposed for rehabilitation comprises sub-areas with sinkholes and underlying deeper cavities or voids in the blanketing layer not reachable with an excavator or sub-areas of residual dolomite (wad) is present in profile to a depth of 10 m.

The combined Dynamic Compaction (DC) and Inverted Filter Method is regarded as a cost effective and practical rehabilitation method to improve subsurface conditions in areas affected by sinkholes to a maximum depth of between 10 m and 15 m below natural ground level.

#### 4.4 Compaction (Backfill) Grouting

Compaction grouting was originally developed in California in the United States during the 1940's to compact beneath and level homes (Brill and Hussin, 1993). In the early 1980's, compaction grouting was first used to treat sinkholes in central Florida, United States (Brill and Hussin, 1993).

The Compaction (Backfill) Grouting Method in layman's terms is a method in which a mix of sand, cement and water is pumped under a specific pressure as determined by the investigator, into cavities at depth to fill the void or to densify poor subsurface soils.

It is regarded as a soil compaction technique in which the density of the soil is improved by introducing a thick grout under pressure into the soil (Byrne *et al.*, 1995). The thick grout forms an enlarged bulb or series of bulbs in the soil and in so doing, it displaces the soil immediately surrounding the bulb, thereby increasing its density (Byrne *et al.*, 1995).

Swart (1991) specifies in his research done on grouting of the dolomites of the Far West Rand that bulbs can be anything up to a metre and more in diameter and densification occurs within a radius of 0,3 m to 3,7 m from the bulb (after Warner, 1982). However, with compaction grouting it is generally only possible to obtain an average overall density of about 90% Modified AASHTO (Byrne *et al.*, 1995).

One of the objectives when compaction grouting a soil mass is to attempt to even out the volume of grout injected over the whole area (Byrne *et al.*, 1995). The percentage replacement should be decided on and the volumes of grout controlled according to this figure (Byrne *et al.*, 1995). However, in a dolomite environment, unforeseen conditions

such as the presence and extent of cavities will have a major influence on the volume of grout to be injected.

Hussin (2012) recommends the following equation to calculate grout quantities:

$$G_p = T \times \pi \times r^2 \times n \times V_r \times U_F$$

Where:

T = Thickness of soil to be grouted.

r = radius of effective treatment area (typically 0.9 meters, reductions can be made for clayey components found in soil section).

n = Porosity ( $V_v/V_t$ ) of dominant soil types. Typically: SMloose=0.45, SMdense=0.25; CLsoft=0.55, CLstiff=0.37).

$V_r$  = Void reduction factor is the amount you expect the porosity to be reduced, 30% reduction is typical.

$U_F$  = Uncertainty factor (10% - 75%). Depends on confidence in soil location and composition.

$G_p$  = Amount of grout estimated per grout point

The above mentioned equation calculates the volume of grout cylinder injected into the ground considering the thickness of each sequence of unique soil found in the borings. Factors are added for the assumed porosity, void reduction, continuity and uncertainty of each material found in the borings. The problem with this calculation is that it is greatly dependent on the information obtained in the borings and in particular on the assumed extent and variation of the soil properties occurring between boring locations (Zisman, 2015). Where the soil and rock conditions are relatively uniform grout estimates are generally more accurate, but where a relatively irregular rock surface and soil conditions prevail, the greater the likelihood for error in estimates of grout quantities using the above mentioned formula of Hussin (Zisman, 2015). Higher grout quantities can however be expected when the relief in the rock surface increases or if abrupt changes in lithology are found between boreholes (Zisman, 2015).

#### 4.4.1 Method of Rehabilitation

There are no clearly defined design guides for compaction (backfill) grouting (Byrne *et al.*, 1995). The design phase generally forms part of the grouting process and comprises monitoring the degree of improvement being achieved and adapting the grouting process as required (Byrne *et al.*, 1995).

PW344 (2010) specifies the grouting of subsurface cavities with a pumpable concrete or soilcrete mixture. Work comprises the pumping of grout mix directly from the mixing truck or stationary mixer into 50 mm HDPE housing connected to 50 mm steel piping down a previously drilled borehole to depths as indicated by the Engineer. Execution of each pumping operation shall be continuous.

The Compaction Grouting Plant (or Equipment) comprises the following components (PW344, 2010):

- A mobile concrete pump/pumping truck with 20 m<sup>3</sup> pump capacity per hour, equipped with suitable hoses and connectors for the required pumping pressures. The pump shall be equipped with suitable, calibrated pressure gauges to record pumping pressures up to 1,5 MPa (PW344, 2010).
- Grout viscosity measuring instruments: Use of an appropriate flow metre for the duration of grouting (PW344, 2010).
- The grout pipes shall consist of 50mm high-pressure seamless steel pipes, to suit the required pumping pressures, lowered to the desired depth into the borehole. The surface end shall be provided with a collar or crossbar to prevent the pipe from slipping into the borehole as well as a reusable coupling to fit that of the pumping unit (PW344).

#### Grouting Mixtures:

- The grout provided shall be free of stones, lumps, foreign soils or any other debris. Mining slimes may not be used as a special requirement (PW344, 2010).
- SANS 2001-BE3 (2012) specifies, the grout shall comprise a pumpable mix of sand, cementitious binder, bentonite (optional) and water with a slump of between 125 mm and 200 mm. Sand may be blended with gold mining slimes up to 50% (mass fraction), provided the properties of the grout are not adversely affected by the chemical composition of the slimes. Cementitious binder shall be cement with up to 50% (mass fraction) of pulverized fuel ash (PFA). Minimum binder content shall be 150 kg/m<sup>3</sup> of grout. Plasticizing, accelerating or retarding agents may be added.
- The consistency/viscosity of the grout mixture must not exceed 400 mm on the Colcrete Flow metre and if possible be limited to 350 mm. Consistency measurements must be recorded at intervals of 12 m<sup>3</sup> (PW344, 2010).
- The following grout types or mixtures may be used (PW344, 2010):
  - 1,0-2,0 MPa / 70:30 OPC:FA self-compacting concrete utilising a mixture of crusher- and filler sand.
  - 20:1 filler sand:cement.
  - 50 kg:1m<sup>3</sup> Cement: Soil (Soil to be silty sand with P.I. not exceeding 14).
- Byrne *et al.* (1995) specifies a sand/cement grout with a slump of between 25 mm and 75 mm is used for compaction grouting. It does not have to meet any strength requirements as the objective is not to form a structural element in the ground but to compact the ground itself (Byrne *et al.*, 1995). Cement contents can vary from zero to 500 kg per cubic metre but 300 kg per cubic metre is more typical (Byrne *et al.*, 1995). Flyash is often used as a substitute for up to 50 percent of the cement as flyash extends the working life of the grout and improves workability (Byrne *et al.*, 1995). Retarders are also used for the same purpose (Byrne *et al.*, 1995). The grading of the sand is important to ensure the workability of the mix, even under high pressure, often two or more sands are blended to produce the ideal grouting (Byrne

*et al.*, 1995). If a well graded sand is not available, a bentonite slurry can be blended with the sand and the cement partially substituted by flyash to aid the workability (Byrne *et al.*, 1995).

#### Pressure restrictions and pumping rates:

- The boreholes must be pumped to a pressure not exceeding 15% of the overburden pressure of the material that covers the cavity. Overburden pressure shall be calculated with material properties taken as that of loose sand (PW344, 2010).
- During injection of grout, the level of the ground surface and any surrounding infrastructure shall be monitored to ensure that heave does not occur (SANS 2001-BE3, 2012).
- The intention of grouting is to fill cavities and voids, not to compact the ground or cause hydro-fracturing (SANS 2001-BE3, 2012). Grout injection pressures (allowing for delivery hose losses) should typically be around 1 MPa (10 bar) below a depth of 10m reducing linearly to surface above this depth (SANS 2001-BE3, 2012). The upper few metres of the hole are generally gravity grouted (i.e. the hole is simply filled without injection pressure). The standing pressure required on completion of each stage (sustained pressure on grout measured over a minimum of 10 seconds) should be specified by the competent person (SANS 2001-BE3, 2012). Where large quantities of grout are injected in any one stage without achieving the specified standing pressure, the injection of grout may be suspended once a specified limiting quantity of grout has been pumped, the grout tube withdrawn and the stage re-injected after the grout in the hole has set for at least 24 hours (SANS 2001-BE3, 2012). Limiting volumes of grout per stage should be specified by the competent person (SANS 2001-BE3, 2012).
- The pumps generally have a pressure capability of 40 Bar to 60 Bar, but a limiting pressure of 20 Bar at the head of the grout pipe is a typical figure for deep compaction grouting (Byrne *et al.*, 1995). The pumping rate should be in the range between 15 and 100 litres per minute. The rate should be lower in soils with poor drainage characteristics and when the compaction process is carried out close to the ground surface. Higher rates can be used in free draining soils with significant cover.
- During the planning phase of a grouting programme, for cost estimate purposes, the following grout pressures are usually specified:
  - Soil overburden: 0,1 MPa (or 1 Bar)
  - Highly weathered rock: 0,5 MPa (or 5 Bar)
  - Hard rock: 1,0 MPa (or 10 Bar)
- Schulze-Hulbe (1987) specifies that the following variables would affect the grout take and therefore the stability of a particular area:
  - Thickness of residual dolomite (wad).
  - The bedrock depth and gradient.
  - Overburden consistency.

### Grouting Field Report:

- The field report will contain the grout mix, viscosity (or consistency) measurements, volume of grout pumped per stage, depth of grouting stages, method of grouting and finishing pressures for each borehole (PW344, 2010 and SANS 2001-BE3, 2012).

### Grouting Sequence:

- Compaction (backfill) grouting is usually planned as a series of primary and secondary points on a grid. The centres at which the points are arranged are in the 1,0 m to 4,0 m range but 1,5 m to 2,0 m is more common; if compaction near the surface is required, the points have to be positioned at the closer spacing (Byrne *et al.*, 1995). All the primary points are drilled and grouted first, typically positioned 3m from each other, followed by the secondary points some days later (Byrne *et al.*, 1995). The secondary points are positioned midway between the primary points. A tertiary stage could be used as well if found necessary.
- Grouting will typically start first in the area where a cavity, void or residual dolomite (wad) with no sample and air return was recorded during the stability investigation.
- The primary grouting boreholes will typically have the highest grout takes in areas of cavities or voids, with the tertiary grouting boreholes (if required) adjacent to primary and secondary grouting boreholes having lower grout volumes.

A schematic representation of a grouting grid comprising primary, secondary and tertiary grouting points to rehabilitate a sinkhole is illustrated in Figure 15.

### Grouting Method:

- Upstage Grouting (SANS 2001-BE3, 2012): Is undertaken from the bottom of a predrilled borehole. Grout is injected 1,0 m to 2,0 m long stages up the length of the borehole, raising the grout tube to the top of the next stage on completion of each grout injection.
- Downstage Grouting (SANS 2001-BE3, 2012): Is used in unstable ground where collapse of the hole and air loss during drilling has prevented drilling the hole to the required depth in a single operation. In such cases, the hole is advanced through the unstable area in 1,0 m to 2,0 m stages that are then grouted and the grout allowed to set for at least 24 hours. The hole is then re-drilled and advanced to the depth of the next stage.
- Downstage and Upstage Grouting combined: A combination of upstage and downstage grouting is considered where for example the blanketing layer covering a cavity is thin and a stable working environment needs to be created first by downstage grouting, followed by upstage grouting of the balance of the stratum (Byrne *et al.*, 1995). In addition, much higher pressures can then be applied at depth to inject grout, due to the stable surficial environment created by downstage grouting.

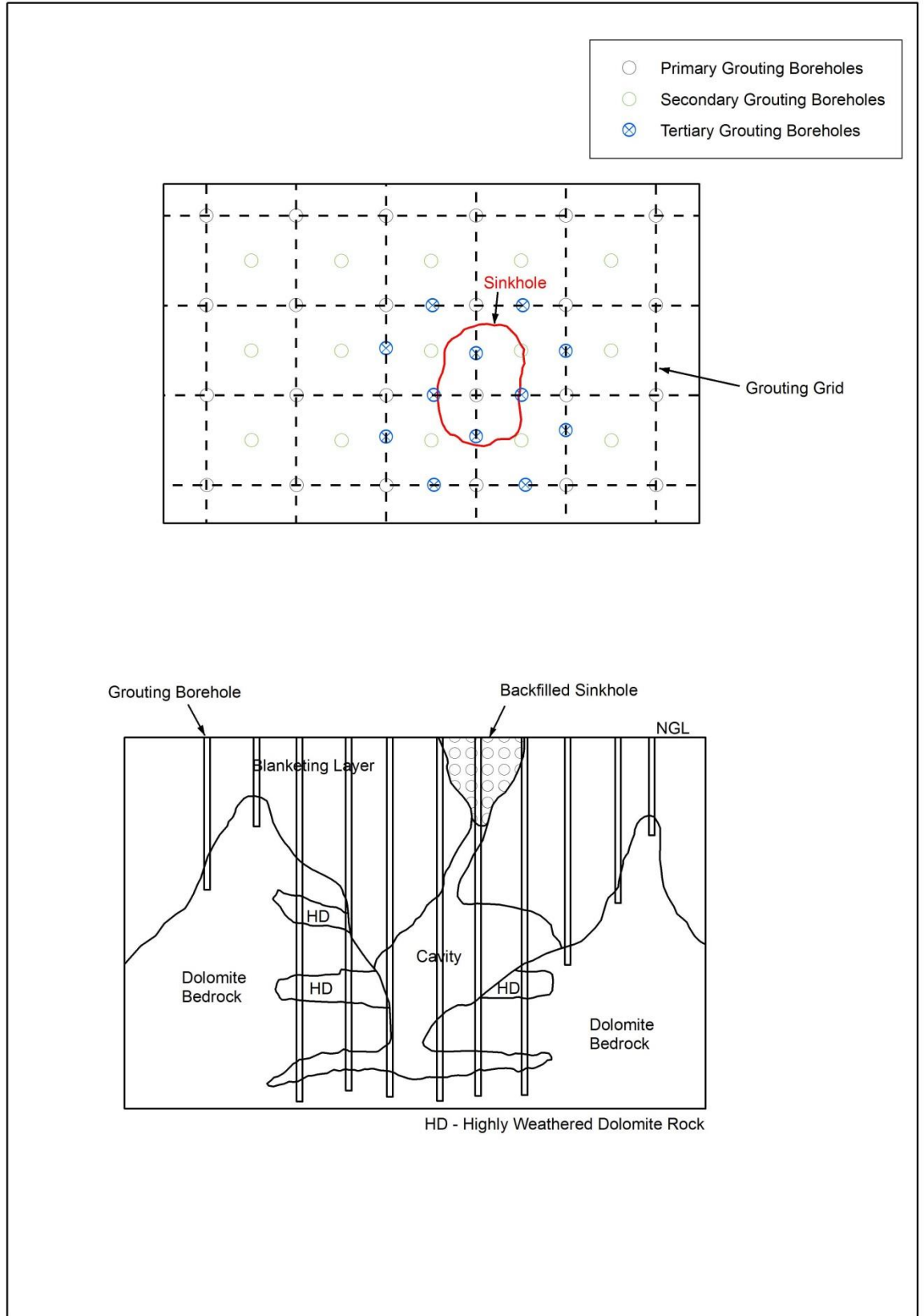


Figure 15: Schematic representation of a grouting grid to rehabilitate a sinkhole.



A schematic representation of the upstage and downstage grouting method (after the Water Resources Commission, NSW Australia, 1981) is illustrated in Figure 16.

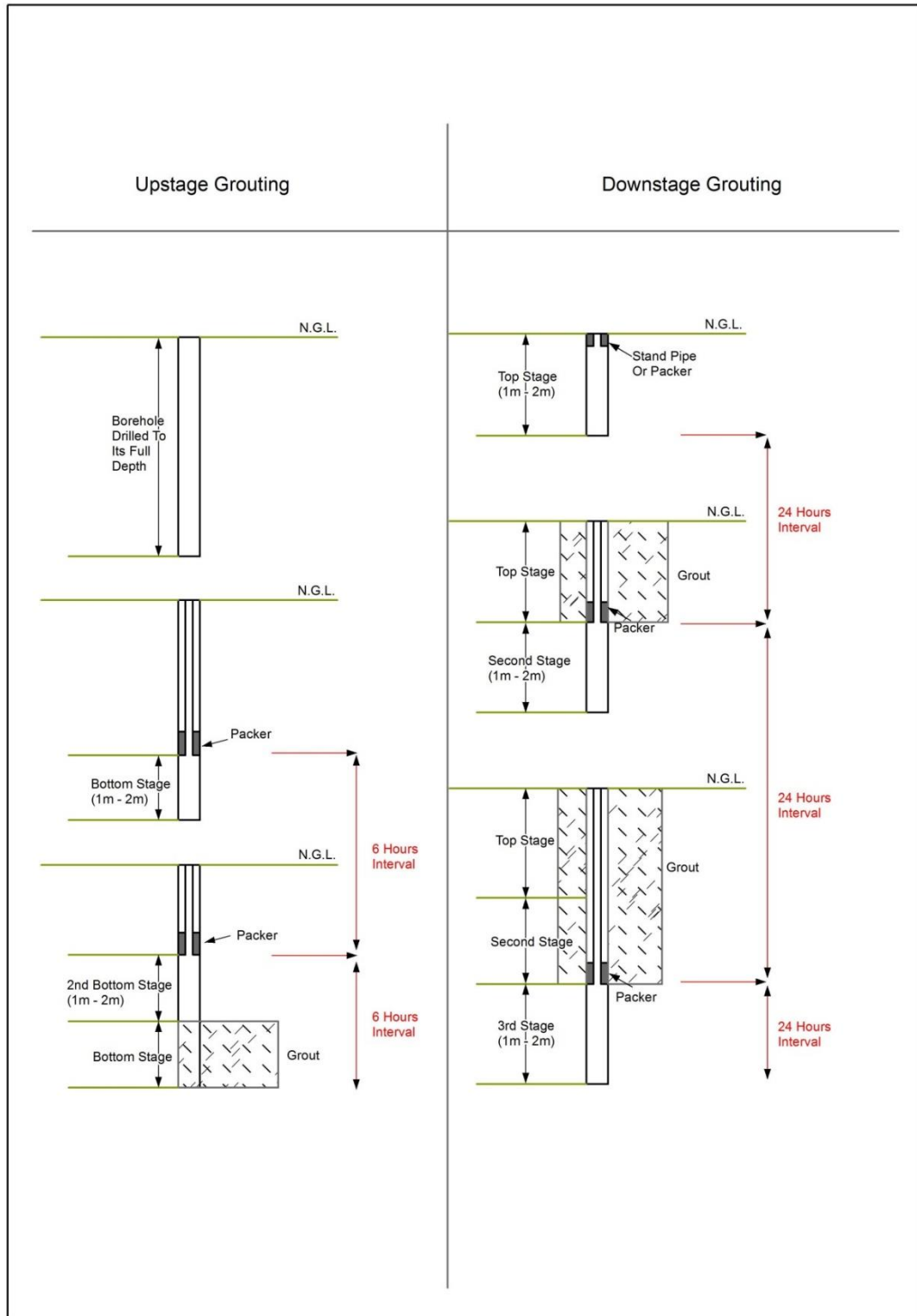


Figure 16: Schematic representation of the upstage and downstage grouting method (after Water Resources Commission, NSW Australia, 1981).

#### 4.4.2 Application of the Compaction Grouting Method

The Compaction Grouting Method can be considered under the following conditions:

- Can be used to improve subsurface conditions to variable depths ranging from ground surface to more than 60 m. However compaction (backfill) grouting is a very expensive soil improvement technique and is mainly considered where cavities or poor subsurface conditions exist at depths that cannot be treated by means of the Inverted Filter Method or the Dynamic Compaction Method. Therefore a depth factor of more than 12 m can be stated as applicable for the use of the grouting method. The grouting method may also be considered at depths shallower than 12 m in areas where subsurface conditions need to be improved close to existing structures that cannot be demolished due to their importance and where other rehabilitation methods such as the Inverted Filter or Dynamic Compaction Methods may cause further instability of the structure.
- One of the advantages of compaction grouting is that it can be done below structures (at a 20° angle from vertical or from vertical within structures with the use of smaller accessible drilling rigs) and as close as 1 m from existing structures.
- Densification of highly compressible residual dolomite (wad) or loose soils.
- Filling of voids above bedrock or cavities within bedrock.
- As compaction grouting causes ground heave it can be used to raise footings to its original level that have settled. However, careful monitoring is required during the grouting process to not cause more structural damages where grout is pumped under to high pressures. Swart (1991) specifies that where light structures need to be lifted, compaction grouting should be exercised at 2 m to 3 m depth, whilst heavy structures may need to be pumped at 4 m to 6 m depth (after Graf, 1996). Lifts as much as over 300 mm have been achieved (Swart, 1991). At the Fort Campbell Military Installation the US Army constructed a 2787 square meters maintenance facility on low mobility grout columns after a cavity was encountered during the initial investigation (Shifflett, 2015). The intend of the grouting programme was not to prevent the development of a sinkhole but to improve the foundation support to better survive a sinkhole, the process entailed the grouting of three boreholes into bedrock at each spread footing, determine if a karst feature existed, cap the bedrock and treat the defect in the rock and provide some localized improvement of soft soils through the use of low mobility grout columns under each footing (Shifflett, 2015).

The Compaction Grouting Method is a relatively expensive technique. This method is typically considered to fill deep seated cavities or voids or to densify poor subsurface soils. Or to improve subsurface conditions below existing structures of importance that cannot be demolished.

Cap grouting is recommended when a sinkhole is associated with small but discrete fractures on the bedrock surface and the area to be treated is extensive (Zhou and Beck, 2008). Cap grouting uses low pressure (140 kPa or less) to pump lean cement to cover the sinkhole base, fill voids, plug fissures, and displace soft soil (Zhou and

Beck, 2008). This cement cover provides support to the upper layers and prevents further vertical groundwater percolation (Zhou and Beck, 2008). Grout hole spacing is typically 0.9 m (Zhou and Beck, 2008).

Slurry grouting may also be used to fill cavities at virtually any depth that can be drilled (Zhou and Beck, 2008). This method involves the injection of various mixtures of very fluid grouts into the ground. It can be run along the plane of weakness in the limestone and overburden forming very effective seals, with little to no densification of overburden soil taking place (Zhou and Beck, 2008). Milanovic (2000) recommends large cavities to be filled with rock fills and grout through shafts or large diameter boreholes.

#### **4.5 Combination of Inverted Filter Method and Compaction Grouting**

A combination of these two methods may be considered in areas where sinkhole or subsidence at depth is interconnected with sub-vertical erosion tunnels extending into dolomite bedrock over a distance away from the manifestation at surface of the sinkhole or subsidence. The Inverted Filter Method can be applied to a maximum depth of 12 m. The bulk excavation area will be shaped in a funnel in the area where the sub-vertical erosion tunnel extending into dolomite bedrock before the Inverted Filter Method commences. After completion of the Inverted Filter Method a grouting programme is undertaken to seal off the sub-vertical erosion tunnel extending into dolomite bedrock by means of a grout curtain, or if sufficient funds are available also fill the cavity.

#### **4.6 Combination of Dynamic Compaction and Grouting Method**

The Dynamic Compaction Method has been discussed in Section 4.2 and the Compaction Grouting Method in Section 4.4 of this document. A combination of these two methods may be considered in areas of major trafficking, such as landing strips, roads and railway lines, where a sinkhole occurred and cavernous conditions exists at a depth greater than 10 m.

As specified by Byrne *et al.* (1995) only a 90% compaction effort is typically obtained with compaction grouting. Major roads and railway lines require subsurface layers compacted to at least 95% of Modified AASHTO compaction effort. Therefore compaction grouting can be carried out to fill the cavity or cavities at depth and Dynamic Compaction conducted to create an engineered earth mattress providing the required bearing capacity for major transport services.

#### **4.7 Self-Compacting Concrete or Soil-cement Mix**

Self-compacting concrete: Shall comprise of a pumpable concrete mix that requires no external vibration to achieve consolidation, with a 28 day cube strength greater than 5 MPa (SANS 2001-BE3, 2012). For sinkhole rehabilitation a strength of 10 MPa is typically specified.

Soil-cement mix: Shall comprise a pumpable, high slump mix of soil and cementitious binder with a 28 day cube strength greater than 2 MPa (SANS 2001-BE3, 2012).

Unless otherwise specified, the material shall be placed using a concrete pump or a suitable chute extending to within 3 m of the surface of the pour (SANS 2001-BE3, 2012). Free-fall placement shall only be permitted if sanctioned by the competent person and if segregation does not occur (SANS 2001-BE3, 2012).

Self-compacting concrete or soil-cement mix placed under gravity may be used for chocking the throat of a sinkhole, to plug grykes, or forming a stable working platform at the base of a sinkhole, or for mass filling of cavities or runnels (SANS 2001-BE3, 2012).

## **4.8 Chemical Grouting**

### **4.8.1 Permeation Chemical Grouting**

In South Africa, traditionally Permeation Grouting (also called pressure grouting) is used to reduce the permeability of the subsurface rock mass in areas of dam walls, by means of pumping a soil and cement slurry with relevant additives such as bentonite under high pressure into the subsurface, creating a grout curtain to ensure watertightness of the dam. The high water: cement ratio of grouting mixes used for permeation grouting in order to ensure good penetration is, however, not applicable in a dolomite environment. The high water content and viscosity of these grout mixes may cause more subsurface erosion and excessive grout losses due to grout running away. Zhou and Beck (2008) describes the use of jet grouting where the filling of a sinkhole throat is too stiff to displace with high pressure. This process involves pumping a fluid grout into the soil with a rotating high-pressure jet which erodes soil and cuts stiff clays and soft erodible rock into gravel to small boulder-sized pieces. Pressures of 30 to 50 MPa are typically used and the large soil particles, including sand and gravel in the sinkhole filling, mix with the grout to produce a mixed-in-place concrete.

Permeation chemical grouting comprises a completely fluid mixture of chemicals. It forms a stone-like material by injecting polyurethane based grout into the subsurface under pressure. The chemical grout material permeates the soil and solidifies to increase the strength of the stratum and its load bearing characteristics. This method is especially effective in shallow soils and is typically used in Florida to fill sinkhole voids and densifying loose soils that exist within 5 m of the surface.

According to the web page of the company Earthtech, the process involves drilling a hole and grouting in a sleeve port pipe (Retrieved 2014). This pipe has holes along its length and the thin grout is injected under pressure to permeate the soil and harden the granular soil into a solid mass. The resulting soil is not as permeable by water and it is much stronger for support. It may be used to strengthen existing foundations or to fill voids.

### **4.8.2 Expansive Chemical Grouting**

The injection of expansive foam that fills voids and re-levels foundations.

One such method is the URETEK Deep Injection Process (Retrieved 2014). Where the Dynamic Cone Penetrometer (DCP) testing method is used to carry out an evaluation of subsurface soils conditions in the soil or below the floor of a structure and to determine placement and volume of the geo-polymer required.

The expanding geo-polymer is placed precisely at the soil strata depth where soil compaction and densification is needed.

The URETEK geo-polymer is injected in the holes created by DCP, using a controlled, low-impact process. Multiple injections at varying depths create columns of vertical support. This 'top down' injection method is often used on shallow injection applications as it strengthens the upper layer of soil to help contain the pressures of the lower levels of compaction.

Once injected, the geo-polymer material expands up to 15 times the material's liquid volume and strengthens to 90% within 30 minutes. This rapid expansion is what causes compaction. Through this non-destructive process, soil compaction and densification occurs and void areas are filled and fully stabilized.

This method is applicable for the rehabilitation of small to medium size sinkholes located within a depth of 5 metres below ground surface.

#### **4.9 History of Sinkhole and Subsidence Rehabilitation in South Africa**

Sinkholes and subsidences on dolomite started to appear at an accelerated scale in the late 1950's to early 1960's, as a result of dewatering of dolomite compartments on the Far West Rand. The most events occurred during the period 1967 to 1996 due to dewatering, with a decrease in events from 1997 (Richardson, 2013) caused mainly by ingress water after 1997.

In the City of Tshwane very few events were reported before 1970 with more than a tenfold increase of events recorded after 1970 up to 2000 due to ingress water and periods of heavy rainfall. Since 2000 to 2010 there was a markable decrease of more than 50% events reported (Richardson, 2013).

In the Ekurhuleni Metropolitan Municipality, the Council for Geoscience only have three events recorded between 1980 to 1990, five events between 1991 to 2000 and 93 events were recorded between 2001 to 2010 of which 9 events is related to dewatering (Richardson, 2013). The marked increase in events after 2000 is due to better recording by the Ekurhuleni Metropolitan Municipality by means of the appointment of dolomite specialist consultancy companies to assist with the management of dolomite within the municipal area of jurisdiction. Heath and Keyter (1996), however, refer to the occurrence of 25 sinkholes in the Katorus area (Katlhlong, Vosloorus and Tokoza) between 1986 and 1996. Jones and Wagener (2004) recorded 19 dolomite stability events in the Katorus area during the beginning of 2004 and a total of 20 sinkholes were recorded in the Bapsfontein area in a radius of 2 km by Jones and Wagener during an inspection in 2004, after a very large sinkhole (60m diameter and 25m deep) occurred in 2004 due to excessive water abstraction for irrigation purposes by farmers, south-

west of the Bapsfontein Hotel. An additional 4 instability features were recorded in the Bapsfontein area by the company Knight Piésold during 2007. The first sinkhole within the Bapsfontein area was recorded as early as 1980 by the Department of Water Affairs.

It should, however, be noted that the first sinkhole in the Ekurhuleni Metropolitan Municipal area was recorded by Brink in the Natalspruit Dolomite Groundwater Compartment during 1964. The sinkhole appeared at the base of a 4 m deep gravel quarry adjacent to the N3 National Highway approximately 20 km north-west of the town Heidelberg, Gauteng. The sinkhole formed due to the accumulation of rainwater in the quarry causing subsurface erosion of dolomitic soils into an 18 m deep cavity situated between the quarry and the N3 National Highway. Reference is also made of the occurrence of sinkholes in the Clayville area during the 1960's (Roelofs, 1981).

Available literature, documentation or published case studies on the rehabilitation of sinkholes and subsidences in South Africa are limited. Numerous Newspaper articles, however, exist on sinkholes and subsidences that occurred on the West Rand, in the City of Tshwane and the Ekurhuleni Metropolitan Municipal areas.

Reference is made of the sinkhole or subsidence rehabilitation method used by the following authors:

#### 4.9.1 West Rand District

- De Kock (1981) refers to the use of a suspended cable bridge, comprising a heavy structural mesh, embedded in concrete with anchor beams to prevent the occurrence of a sinkhole or a subsidence along a section of approximately 8 km of the P89-1 road between Carletonville and Randfontein, prone to sinkhole formation located within the dewatered Bank Dolomite Compartment and a section of 480 m of the P89-1 road located in the dewatered Oberholzer Dolomite Compartment in an area of a palaeo-sinkhole.
- Engelbrecht (1981) refers to the use of slimes filling as a method to fill voids and stabilize the ground surface along a 120 m section of the Provincial Road P111/1 opposite the No. 4 Slimes Dam of the Blyvooruitzicht Gold Mine, after slimes from the dam had been allowed to flow into nearby sinkholes, located in the dewatered Oberholzer Compartment, during May 1980. Filling of the sinkholes was immediately stopped as a result of the suspected subsurface erosion caused by the free flowing mixture of water and slimes flowing into the sinkholes. A subsidence 120 m long and 20 m wide and up to 17 m deep in some places developed due to the free flowing slimes as proven by ten percussion boreholes, with wet slimes encountered in some boreholes. To stabilize the road surface, the voids intersected in the boreholes were filled with a thick mixture of slimes and water (1 m<sup>3</sup> dry slimes to 200 litres water) filling the cavities from the bottom upwards by using pipes placed into the boreholes. The slimes was allowed to settle during the evenings when no filling was done in order to establish a fairly compact layer before depositing the next layer of slimes when filling was resumed. Approximately 7300 m<sup>3</sup> slimes had been pumped into the voids. The slimes filling of the voids was put to the test in 1981 when a borehole was sunk next to one of the boreholes filled with slimes previously. The test borehole

intersected a similar void filled with moist slimes giving a drilling resistance and no loss of air over the total depth of the void indicating complete filling and that the injected slimes had not been transported since injection.

- Wolmarans (1984) refers to a case study where serious cracks developed in a portion of the mine offices of the Doornfontein mine housing the sampling section on 30 March 1982, after two tremors measuring 2,0 and 2,4 respectively occurred the night before. Structural crack repairs were immediately done but they re-opened a month later. A survey was then conducted on the water lines after more cracks started to appear and the observation of a wet soil zone along the western wall. A severely rusted and leaking water line of which no one knew was discovered and after more inspections more unknown water lines were discovered not indicated on the site plan. All water and sewer lines were immediately replaced. Eight boreholes were drilled of which the one drilled within the area of the wet zone revealed a cavity between a depth of 19,8 m to 32 m below ground surface. Boreholes drilled to both sides of the borehole that encountered the cavity revealed shallow dolomite bedrock. A second cavity 7 m away from the first one was encountered. Grouting of boreholes was carried out, however, after 10173 m<sup>3</sup> of grout were pumped it was clear that the cavities are not filling up and it was decided to stop with grouting. A level peg, set in a block of concrete and anchored in compacted chert rubble, was installed at a depth of 12 m in one borehole and the situation monitored for three months during which no movement occurred and the building started to stabilize.
- Gregory *et al.* (1988) refers to the use of grouting to protect a major road (P45-1) near Westonaria, covering an area of 40 m wide and 2 195 m long section, from the effects of sinkhole development on the Far West Rand prior to dewatering of the Gembokfontein Groundwater Compartment that commenced in 1986. The work was carried out by Van Wyk & Louw Incorporated. Areas of potential high risk were identified. Grouting in these areas commenced in the hole where the dolomite or cavities occurred at greatest depth. Dolomite bedrock depth varying between 10 m to 40 m and to 70 m in defined grykes. The grouting consisted of a primary, secondary and tertiary phase, resulting in a final borehole spacing of 5 m. A very viscous grout containing 10% by weight of cement and additives such as bentonite was used.
- Swart (1986) describes the stabilization of sections of a provincial road comprising a number of subsidences, midway between Carletonville and Westonaria. A mixture, consisting of 20 parts slimes, 1 part cement and sufficient water to make a fluid, was poured into uncased boreholes, until they were full. Laboratory tests conducted by Venter in 1985 revealed that grout with a cement content of 4% will develop a compressive strength comparable to a very dense soil.
- Swart (1991 and 2001) describes the results of more than 50 grouting projects, conducted over a period of 17 years, aimed at the geotechnical improvement of building sites in the Far West Rand area. These projects involved the drilling of a number of boreholes per site to evaluate the weathering of the dolomite bedrock and the spatial relationship of features such as cavities and zones of poorly compacted residual material that could lead to ground surface instability. Five different typical `dolomitic conditions` were identified, namely:

- Throats, typically 8 m in diameter.
- Basins, typically 35 m in diameter. Volume of grout can be excessive with the possibility that the subsurface cavity is not completely filled.
- Troughs, typically 150 m wide.
- Horizontal cavities.
- Naturally stabilized surficial material.

Grouting was carried out at all of the sites by means of injecting a mixture of mine tailings (slimes) 63%, cement (3,5%) and water (32%) to prevent further ground movements. Some boreholes were gravity fed with the grout mix or grout was injected up to a maximum pressure of 1 MPa. The grouting programmes carried out at the various sites were regarded as successful, however, 10% of the 3000 boreholes that were grouted accepted excessive quantities of grout and was ascribed to unrestrained lateral subsurface flow of grout to a point well beyond the boundaries of the grouting site.

- An oblong-shaped depression of 0,1 m deep with its long axis measuring 10 m in length was noted on the north to south aligned Provincial Road P61/3, 1 km north of Carletonville in 1983 (Swart, 2001). The depression was investigated and grouted under pressure (only in 1999) by means of 30 boreholes during 1983 and in 1999 to stabilize the ground. Boreholes on the eastern side of the road encountered more cavernous conditions and deeper bedrock than boreholes drilled to the west of the road. At all times the viscosity of the grout was maintained at between 250 and 280 mm on the Colcrete flowmeter, by adjusting the water content of the mixture. After some 837 m<sup>3</sup> of conventional grout used on the West Rand (mine tailings mixed with 5% cement) had been accepted, the mix was thickened (10% cement) in an attempt to stem the lateral flow of grout. A gravity survey conducted in 1998 revealed that the depression is associated with a gravity trough located to the east of the road, that may present a much larger cavernous feature than expected and explain the very large grout acceptance in boreholes. Additional boreholes were drilled in the road and grouted with a mixture of slimes with 10% cement and 4% CaCl as an accelerator. However the level of grout remained at 22 m depth and very high grout takes were recorded. It was decided to discontinue grouting as grout was still escaping from the targeted area along a cavernous zone between 20 m and 29 m below natural ground level, with grout probably flowing towards the east and the cavernous ground below the road could not be stabilized by means of a slimes/cement grout mixture because of uncontrolled lateral flow.

It was then decided to construct subsurface barriers by pouring concrete (25 MPa pump mix with a 150 mm slump) into closely spaced (1 m apart) boreholes (250 mm diameter) located along three lines. The first line was positioned on the eastern side of the road, the second on the western side of the road and the third between and perpendicular to line 1 and line 2 over the road. The total volume of concrete required for the three barrier lines was 100 m<sup>3</sup> and thereafter only 111 m<sup>3</sup> of slimes/cement grout was required to fill the critical zone below the road. The road was opened for traffic again in July 1999.



- Roux *et al.* (2013) describes the use of the dynamic compaction and grouting methods to rehabilitate three sinkholes. Two sinkholes, each approximately 10 m in diameter occurred on the northern side of the N14 National Road near Carletonville in December 2007, due to a silted up box culvert. A third sinkhole of approximately 4 m diameter appeared on the southern side of the road shortly after the first two occurred. The dolomite bedrock was intercepted at 7 m to 25 m in the nine boreholes drilled in or immediately adjacent to the sinkhole area. A total of 116 boreholes were drilled as primary (grid spacing of 3,4 m) and secondary points to inject grout. The grouting mix of 2 MPa strength was limited to a maximum slump of 150 mm. A total of 406,98 m<sup>3</sup> volume of grout was pumped into the boreholes to stabilise the area. In addition the stormwater system was upgraded and a new road constructed, before the 14 km section of the N14 road was reopened.

#### 4.9.2 City of Tshwane

- In 1973 sinkholes occurred due to surface water ponding during the relocation of the Germiston-Pretoria railway line (Jennings, 1966). In 1937 to 1938 the southern abutment of the Fountains Viaduct in Pretoria subsided into a compressible layer of residual dolomite (wad). The southern abutment of the bridge was placed on a 2 m thick hard chert as determined by a 2 m long jack hammer. Unfortunately the chert was underlain by a 2 m thick layer of residual dolomite (wad) followed at depth by competent chert and dolomite. The abutment was underpinned by excavating the residual dolomite (wad) in sections down to a depth of 4 m and back-packing the excavation with bags of a dry sand and cement mix which was then wetted in place. No further movement has been recorded, and the bridge is still in daily use.
- After the culvert was lengthened in concrete to accommodate double lines in 1937 the eastern bypass comprising a cut and fill operation unfortunately altered the natural drainage causing surface water ponding along the railway line at specific discharge points into the field, causing the formation of sinkholes due to the concentration of large quantities of water (Rauch, 1981). The ground under the railway lines was affected by this over a distance of 150 m. It was decided to build a temporary deviation and investigate the affected area. All dolomite pinnacles were exposed by means of excavation and the excavation areas between pinnacles was backfilled with dump rock to form a rock layer wedged in between buttresses of solid dolomite; followed by compacted earthfill up to original ground level and restoring of the earth embankment before replacing the electrified double lines in their original position (Rauch, 1981).

#### 4.9.3 Ekurhuleni Metropolitan Municipality

- Knight Hall Hendry and Associates (1993) repaired a very large subsidence with peripheral cracks that occurred along the R25 (or P6) Provincial Road, just north of the crossing between the R50 and R25 Roads at Bapsfontein by means of grouting.
- A very large subsidence (20 m diameter and 0,3 m deep) along the R25 Road just north of the former Bapsfontein Informal Settlement was investigated by Gautrans

during 2004 and rehabilitation work carried out. It is, however, uncertain what was done in terms of rehabilitation at that time. It was observed on 11 October 2007 during a site visit by the author to the Bapsfontein area that the subsidence was re-activated with a trend towards the former Bapsfontein Informal Settlement measuring 50 m in diameter and 0,3 m deep. The re-activated subsidence was rehabilitated by means of a combination of Dynamic Compaction and the Inverted Filter Method by the company Vela VKE around 2010.

#### 4.9.4 General

- Day (1981) and Wagener (1985) describes the use of dumprock and chert gravel mattresses (also referred to as an engineering designed soil raft) of 2 m to 8 m thickness (although in excess of 4 m are seldom used) as a reduction method of the risk of sinkhole formation at shallow depth. This can be referred to now a day as the use of the Inverted Filter Method. Mattresses can be used on profiles with shallow, intermediate or deep soil cover. Wagener (1995), Type A (pinnacle and boulder dolomite less than 3 m from natural ground surface), B (pinnacle and boulder dolomite overlain by moderately thick overburden between 3 m and 15 m below natural ground surface) or C (pinnacle and boulder dolomite overlain by thick overburden more than 15 m below natural ground surface) profiles. The main advantage is a reduction in bearing pressure on the underlying material and the control of both total and differential settlements.

## 5. SINKHOLES AND SUBSIDENCES ON THE EAST RAND

In order to understand the formation of sinkholes and subsidences of a specific study area, the related geology and geohydrology and more specific the dolomite in that area, extensive research and investigations ranging from site specific to regional level are required.

The author is fortunate enough to be involved with the dolomite risk management of the Ekurhuleni Metropolitan Municipal (EMM) area of jurisdiction on the East Rand, as consultant on an as and when required basis, since mid-2005. As part of the Dolomite Risk Management Strategy (DRMS) for EMM, policies and procedures have been developed over the years to reduce the likelihood of sinkholes and subsidences occurring. This involved the gathering of data, creating a regional database system, undertaking education and public awareness campaigns, developing emergency reaction plans and formulating policies for appropriate future land use development. The multi-faceted approach to manage the dolomite areas in EMM entail the following (Sudu and Kleinhans, 2014):

- A communication campaign was launched in 2007 to raise public awareness and a municipal training programme was launched in 2011 on the requirements and specifications for development on dolomite land to inform municipal employees working in dolomite areas. The communication campaign included the distribution of pamphlets and CD's to various reader groups (school children, home-owners, farmers, students).
- Evaluation of all township developments on dolomite land since end of 2007 to ensure the required investigations and land-use comply with current dolomite specifications. All building plans for sites on dolomite have been evaluated since 2011 to ensure foundation design and all wet services comply with dolomite specifications.
- Development of a Global Information System (GIS) for dolomite land to assist in the decision making and planning processes was launched in 2008, and consisting of the following layers: Cadastral information, topographical data, regional geology, dolomite land distribution, dolomite groundwater information, site specific investigations, residual gravity, borehole positions, ground movement incidents (sinkholes, subsidences and mine related) and regional Dolomite Hazard Zonation.
- Specific areas were identified on dolomite land requiring upgrade of existing water bearing services. However, funds were not as yet allocated to execute the required work.
- The monitoring of groundwater levels and abstraction in the various dolomite groundwater compartments within the EMM area of jurisdiction: A groundwater monitoring drilling programme, including the drilling of approximately 80 boreholes, was conducted during the period 2009 to 2011 for the Southern Region of EMM, with the drilling planned for the Northern Region in the 2013 to 2014 financial year and for the Eastern Region in the 2014 to 2015 financial year. Limited groundwater monitoring boreholes exists in the Northern and Eastern Regions. Groundwater levels

are measured on a three month interval since 2010 by the dolomite consultants of EMM, thereby creating a groundwater level database. Quarterly meetings are held between EMM, Council for Geoscience (CGS) and Department of Water Affairs (DWA) as part of the monitoring and control of groundwater in EMM. For new residential developments on dolomite land, a guarantee letter of 'Groundwater monitoring and control' signed by the EMM must be submitted by the dolomite competent person to the CGS, if the development of such an area is located within one of the dolomite groundwater compartments located within the EMM area of jurisdiction.

- Emergency Reaction Plan: As and when required tenders are in place for geophysical investigations, dolomite specialist consultants, percussion drilling, Dynamic Probe Super Heavy (DPSH) testing and sinkhole rehabilitation by a specialist contractor, since 2010. Thereby immediate actions can be taken if a sinkhole occurs, by a highly trained and dedicated reaction team.
- A Dolomite Policy and By-Laws for development on dolomite land was developed during 2012 and 2013, taking cognisance of the regulations as specified in SANS 1936. This is currently in the public domain as part of the Public Participation process and will be implemented soon.
- Establishing a Geotechnical Department: The appointment of the necessary dolomite competent professionals to manage and control dolomite risk within EMM is in progress.

As mentioned very little is known on the formation of sinkholes and subsidences on the East Rand in the Ekurhuleni Metropolitan Municipal area. Apart from the sinkholes and subsidences that have occurred in the Bapsfontein area that are well documented and recorded by Jones and Wagener (between 2004 and 2005) the then consultants of EMM, no other scientific publications or papers could be found on the sinkholes or subsidences of the East Rand and no published information is available on the rehabilitation of sinkholes and subsidences on the East Rand.

It is therefore the intention to present the experience gained during the last ten years, specifically on the occurrence of sinkholes and subsidences on the East Rand and the rehabilitation work performed.

## **5.1 Geology of the Ekurhuleni Metropolitan Municipal area on the East Rand**

The regional geology of the study area based on the 1:250 000 scale published geological map of Pretoria (2528) and the East Rand (2628) is indicated on Figure 17. The different Formations of the Malmani Subgroup are indicated on Figure 4.

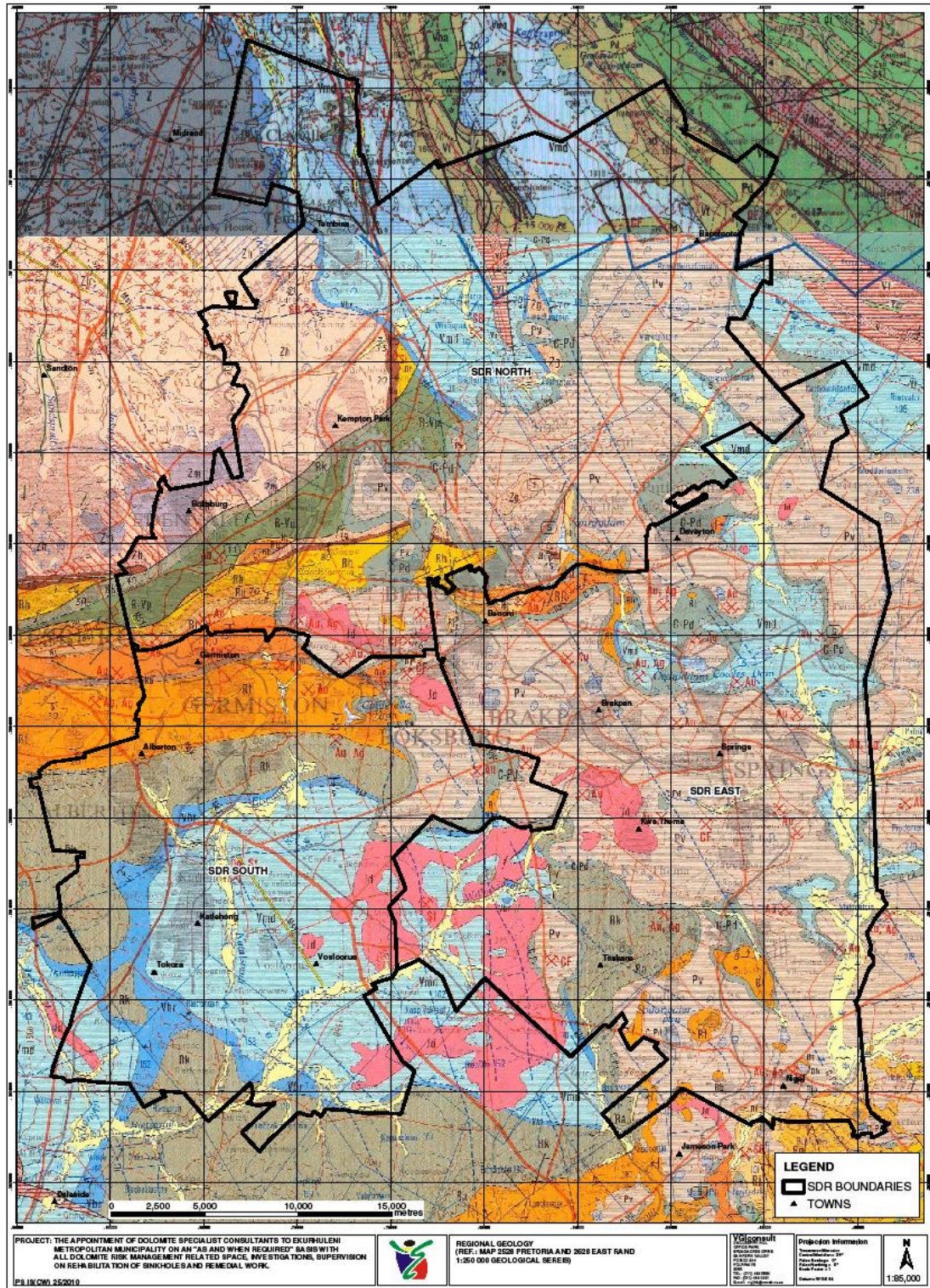


Figure 17: Published 1:250 000 geological maps of Pretoria (2528) (after Geological Survey of South Africa, 1978) and the East Rand (2628) (after Geological Survey of South Africa, 1986).

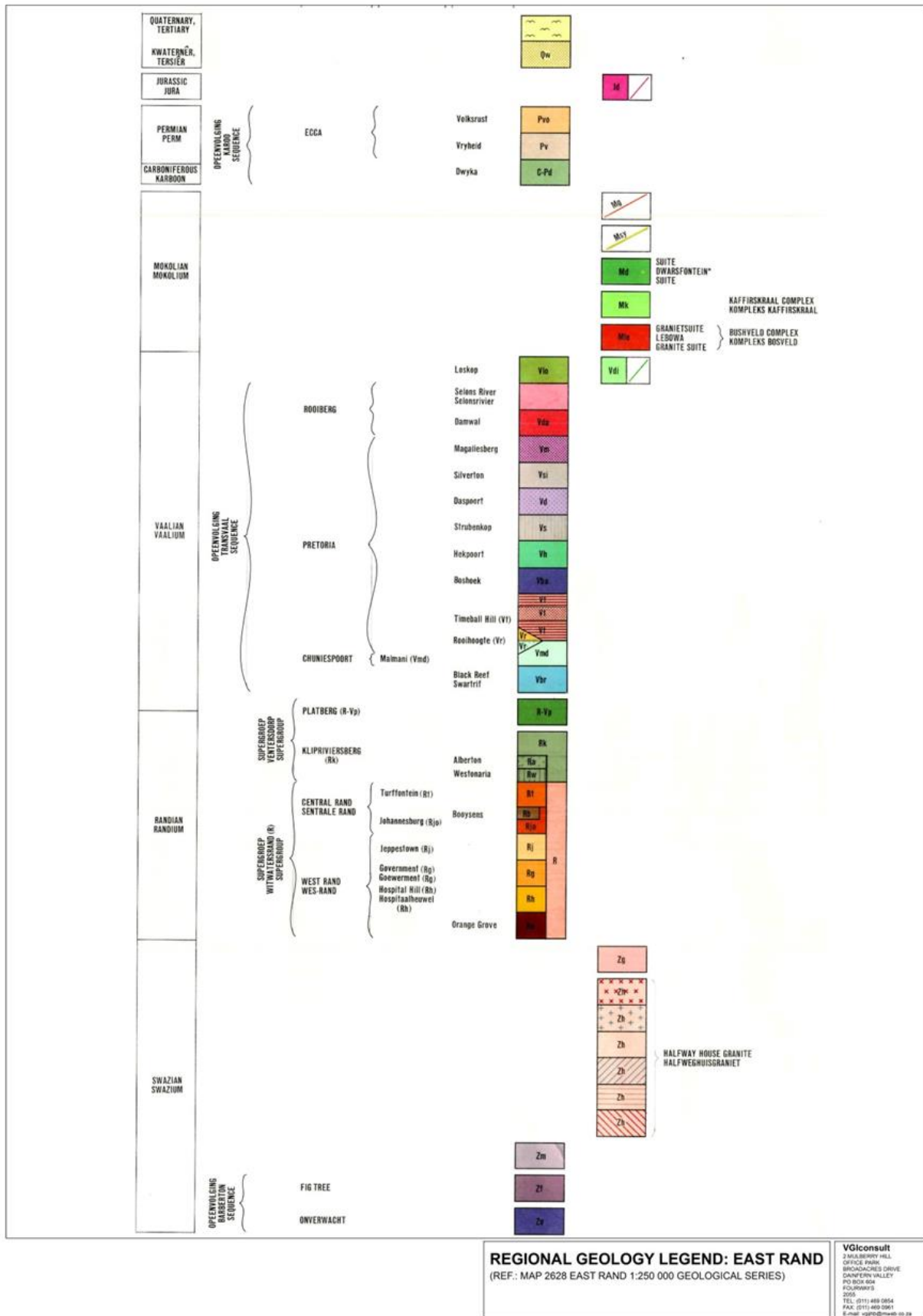


Figure 17: Regional Geology Legend - East Rand

### 5.1.1 Southern Regional Area

The Southern Region of the Ekurhuleni Metropolitan Municipal Area is underlain by the following:

- More than 50% of the Southern Regional area is directly underlain by dolomite and chert with localized shale bands, of the Monte Christo Formation, Malmani Subgroup of the Chuniespoort Group of the Transvaal Supergroup.
- The Malmani Subgroup is bordered by quartzite, shale, conglomerate, and wad in places, of the Black Reef Formation to the north, west and south.
- The Black Reef Formation is bordered by basaltic lava, agglomerate and tuff of the Klipriviersberg Group of the Ventersdorp Supergroup to the north, west and south. An isolated portion of the Klipriviersberg Group is also present within the Black Reef Formation in the south-western portion of the Southern Regional area.
- Sandstone, shale and carbonaceous shale of the Vryheid Formation of the Ecca Group of the Karoo Supergroup occur in the north-eastern portion of the area. Diamictite and shale of the Dwyka Formation of the Karoo Supergroup occurs sporadically around the Vryheid Formation.
- The dolomite and chert is intruded by dolerite sills of the Karoo Supergroup in the eastern portion of the area and in the south-western corner.
- Syenite intrusions may be encountered occasionally. A prominent north-west to south-east aligned syenite intrusion occurs in the central Natalspruit Dolomite Groundwater Compartment.
- Rocks of the Turffontein Subgroup (quartzite, sandy shale and conglomerate) and the Johannesburg Subgroup (quartzite and conglomerate) of the Central Rand Group of the Witwatersrand Supergroup occur in the northern portion of the study area.
- Recent deposits mainly alluvial associated with the Elsburgspruit, Natalspruit and Rietspruit all flowing southwards into the Klipriver occurs in the area.

### 5.1.2 Northern Regional Area

The Northern Region of the Ekurhuleni Metropolitan Municipal Area is underlain by the following:

- The northern portion of the Northern Regional area is directly underlain by dolomite of the Malmani Subgroup. From west to east by, chert-poor dolomite of the Oaktree Formation, chert-rich dolomite of the Monte Christo Formation, chert-poor dolomite of the Lyttelton Formation and chert-rich dolomite of the Eccles Formation. Dolomite of the Monte Christo Formation is also encountered in the south-eastern portion of the area.
- Shale and quartzite of the Timeball Hill Formation of the Pretoria Group of the Transvaal Supergroup is sandwiched between the dolomites of the Malmani Subgroup in the northern portion of the area. The Timeball Hill Formation also occurs

as a second north-west to south-east aligned ridge in the north-eastern corner of the study area.

- North-west to south-east aligned syenite intrusions are present within the dolomite, especially in the Tembisa and Clayville areas. A number of large syenite intrusions are present within the area acting as groundwater barriers, compartmentalizing the dolomite.
- The Malmani Subgroup in the northern portion of the area is bordered by quartzite, shale, conglomerate, and wad in places, of the Black Reef Formation to the west and by diamictite and shale of the Dwyka Formation of the Karoo Supergroup to the south and east. Patches of undifferentiated granite and gneiss of Swazian age and sandstone and shale of the Vryheid Formation of the Karoo Supergroup exist in the dolomites. The Malmani Subgroup encountered in the south-eastern portion of the area is bordered by diamictite and shale of the Dwyka Formation all around.
- Sandstone, shale and coal beds of the Vryheid Formation of the Ecca Group of the Karoo Supergroup are encountered between the two areas indicated as directly underlain by dolomite of the Malmani Subgroup. However, the Vryheid and Dwyka Formations of the Karoo Supergroup are underlain by dolomite at depth and as such these areas are also regarded as dolomitic land. Dolerite intrusions of the Karoo Supergroup occur in the southern portion of the area.
- The Black Reef Formation to the west is bordered by granite and gneiss of the Pretoria-Johannesburg inlier of Swazian age (also called the Halfway House Granite Dome), Orange Grove Formation (quartzite with interbedded shale and conglomerate) and Hospital Hill Subgroup (partially ferruginous shale, quartzite and banded ironstone) of the West Rand Group Witwatersrand Supergroup, Platberg Group (breccia, conglomerate, greywacke and shale) and Klipriviersberg Group (basaltic lava, agglomerate and tuff) of the Ventersdorp Supergroup.
- Rocks of the Central and West Rand Group of the Witwatersrand Supergroup occur in the southern portion of the study area.
- Recent deposits mainly alluvial associated with the Kaalspruit and Blesbokspruit and its tributaries occur in the northern and south-eastern portion of the area.

### 5.1.3 Eastern Regional Area

The Eastern Region of the Ekurhuleni Metropolitan Municipal Area is underlain by the following:

- More than 50% of the Eastern Regional area is regarded as dolomite land, with large portions of the dolomite of the Monte Christo Formation and the Oaktree Formation of the Malmani Subgroup of the Chuniespoort Group of the Transvaal Supergroup covered by sandstone, shale and coal beds of the Vryheid Formation of the Ecca Group of the Karoo Supergroup. The dolomite is typically directly surrounded by diamictite and shale of the Dwyka Formation of the Karoo Supergroup. Dolomite of the Monte Christo Formation also occurs in the south-western portion of the area, intruded by a large number of Karoo Supergroup dolerite sills and dykes.



- The Malmani Subgroup is bordered by shale and quartzite of the Black Reef Formation in sub-areas.
- Basaltic lava, agglomerate and tuff of the Klipriviersberg Group of the Ventersdorp Supergroup are present in the southern portion of the Eastern Regional area.
- Rocks of the Turffontein Subgroup and the Johannesburg Subgroup of the Central Rand Group of the Witwatersrand Supergroup occur in the northern and southern portion of the study area. Shale, quartzite, conglomerate and amygdaloidal lava of the Jeppestown Subgroup and quartzite, greywacke, conglomerate, shale and tillite of the Government Subgroup, both of the West Rand Group, Witwatersrand Supergroup occurs in the south-eastern corner of the area.
- Recent deposits mainly alluvial associated with the Rietspruit and Blesbokspruit and its tributaries occur in the eastern and south-western portion of the area.

#### 5.1.4 Typical Soil Profiles on Dolomite on the East Rand

Two typical dolomite profiles are illustrated in Figure 18. The upper figure (after Wagener, 1985) illustrates a shallow dolomite bedrock environment, while the lower figure (after Waltham and Fooks, 2003) illustrates a shallow and deep dolomite bedrock environment.

##### 5.1.4.1. *Southern Regional Area*

The typical dolomite profiles anticipated in the Southern Region of the Ekurhuleni Metropolitan Municipal Area are as follows:

- The dolomite bedrock is regarded as shallow or close to ground surface with grykes (narrow deeply weathered dolomite zones typically filled with residual dolomite (wad)). However, dolomite bedrock has also been encountered as outcrop at ground surface and to a maximum depth of approximately 45 m, as proven by numerous dolomite stability investigations carried out in the area.
- The blanketing layer above dolomite bedrock may typically comprise of one of the following:
  - Colluvium and or residual chert underlain by residual dolomite (ferroan soils and wad). Residual shale may also be encountered in sub-areas in the profile.
  - Residual dolomite (wad and / or ferroan soils), with or without a colluvium cover.
  - Colluvium and residual chert.
  - In areas of Karoo cover: Colluvium, residual sandstone and / or shale, underlain by residual chert and / or residual dolomite (ferroan soils and /or wad). Materials of the Dwyka Formation may be encountered in sub-areas below the colluvium.
  - Colluvium and residual syenite, underlain by residual dolomite (ferroan soils and /or wad). Or the residual dolomite is underlain by residual syenite in sub-areas.

- Residual dolerite in areas of dolerite intrusions (sills and dykes).

The first two profiles presented above are encountered the most in the Southern Region.

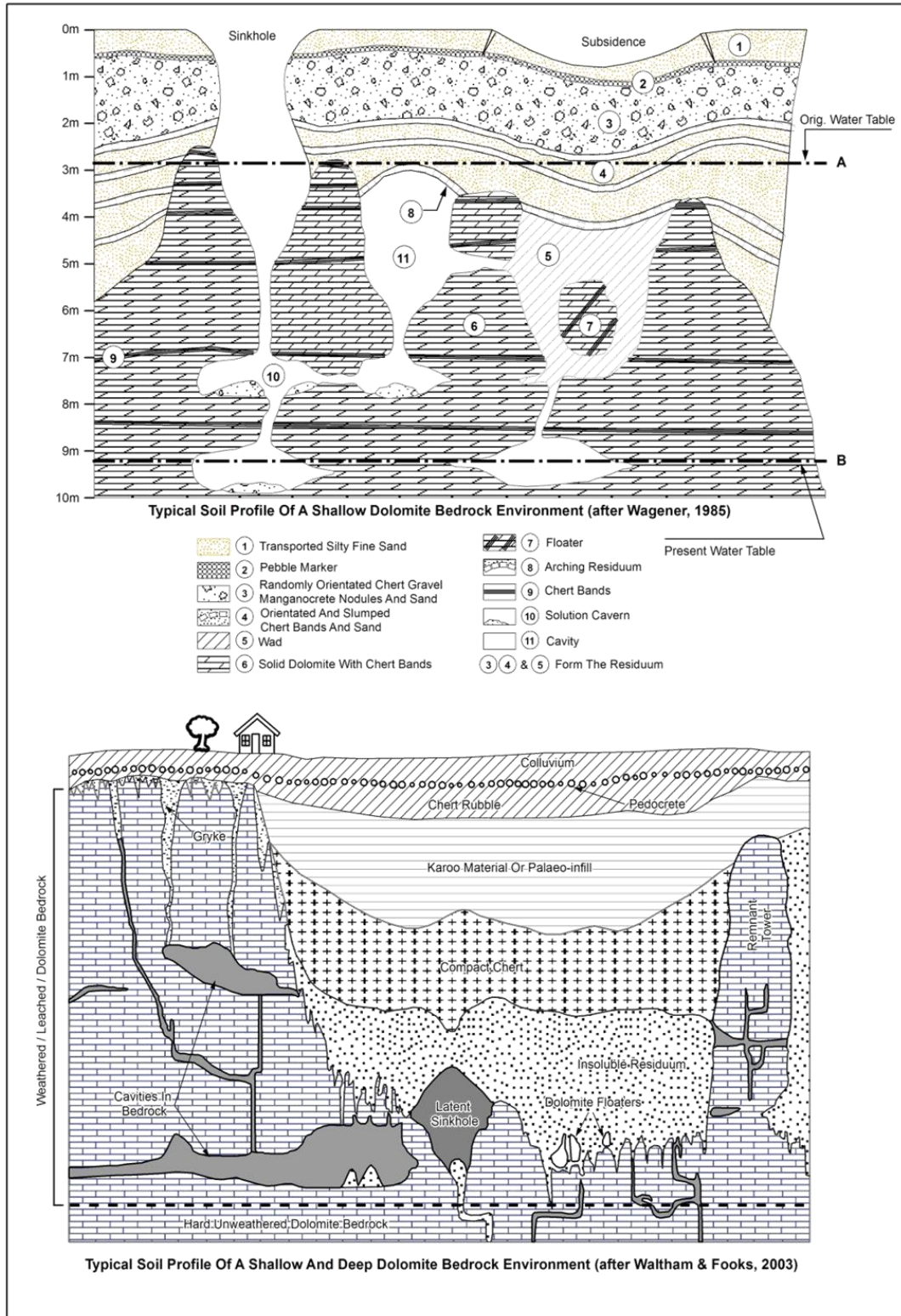


Figure 18: Typical Dolomite Profiles

#### 5.1.4.2. *Northern Regional Area*

The typical dolomite profiles anticipated in the Northern Region of the Ekurhuleni Metropolitan Municipal Area are as follows:

- The dolomite bedrock varies considerably, from dolomite bedrock at ground surface to a depth of more than 60 m and even more than a 100 m (sub-areas in the Bapsfontein dolomite region).
- The blanketing layer above dolomite bedrock may typically comprise of one of the following:
  - Colluvium and or residual chert (and residual chert interlayered with residual syenite or residual shale in sub-areas), underlain by residual dolomite (ferroan soils and wad).
  - Colluvium and residual chert (and residual chert interlayered with residual syenite or residual shale in sub-areas).
  - In areas of Karoo cover or inliers: Colluvium, residual sandstone and / or shale, underlain by residual chert and / or residual dolomite (ferroan soils and /or wad). Materials of the Dwyka Formation may be encountered in sub-areas below the colluvium. Or colluvium and residual sandstone and / or shale.
  - Colluvium and residual syenite, underlain by residual dolomite (ferroan soils and /or wad).
  - Thin to very thick horizon of residual dolomite (wad and / or ferroan soils), with or without a colluvium cover.
  - Residual syenite in areas of syenite intrusions (sills and dykes).

#### 5.1.4.3. *Eastern Regional Area*

The typical dolomite profiles anticipated in the Eastern Region of the Ekurhuleni Metropolitan Municipal Area are as follows:

- The dolomites in the eastern portion generally presents a deep profile with dolomite bedrock typically encountered at a minimum depth of 20 m and a maximum depth of more than 60 m and even more than 100 m. However, some geopractisioners encountered dolomite bedrock at a depth as shallow as 4 m below natural ground level.

The dolomite encountered in the south-western portion presents similar conditions as encountered in the Southern Region.

- The blanketing layer above dolomite bedrock may typically comprise of one of the following:
  - In areas of Karoo cover or inliers: Colluvium, residual sandstone and / or shale, underlain by residual chert and / or residual dolomite (ferroan soils and /or wad). Materials of the Dwyka Formation may be encountered in sub-areas

below the colluvium. Or colluvium and residual sandstone and / or shale to a depth of more than 100m.

- Colluvium and residual chert. Or colluvium and residual chert (and residual chert interlayered with residual syenite in sub-areas).
- Colluvium and or residual chert (and residual chert interlayered with residual syenite or residual shale in sub-areas), underlain by residual dolomite (ferroan soils and wad).
- Residual dolerite in areas of dolerite intrusions (sills and dykes).

## 5.2 Geohydrology of the Dolomite Groundwater Compartments of the Ekurhuleni Metropolitan Municipal Area

Since 2008 the Ekurhuleni Metropolitan Municipality has been monitoring a number of boreholes in the Natalspruit Dolomite Groundwater Compartment. In June 2010, 49 additional boreholes were drilled to augment the existing monitoring network. In 11 of these boreholes, no groundwater levels were recorded at the time of drilling and establishment. However in four of these eleven boreholes, groundwater levels were recorded in the July monitoring cycle. The engineering geological log of each borehole with co-ordinates, a photo of each well and the groundwater levels of each borehole presented in a series of graphs is captured and updated on a quarterly base on the EMM dolomite database.

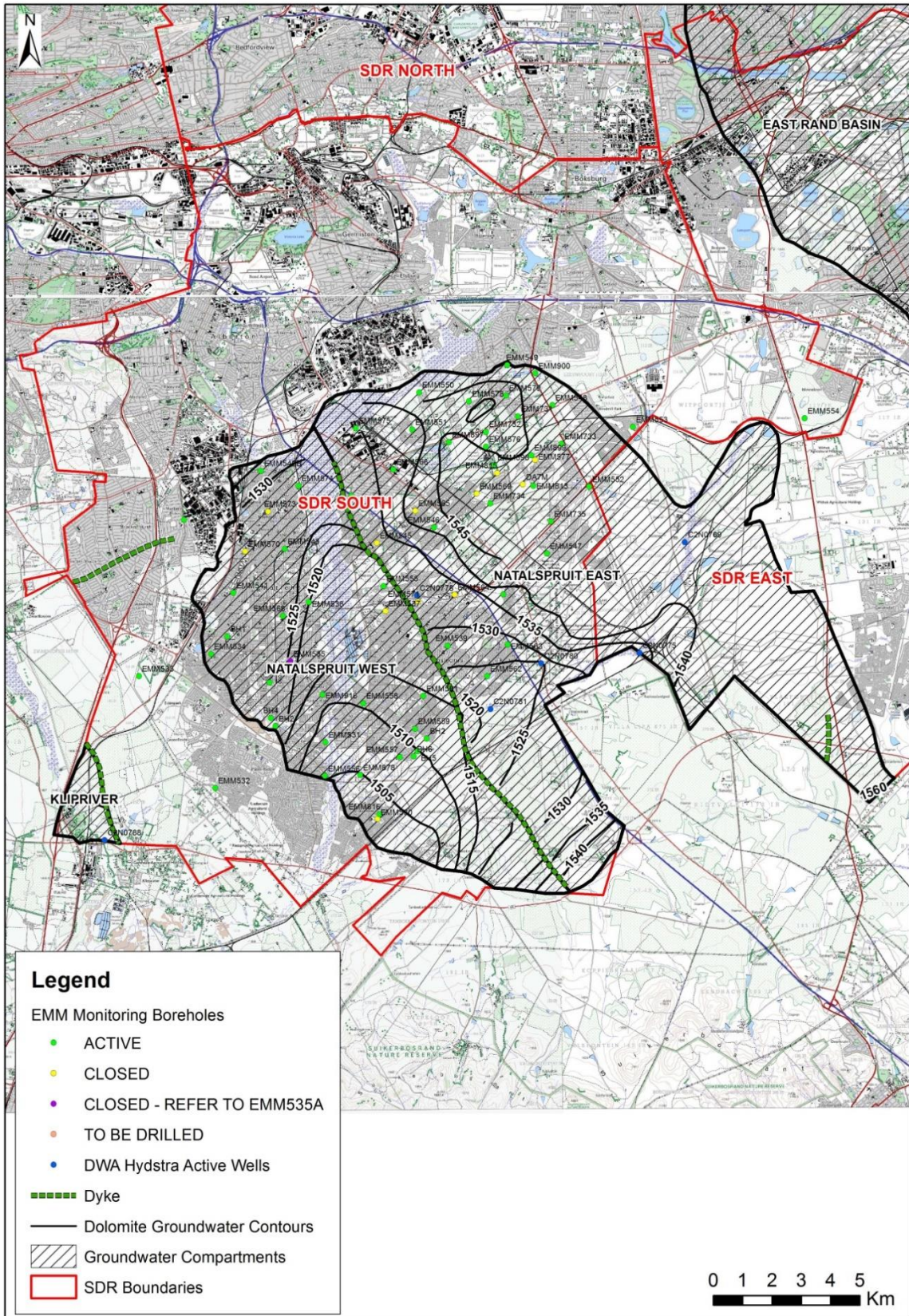
In addition, since the 1960's the Department of Water Affairs has been maintaining a monitoring network in the greater Ekurhuleni Metropolitan Municipal area. Dolomite groundwater level results have been requested for selected monitoring stations within the Southern Region. This information is also presented in a series of graphs and the monitoring stations were visited, photos taken and co-ordinates verified.

### 5.2.1 Southern Regional Area

The various dolomite groundwater compartments, groundwater elevation contours in metres above mean sea level (mAMSL) and the groundwater monitoring boreholes for the Southern Region of the Ekurhuleni Metropolitan Municipality is presented in Figure 19.

A total of 71 groundwater monitoring boreholes have been drilled in the Southern Region, of which 58 was still active by mid-2013 and 13 was lost due to vandalism (Figure 19). Four active DWA groundwater monitoring boreholes exist within the Southern Region (Figure 19). An additional 13 EMM groundwater monitoring boreholes are to be drilled in selected areas requiring more intensive monitoring.

According to the Directorate of Geohydrology of the Department of Water Affairs report number GH3408, the Southern Region falls within the catchment area of the Natalspruit. Several syenite and diabase dykes with a preferred North-South and North-west to South-east orientation form impervious barriers in the dolomite aquifer, compartmentalising the dolomite.



**Figure 19: Dolomite groundwater compartments, groundwater elevation contours and groundwater monitoring boreholes for the Southern Region (VGIconsult Projects Dolomite Database, 2014).**

Various sub-horizontal sills intrude the sedimentary strata and extend as outcrops in a westerly direction as far as the eastern bank of the Natsalspruit. On a regional scale groundwater levels indicate groundwater flow converging on to main streams and southwards towards the Vaal River. Stream water levels coincide with groundwater levels throughout the dolomite area.

The Natsalspruit basin is characterized by a subdued topography. The basin is drained by the Rietspruit, the Elsburgspruit and the Natsalspruit. The Rietspruit joins the Klipriver south of Klipriver town where it flows southwards to join the Vaal River at Vereeniging.

Groundwater levels converge on the streams of the Natsalspruit, Elsburgspruit and Rietspruit. The NW-SE orientated dyke through Vosloorus Township forms a long groundwater barrier, subdividing the Natsalspruit Dolomite Groundwater Compartment into the Natsalspruit West and Natsalspruit East Sub compartments. A step occurs along its entire length except where the dyke crosses the Rietspruit and groundwater crosses the barrier (Figure 19).

The groundwater level in the Natsalspruit-West Sub-Compartment varies from 1505 m AMSL in the South to 1530 m AMSL in the North. The groundwater level in the Natsalspruit-East Sub-Compartment varies from 1520 m AMSL in the South-west to 1560 m AMSL in the South-east.

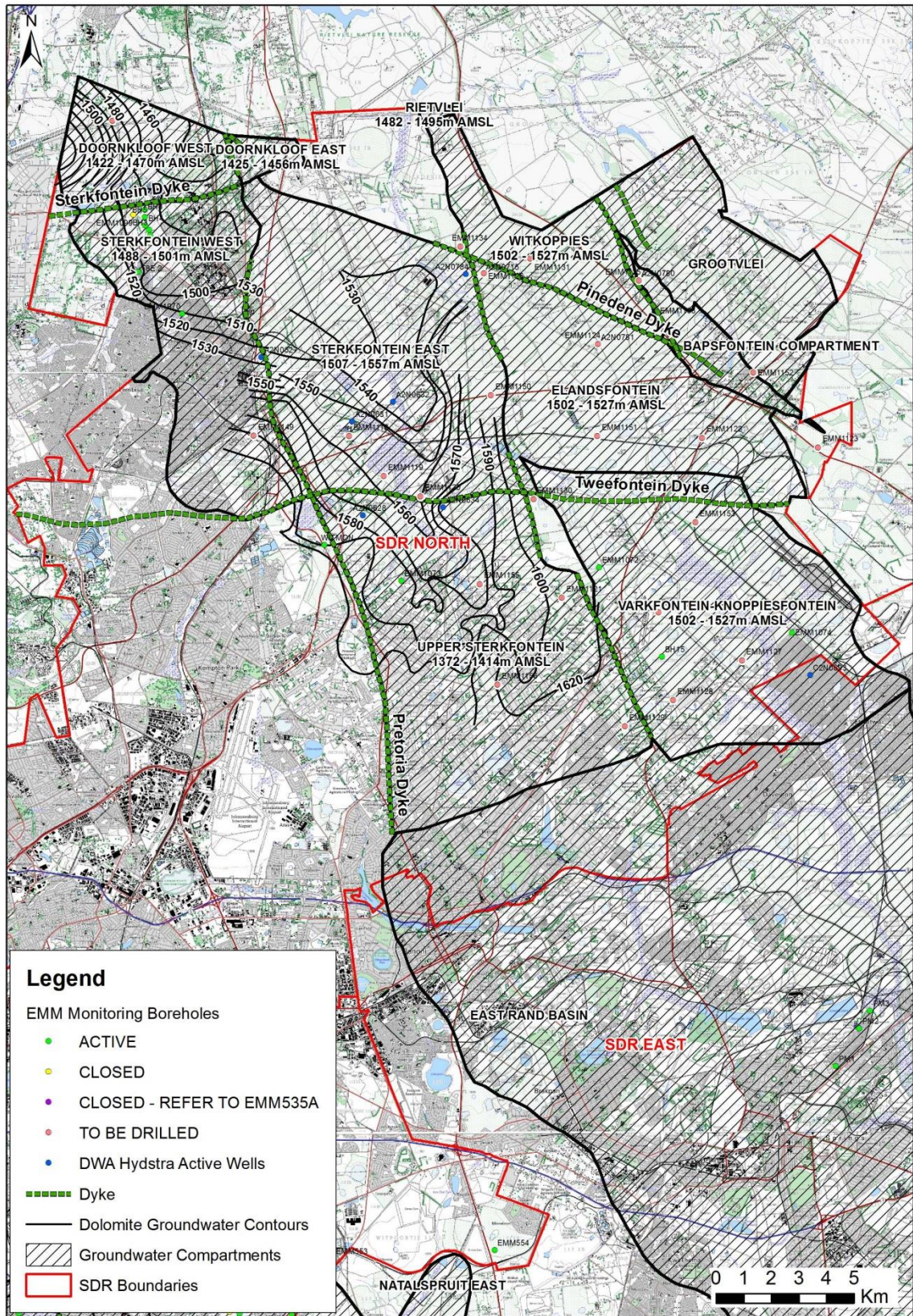
The Natsalspruit Compartment experiences a positive mean net change in hydrostatic head as observed from the earliest to the most recent rest water levels on record. This is confirmed by the raw data sourced from the Department of Water Affairs.

### 5.2.2 Northern Regional Area

The various dolomite groundwater compartments, groundwater elevation contours in metres above mean sea level (m. AMSL) and the groundwater monitoring boreholes for the Northern Region of the Ekurhuleni Metropolitan Municipality is presented in Figure 20.

A total of 16 groundwater monitoring boreholes have been drilled in the Northern Region, of which 15 was still active by mid-2013 and 1 was lost due to vandalism (Figure 20). Nine DWA groundwater monitoring boreholes exist within the Northern Region of which the status (active or closed) is unknown (Figure 20). Twenty-six additional groundwater monitoring boreholes are planned.

The geohydrology of the dolomite aquifers south of Pretoria, stretching to Kempton Park on the East Rand was investigated in detail in the 1980's by various officials of the Department of Water Affairs. In 2004 the Department commissioned the investigation of this water resource, situated in Quaternary catchments A21A and A21B within the Crocodile (West) and Marico Water Management Area, due to rapid urbanization and extensive agricultural activity.



**Figure 20: Dolomite groundwater compartments, groundwater elevation contours and groundwater monitoring boreholes for the Northern Region (VGIconsult Projects Dolomite Database, 2014).**

According to the Directorate of Geohydrology of the Department of Water Affairs project number 2002-316, the Northern Region can be subdivided into the following Dolomite Groundwater Compartments and Sub-Compartments from north to south:

- Doornkloof West Sub-Compartment: This compartment is confined by the Johannesburg-Pretoria Granite Inlier (also called the Halfway House Granite Dome) to the west, Irene Dyke to the north, the Pretoria Dyke to the east and the Sterkfontein Dyke to the south. The groundwater level in the compartment varies from 1422 m AMSL in the west to 1570 m AMSL in the north-east.
- Doornkloof East Sub-Compartment: This compartment is confined by the Irene Dyke in the north, Pretoria Group in the east, Sterkfontein Dyke in the south and Pretoria Dyke in the west. The average groundwater level in the compartment varies from 1425 m AMSL to 1456 m AMSL.
- Rietvlei Compartment: This compartment is confined by the Pretoria Group in the north, east and west and the Sterkfontein Dyke and Witkoppies Compartment in the south. The Sterkfontein Dyke forms the southern boundary of the Rietvlei Compartment. Large-scale pumping of groundwater from the compartment has resulted in the lowering of the groundwater table and consequently drying-up of springs. The average groundwater level in the compartment varies from 1482 m AMSL to 1495 m AMSL.
- Sterkfontein-West Sub-Compartment: This compartment is confined by the Johannesburg-Pretoria Granite Inlier (also called the Halfway House Granite Dome) to the west, the Sterkfontein Dyke to the north, the Pretoria Dyke to the east and the Tweefontein Dyke to the south.

The groundwater level in the compartment varies from 1490 m AMSL in the north-east to 1530 m AMSL in the south-east. The average value for this compartment varies between 1488 m AMSL to 1501 m AMSL.

- Sterkfontein-East Sub-Compartment: This compartment is confined by the Pinedene Dyke in the north, a non-continuous dyke to the west and the Tweefontein Dyke to the south. The groundwater level in the compartment varies from 1530 m AMSL in the north to 1560 m AMSL in the south. The average value for this compartment varies between 1507 m AMSL to 1557 m AMSL.
- Witkoppies Compartment: This compartment is confined by the Pretoria Group in the west, the Grootvlei Compartment and a dyke to the east, the Sterkfontein Dyke in the north and the Pinedene Dyke in the south. The average groundwater level in the compartment varies from 1502 m AMSL to 1527 m AMSL.
- Grootvlei Compartment: This compartment is confined by the Pretoria Group in the north-east and the Bapsfontein Compartment in the south-west. No groundwater levels are available for the Grootvlei Compartment.



- Bapsfontein Compartment: This compartment is confined by the Pinedene Dyke to the south to south-west and bordered by the Grootvlei Compartment to the north and north-east. No groundwater levels are available for the Bapsfontein Compartment.
- Elandsfontein Compartment: This compartment is confined by the Pinedene Dyke to the north and north-east, the Tweefontein Dyke to the south and a non-continuous dyke to the west. The average groundwater level in the compartment varies from 1502 m AMSL to 1527 m AMSL.
- Upper Sterkfontein Compartment: This compartment is confined by the Tweefontein Dyke in the north, a non-continuous dyke in the east and bordered by the East Rand Basin to the south. The groundwater level in the compartment varies from 1560 m AMSL in the north to 1620 m AMSL in the south. The average groundwater level in the compartment varies from 1372 m AMSL to 1414 m AMSL.
- Varkfontein-Knoppiesfontein Compartment: This compartment is confined by the Tweefontein Dyke in the north, bordered by the Upper Sterkfontein Compartment to the west and the East Rand Basin to the south. The average groundwater level in the compartment varies from 1502 m AMSL to 1527 m AMSL.

### 5.2.3 Eastern Regional Area

The Eastern Regional Area of the Ekurhuleni Metropolitan Municipal area is located within the East Rand Basin. No groundwater information is currently available for the East Rand Basin and the groundwater conditions are unknown. Three EMM groundwater monitoring boreholes and three DWA groundwater monitoring boreholes exists within the East Rand Basin. The groundwater monitoring boreholes for the Eastern Region of the Ekurhuleni Metropolitan Municipality is presented in Figure 21.

## 5.3 Recorded Sinkholes and Subsidence in Ekurhuleni

A total of 241 ground movement incidents have been recorded in the Ekurhuleni Metropolitan Municipal area since 2005 to mid-2013. This also includes the ground movement incidents in the Bapsfontein area recorded during 2004 by Jones and Wagener and mining related ground movement incidents.

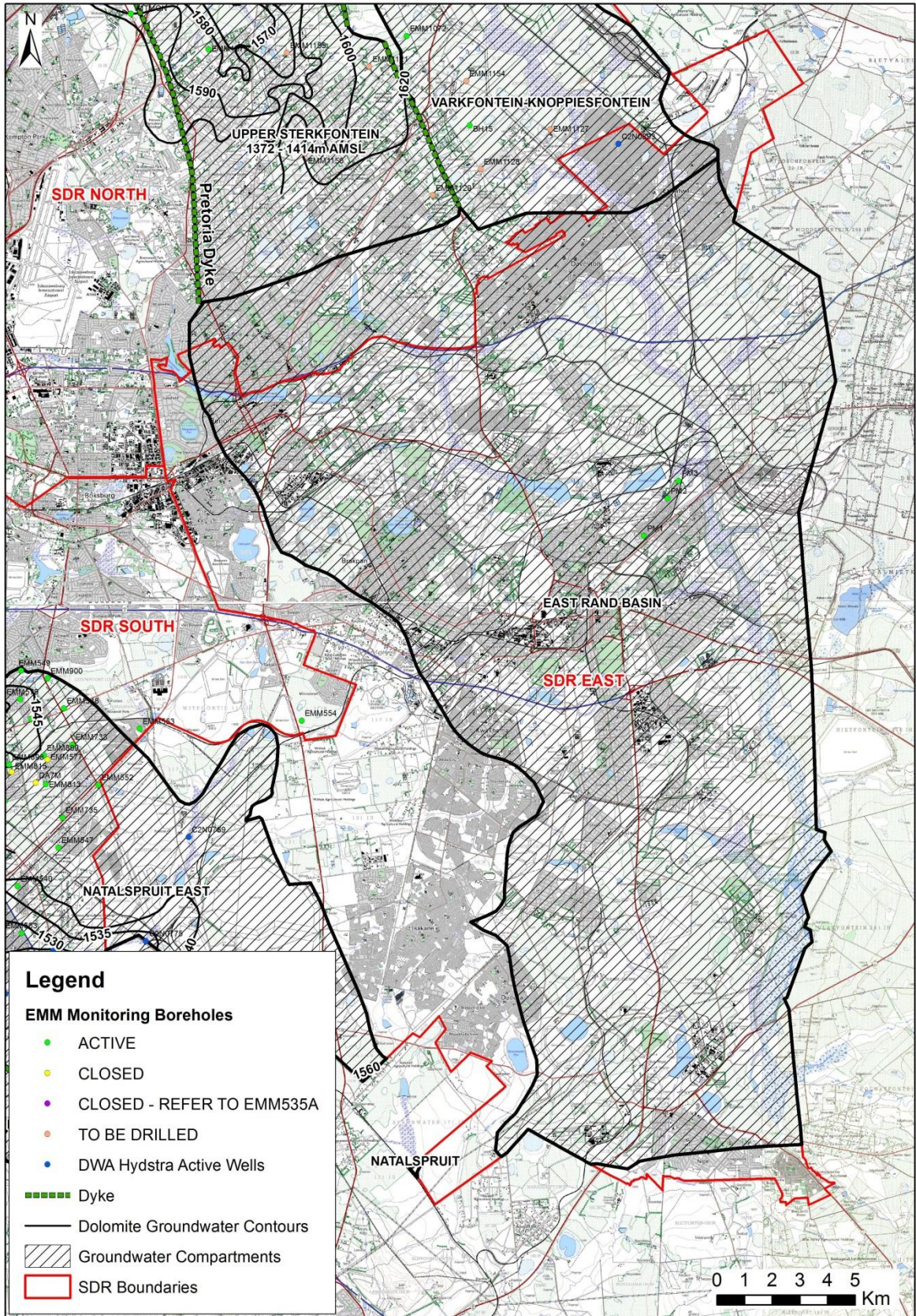
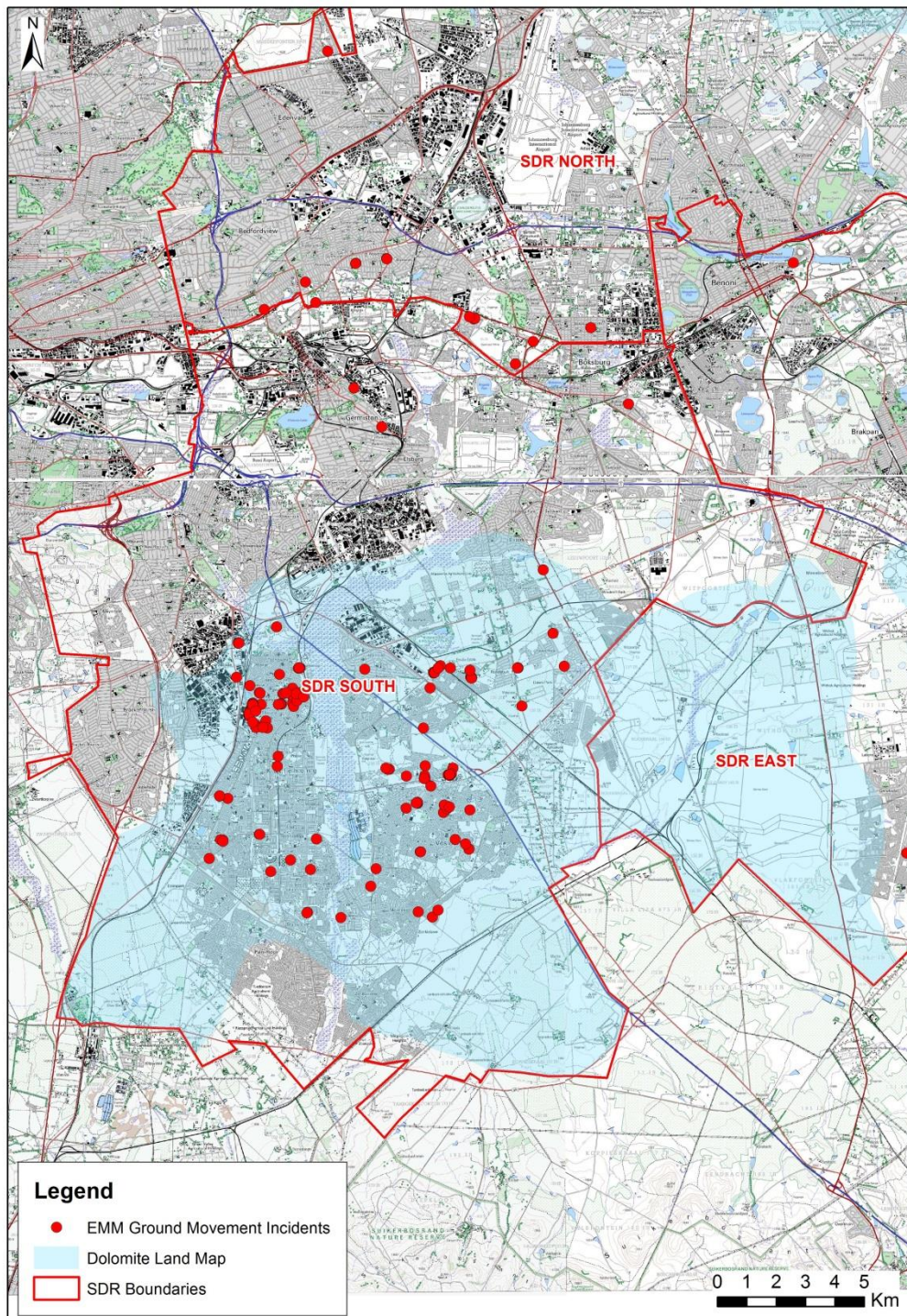


Figure 21: Groundwater compartments and monitoring boreholes for the Eastern Region (VGIconsult Projects Dolomite Database, 2014).

### 5.3.1 Southern Regional Area

All ground movement incidents as recorded since 2005 up to July 2013 is presented on Figure 22. A total of 141 ground movement incidents had been recorded in the Southern Region of the Ekurhuleni Metropolitan Municipal area. A large number of sinkholes and subsidences are concentrated in the northern portion of the town Katlehong.



**Figure 22: Recorded Ground Movement Incidents in the Southern Region (VGIconsult Projects Dolomite Database, 2014).**

All the dolomite-related sinkholes or subsidences have been caused by ingress of water. Approximately 85% of instability events were caused by leaking or broken sewer lines comprising old vitrified clay or uPVC pipes. Approximately 7% of instability events were caused by leaking PVC water lines or broken water valves, approximately 4% by surface water ponding and 3% by concrete stormwater lines not properly sealed at joints.

The typical sinkhole size ranges from 3 m to 6 m extending to variable depths. Sinkholes smaller than 2 m diameter and very large-size subsidences (> 15 m diameter) had also been recorded in the Southern Region.

Although most of the recorded ground movement incidents are related to ingress of water on dolomite, some of the incidents are related to rodent activities and poor workmanship of structures.

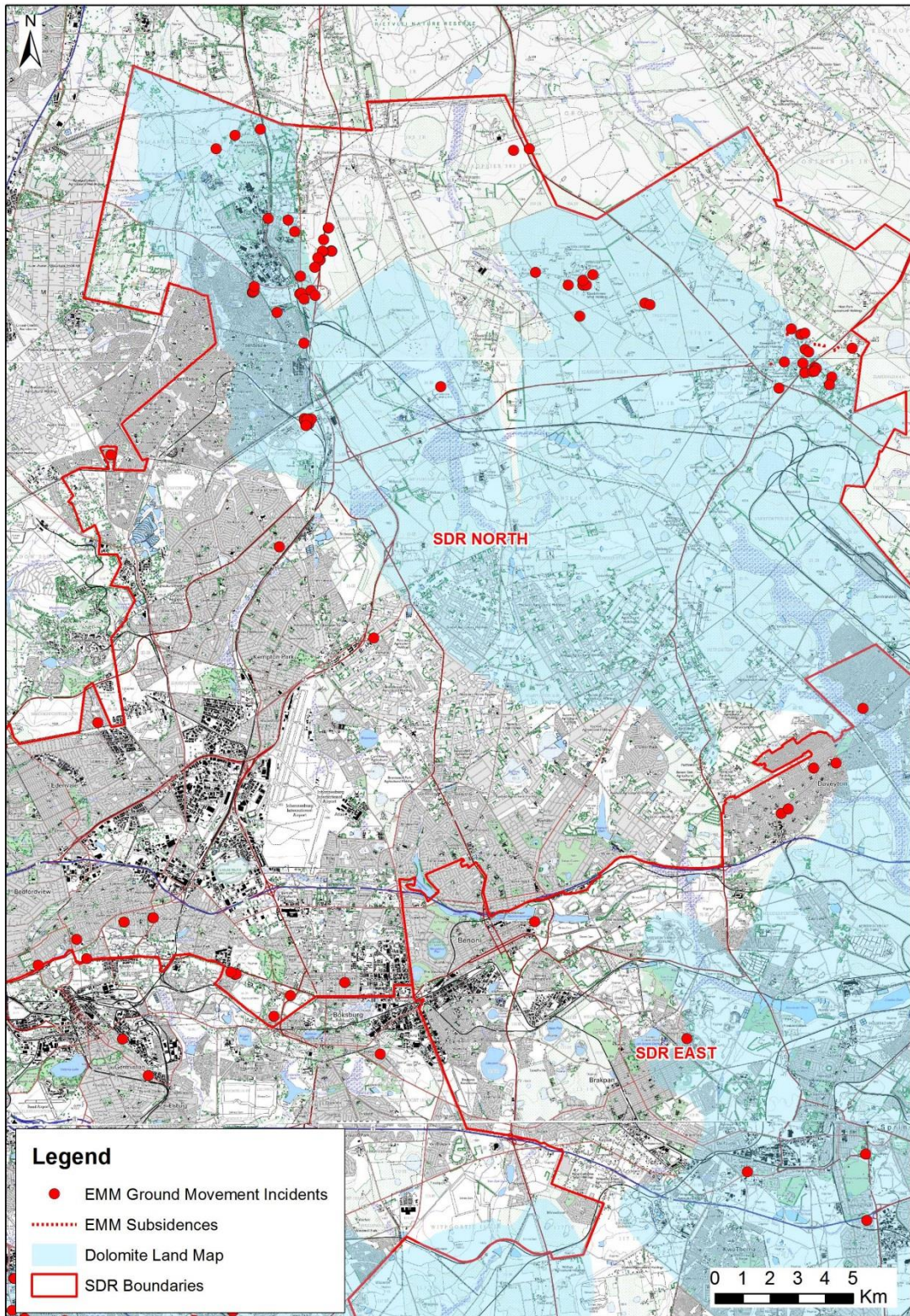
Some ground movement incidents are recorded in the northern portion of the Southern Region of the Ekurhuleni Metropolitan Municipal area on non-dolomitic land in the Germiston, Boksburg and Benoni areas. Those in the Germiston and Boksburg areas are related to collapsed mine shafts. The sinkhole recorded in Benoni is related to the erosion of a concrete stormwaterline by acidic industrial water released into the municipal system that caused subsurface erosion and a cavity to a depth of approximately 8m below natural ground level.

### 5.3.2 Northern Regional Area

All ground movement incidents as recorded since 2004 up to July 2013 is presented on Figure 23. A total of 83 ground movement incidents had been recorded in the Northern Region of the Ekurhuleni Metropolitan Municipal area, also including all the ground movement incidents as recorded by Jones and Wagener in 2004 for the Bapsfontein area.

Ground movement incidents in the Northern Region are related to both ingress of water and dewatering of dolomite groundwater compartments. Sinkholes and subsidences in the commercial, industrial and residential developed Olifantsfontein, Clayville and Tembisa areas were caused by ingress of water, such as leaking uPVC sewer and PVC water lines and ponding surface water. The typical sinkhole size caused by ingress of water ranges from 3m to 7m extending to variable depths. Sinkholes smaller than 2 m diameter have also been recorded in the Northern Region.

All sinkholes and subsidences recorded east of the R21 National Road were caused by dewatering of the Bapsfontein, Elandsfontein and Sterkfontein-East Dolomite Groundwater Compartments. The 24 sinkholes and subsidences recorded in the Bapsfontein region are all related to dewatering due to the over-utilising of groundwater from the Bapsfontein Dolomite Groundwater Compartment mainly for irrigation purposes.



**Figure 23: Recorded Ground Movement Incidents in the Northern Region (VGIconsult Projects Dolomite Database, 2014).**

The sinkhole that occurred at Bapsfontein in January 2004 measuring 60 m diameter extending to a depth of 25 m deep. Typically the sinkholes and subsidences that formed due to dewatering are large to very large in the Northern Region.

Some ground movement incidents are recorded in the southern portion of the Northern Region of the Ekurhuleni Metropolitan Municipal area on non-dolomitic land in the Germiston and Boksburg areas and are related to mining incidents or natural erosion caused by leaking subsurface wet services.

### 5.3.3 Eastern Regional Area

All ground movement incidents as recorded since 2005 up to July 2013 is presented on Figure 24. A total of 17 ground movement incidents had been recorded in the Eastern Region of the Ekurhuleni Metropolitan Municipal area.

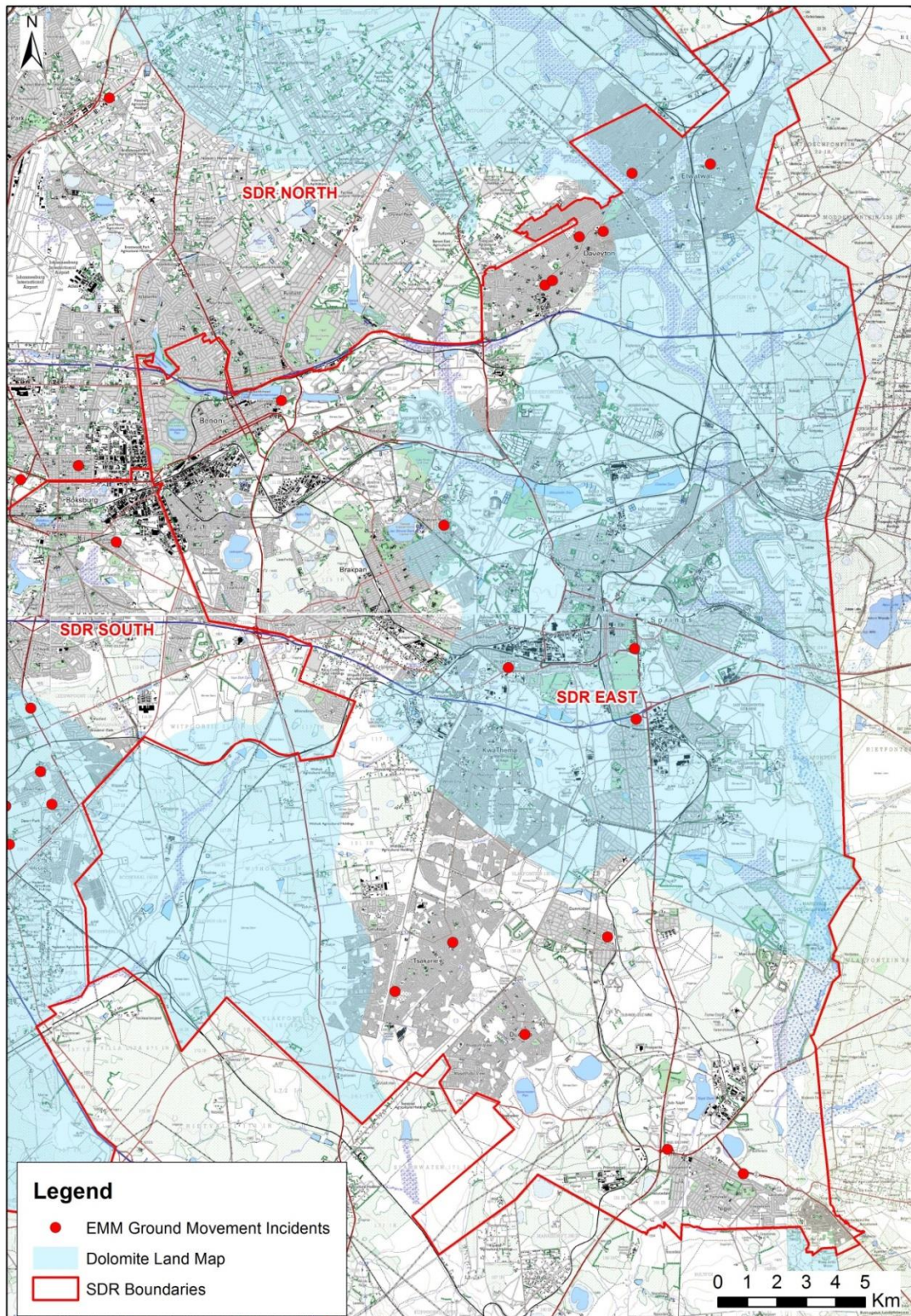
It should although be noted that none of the recorded ground movement incidents are related to dolomite.

In the Daveyton and Etwatwa regions incidents are related to old wet services such as manholes or pit latrines not properly backfilled or material used for backfilling not compacted or due to natural erosion of subsurface soils or structural damages caused by poor workmanship.

The incident recorded in Brakpan is related to surface water ponding and natural erosion of loose transported materials.

The incidents recorded for the Springs, Dunnottar and Nigel areas are related to collapsed mineshafts, shallow coal undermining and one incident in Springs is related to termite activities. The Tsakane and Duduza townships are not underlain by dolomite and ground movement incidents are related to swelling clays, water seepage problems and poor workmanship of structures.

All the ground movement incidents recorded are typically less than 1 m in diameter and extending to less than 1 m depth. Those caused by collapsed mine shafts and shallow coal undermining are typically more than 10 m in diameter and up to 30 m in diameter.



**Figure 24: Recorded Ground Movement Incidents in the Eastern Region (VGIconult Projects Dolomite Database, 2014).**

## 6. EVALUATION CRITERIA FOR DOLOMITE-RELATED SINKHOLES AND SUBSIDENCES TO DETERMINE APPLICABLE REHABILITATION METHODS

A number of determining factors need to be established and analysed after the occurrence of an event (e.g. sinkhole or subsidence) in order to develop the geological model, determine the impact of external influencing factors and select the most appropriate rehabilitation method.

The various determining factors considered and influencing the decision making process on the most appropriate rehabilitation method will be discussed.

### 6.1 Sinkhole or Subsidence Size

The terminology used in terms of the size of the event (sinkhole or subsidence) is defined as follows (Buttrick et al., 2001 and 2011):

**Table 5: Sinkhole or subsidence size (after Buttrick et al., 2001 and 2011).**

Maximum diameter of surface manifestation (in metres)	Terminology
< 2	Small-size
2 – 5	Medium-size
5 – 15	Large-size
> 15	Very large-size

### 6.2 Cause of Sinkhole or Subsidence Formation

Sinkhole or subsidence formation in South African dolomite karst is typically evaluated from an ingress of water and groundwater level drawdown perspective (Buttrick et al., 2001 and 2011).

Although both will be discussed in this section it should be noted that the focus of the thesis is on the investigation and rehabilitation of dolomite-related sinkholes and subsidences within a non-dewatering environment.

- *Ingress of water:* In the Urban Edge the cause of sinkhole or subsidence formation is mostly related to ingress of water associated with leaking or broken subsurface wet services, including water lines and valves, sewer lines and manholes and stormwater. Poor surface water run-off causing the ponding of water in low lying areas or against boundary walls that did not make provision for surface water run-off.

A large number of existing subsurface wet services in towns have already reached their expected lifespan, and municipalities have rarely budgeted for the replacement or upgrade thereof. The occurrence of leakages is likely to increase over time, and concomitant therewith the rate of sinkhole and subsidence formation on dolomite.

- *Groundwater level drawdown:* Dewatering of dolomite groundwater compartments are typically associated with the over-utilisation of groundwater for agricultural



purposes or drawdown related to mining activities. Some of the dolomite groundwater compartments in the Northern Region of EMM are experiencing major groundwater level drawdown; including the Bapsfontein, Elandsfontein and Sterkfontein-East Dolomite Groundwater Compartments; which has seen the occurrence of some large to very large size sinkholes and subsidences.

Even though the site-specific groundwater level (or levels) should be established, an understanding of the regional groundwater levels of the specific dolomite groundwater compartment and where the site specific groundwater level fits into the regional environment is important. An evaluation of the historical and current regional groundwater levels of the dolomite groundwater compartment is required in order to know if groundwater level drawdown is taking place.

The impact of groundwater level drawdown can only be mitigated by controlling, monitoring and managing groundwater discharge in dolomite compartments.

### 6.3 Geological Model

The data needed for the compilation of the 3D geological model is generally gathered from geophysical surveys, specifically gravity surveys, followed by drilling of percussion boreholes, placed on gravity anomalies and in the area surrounding the sinkhole or subsidence.

The geophysical surveys are useful to indicate possible subsurface structures (e.g. cavities, voids, dykes, faults or geological contacts). In the South African karst environment the gravity method is regarded as the most successful geophysical method to determine dolomite bedrock topography and the thickness and density of overburden material (Kleywegt and Pike, 1982).

The drilling of rotary percussion boreholes is one of the most reliable methods to obtain point data when assessing the extent of subsurface erosion related to sinkholes and subsidences, depth to dolomite bedrock, composition of the blanketing layer and the depth to the groundwater level.

At sites with restricted access the Dynamic Probe Super Heavy (DPSH) Test Method can be used to determine the consistencies of the various soil horizons and to determine if cavities or shallow bedrock are present.

In a shallow dolomite environment (bedrock within 6 m (maximum 8 m)) an excavator can be used to expose subsurface conditions.

On limestones in the United States and in Europe geophysical methods including Ground Penetration Radar (GPR), Electrical Resistivity (ER) and Seismic Refraction (SR) tests are commonly used to map the rock surface, determine subsurface characteristics and locate subsurface cavities (Kannan, 1997 and Gutierrez *et al.*, 2014). Due to the particular composition of the overburden on South African karst these geophysical methods are not very successful in delineating voids in the overburden or cavities within bedrock.

The simplicity or complexity of the geological model is based on the evaluation of the blanketing layer, dolomite bedrock and depth of the groundwater table.

### 6.3.1 Blanketing Layer

#### 6.3.1.1. *Composition and thickness*

The typical dolomite profiles encountered on the East Rand has been discussed in detail in Section 5.1.4. The following conditions can be associated with or the contribution of sinkhole or subsidence formation:

- Presents a high mobilization potential if material susceptible to subsurface erosion and consolidation is present in the profile, including *low density and compressible residual dolomite (wad and ferroan soils), gap-graded residual chert and soils of high permeability*. The mobilization potential increases where a substantial horizon of material with a low density (wad) are present in the profile; presence of voids (or disseminated receptacles) that may be able to accommodate mobilized material from overlying horizons; and sample and air losses recorded during drilling.
- *Vertical or subvertical intrusive or shale directly adjacent to residual dolomite (wad)*: Typically intrusive or shale is regarded as material with a low mobilization potential adding stability to the blanketing layer. However, the contact zone between these materials of low mobilization potential and the dolomite residuum may sometimes act as a contributing factor to the formation of a sinkhole or a subsidence, acting as a pathway (creates erosional tunnel directly adjacent to competent material) for mobilized material susceptible to subsurface erosion from above, downwards into a void or cavity at depth.
- *Presence of faults or fracture zones*: Depending on the nature of the faults or fracture zones present, these may act as preferential pathways or conduits to voids below.
- *Roof capping material over a void or cavity*: The geological profile is regarded as complex from a rehabilitation perspective where residual dolomite (wad) is overlain by a horizon of competent chert (highly weathered soft rock chert) with subsurface erosion taking place within the residual dolomite (wad) creating a void or disseminated voids (receptacles) below the competent chert horizon.
- *Geotechnical characteristics of material in the blanketing layer*: The grading, density and permeability of horizons in the blanketing layer also plays a vital role, as soil types comprising silty and clayey material with a low permeability will have a higher resistance against subsurface erosion, whilst sandy soils with a high permeability and typical low density may be more susceptible to subsurface erosion.
- *Presence of a paleo instability feature*: A paleo-sinkhole or subsidence may present an area of high susceptibility for re-activation.

## 6.3.2 Dolomite Bedrock

### 6.3.2.1. *Dolomite Bedrock Depth*

- The depth to dolomite bedrock has an influencing factor on the maximum potential size (in diameters and depth) sinkhole or subsidence. Small to medium size sinkholes or small to very large size subsidences are typically associated with dolomite bedrock at shallow to intermediate depths (less than 15 m) and medium to very large size sinkholes or subsidences are associated with a deep dolomite bedrock (more than 15 m). In areas of a shallow dolomite bedrock environment material susceptible to subsurface erosion including residual dolomite (wad) is typically at or close to ground surface presenting a profile with a much higher mobilization potential for sinkhole or subsidence formation, especially when subsurface wet surface are located above or within this material. In areas of a deep dolomite bedrock environment a thicker blanketing layer exists, potentially comprising thick layers of material susceptible to subsurface erosion. It should however be noted that a receptacle must be present at depth to accommodate material, for both a shallow and deep dolomite bedrock environment in order for a sinkhole or a subsidence to develop. The size of the receptacle will also play a role in the size sinkhole or subsidence that will occur.

### 6.3.2.2. *Dolomite Bedrock Morphology*

- The karst landscape associated with the weathering process of dolomite can create variable bedrock morphology, ranging from simple to very complex, depending on the stage of karst development (i.e. juvenile, youthful, mature, complex or extreme (Waltham and Fookes, 2003)) and the presence of faults, fractures and intrusions. A simple geological model from a dolomite bedrock morphology perspective is typically associated with juvenile karst (Waltham and Fookes, 2003) where the dolomite bedrock is gently undulated to nearly horizontal with a homogeneous blanketing layer. A very complex geological model comprises dolomite bedrock at variable depth over a short lateral distance, presence of geological structures and a heterogeneous blanketing layer typically comprising horizons of residual dolomite (wad and/or ferroan soils), with dolomite bedrock presented by pinnacle rockhead, grykes (deeply weathered joint or 'solutionally enlarge joint' (in Brink, 1979) typically filled with wad and comprising voids), cavities within dolomite bedrock and remnants of the original dolomite bedrock presented as floaters in the blanketing layer.
- The steep gradient associated with dolomite bedrock pinnacles is a contributing factor to the formation of sinkholes and subsidences, but more specifically sinkholes when located close to surface in an area of a leaking subsurface wet service. The areas between dolomite bedrock pinnacles are typically filled with residual dolomite (wad) and may comprise voids. Subsurface erosion of residual dolomite (wad) highly susceptible to mobilisation will take place along the dolomite bedrock pinnacle rockface. First creating an erosion tunnel that will over time manifest into a sinkhole at surface, if the leak on the subsurface wet service is allowed to continue over time.

### 6.3.3 Groundwater Level

The depth or position of the groundwater level in the dolomite profile, especially in the blanketing layer, determines the susceptibility for sinkhole or subsidence formation.

#### 6.3.3.1. *In Dolomite Bedrock*

- Where the groundwater level is located within dolomite bedrock and the blanketing layer comprises a horizon or horizons of highly susceptible residual dolomite (wad or ferroan soils) and voids, and/or cavities are present within dolomite bedrock above the groundwater level, the residual dolomite (wad) will be mobilised downwards by means of subsurface erosion into the void and or cavities creating a sinkhole, if triggered by a leaking subsurface wet service or the ponding of surface water.
- A subsidence may also develop in the same scenario, where the downwards migration of water through residual dolomite causes a state of densification (compaction) of the low density residual dolomite or voids that are exposed in profile can accommodate material from above.

#### 6.3.3.2. *In the Blanketing Layer*

- If the groundwater level is located within the blanketing layer, above material with a high mobilization potential, a sinkhole or a subsidence will not occur. However, if the groundwater level is located partially within residual dolomite (wad) with a high mobilization potential, a subsidence may also occur due to the densification of the residual dolomite (wad). In addition, if voids are also present within the portion of residual dolomite (wad) above the groundwater level, a possibility exists for the formation of a sinkhole, if triggered by a leaking subsurface wet service or ponding surface water.
- Where the original groundwater level is located within the blanketing layer, above material with a high mobilization potential and suddenly drawn down exposing these materials, voids and deeper lying cavities within bedrock, a sinkhole or subsidence will occur. The Bapsfontein sinkholes are good examples of this.

It should be noted that the majority of sinkholes and subsidences investigated and rehabilitated within EMM have not been caused by an artificially lowered groundwater table. The groundwater level is typically either located in dolomite bedrock or at a depth greater than the affected profile. A perched groundwater table was, however, encountered on some of the sites in profile that influenced the rehabilitation procedure.

## 6.4 Depth and Lateral Extent of Impact

### 6.4.1 Depth of Impact

One of the most important factors influencing the rehabilitation approach is the depth below surface to which rehabilitation is required. For rehabilitation purposes sinkholes or subsidences can be evaluated according to the same influencing factors grouped under a specific depth of impact.

**Table 6: Impact depth of instability feature considered in rehabilitation process**

Impact Depth of Instability Feature (in metres)	Terminology
< 8	Shallow depth
< 15	Intermediate depth
> 15	Great depth

The depth of impact refers to the depth to which the subsurface profile is anticipated to have been influenced during the development of a sinkhole or subsidence. For a shallow depth of impact < 8 m, the throat of the sinkhole or lower limit of subsidence is reachable by an excavator if all other influencing factors allow the use of such large and heavy equipment. For an intermediate depth of impact (maximum 15 m), various rehabilitation procedures or a combination of procedures may be considered and will depend on the geological model and external influencing factors such as accessibility for rehabilitation equipment and the impact on existing infrastructure. For a great depth of impact (more than 15 m), the base of the sinkhole can only be reached by means of drilling.

Zhou and Beck (2008) divide sinkholes into shallow and deep sinkholes for mitigation purposes. Shallow sinkholes are, according to them, those that are not more than 10 m deep, and their bases are reached by a regular backhoe. Deep sinkholes are more than 10 m deep, and drilling rigs are needed to reach their bases.

### 6.4.2 Lateral Extent of Impact

The visual impact at ground surface, caused by a sinkhole or a subsidence does not always define the depth and lateral extent of instability. The receptacle at depth, either may it be a void within the blanketing layer or a cavity in dolomite bedrock, or both, that accommodated overlying material highly susceptible to subsurface erosion, may be located over a distance as much as 20 m away from the original area of impact at ground surface or directly below the area of visual impact at depth.

The evaluation of the impact at depth caused by a sinkhole or subsidence should therefore consider covering a surface area typically of 10 m to more than 50 m surrounding the sinkhole or subsidence area to ensure the instability feature has been thoroughly investigated. The distance of evaluation will depend on the observed size sinkhole or subsidence. The lateral extent of impact of an instability feature considered in the rehabilitation process is tabulated in Table 7.

**Table 7: Lateral extent of impact of instability feature considered in rehabilitation process.**

Lateral Extent of Impact (diameter)	Extent of Surface Area Affected
< 10 m	Small
< 20 m	Medium
< 50 m	Large
> 50 m	Very Large

## 6.5 Depth and Extent of Triggering Mechanism (Ingress of Water)

### 6.5.1 Depth of Triggering Mechanism

The position or locality at depth of the broken or leaking subsurface wet service (i.e. water, sewer or stormwater) or surface water ponding in correlation to the instability feature is a preliminary indication on the extent of the affected area to be investigated and the origin of the sinkhole or the subsidence.

- The damaged type and depth of wet service and pipe diameter will have variable impacts in terms of the size sinkhole or subsidence and extent below ground surface. A broken bulk PVC water line pipe with a diameter typically ranging between 200 mm to 450 mm or a broken water valve will cause severe subsurface erosion due to water released under pressure entering the subsurface ground profile and can affect a vast area with multiple sinkholes, with the immediate occurrence of a sinkhole at ground surface in the area of the broken water line or valve interconnected via erosion tunnels with voids or cavities at depth over a lateral extent. Bulk water lines are typically located at a depth of between 1,0 m to 1,5 m below ground surface and waterlines to houses within 0,6 m from ground surface.
- Gravity flow in bulk sewer lines typically comprising 160 mm to 300 mm diameter vitrified clay or uPVC pipes requires the placing of the subsurface wet service at depths ranging between 2 m to as much as 8 m. Sewer pipes to houses of 110 mm diameter are typically placed at a depth between 1 m to 2 m below natural ground surface. The occurrence of a sinkhole or a subsidence due to a blocked, broken or disconnected sewer line or concrete manhole can occur instantly or over a long period of time and the size of the instability feature can vary from small to very large depending on the subsurface profile.
- Subsurface stormwater pipes typically comprise 300 mm to 1200 mm diameter spigot and socket concrete pipes with rubber rings or seals and requires gradient flow. As such these pipes may be placed between depths of 1 m to up to 8 m below natural ground surface. Sinkholes and subsidences caused by a blocked, disconnected or broken subsurface stormwater pipe typically starts to appear after heavy rainfall. Water expelled from the affected stormwater pipe may cause sinkholes or subsidences in the immediate area of leakage or may first cause tunnel erosion directly below the rigid stormwater pipe over a distance and then form a sinkhole.

- Sinkholes and subsidences may also be caused below and adjacent to concrete lined canals and channels at joints not properly sealed or due to overflow causing surficial and subsurface erosion along the rigid structure.

Taking the above into consideration distinction can be made between various depths of impact associated with the triggering mechanism.

**Table 8: Impact depth of triggering mechanism considered in rehabilitation process**

Impact Depth of Triggering Mechanism (in metres)	Terminology
< 2	Shallow depth
< 6	Intermediate depth
< 10	Great depth

All affected wet services are replaced during the sinkhole or subsidence rehabilitation and soil improvement process. It is therefore critical that the depth and extent of the damaged subsurface wet service and subsurface erosion caused by such is known before rehabilitation work commences.

Typically all water pipes and sewer manholes and pipes are replaced with HDPE butt welded material. Stormwater is replaced with properly sealed spigot and socket concrete pipes or HDPE butt welded pipes in specific areas of high traffick.

#### 6.5.2 Lateral Extent of Triggering Mechanism

Distinction is made between point source and multiple triggering mechanism points that has an influence on the lateral extent of impact and affected wet services that needs replacement.

- Point source triggering mechanism: Defined as a single point of water ingress. For example one position or locality where a pipe is broken or leaking.
- Multiple triggering mechanism points: Defined as multiple points of water ingress. For example a malfunctioning sewer line with numerous leaks or cracks over pipe distance or more than one leak on a water line.

### 6.6 External Influencing Factors

#### 6.6.1 Impact on Existing Infrastructure

The position of the sinkhole or subsidence and damaged subsurface wet service in correlation to the position of existing infrastructure plays a vital role in the rehabilitation procedures to be followed.

Infrastructure such as buildings, roads, overhead cables, subsurface services (for

example gas pipes, water mains, electrical cables) that cannot be demolished, shut down or rerouted during the rehabilitation process need to be considered when the rehabilitation methodology is decided upon.

Where a sinkhole or a subsidence is located partially under a building, with no severe structural damages to the structure and the building is of such importance that it cannot be demolished, difficulty may be experienced in obtaining adequate or good quality information to assess the depth and extent of the instability below the structure. In addition, provision will need to be made to temporarily support the existing structure before the rehabilitation process and to do soil improvements below the structure during the rehabilitation process.

Existing infrastructure can sometimes prevent a detailed investigation of the sinkhole or subsidence due to access constraints, for example inadequate access for a drill rig, to the area of interest which can lead to the area of impact being inadequately or incorrectly determined. This may lead to follow-up phases of rehabilitation of instability features such as erosion tunnels, cavities and voids discovered during the original rehabilitation process.

Where it is an economically feasible option, structures should be demolished, the area properly investigated, rehabilitated and structures then rebuilt, with appropriate precautionary measures.

Subsurface services located within the area proposed for rehabilitation that cannot be rerouted will require supporting.

Permission should be obtained from external service providers (such as telecommunication, electrical, water and gas) if any of their services are located within the sinkhole or subsidence area proposed for investigation and rehabilitation.

The rehabilitation method proposed should not have a negative impact on existing structures in the area surrounding the sinkhole or subsidence proposed for rehabilitation. Especially if the Dynamic Compaction (DC) method is proposed as rehabilitation method, care should be taken that an adequate distance between the area where it will be used and existing structures prevail to ensure that the DC method does not cause structural cracks.

Existing infrastructure, causing access constraints for rehabilitation equipment can also lead to the use of a rehabilitation method other than what would have been the most appropriate for the specific geological model or setting.

#### 6.6.2 Socio-Economic Impact

As already mentioned in Section 2.8, the formation of sinkholes or subsidences have negative social and financial implications in the affected and immediately surrounding areas, resulting in the relocation of entire communities to safer ground, severe damage to infrastructure or even loss of human life (Waltham *et al.*, 2005; Buttrick *et al.*, 2011).



Most communities that need to be relocated temporarily (during the rehabilitation process) or permanently (sterilisation of land) outside the area affected by a sinkhole or a subsidence are not doing so willingly. From a social perspective, each person plays a certain role in a community, as such if they are removed from their current environment to a new environment (typically integrated with an existing community), they lose their specific role (or status) in the community. The perception is also that the relocation to another area may lead to the loss of property ownership and financial income. In addition, some people may now be located further from their workplace causing an increase in their travel expenses and a decrease in income.

Poor investment confidence due to the exposure to a sinkhole or a subsidence may also arise. Typically when a sinkhole or a subsidence occur, the area is immediately fenced off, including affected roads. This prevents direct access to businesses located within the surrounding affected area. Potential clients may find it to be time-consuming using alternative routes to get to the specific business within the affected area and seek the same business somewhere else.

### 6.6.3 Impact by Third Parties

Where the cost implications related to the rehabilitation will be excessive sterilization of the affected land is typically recommended. However, this decision may be overruled by third parties, such as government authorities or insurance companies, enforcing the rehabilitation of affected structures and land. Such a case is presented in Case Study 8 under Appendix H at the back of the thesis.

In any developed township specific rights have been allocated to stands by the controlling municipality that needs to be respected. If a sinkhole or a subsidence occurs on land where specific rights have been awarded, the municipality by law is forced to rehabilitate the affected land and infrastructure if an alternative property similar to or better, can not be provided to the owner of the property.

### 6.6.4 Financial Impact

Available funds to properly rehabilitate a sinkhole or a subsidence can be regarded as the biggest constraint. Insurance Companies typically have restrictions on payouts and the methodology of sinkhole or subsidence rehabilitation. They may consider rehabilitation methods (to stay within budget) that are not necessarily the best rehabilitation method or methods (or those recommended) to properly rehabilitate the affected area.

Municipalities acting in a responsible manner with regards the management of dolomite areas, including the rehabilitation of sinkholes and subsidences, will typically base their allocation of funds for sinkhole and subsidence rehabilitation on the number and cost of sinkholes and subsidences rehabilitated in the previous year with a 10% increase for the next year. In the event that more sinkholes or subsidences occur than what was budgeted for, funds are not available for the rehabilitation of unforeseen sinkholes or subsidences.

There are although municipalities that do not act in a responsible manner, not budgeting for the rehabilitation of sinkholes and subsidences or allocating the funds originally budgeted for rehabilitation to other projects of more importance at that stage. Therefore no funds are available in the event that a sinkhole or a subsidence occur.

#### 6.6.5 Land Use After Rehabilitation

Typically, the same land use is requested after rehabilitation. Furthermore, the proposed land use post-rehabilitation affects the choice of rehabilitation method.

In areas where the cost implications related to the rehabilitation will be excessive and a potential for reoccurrence exists after rehabilitation, consideration should be given to the sterilization of land. In areas where structures have been affected by a sinkhole or a subsidence, demolition and rebuilding is critical, the rehabilitation must render subsurface conditions suitable for the specific land use and permitted in terms of dolomite standards and regulations.

Financial constraints (inadequate funds to rehabilitate a sinkhole or subsidence) can also cause a change in land-use, called “dezoning of land” or even sterilization of land. In the event that a sinkhole or a subsidence occurs and adequate funds are not immediately available to rehabilitate the affected area, the affected land may be temporary sterilized until adequate funds are available for rehabilitation.

### 6.7 Rehabilitation Methods and Criteria

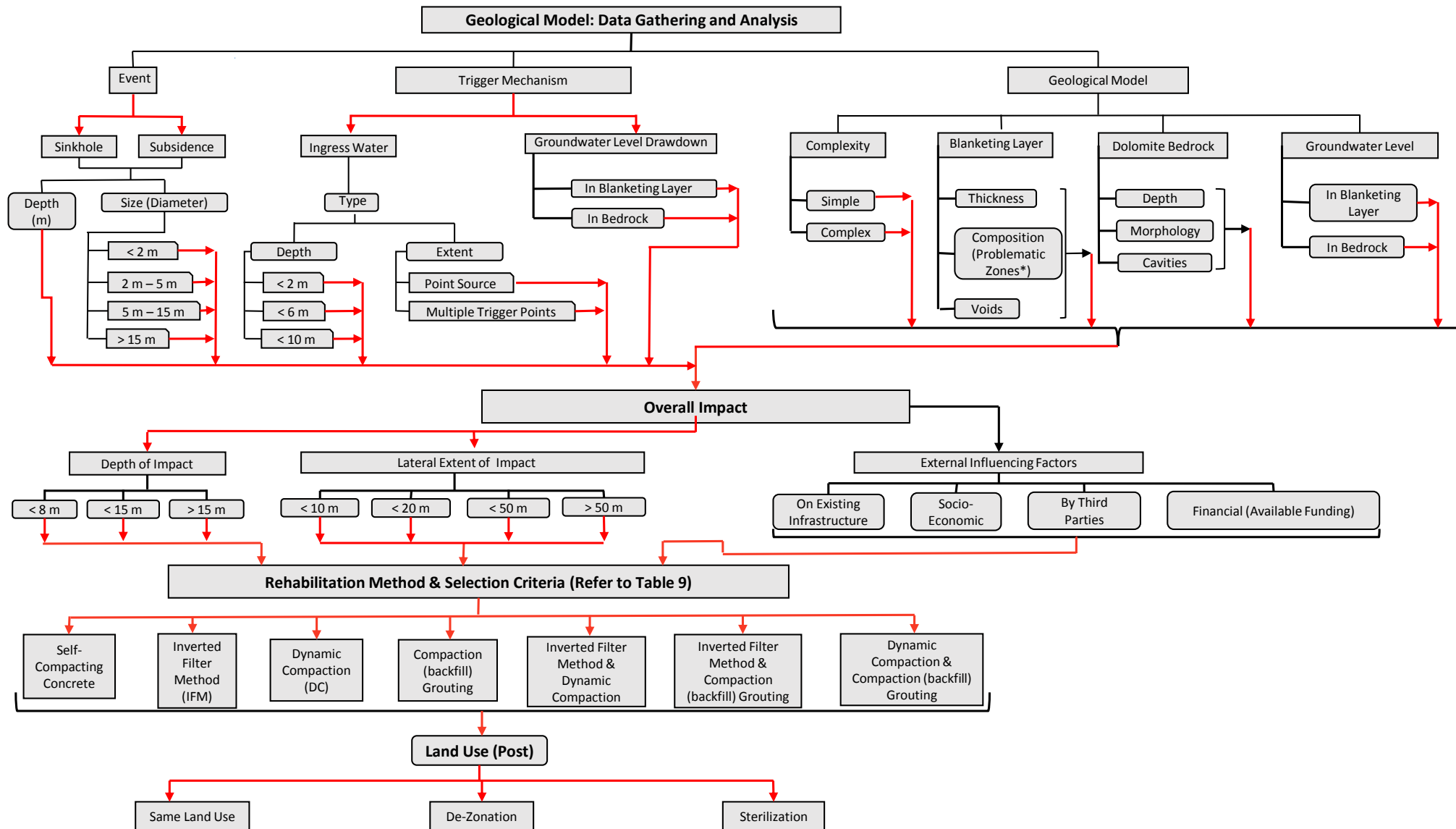
The various rehabilitation methods and their applications has been discussed in detail in Chapter 4. A summary is provided of each rehabilitation method, their applications and external influencing factors to consider in Table 9.

### 6.8 Evaluation Process of Sinkholes or Subsidences and Selection of Rehabilitation Method

The evaluation process of sinkholes or subsidences, including all influencing factors considered and the selection of the rehabilitation method is presented in Flow Chart 1. As illustrated by the flow chart, the overall impact factors, depth of impact and lateral extent of impact are determined by the following factors: Event (depth and size (diameter)), trigger mechanism (ingress water (type, depth and extent) or groundwater level drawdown) and the geological model (complexity, blanketing layer (thickness, composition (problematic zones and depth) and voids), dolomite bedrock (depth, morphology and presence of cavities) and groundwater level (in blanketing layer or in bedrock). The selection of the most appropriate rehabilitation method depends on the land use proposed after rehabilitation and the overall impact factors, including: Depth of impact, lateral extent of impact and external influencing factors. External influencing factors to consider in the selection of the rehabilitation method including: Impact on existing infrastructure (current land-use), financial (available funds), socio-economic factors and the role of third parties.

**Table 9: Rehabilitation methods, applications and external influencing factors to consider.**

Rehabilitation Method	Application	Sinkhole or Subsidence Size (diameter)	Depth of Impact (m)	Lateral Extent of Impact	External Influencing Factor (Existing Infrastructure)
Self-compacting Concrete or Soil-Cement Mix	Choking of sinkhole throat or mass filling of cavities or runnels.	Sinkholes: < 2m - 5 m. Subsidence: < 2 m - > 15 m (only soil-cement mix)	< 6 m (or throat visible within 8 m)	< 10 m	Within 1 m or below structures (if adequate sinkhole opening exist).
Inverted Filter Method (IFM) (including the use of Self-Compacting Concrete/Soil Cement Mix or Geotextile layers)	Backfilling sinkhole or subsidence, including blocking of throat followed by layers of progressively finer material compacted at specific compaction effort. Preferably no capping layers above problematic horizons.	Sinkholes: < 2m - > 15 m Subsidence: < 2 m - > 15 m	< 6 m (or throat visible within 8 m); or < 12 m (terrace at 6 m). Depths of up to 16 m reachable (if adequate space is available for bulk excavation).	< 10 m - > 50 m	Located outside area proposed for bulk excavation.
Dynamic Compaction (DC)	Compact and densify poor subsurface dolomite residuum (wad) or soil layers with loose consistency. Collapse subsurface voids. Preferably no capping layers above problematic horizons.	Sinkholes: 5 m - > 15 m Subsidence: 5 m - > 15 m	10 m - 15 m	< 20 m - > 50 m	All sub-surface services removed or relocated outside DC area. At least 50 m away from structures. Within 50 m (but not closer than 20 m) excavate trench.
Compaction (backfill) Grouting	Fill voids and cavities at depth or to densify poor subsurface soils, down a predrilled borehole; not treatable by means of IFM or DC.	Sinkholes: < 2m - > 15 m Subsidence: < 2m - > 15 m	From ground surface to > 60 m; but typically from > 12 m below ground surface.	< 10 m - < 50 m	Within 1 m or below structures.
Combined Inverted Filter Method and Dynamic Compaction (Probing)	Chocking of sinkhole throat or collapsing of voids or cavities at depth not reachable with excavator. Compact and densify poor subsurface soils above and surrounding sinkhole areas. Preferably no capping layers above problematic horizons.	Sinkholes: 5 m - > 15 m Subsidence: 5 m - > 15 m	10 m - 15 m	< 20 m - > 50 m	All sub-surface services removed or relocated outside DC area. Located outside area proposed for bulk excavation and DC Probing Areas at least 50 m away from structures; if within 50 m (but not closer than 20 m) excavate trench.
Combined Inverted Filter and Compaction Grouting	Backfilling sinkhole or subsidence, including blocking of throat followed by layers of progressively finer material compacted at specific compaction effort; and seal off sub-vertical erosion tunnels, fill voids and cavities at depth over a distance away from feature.	Sinkholes: 5 m - > 15 m Subsidence: 5 m - > 15 m	> 15 m	< 20 m - > 50 m	Located outside area proposed for bulk excavation.
Combined Dynamic Compaction and Grouting	Areas of major traffic, where cavernous conditions exist at a depth greater than 10 m and compaction efforts of 95% to 98% is required closer to surface.	Sinkholes: 5 m - > 15 m Subsidence: 5 m - > 15 m	> 15 m	< 20 m - < 50 m	All sub-surface services removed or relocated outside DC area. At least 50 m away from structures. Within 50 m (but not closer than 20 m) excavate trench.



Flow Chart 1: Process of sinkhole or subsidence evaluation and selection of the rehabilitation method.

## 7. DOLOMITE-RELATED SINKHOLE AND SUBSIDENCE GEOLOGICAL MODELS AND RECOMMENDED REHABILITATION METHODS

### 7.1 Introduction

The sinkhole and subsidence rehabilitation method should not be prescriptive, given the vast number of variables involved. Each sinkhole or subsidence is unique and a site specific set of criteria for the rehabilitation of the feature must be developed to ensure proper stabilisation and safe future use of the area.

Basic principles can, however, be adhered to, such as:

- Ensuring that the cause of the sinkhole or subsidence has been identified and removed;
- The position and extent of the receptacles have been determined and erosion paths sealed best as possible;
- The eroded area and possible voids properly densified or backfilled;
- A proper impervious blanket created;
- Ensuring that all subsurface wet services comply with industry standards and that proper surface drainage exists.

A comprehensive understanding of the affected area is essential for cost effective and practical rehabilitation measures. It is therefore, as a rule, required to perform a thorough site investigation of the feature as well as surrounding area in accordance with methods as described in Chapter 3. Rehabilitation of only a portion of the affected area will in most instances lead to propagation of the problem to adjacent areas.

The process of sinkhole or subsidence evaluation and the selection criteria of the rehabilitation method that was developed during this research study and presented in Chapter 6, will be illustrated by means of seventeen generic geological models. This will provide a broad base understanding of different dolomite environments, their susceptibility to sinkhole or subsidence formation and best practice rehabilitation, as seen by the author.

Even though each sinkhole or subsidence is unique, the evaluation of the various influencing factors considered to determine the most appropriate rehabilitation method are the same. The same approach is therefore suggested in other regions affected by sinkholes and subsidences (Kleinhans and Van Rooy, 2016).

Similar or near similar geological scenarios may exist in other dolomite or limestone regions and the various generic geological models and rehabilitation methods developed for the East Rand may serve as a guideline on the most appropriate rehabilitation methods in similar geological scenarios (Kleinhans and Van Rooy, 2016).

The seventeen generic sinkhole and subsidence geological models present the typical geological models for the East Rand as observed during the investigation and rehabilitation of more than 60 sinkholes and subsidences.

From a practical point of view the seventeen generic sinkhole and subsidence geological models, with the evaluation process (also presented on a flow chart) and recommended rehabilitation methods, are grouped together under the specific depth of impact as follows:

<b>Depth of Impact</b>	<b>Geological Model &amp; Rehabilitation Method</b>
< 8 m	1 to 8
< 15 m	9 to 12
> 15 m	13 to 17

Ten case studies on the investigation and rehabilitation of sinkholes and subsidences on the East Rand are presented in Appendices A to J for further indepth reading. Some of the generic geological models and recommended rehabilitation methods are based on the case studies.

Each of the case studies provides a brief history, description of geological subsurface conditions and the detailed rehabilitation work carried out.

For ease of reference a summary is provided on each of the seventeen generic geological models, influencing factors, recommended rehabilitation method and relevant case study in Table 10.

**Table 10: Summary of geological models, influencing factors, recommended rehabilitation method and relevant case study.**

Model	Event	Size (diam.) & Depth (m)	Trigger Mechanism	Geological Model	Lateral Extent of Impact (m)	External Influencing Factors	Rehabilitation Method	Land Use Pre- and Post Rehabilitation	Case Study
<b>Impact to a depth of 6 m (maximum 8 m)</b>									
1	Subsidence	15 & 0,5	Point Source: Leak on sewer connection (150mm diameter vitrified clay and 200mm diameter Class 6 HDPE pipe) @ 4 m	Complexity: Simple, homogeneous profile: Blanketing layer (5m – 7m thick): Ferruginised colluvium (1m), 4m to 6m thick residual dolomite (wad); void: < 1m high, encountered between 2m and 3m. Dolomite bedrock: @ 5m - 7m; gentle karst; no cavities. Perched groundwater level @ 4m.	< 50	Less than 1m from house, structural damages beyond repair, house demolished.	Inverted Filter Method to a maximum depth of 6m.	Pre: Residential house and road. Post: Rebuilding of house on reinforce concrete raft foundation, catering for a loss of support of 5m diameter & reinstatement of road.	3
2	Sinkhole	1 & 2	Point Source: Broken 160mm diameter uPVC sewer pipe @ 3m.	Complexity: Simple, homogeneous profile: Blanketing layer (7m – 8m thick): Road fill (1m), 5m – 6m thick residual syenite, 1m thick residual dolomite (wad); no voids. Dolomite bedrock: @ 8m; gentle karst; no cavities.	< 10	Road in residential area, no impact on structures.	Inverted Filter Method to a maximum depth of 7m.	Pre: Road. Post: Reinstatement of road.	-
3	Sinkhole	2 & 2	Point Source: Broken 110mm diameter uPVC midblock sewer pipe @ 2m.	Complexity: Simple, homogeneous profile: Blanketing layer (3m thick): Residual chert (1m), 2m thick residual dolomite (ferroan and wad soils); no voids (possibility exist within deeper grykes). Dolomite bedrock: @ 3m with 1m wide grykes and smaller, extending to a depth of approximately 8m; gentle karst with deeper weathered narrow grykes; no cavities.	< 10	No access constraints. Houses located outside proposed bulk excavation area.	Inverted Filter Method to a maximum depth of 3m and 1m over excavation of deeper grykes	Pre & Post: Garden areas of residential stands and wet service servitude.	-
4	Sinkhole	5 & 3	Point Source: Broken water valve @ 0,6m.	Complexity: Complex, due to weathering profile. Blanketing layer (2m – 4m thick): Colluvium (1m), residual chert (1m), residual syenite (1m), <1m thick residual dolomite (wad); 1m diameter subsurface erosion tunnel extending downwards into dolomite bedrock. Dolomite bedrock: @ 2m – 5m with 1m diameter sub-vertical erosion tunnel extending to a depth of 7m where it enters a cavity of approx. 4m diam. and 2m high; mature karst; gentle karst with deeper weathered eroded grykes.	< 20	Erosion tunnel and cavity extending below house, damaged stand boundary walls caused access constraints – demolished.	Inverted Filter Method to a maximum depth of 5m and backfilling of cavity with self-compacting concrete to a depth of 9m.	Pre: House with garden area and boundary walls and road. Post: House stabilized, reinstate garden, boundary walls and road.	2

**Table 10 (continue): Summary of geological models, influencing factors, recommended rehabilitation method and relevant case study.**

Model	Event	Size (diam.) & Depth (m)	Trigger Mechanism	Geological Model	Lateral Extent of Impact (m)	External Influencing Factors	Rehabilitation Method	Land Use Pre- and Post Rehabilitation	Case Study
<b>Impact to a depth of 6 m (maximum 8 m)</b>									
5	Sinkhole	2 & 7	Point source: Ponding surface run-off water from tap left open over night.	Complexity: Complex, with horizontal and sub-vertical orientated soil horizons. Blanketing layer (5m – 8m thick): Colluvium (1m), residual chert (3m – 6m), 1m – 3m thick residual dolomite (wad) & <1m thick interlayered residual dolomite and shale (sub-areas), with sub-vertical to vertical shale horizon cutting through profile; 2m high void encountered between 5m and 7m depth. Dolomite bedrock: @ 5m - 8m, no cavities; mature karst (variable bedrock depth) with sub-vertical to vertical intrusion.	< 10	None, all structures demolished as part of rehabilitation process of much bigger area.	Inverted Filter Method to a maximum depth of 7m – 8m.	Pre: Low cost housing. Post: Rebuilding of houses, placed on reinforced concrete raft foundations, catering for a loss of support of 5m diameter.	4
6	Sinkhole	4 & 4	Multiple trigger points: multiple cracks and disconnected 160mm diameter uPVC sewer line over a distance of 20m @ 4m	Complexity: Complex, due to highly variable bedrock profile. Blanketing layer (1m – 8m thick): Colluvium (1m), residual chert (1m – 2m), 4m – 6m thick residual dolomite (wad) with 1m to 2m diameter dolomite floaters; void encountered between 5m and 8m in a gryke. Dolomite bedrock: @ 1m – 8m, pinnacle dolomite bedrock with adjoining v-shaped grykes; cavities between 5m and 8m depth in dolomite rock.	> 50	No access constraints.	Inverted Filter Method to a maximum depth of 8m and use of self-compacting concrete in V-shaped gryke sections.	Pre and Post: Road (reinstated), sewer servitude and garden areas of stands.	1
7	Sinkhole	2 & 1,5	Point source: Leak on 200mm diameter steel water pipe @ 1m.	Complexity: Complex, due to competent capping horizon above problematic hoizons. Blanketing layer (4m - >10m thick): Colluvium (1m), highly weathered soft rock chert (3m), 1m – 3m (but up to 10m thick in sub-areas) residual dolomite (wad); large void (6m diameter and 6m high) encountered from a depth of 4m below highly weathered soft rock chert capping layer. Dolomite bedrock: @ 4m on both sides of void, extending to more than 10m in the central portion of void area.	< 10	No access constraints or structures affected.	Modified Inverted Filter Method to a maximum depth of 9m; void backfilled with soilcrete via open borehole casings.	Pre and Post: Paved road servitude (reinstated).	Part of 6
8	Sinkholes & Subsidence	4 & 3; 2 & 2; 4 & 1	Ponding of surface run-off water in low lying area, covering a large surface area.	Complexity: Complex, due to highly variable bedrock profile and residual dolomite (wad) located between dolomite rock horizons. Blanketing layer (1m – 9m thick): Colluvium (1m), residual chert (1m) in sub-areas, 1m – 5m thick residual dolomite (wad); void encountered between a depth of 2m and 4m. Dolomite bedrock: Appears to be at 1m – 5m, however highly weathered bedrock profile presents bedrock @ 9m; highly jointed vertically and horizontally, joints filled with residual dolomite (wad); cavities between 4m & 5m and 5m and 9m.	< 50	No access constraints; electrical pylon located <10m from instability features.	Compaction (backfill) grouting to a maximum depth of 8m to 9 m and area landscaped.	Pre and Post: Open field and electrical servitude; stabilize electrical pylon, landscaped area to improve surface run-off water.	-



**Table 10 (continue): Summary of geological models, influencing factors, recommended rehabilitation method and relevant case study.**

Model	Event	Size (diam.) & Depth (m)	Trigger Mechanism	Geological Model	Lateral Extent of Impact (m)	External Influencing Factors	Rehabilitation Method	Land Use Pre- and Post Rehabilitation	Case Study
<b>Impact to a depth of 15m</b>									
9	Subsidence	30 & 1; 1 & 1	Multiple trigger points: 160mm diameter uPVC sewer line broken & disconnected at a number of points over a distance of 120m, at a depth of 4,5m.	Complexity: Complex, due to heterogenic profile. Blanketing layer (8m – 16m thick): Colluvium (1m – 2m), residual chert (1m – 5m & absent sub-areas), 2m – 14m thick residual dolomite (wad & ferroan soils) with dolomite floaters, 1m – 2m thick residual shale encountered within residual dolomite between a depth of 7m and 9m; voids encountered between 6m – 7m & 3m – 15m. Dolomite bedrock: @ variable depth of 8m – 16m; cavity encountered between 14m & 17m.	> 50	Large number of residential structures damaged and partially subsided, all affected structures demolished.	Dynamic Compaction Method: Bulk excavation down to a depth of 4m, over-excavation of subsidence throat down to 10m (Dynamic Probing). Soil improvement to a maximum depth of 15m.	Pre & Post: Rebuilding of low cost houses, placed on reinforced concrete raft catering for 5m diameter loss of support.	4
10	Sinkhole	4,5 by 2 & 2,5	Point source: Broken 150mm diameter vitrified midblock sewer line at 3,5m.	Complexity: Complex, due to weathered rock above & within problematic horizons. Blanketing layer (3m – 15m thick): Residual chert (2m – 4m), residual dolomite (wad & ferroan soils) to a depth of 4m & 14m with 3m thick horizon of soft rock dolomite between a depth of 6m & 9m. No voids. Dolomite Bedrock: @ variable depth of 3m – 15m; no cavities.	< 10	Sinkhole partially extending below double storey house (access constraints), overhead electrical cables located in affected area & water line. No structural damages.	Compaction (backfill) grouting below structure, to a maximum depth of 15m. Sinkhole below structure backfilled with self compacting concrete & remaining open portion of sinkhole backfilled with soilcrete.	Pre & Post: Existing structure stabilized.	9
11	Sinkhole	4 & 8	Point source: 300mm diameter uPVC broken bulk sewer line @ 6m.	Complexity: Complex, heterogeneous profile. Blanketing layer (4m – 15m thick): Colluvium (1m – 2m or absent), residual chert (1m – 5m), 1m – 9m thick residual dolomite (wad), interlayered residual dolomite & shale/syenite in sub-areas between a depth of 4m & 15m; void encountered between a depth of 6m & 9m. Dolomite bedrock: @ variable depth of 6m – 15m, no cavities.	< 20	Concrete palisade fence – removed.	Inverted Filter Method and Dynamic Compaction (Probing) to a maximum depth of 14m	Pre & Post: Sewer servitude along provincial road.	5
12	Sinkhole	3 & 2	Point source: 160mm diameter uPVC sewer line disconnected from concrete manhole @ 3m.	Complexity: Complex, due to weathered rock & floaters located within problematic horizons. Blanketing layer (8m – 13m thick): Colluvium (1m), 8m – 13m thick residual dolomite (wad) with highly weathered soft rock dolomite horizons (1m -2m thick) between a depth of 3m & 10m. No voids. Dolomite bedrock: @ 8m – 13m, no cavities.	< 10	None.	Inverted Filter Method to a maximum depth of 10m.	Pre: Road with servitude. Post: Reinstate road	-

**Table 10 (continue): Summary of geological models, influencing factors, recommended rehabilitation method and relevant case study.**

Model	Event	Size (diam.) & Depth (m)	Trigger Mechanism	Geological Model	Lateral Extent of Impact (m)	External Influencing Factors	Rehabilitation Method	Land Use Pre and Post Rehabilitation	Case Study
<b>Impact to a depth of more than 15 m</b>									
13	Sinkhole	3 & 5	Point source: Broken 300mm diameter uPVC water line @ 1,5m.	Complexity: Complex, due to deeply weathered dolomite zone presenting gryke. Blanketing layer (1m – 29m thick): Residual chert (1m – 8m), 1m – 29m thick residual dolomite with 1m – 3m thick horizon of highly weathered soft rock dolomite between a depth of 5m & 8m. Although no voids encountered, possibility of void at bedrock depth as presented. Dolomite bedrock: @ 1m – 29m, presenting a gryke; no cavities.	< 20	Sinkhole in road & residential structure within 10m from sinkhole, severely cracked & portion subsided. Third parties – Public Protector.	Inverted Filter Method and Compaction (backfill) grouting to a maximum depth of 30m.	Pre: Road, servitude, garden & house. Post: Sterilization recommended due to cost implications; however rehabilitation enforced by Third Party & existing structure stabilized.	8
14	Subsidence	18 & 0,5	Point source: Damaged 75mm diameter PVC water line @ 1m.	Complexity: Complex, due to weathered rock horizon within problematic soils. Blanketing layer (19m – 28m thick): Residual chert (1m), 3m – 20m thick residual dolomite (wad), followed by soft rock dolomite horizon (3m – 6m thick) encountered between a depth of 4m and 27m, underlain by second horizon (1m – 10m thick) residual dolomite; no voids. Dolomite bedrock: @ 19m – 28m, no cavities	< 20	No access constraints. In road & informal settlements removed from affected area.	Inverted Filter Method to a maximum depth of 6m.	Pre & Post: Road (reinstated) & servitude.	-
15	Sinkhole	8 & 4	Point source: Damaged 300mm diameter PVC water pipe @ 1,5m. Additional collapse of 600mm diameter concrete stormwater pipe.	Complexity: Complex, heterogenous profile. Blanketing layer (18m – 23m thick): Road fill (1m – 2m), interlayered residual chert & syenite (1m – 3m thick) in sub-areas, residual syenite and interlayered residual syenite & dolomite (1m – 3m thick) in sub-areas, 3m thick residual dolomite (ferroan soils) in sub-areas, soft rock dolomite encountered between a depth of 9m & 18m; no voids. Dolomite bedrock: @ 18m – 23m; no cavities.	< 20	No access constraints.	Inverted Filter Method to a maximum depth of 11m.	Pre & Post: Road (reinstated) & servitude.	-

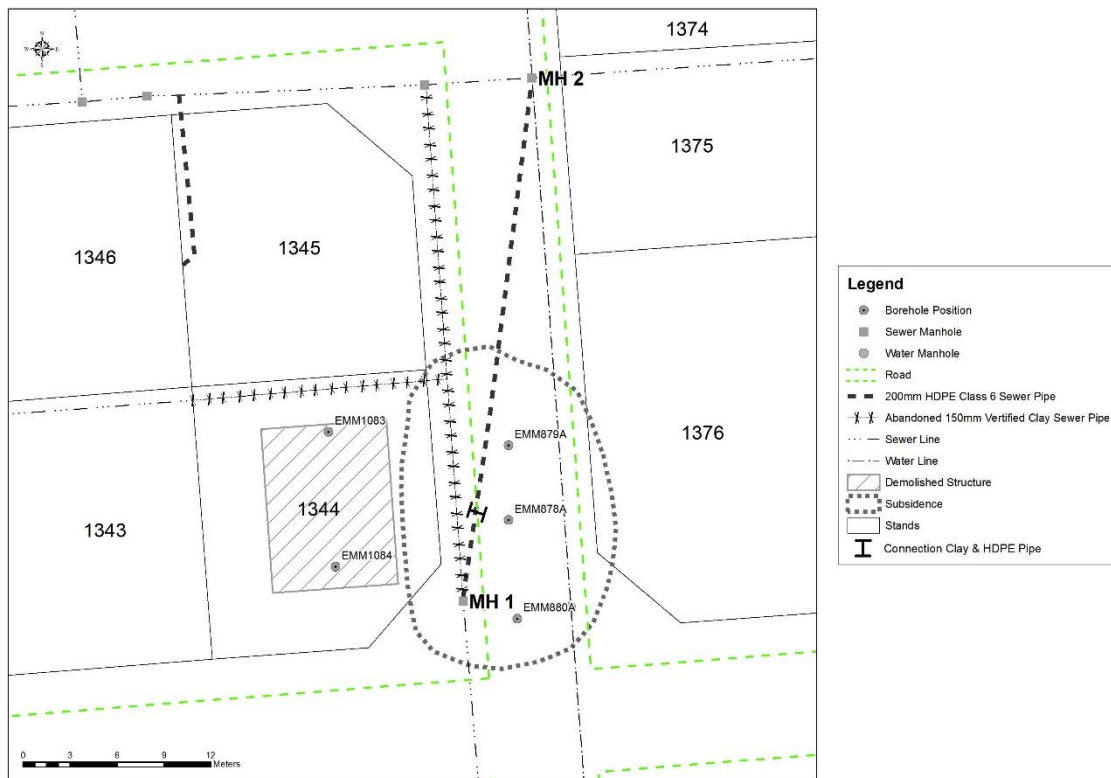
Model	Event	Size (diam.) & Depth (m)	Trigger Mechanism	Geological Model	Lateral Extent of Impact (m)	External Influencing Factors	Rehabilitation Method	Land Use Pre- and Post Rehabilitation	Case Study
<b>Impact to a depth of more than 15 m</b>									
16	Sinkhole	50 & 25	Dewatering: Original groundwater level @ 19m, drawdown to >50m; followed by surface water ponding.	Complexity: Complex, deep heterogenous profile. Blanketing layer (8m – 40m thick): Colluvium (1m – 3m), residual Karoo shale (2m – 10m thick), chert gravel & sand (5m – 27m thick), residual dolomite (25m thick to absent); no voids. Dolomite bedrock: @ 8m – 40m; number of interconnected cavities.	> 50	No access constraints, agricultural land.	Fence off affected area. Placing of soil berm around sinkhole area and landscaping of immediate surrounding area.	Pre: Agricultural land. Post: Sterilization of agricultural land.	-
17	Sinkhole	7 & 5	Point source: Accumulation of surface water run-off against a boundary wall.	Complexity: Complex, thick horizon of low susceptible material above problematic horizon. Blanketing layer (45m thick): Colluvium (1m), residual chert (5m – 7m thick), residual syenite (29m thick), 10m – 15m thick residual dolomite (wad); voids encountered between a depth of 39m & 49m. Dolomite bedrock: @ 35m - >45m; cavities encountered between 40m & 45m depth.	> 50	House <7m from sinkhole.	Compaction (backfill) grouting with grout curtain to a maximum depth of > 50m & capping layer of low permeability material. Alternatively sterilization of land, fence off area, placing of capping layer, soil berms, landscaping of area.	Pre: Open field with house less than 7m away. Post: Sterilization of land, due to cost implications.	10

## 7.2 Impact to a depth of less than 8

Eight geological models, the evaluation process (flow chart) and the most appropriate rehabilitation method for each are presented.

### 7.2.1 Geological and Rehabilitation Model 1

A subsidence of 15 m diameter size extending to a depth of 0,5 m occurred within the street directly east of Stand 1344 in Tokoza, before 2004 (Report No. VGI3355/89 and 89-1). The subsidence did contribute to structural damage to the house on Stand 1344. The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 25.



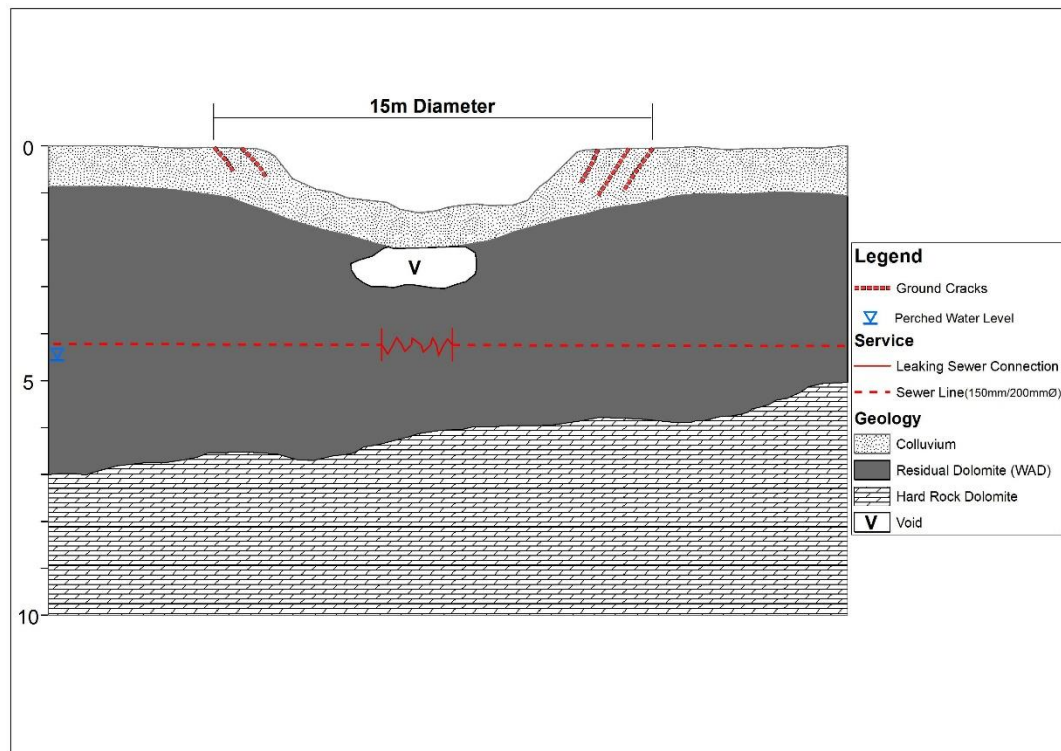
**Figure 25: Plan View of Generic Geological Model 1**

#### 7.2.1.1. Geological Model

The geological model is based on five percussion boreholes. Three boreholes were drilled within the subsidence area and two within the area of the demolished residential structure. The geological model is illustrated in Figure 26.

- Complexity: Simple, presenting a homogeneous profile.
- Blanketing Layer: Comprising a horizon of ferruginised colluvium (1 m) underlain by a horizon of 4 m to 6 m thick residual dolomite (wad), highly susceptible to subsurface erosion or consolidation. Void encountered.
- Dolomite bedrock: At a shallow depth of 5 m to 7 m. No cavities encountered.

- Groundwater Level: In dolomite bedrock. Perched groundwater table at a depth of approximately 4 m.



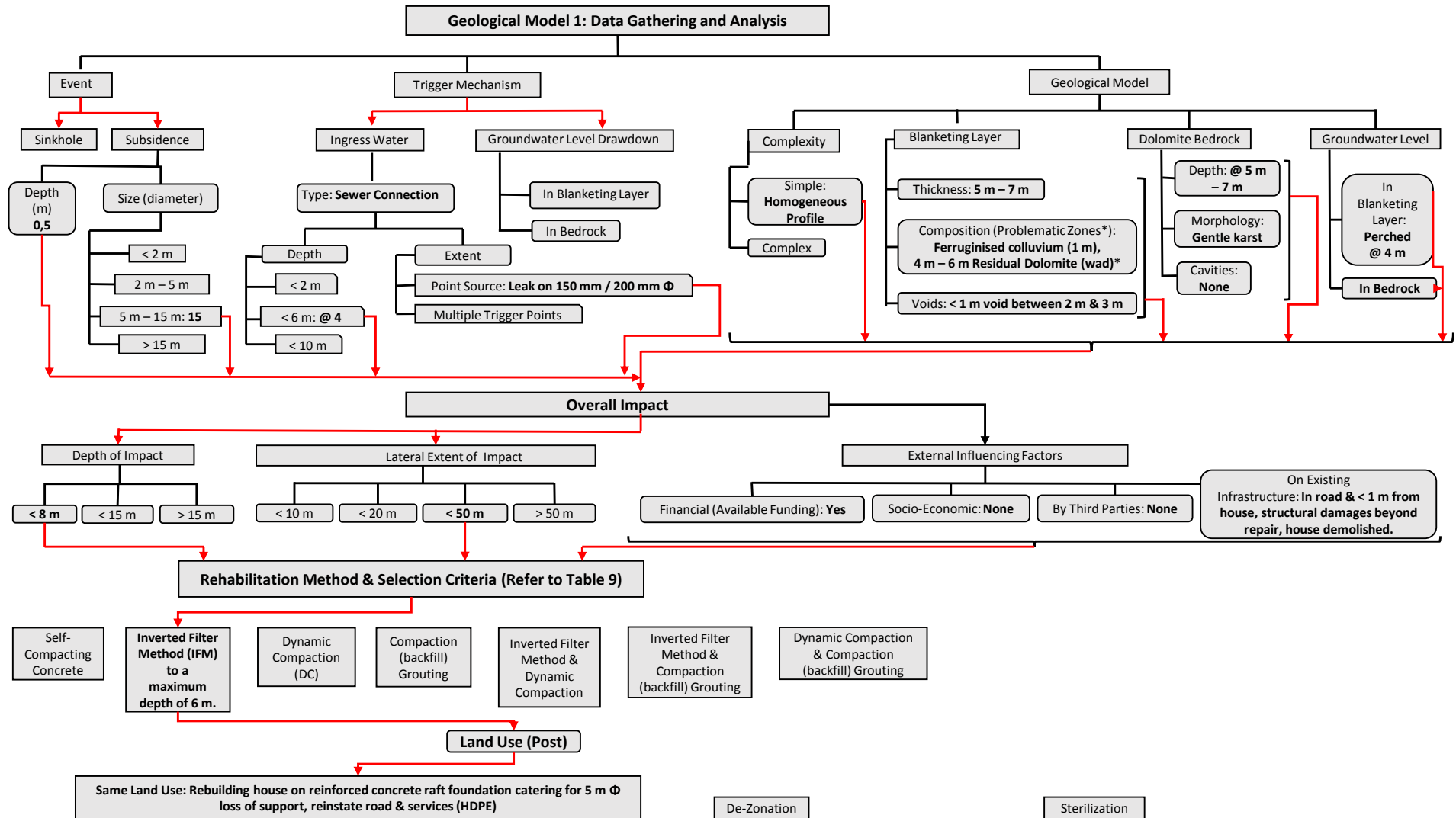
**Figure 26: Generic Geological Model 1**

#### 7.2.1.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: A leak on the connection between a 150 mm diameter vitrified clay and 200 mm diameter Class 6 HDPE sewer pipe, located within residual dolomite (wad) horizon, caused consolidation of the residual dolomite (wad).

#### 7.2.1.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 15 m diameter size subsidence extending to a depth of 0,5 m.
- Depth and extent of triggering mechanism: At a depth of 4 m, point source.
- Impact on existing infrastructure: Subsidence located less than 1 m from residential structure, caused structural damages beyond repair, house demolished.



Flow Chart 2: Generic Geological Model 1 – Process of subsidence evaluation criteria and selection of rehabilitation method

7.2.1.4. Recommended Rehabilitation Method

Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 27).

Entire sewer line located approximately 5 m away from the demolished structure replaced with HDPE butt welded pipe and two HDPE manholes from manhole to manhole over a distance of approximately 32 m.

Reason for using specific rehabilitation method:

- Shallow dolomite bedrock, with residual dolomite (wad) highly susceptible to subsurface erosion or consolidation within maximum reach of an excavator.

As the house was demolished no access constraints for proposed and recommended rehabilitation method. The remaining profile below the excavated area comprises 1 m and less highly susceptible material.

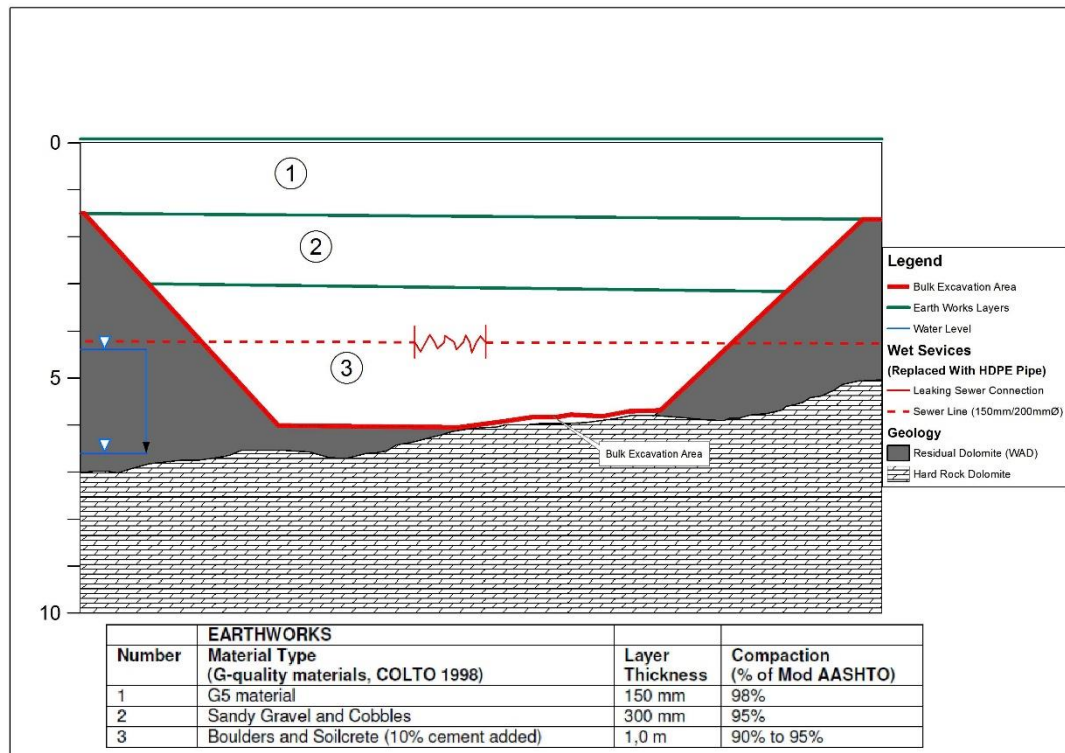


Figure 27: Recommended Rehabilitation Method Generic Geological Model 1

Layer works:

- Number 1: The upper 1,5 m comprising 150 mm G5-quality material is similar to what is normally used, however material were compacted at 98% Modified AASHTO compaction effort and not the specified 95%. As the rehabilitated area is proposed for the rebuilding of a house, strict requirements were followed in terms of the type of material to be used in layer works and their compaction efforts, to create an earth mattress suitable for the rebuilding of a house.

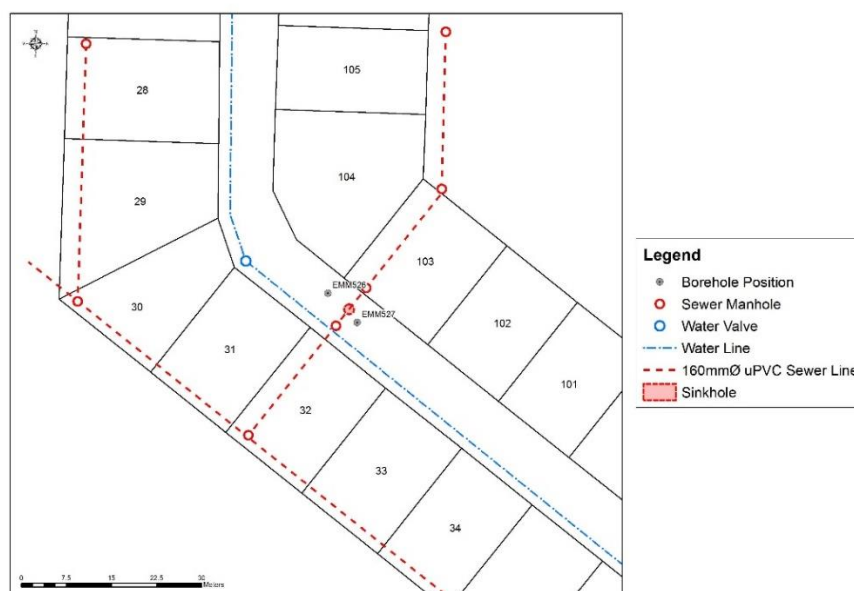
- Number 2: The bulk filling between a depth of 1,5 m to 3,0 m comprising sandy gravel and cobbles placed within 300 mm thick layers compacted at 95% Modified AASHTO deviates from the typical use of G8-quality material placed in layers of 200 mm compacted with a 32 Ton excavator bucket. The layer thickness is a function of the type of material to be compacted, compaction machinery and the required compaction effort.
- Number 3: Bulk filling comprising boulders and 10% cement component in the soilcrete mix deviates from the typical use of 3% to 5% and the use of 200mm layers of G8-quality material. As the profile presents a strong flowing perched water table creating wet conditions within the area of earthworks, stabilising to a depth well above the perched water table (3 m) was required to create a stable platform to work on and the use of the boulders was for volume purposes. In addition, a higher cement percentage absorbs more water and forming a stronger binding.

#### 7.2.1.5. Land use after rehabilitation

Rebuilding of house, on a reinforced concrete raft foundation, catering for a loss of support of 5 m diameter. The subsurface profile after rehabilitation, presents a profile suitable for a residential single storey structure. For more information related to this specific geological and rehabilitation model refer to Case Study 3.

#### 7.2.2 Geological and Rehabilitation Model 2

A sinkhole of 1 m diameter size extending to a depth of 2 m occurred in the road, opposite Stand 103, Itshizi Street, Mailula Section, Vosloorus Extension 3, on 9 April 2010 (Report No. VGI3118R-WO288-2). The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 28.



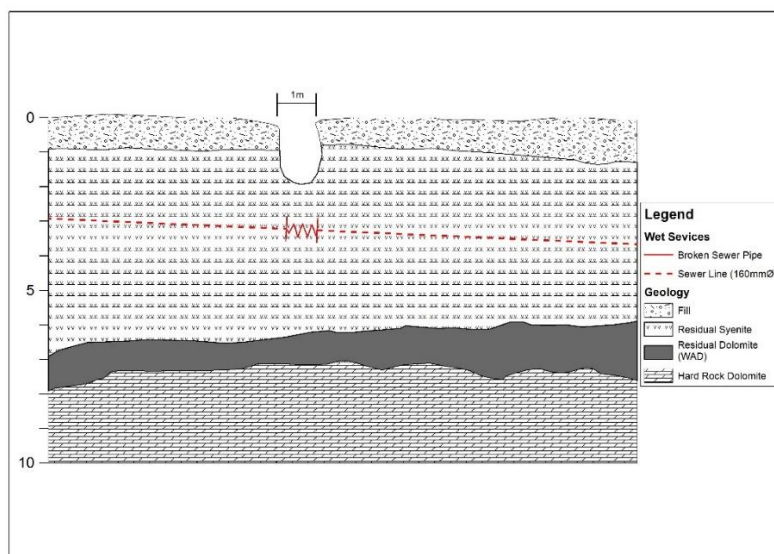
**Figure 28: Plan View of Generic Geological Model 2**



### 7.2.2.1. Geological Model

The geological model is based on two percussion boreholes, positioned on both sides of the sinkhole in the road. The geological model is illustrated in Figure 29.

- Complexity: Simple, presenting a homogeneous profile.
- Blanketing Layer: Comprising a horizon of road fill (1 m) underlain by a horizon of low susceptible residual syenite (5 m to 6 m thick), followed at depth by a horizon of 1 m thick residual dolomite (wad) with a high susceptibility to subsurface erosion or consolidation. No voids encountered.
- Dolomite bedrock: At a shallow depth of 8 m. No cavities.
- Groundwater Level: In dolomite bedrock.



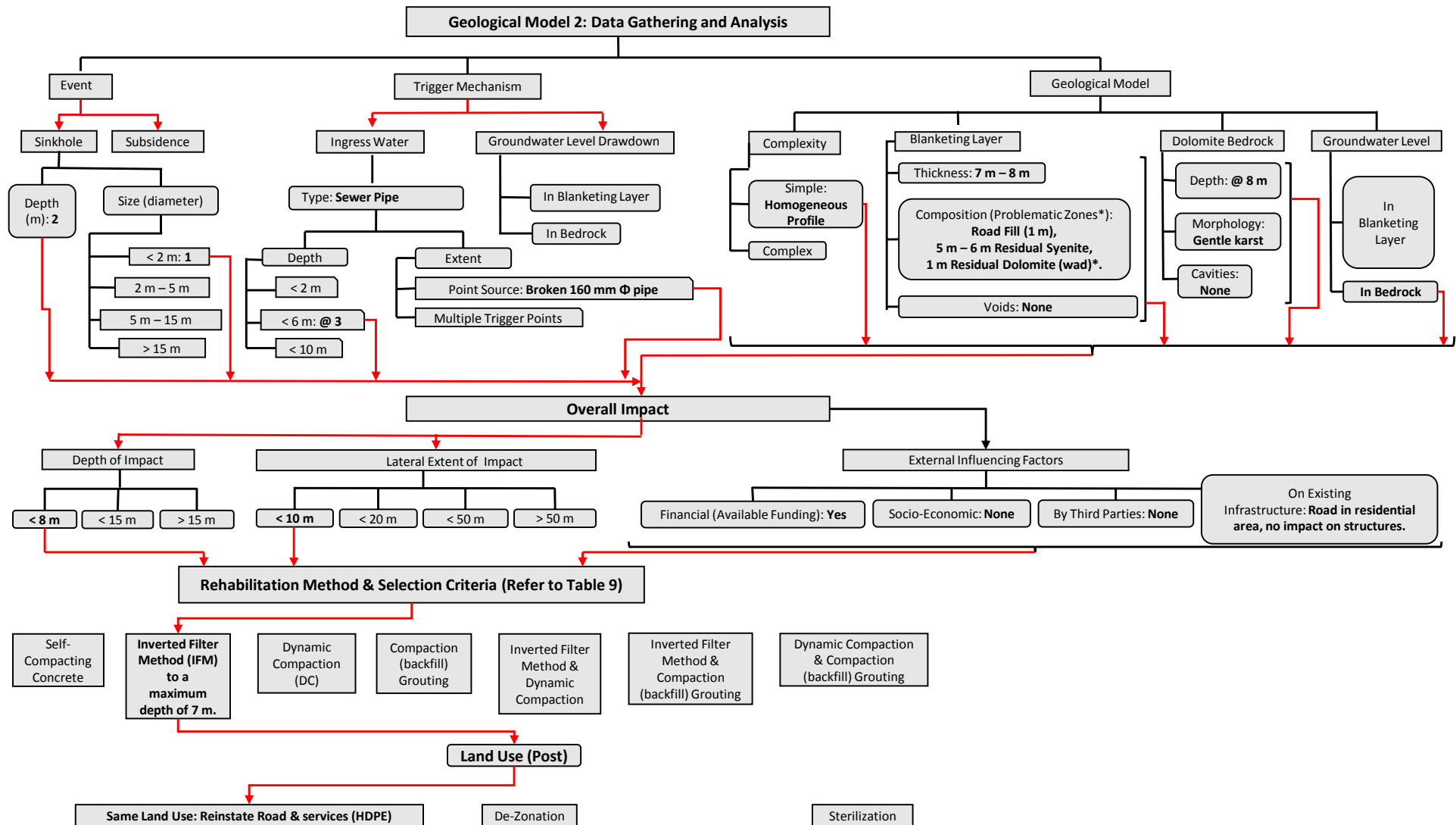
**Figure 29: Generic Geological Model 2**

### 7.2.2.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: Broken 160 mm diameter size uPVC sewer pipe located within residual syenite with low mobilization potential. Effluent from the broken sewer pipe transported downwards into the underlain highly susceptible residual dolomite (wad) caused subsurface erosion.

### 7.2.2.3. Depth and lateral extent of instability feature and triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 1 m diameter size sinkhole extending to a depth of 2 m.
- Depth and extent of triggering mechanism: At a depth of 3 m, point source.
- Impact on existing infrastructure: Road, no impact on structures.



Flow Chart 3: Generic Geological Model 2 – Process of sinkhole evaluation criteria and selection of rehabilitation method

#### 7.2.2.4. Recommended Rehabilitation Method

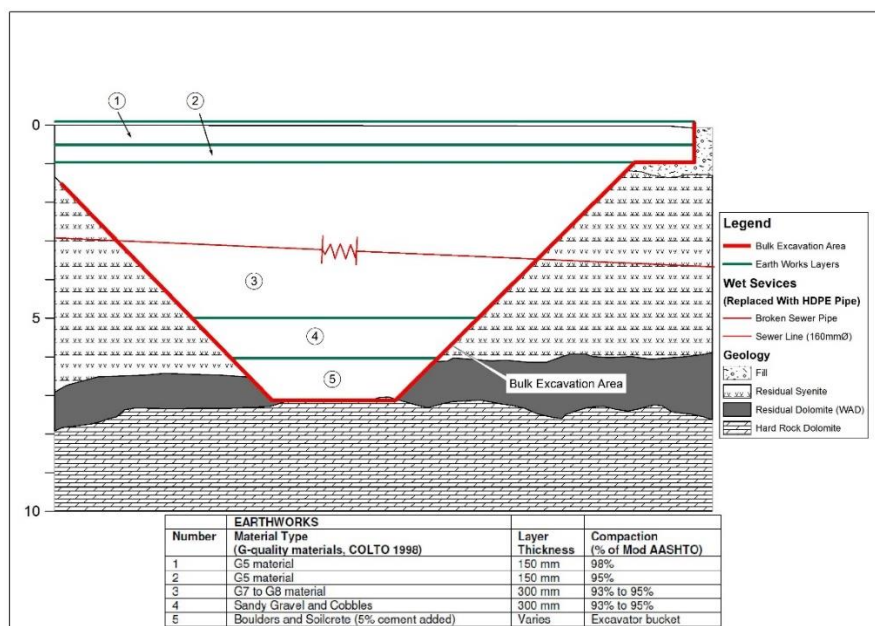
Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 30).

Entire sewer line replaced with HDPE butt welded pipe from manhole to manhole over a distance of approximately 8 m.

Reason for using specific rehabilitation method:

- Shallow dolomite bedrock, with a thin horizon (1 m) of residual dolomite (wad) highly susceptible to subsurface erosion within reach using an excavator and over-excavated trench of 1 m at base.

No access constraints for proposed and recommended rehabilitation method. The remaining profile below the excavated area comprising dolomite bedrock.



**Figure 30: Recommended Rehabilitation Method Generic Geological Model 2**

Layer works:

- Number 1: The upper 0,3 m compacted at 98% Modified AASHTO compaction effort as part of the road layer works.
- Number 2: The upper 1,0 m comprising 150 mm G5-quality material compacted at 95% Modified AASHTO.
- Number 3: The bulk filling between a depth of 1,0 m to 5,0 m comprising G7 to G8-quality material within 300 mm thick layers compacted at 93% to 95% Modified AASHTO deviates from the typical use of G8-quality material placed in layers of 200 mm compacted with a 32 Ton excavator bucket.
- Number 4: The bulk filling between a depth of 5,0 m to 6,0 m comprising sandy gravel and cobbles placed within 300 mm thick layers compacted at 93% to

95% Modified AASHTO deviates from the typical use of G8-quality material placed in layers of 200 mm compacted with a 32 Ton excavator bucket.

- Number 5: Bulk filling comprising boulders and a 5% cement component in the soilcrete mix deviates from the typical use of 200mm layers of G8-quality material. This was done to create a stable platform to work on and the use of boulders for volume purposes.

Even though the residual syenite presents material with a low susceptibility for sinkhole formation, the underlain residual dolomite (wad) that caused subsurface erosion needed to be removed and replaced by more competent material. The dolomite profile in rehabilitated area presents a dolomite profile with a low susceptibility to sinkhole or subsidence formation.

#### 7.2.2.5. Land use after rehabilitation

Reinstatement of road.

#### 7.2.3 Geological and Rehabilitation Model 3

A sinkhole of 2 m diameter size extending to a depth of 2 m occurred on the boundary between Stand 948 and Stand 961 (Buttercup Close Road), Rondebult, during January 2009 (Report No. VGI3118/201/2). The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 31.

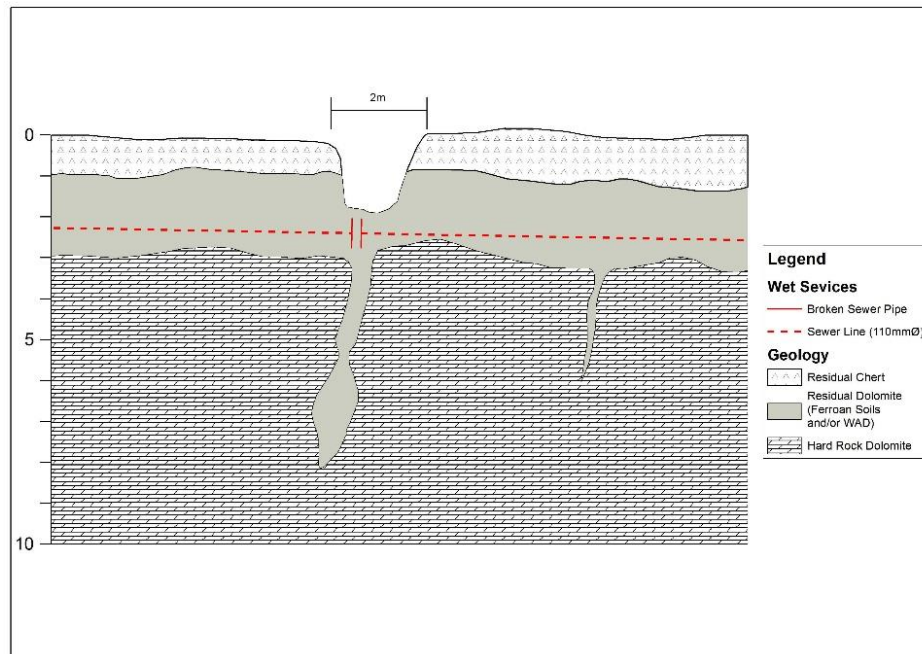


**Figure 31: Plan View of Generic Geological Model 3.**

##### 7.2.3.1. Geological Model

The geological model is based on three percussion boreholes, positioned in the area surrounding the sinkhole and between houses. The position of existing houses made it difficult to place more boreholes. The geological model is illustrated in Figure 32.

- Complexity: Simple, presenting a homogeneous profile.
- Blanketing Layer: Comprising a horizon of residual chert (1 m) underlain by a horizon of 2 m thick residual dolomite (wad and ferroan soils) with a high susceptibility to subsurface erosion or consolidation. No voids encountered.
- Dolomite bedrock: At a shallow depth of 3 m with 1 m grykes and smaller, extending to a depth of approximately 8 m. No cavities.
- Groundwater Level: In dolomite bedrock.



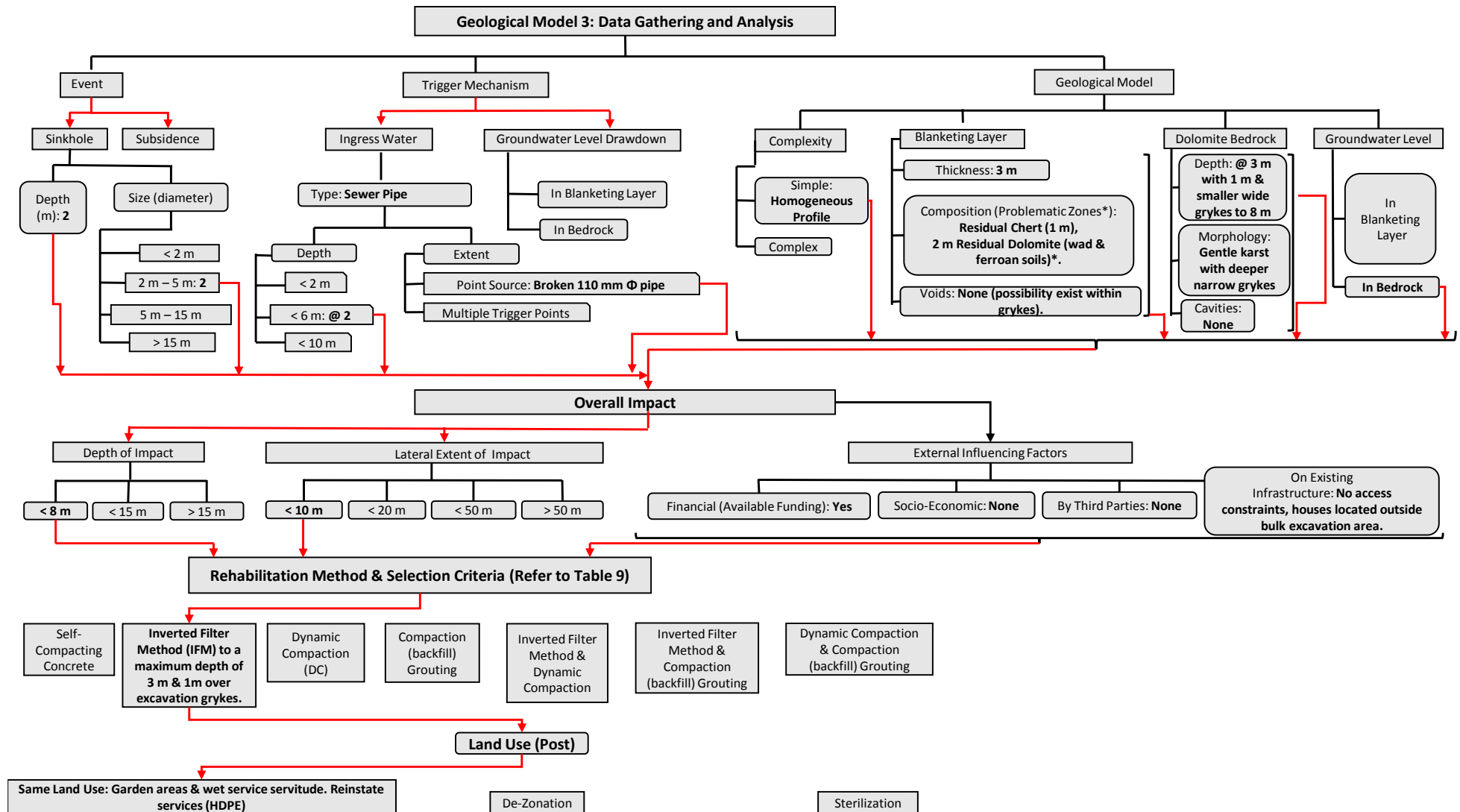
**Figure 32: Generic Geological Model 3.**

#### 7.2.3.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: Broken 110 mm diameter uPVC midblock sewer pipe located within residual dolomite (wad and ferroan soils) with high mobilization potential. Sewage from the broken pipe caused subsurface erosion. Even though no cavities or voids were encountered in profile, a possibility exists for voids within narrow gryke zones to accommodate mobilized material from above.

#### 7.2.3.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 2 m diameter size sinkhole extending to a depth of 2 m.
- Depth and extent of triggering mechanism: At approximately 2 m, point source.
- Impact on existing infrastructure: Houses on both sides of sinkhole, approximately 4 m away.



Flow Chart 4: Generic Geological Model 3 – Process of sinkhole evaluation criteria and selection of rehabilitation method

### 7.2.3.4. Recommended Rehabilitation Method

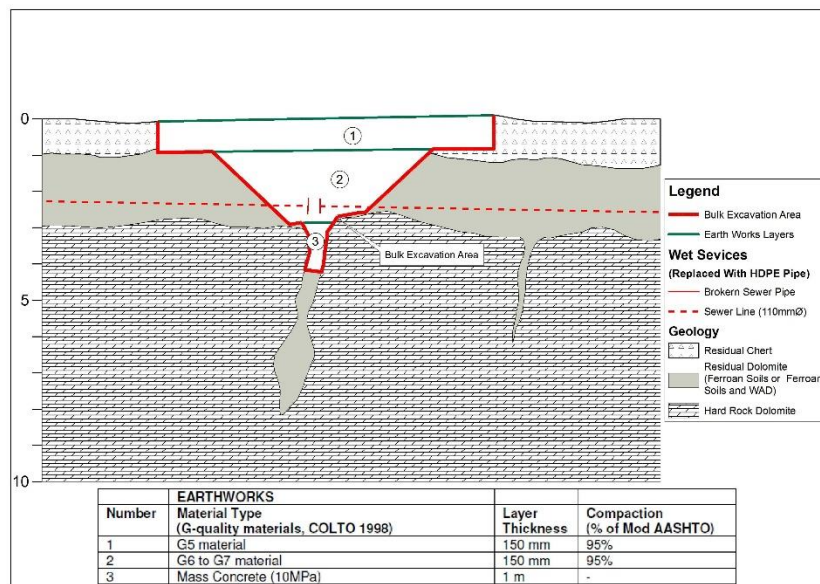
Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 33).

Installation of a new HDPE manhole and sewer line replaced with HDPE butt welded pipe from manhole to manhole over a distance of approximately 25 m.

Reason for using specific rehabilitation method:

- Shallow dolomite bedrock with narrow grykes (filled with residual dolomite and possibility of voids), with a thin horizon (2 m) of residual dolomite (wad and ferroan soils) highly susceptible to subsurface erosion within reach using an excavator.

No access constraints for proposed and recommended rehabilitation method. The remaining profile below the excavated area comprising dolomite bedrock with deeper narrow grykes.



**Figure 33: Recommended Rehabilitation Method Generic Geological Model 3.**

Layer works:

- Number 1: The upper 1,0 m comprising 150 mm G5-quality material compacted at 95% Modified AASHTO.
- Number 2: Bulk filling from a depth of 1 m to 3 m comprising G6 to G7-quality material, placed in layers of 150 mm compacted at 95% Modified AASHTO. Smaller compaction machinery used due to access constraints, therefore a layer thickness of 150 mm selected in order to obtain 95% Modified AASHTO compaction of layers. Deviates from the typical use of 200 mm layers of G8-quality material compacted with a 32 Ton Excavator Bucket.
- Number 3: A 1 m thick layer of 10 MPa mass concrete used to plug the narrow

grykes and create a stable platform. Reinforced concrete slabs could also been considered as alternative.

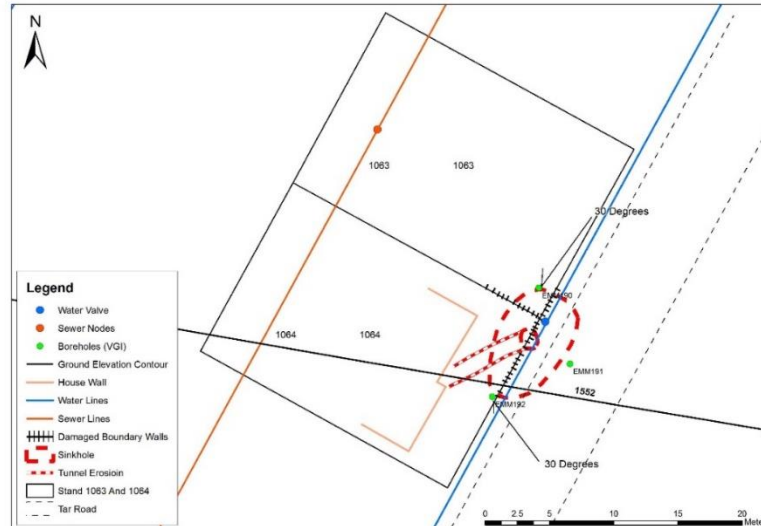
The 2 m thick horizon of residual dolomite (wad and ferroan soils) that accommodated subsurface erosion needed to be removed and replaced by more competent material. The dolomite profile after rehabilitation presents a profile with a low susceptibility for sinkhole or subsidence formation.

#### 7.2.3.5. Land use after rehabilitation

Garden areas of residential stands, wet service servitude.

#### 7.2.4 Geological and Rehabilitation Model 4

A sinkhole occurred on the boundary between Stands 1063 and 1064, Njakata Crescent Street, Vosloorus Extension 2, on 20 November 2008 (Report No. VGI3118/193/2). A 5 m diameter size sinkhole extending to a depth of 3 m with an approximately 1 m diameter size erosion tunnel extending into bedrock to a depth of 7 m where it enters a cavity of approximately 4 m diameter and 2 m high. The erosion tunnel and cavity extending below the house on Stand 1064 and the boundary walls of Stand 1064 is severely damaged. The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 34.



**Figure 34: Plan View of Generic Geological Model 4.**

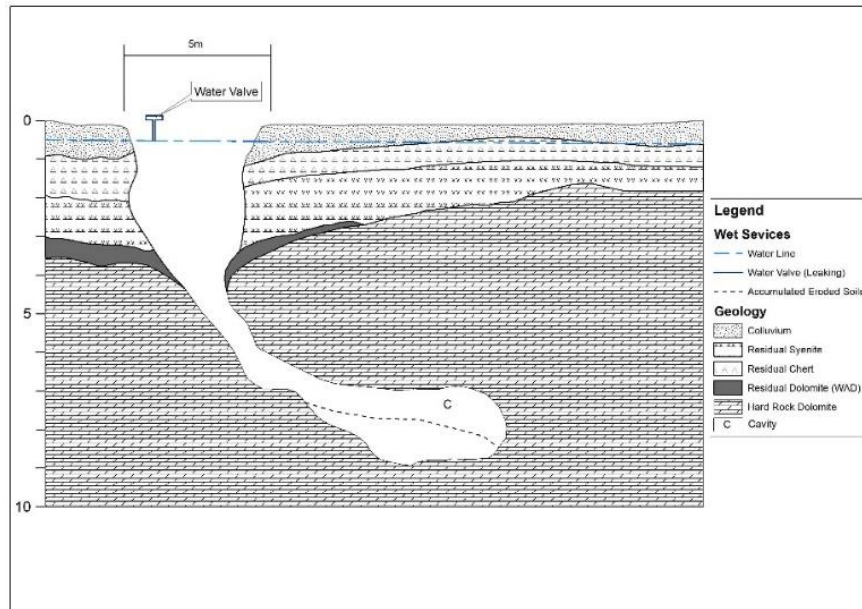
#### 7.2.4.1. Geological Model

The geological model is based on three percussion boreholes positioned in the area surrounding the sinkhole. The geological model is illustrated in Figure 35.

- Complexity: Complex, due to weathering profile.



- Blanketing Layer: Comprising a horizon of colluvium (1 m), residual chert (1 m) and residual syenite (1 m) underlain by a very thin horizon of less than 1 m residual dolomite (wad) with a high susceptibility to subsurface erosion or consolidation. A 1 m diameter subsurface erosion tunnel encountered, extending downwards into dolomite bedrock.
- Dolomite bedrock: At a shallow depth of 2 m to 5 m with 1 m diameter erosion tunnel extending sub-vertical to a depth of approximately 7 m where it enters a cavity of approximately 4 m diameter and 2 m high.
- Groundwater Level: In dolomite bedrock.



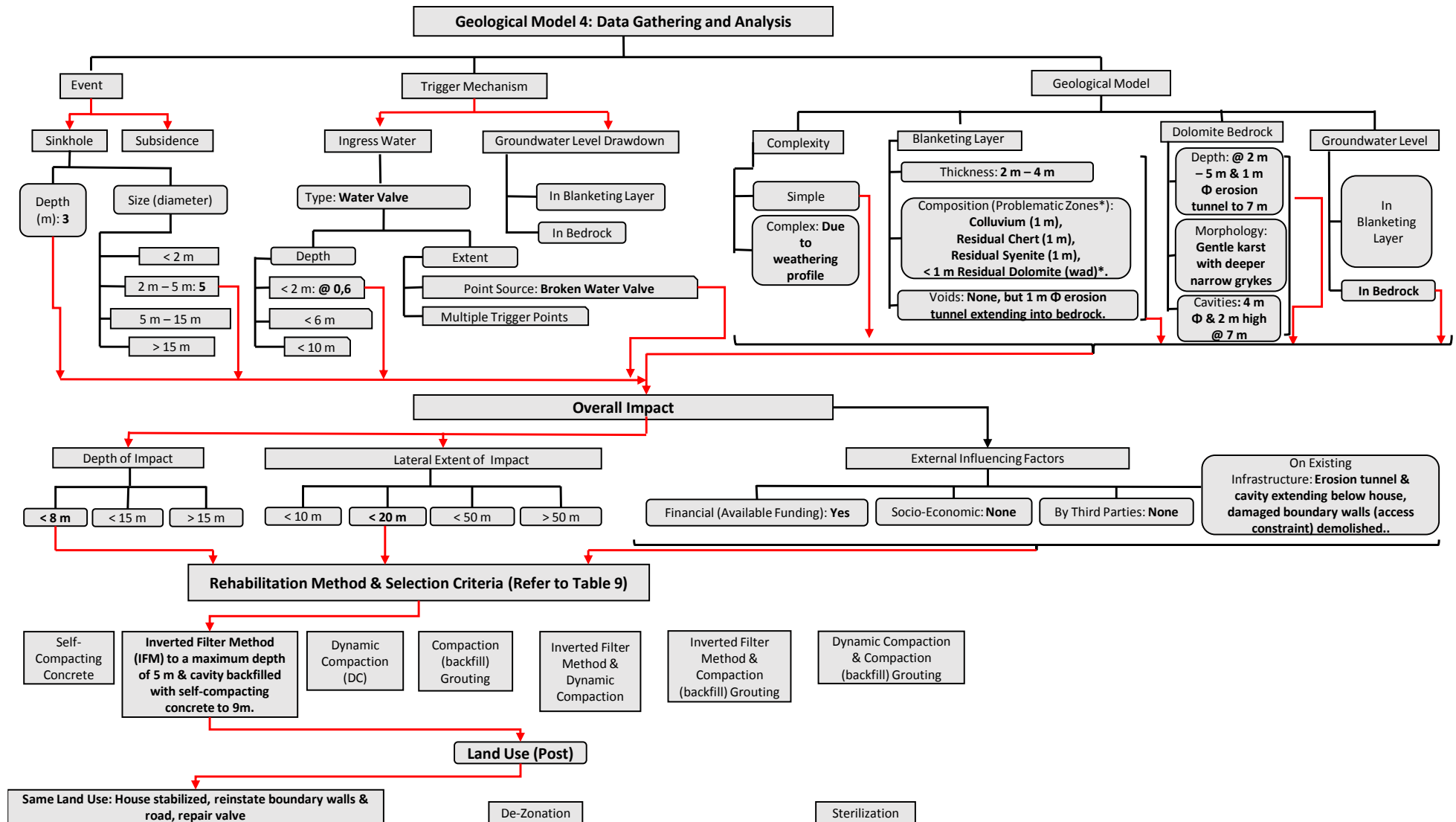
**Figure 35: Generic Geological Model 4.**

#### 7.2.4.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: Broken water valve located within colluvium layer. Water from the broken water valve caused subsurface erosion in the form of an erosion tunnel through the colluvium, residual chert, residual syenite and residual dolomite (wad) with high mobilization potential. Mobilized material was deposited into an open cavity (partially filled with residual dolomite (wad) located within dolomite bedrock.

#### 7.2.4.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 5 m diameter size sinkhole extending to a depth of 3 m; with erosion tunnel extending sub-vertically to 7 m where it enters a 4 m diameter and 2 m high cavity.
- Depth and extent of triggering mechanism: At approximate 0,6 m depth, point source.
- Impact on existing infrastructure: Damage to boundary wall, sinkhole located in residential garden area and below house.



Flow Chart 5: Generic Geological Model 4 – Process of sinkhole evaluation criteria and selection of rehabilitation method

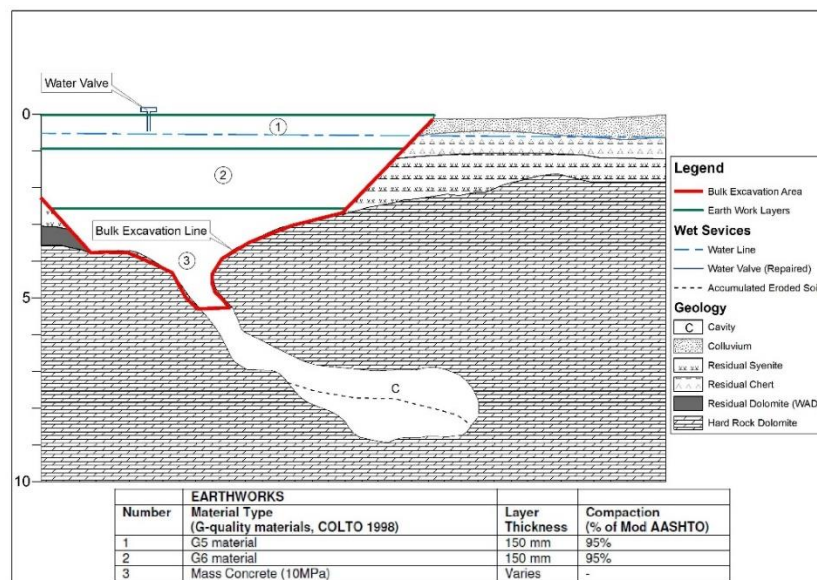
#### 7.2.4.4. Recommended Rehabilitation Method

Inverted Filter Method and use of Mass concrete: Refer to the Rehabilitation Model for various earthworks layers and position of mass concrete (Figure 36). Repair of water valve. Water valve and waterline at a depth of 0,6 m levelled.

Reason for using specific rehabilitation method:

- Shallow dolomite bedrock, with accessible 1 m diameter erosion tunnel into dolomite bedrock entering an open cavity (partially filled with wad), with a very thin horizon (less than 1 m) residual dolomite (wad) directly above dolomite bedrock highly susceptible to subsurface erosion within reach of an excavator.

The existing boundary wall caused access constraints for proposed and recommended rehabilitation method and therefore the boundary walls were demolished. The remaining profile below excavated area comprising dolomite bedrock with erosion tunnel extending downwards into a cavity (partially filled with wad).



**Figure 36: Recommended Rehabilitation Method Generic Geological Model 4.**

Layer works:

- Number 1: The upper 1,0 m comprising 150 mm G5-quality material compacted at 95% Modified AASHTO.
- Number 2: Bulk filling from a depth of 1 m to 2,5 m comprising G6-quality material placed in layers of 150 mm compacted at 95% Modified AASHTO. Due to access constraints for large compaction machinery necessitates use of smaller compaction machinery, a layer thickness of 150 mm was selected in order to obtain 95% compaction of layers. Deviates from the use of 200mm

layers of G8-quality material compacted with a 32 Ton Excavator Bucket.

- Number 3: Mass concrete of 10 MPa was used up to a depth of 2,5m below ground surface to fill the cavity and erosion tunnel; up to a depth where the subsurface erosion area below the house was completely filled and to create a stable platform to work on.

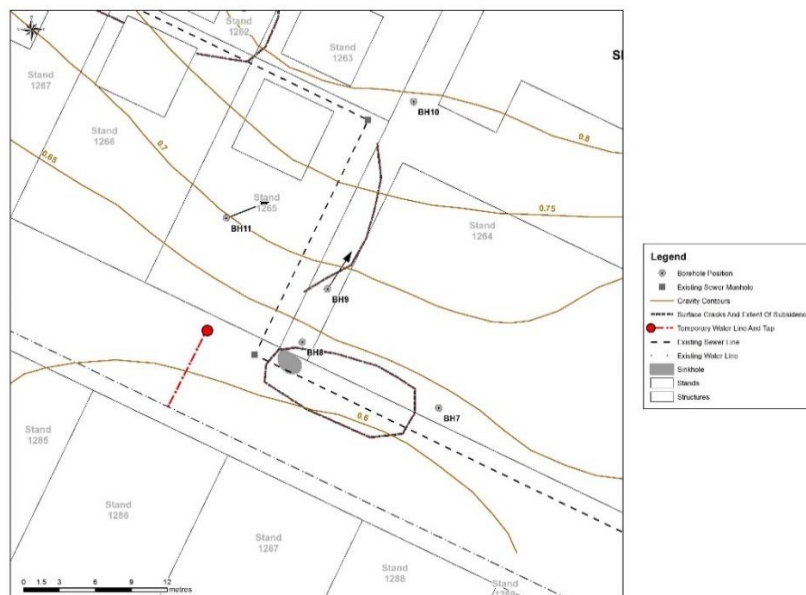
The open erosion tunnel and cavity needed to be filled properly as a house partially straddles the cavity. In addition, the less than 1 m thick horizon of residual dolomite (wad) highly susceptible to subsurface erosion needed to be removed and replaced by more competent material. The rehabilitated profile presents a low susceptibility to sinkhole or subsidence formation.

#### 7.2.4.5. Land use after rehabilitation

Existing residential house and boundary wall stabilized. For more information related to a similar geological and rehabilitation model refer to Case Study 2 in the Appendix.

#### 7.2.5 Geological and Rehabilitation Model 5

A sinkhole of 2 m diameter size extending to a depth of 7 m occurred on the south-eastern corner of Stand 1265, Rondebult Extension 2, during October 2006 (Report No. KHH1366, KHH1378, KHH1387, KHH1562). The affected area, existing infrastructure and positions of boreholes are displayed in Figure 37.

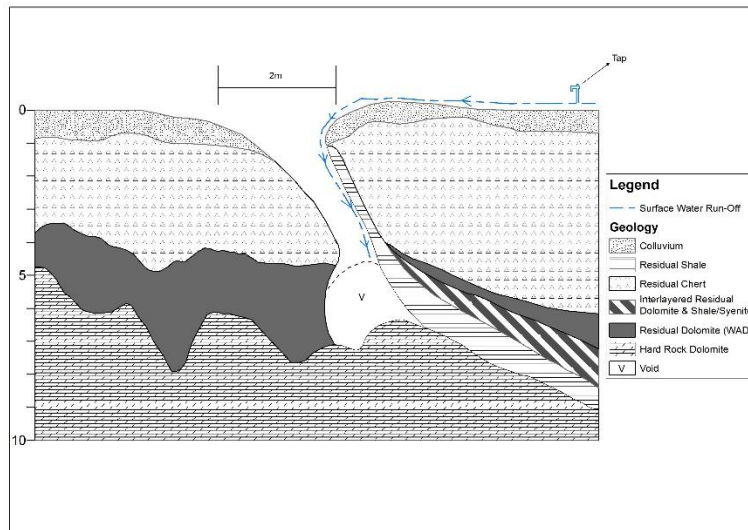


**Figure 37: Plan View of Generic Geological Model 5.**

#### 7.2.5.1. Geological Model

The geological model is based on a gravity survey (10 m station interval), drilling of two percussion boreholes and bulk excavation of the affected area. The geological model is illustrated in Figure 38.

- Complexity: Intermediate to complex, with horizontal and sub-vertical orientated horizons.
- Blanketing Layer: Comprising a horizon of colluvium (1 m) underlain by a horizon of residual chert (3 m to approximately 6 m thick) in turn underlain by 1 m to 3 m residual dolomite (wad), highly susceptible to subsurface erosion or consolidation and a less than 1 m thick horizon of interlayered residual dolomite (wad) and shale in sub-areas. A sub-vertical to vertical shale horizon cuts through the profile. Void encountered.
- Dolomite bedrock: At a shallow depth of 5 m to 8 m.
- Groundwater Level: In dolomite bedrock.



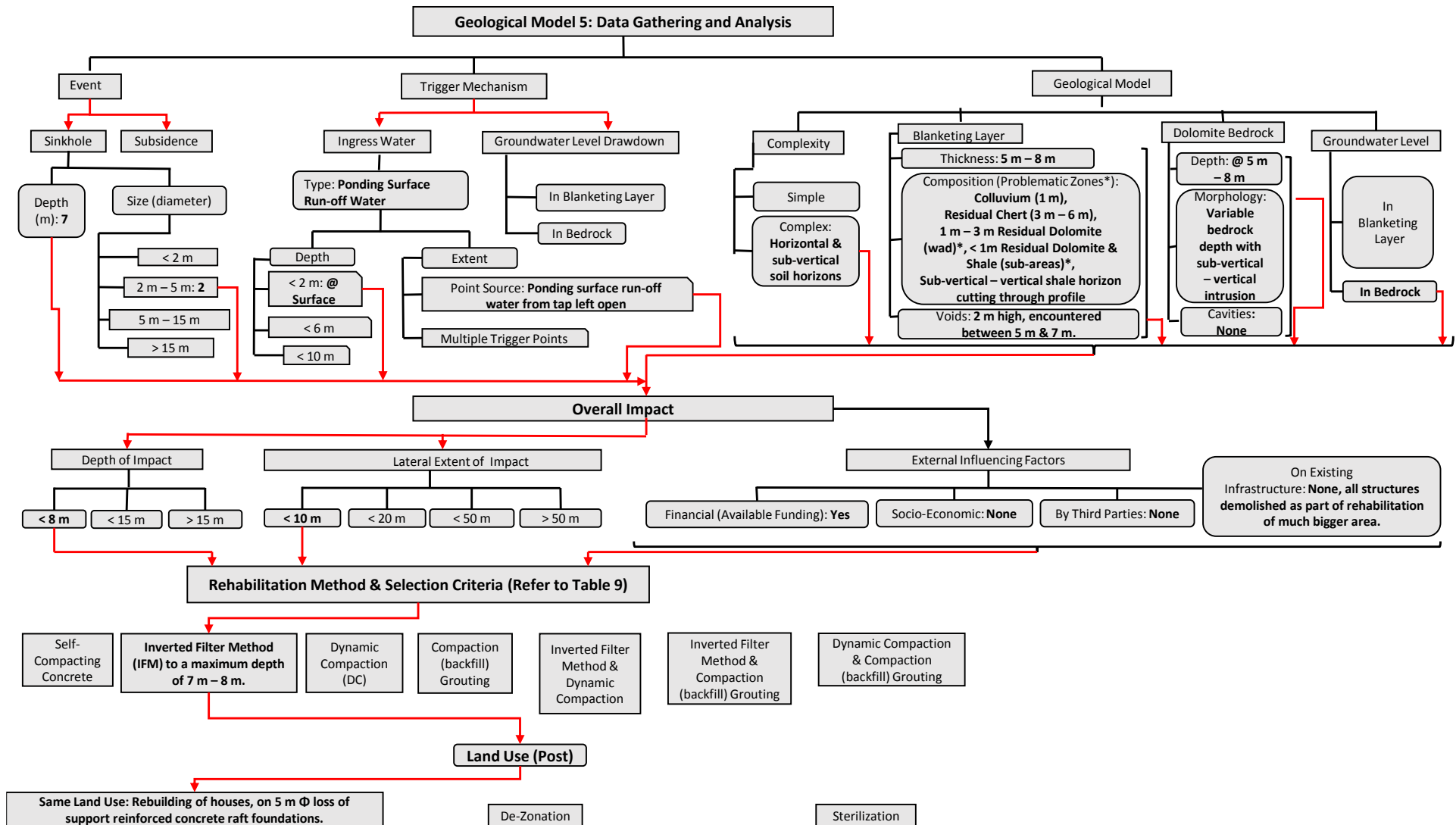
**Figure 38: Generic Geological Model 5.**

#### 7.2.5.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: Surface water run-off from a tap left open more than 24-hours ponding in a low lying area. The infiltration of water at a concentrated point on surface caused sub-surface erosion of susceptible materials along the shale interface and deposited mobilized material into a void located within the residual dolomite (wad) at depth.

#### 7.2.5.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 2 m diameter size sinkhole extending to a depth of 7 m.
- Depth and extent of triggering mechanism: At surface, point source.
- Impact on existing infrastructure: None as all structures were demolished as part of rehabilitation process for a much bigger area.



Flow Chart 6: Generic Geological Model 5 – Process of sinkhole evaluation criteria and selection of rehabilitation method

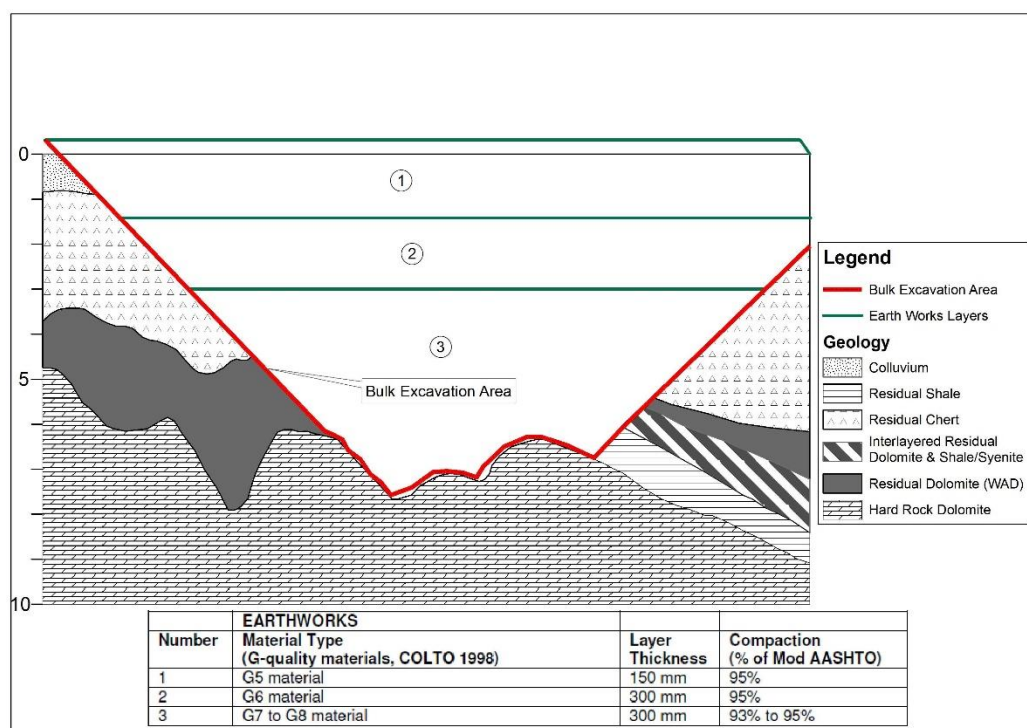
#### 7.2.5.4. Recommended Rehabilitation Method

Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 39).

Reason for using specific rehabilitation method:

- Shallow dolomite bedrock, with residual dolomite (wad) highly susceptible to subsurface erosion or consolidation within maximum reach of an excavator.

As the houses were demolished the recommended rehabilitation method were not affected by access constraints. Remaining profile below excavated footprint area comprising dolomite bedrock.



**Figure 39: Recommended Rehabilitation Method Generic Geological Model 5.**

Layer works:

- Number 1: The upper 1,5 m comprising 150 mm layers of G5-quality material compacted at 95% of Modified AASHTO.
- Number 2: The bulk filling between a depth of 1,5 m to 3,0 m comprising G6-quality material placed within 300 mm thick layers compacted at 95% Modified AASHTO deviates from the typical use of G8-quality material placed in layers of 200 mm compacted with a 32 Ton excavator bucket.
- Number 3: The bulk filling between a depth of 3,0 m to 8,0 m comprising G7 to G8-quality material within 300 mm thick layers compacted at 93% to 95% Modified AASHTO deviates from the typical use of G8-quality material placed in layers of 200 mm compacted with a 32 Ton excavator bucket.

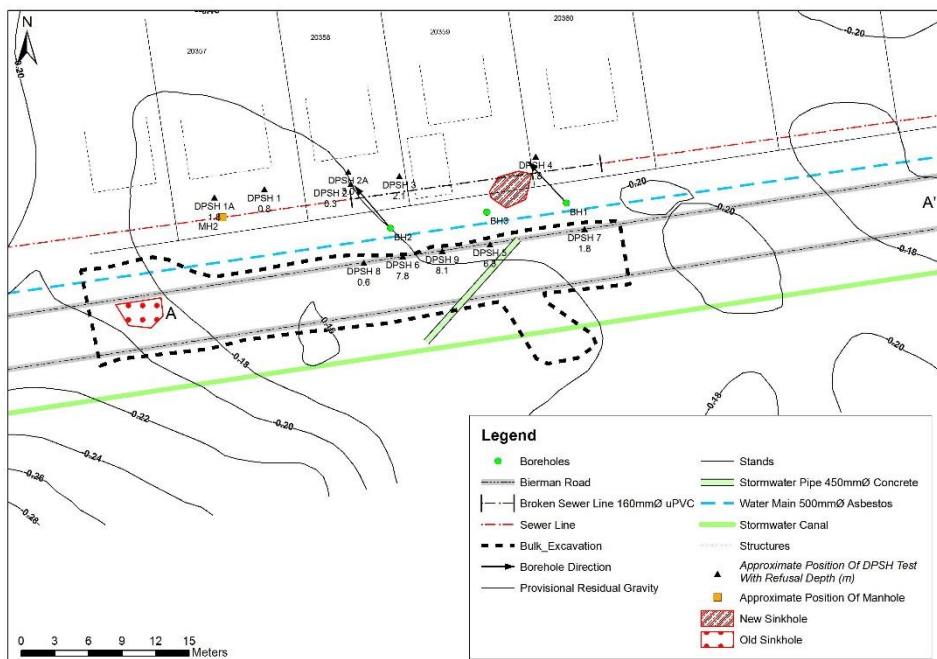
As the rehabilitated area is proposed for the rebuilding of houses, strict requirements were followed in terms of the type of material to be used in layer works and their compaction efforts, to create an earth mattress suitable for the rebuilding of houses.

#### 7.2.5.5. Land use after rehabilitation

Rebuilding of low cost houses each placed on a reinforced concrete raft foundation, catering for a loss of support of 5 m diameter. The rehabilitated profile, of low susceptibility to mobilisation and erosion is deemed suitable for residential single storey structures. For more information related to a similar geological and rehabilitation model refer to Case Study 4.

#### 7.2.6 Geological and Rehabilitation Model 6

A sinkhole of 4 m diameter size extending to a depth of 4 m occurred in the south-eastern corner of Stand 20359 on 14 March 2006 (Report No. KHH1383 and KHH1456). The affected area, existing infrastructure and the positions of boreholes and DPSH tests are displayed in Figure 40.



**Figure 40: Plan View of Generic Geological Model 6.**

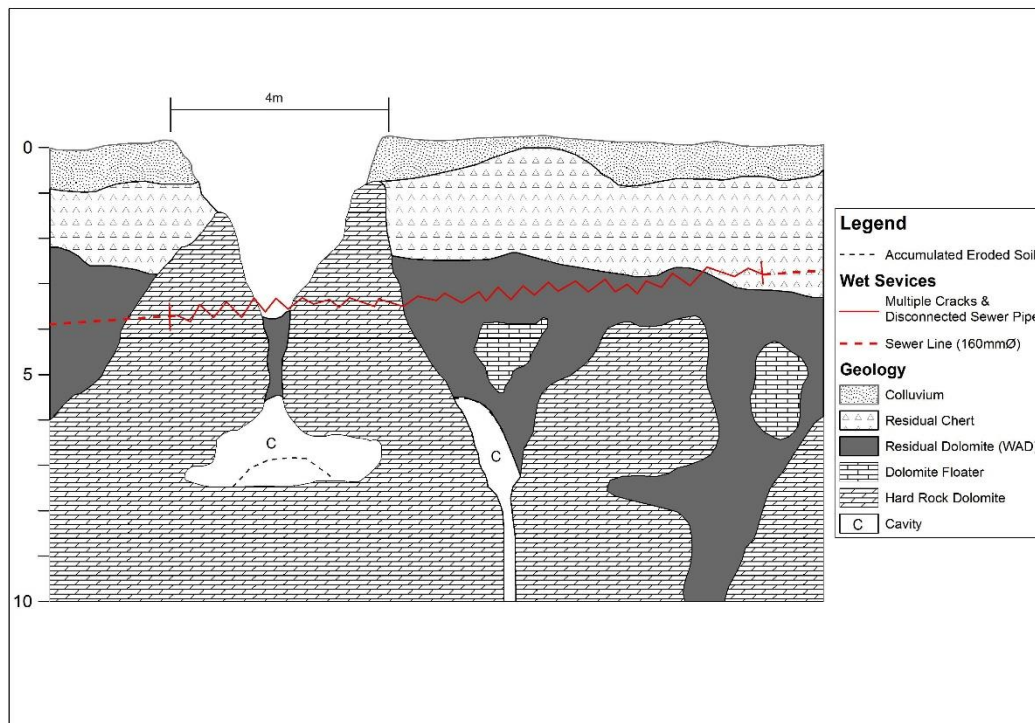
#### 7.2.6.1. Geological Model

The geological model is based on a gravity survey (10 m station interval), three percussion boreholes drilled to the south of the sinkhole, a number of DPSH tests and bulk excavation of the affected area. The geological model is illustrated in Figure 41.

- Complexity: Complex, due to a highly variable bedrock profile.



- Blanketing Layer: Comprising a horizon of colluvium (1 m) underlain by a horizon of residual chert (1 m to 2 m thick), followed at depth by a horizon of 4 m to 6 m thick residual dolomite (wad) with 1 m to 2 m diameter dolomite floaters, highly susceptible to subsurface erosion or consolidation. Voids encountered.
- Dolomite bedrock: Pinnacled dolomite bedrock from a depth of 1 m to 8 m, adjoining v-shaped grykes. Cavities present.
- Groundwater Level: In dolomite bedrock.



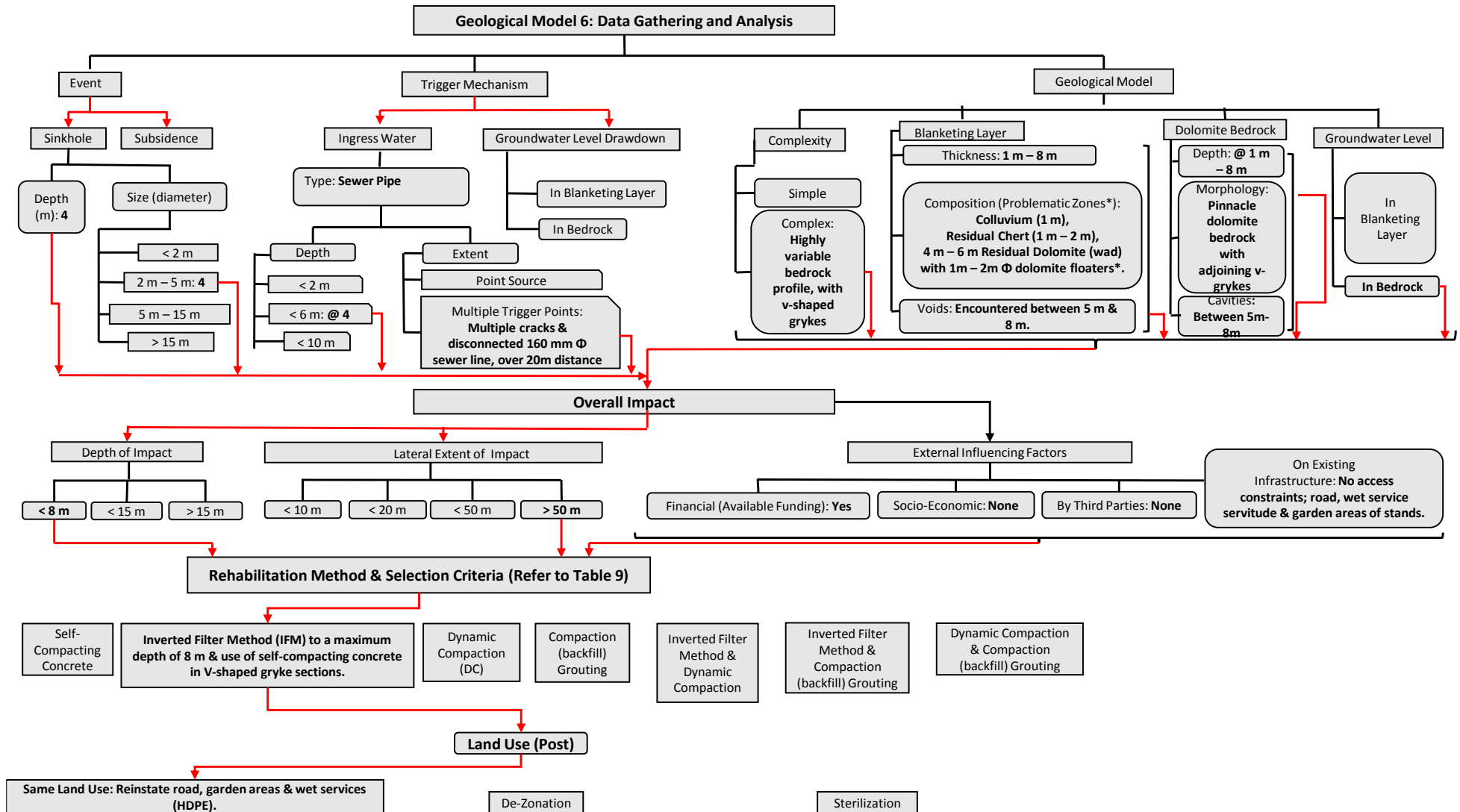
**Figure 41: Generic Geological Model 6.**

#### 7.2.6.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: Multiple cracks and disconnected 160 mm diameter uPVC sewer line. Sewage from the large section of malfunctioning sewer pipe caused subsurface erosion of residual dolomite (wad) highly susceptible to subsurface erosion. The mobilized residual dolomite was transported downwards along the face of dolomite bedrock pinnacles and deposited into voids and cavities at depth.

#### 7.2.6.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 4 m diameter size sinkhole extending to a depth of 4 m.
- Depth and extent of triggering mechanism: At a depth of approximately 4 m, 20 m section of pipe malfunctioning.
- Impact on existing infrastructure: Sinkhole located in sewer servitude and road.



Flow Chart 7: Generic Geological Model 6 – Process of sinkhole evaluation criteria and selection of rehabilitation method

7.2.6.4. Recommended Rehabilitation Method

Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 42). The entire sewer line was replaced with a HDPE butt welded pipe from manhole to manhole, over a distance of approximately 100 m and construction of new HDPE manholes.

Reason for using specific rehabilitation method:

- Shallow pinnacle dolomite bedrock with v-shaped grykes between pinnacles filled with residual dolomite (wad) and voids, highly susceptible to subsurface erosion within maximum reach of an excavator.

No access constraints. Remaining profile below excavated area comprising residual dolomite (wad) along grykes between pinnacle dolomite bedrock.

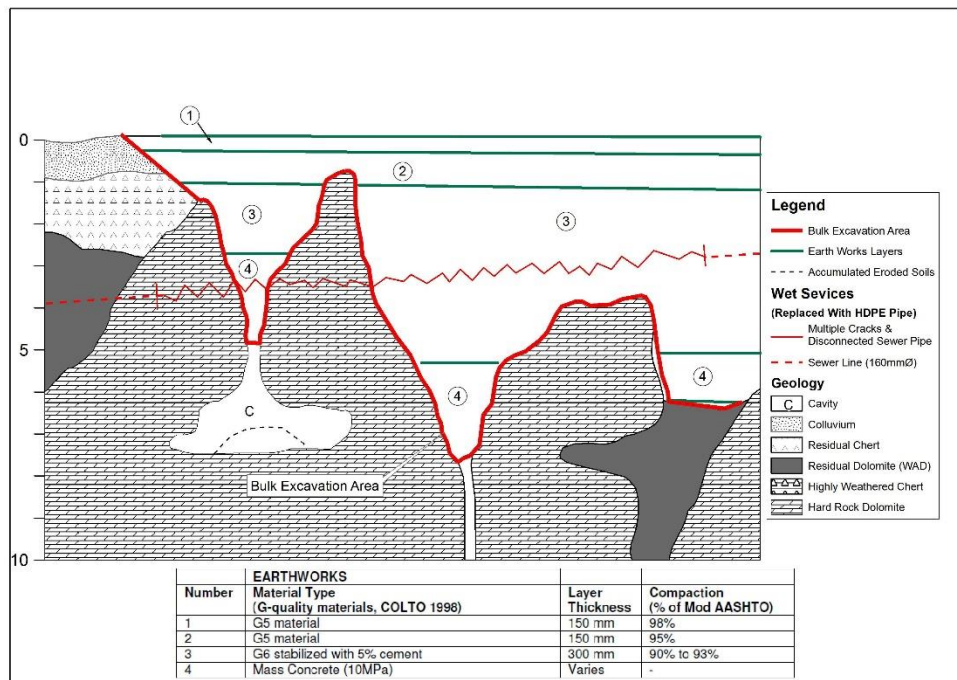


Figure 42: Recommended Rehabilitation Method Generic Geological Model 6.

Layer works:

- Number 1: The upper 0,3 m compacted to 98% Modified AASHTO compaction effort as part of the road layer works.
- Number 2: The upper 1,0 m comprising 150 mm G5-quality material compacted at 95% Modified AASHTO.
- Number 3: Backfilled up to 1,0 m below ground surface in 300 mm thick layers of G6-quality material stabilized with 5% cement compacted to between 90% to 93% Modified AASHTO. The 5% cement was added to give strength to the material emplaced in the narrow gryke areas. As access for the compaction equipment was difficult smaller machines and lower compaction efforts specified.

- Number 4: The V-shaped grykes located between dolomite bedrock pinnacles were filled with 10 MPa mass concrete up to variable depths of 3 m to 6 m below ground surface to create a stable working platform and sealing of erosion pathways.

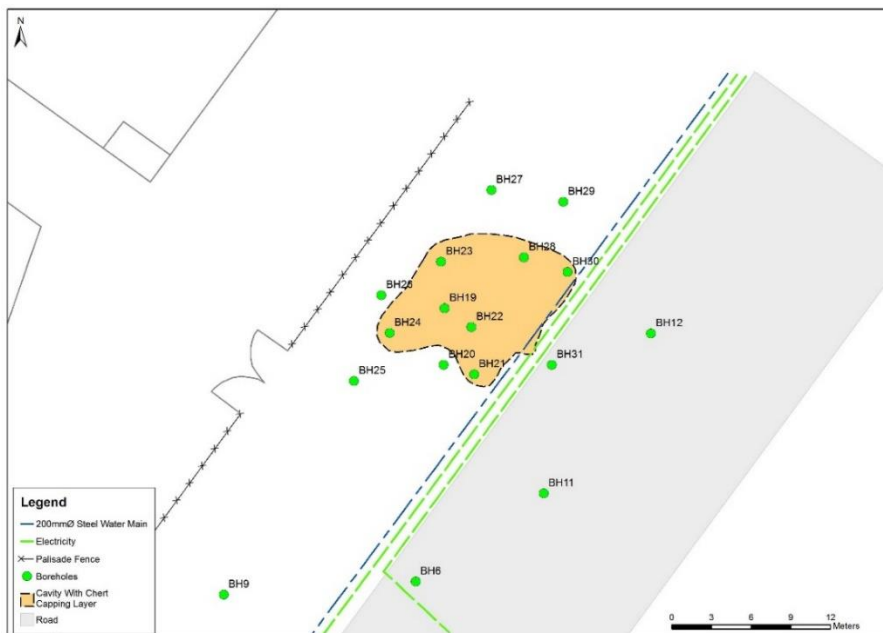
As the area presented a number of voids and cavities which could lead to the formation of more sinkholes, the above mentioned rehabilitation method was required to ensure all receptacle areas were sealed and highly susceptible residual dolomite (wad) removed and replaced with competent material to create an earth mattress suitable for the construction of a road.

#### 7.2.6.5. Land use after rehabilitation

Road, sewer servitude and garden area of house. For more information related to a similar geological and rehabilitation model refer to Case Study 1.

#### 7.2.7 Geological and Rehabilitation Model 7

A sinkhole of 2 m diameter size extending to a depth of 1,5 m connected with a void below a soft rock chert capping layer was observed during bulk excavation work for the rehabilitation of a sinkhole on the eastern boundary of M.C. Botha Road during April 2007 (Report No. KHH1474, KHH1516 and KHH1519). The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 43.



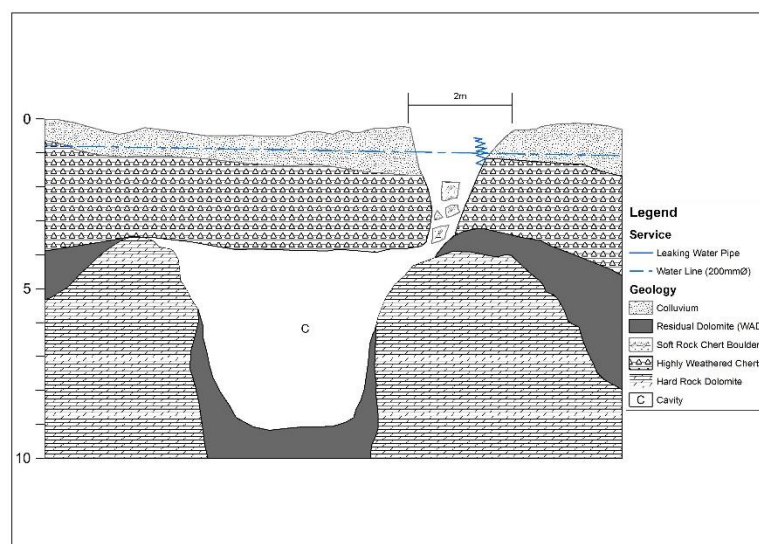
**Figure 43: Plan View of Generic Geological Model 7.**

#### 7.2.7.1. Geological Model

The geological model is based on twelve percussion boreholes drilled around and

above the void. The geological model is illustrated in Figure 44.

- Complexity: Complex, due to competent horizons above problematic horizons.
- Blanketing Layer: Comprising a horizon of colluvium (1 m) underlain by a horizon of highly weathered soft rock chert (3 m thick) followed at depth by a horizon of 1 m to 3 m thick but up to 10 m thick in subareas residual dolomite (wad), highly susceptible to subsurface erosion or consolidation. Large void (6 m diameter and 6 m high) encountered in residual dolomite (wad) below soft rock chert.
- Dolomite bedrock: At a depth of 4 m on both sides of the void extending to a depth of more than 10m in the central portion of void area.
- Groundwater Level: In dolomite bedrock.



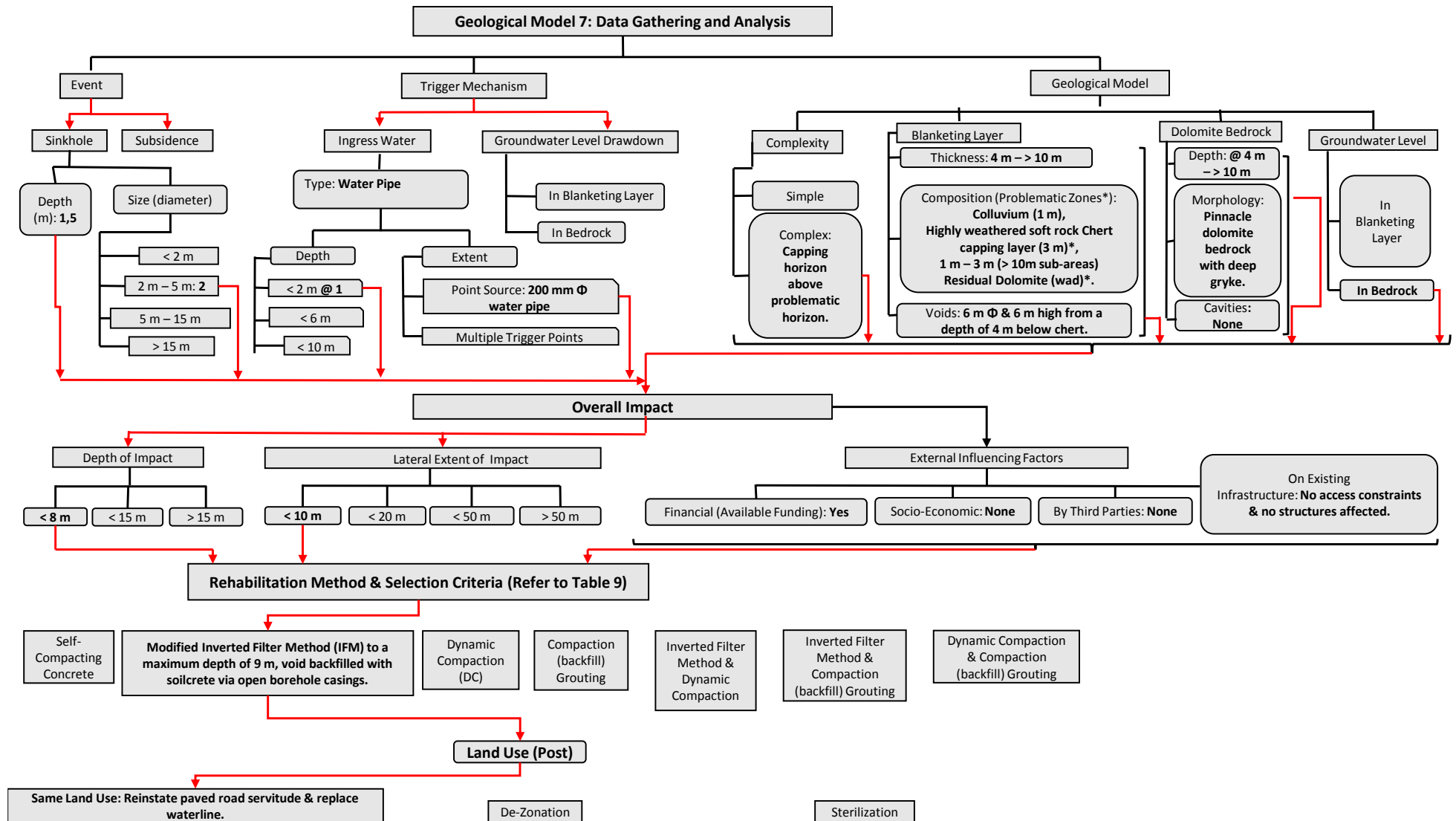
**Figure 44: Generic Geological Model 7.**

#### 7.2.7.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: Leak on 200 mm diameter steel pipe. Water migrating downwards through a fractured and jointed highly weathered soft rock chert capping zone (representing chert boulders), causing subsurface erosion of underlying residual dolomite (wad) into the open void below the chert capping.

#### 7.2.7.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 2 m diameter size sinkhole extending to a depth of 1,5 m.
- Depth and extent of triggering mechanism: At a depth of 1 m, point source.
- Impact on existing infrastructure: Sinkhole located in road reserve of a main street, no structures affected in immediate area.



Flow Chart 8: Generic Geological Model 7 – Process of sinkhole evaluation criteria and selection of rehabilitation method

7.2.7.4. Recommended Rehabilitation Method

Modified Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 45). Leak on waterline repaired.

Reason for using specific rehabilitation method:

- The highly weathered soft rock chert capping with dolomite abutments on both sides of the void provide a competent layer that should not be removed. To access the void below the competent soft rock chert capping boreholes were drilled into the void during the investigation phase and equipped with casings in order to gravity feed the void below the competent chert capping to fill the receptacle.

No access constraints existed for the proposed rehabilitation method.

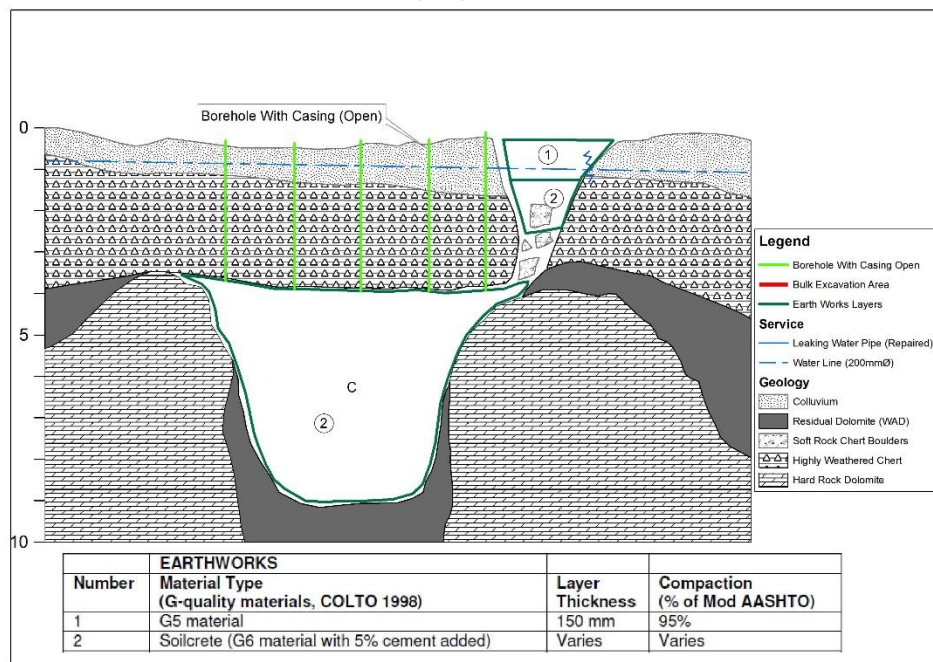


Figure 45: Rehabilitation Method Generic Geological Model 7.

Rehabilitation work recommended:

- As the chert capping presents a competent horizon it is only necessary to fill the void below it with material (without any strength requirements) to fill/choke the receptacle area.
- Number 1: The upper 1,0 m comprising 150 mm G5-quality material compacted at 95% Modified AASHTO maximum dry density at optimum moisture content.
- Number 2: Filling of the void via open casings by means of the pumping of soilcrete (comprising G6-quality material and 5% cement) until completely filled. Alternatively, selfcompacting concrete can also be pumped into the void, however at a much higher cost.

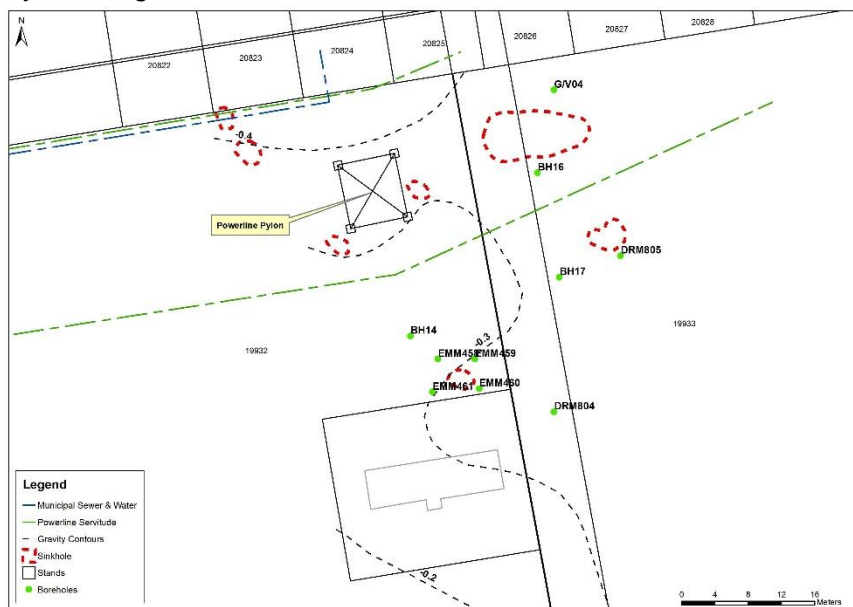
As the rehabilitated area constitutes a road servitude, no real strength parameters are required and only removal of the void to prevent sinkholes in close proximity to the area where the chert capping is possibly absent.

#### 7.2.7.5. Land use after rehabilitation

Paved road servitude.

#### 7.2.8 Geological and Rehabilitation Model 8

Various sinkholes have been reported in the immediate area since the 1980's. The two sinkholes and one subsidence illustrated in the geological model Figure 47 is located to the west (Figure 46 – Plan View). The first sinkhole (dimensions of 4 m diameter and extending to a depth of 3 m) occurred during March 2009; the second sinkhole (dimensions of 2 m diameter and extending to a depth of 2 m) and the subsidence (dimensions of 4 m diameter extending to a depth of 1 m) occurred during the period 2007 to 2009 (Report No. VGI3118R-WO152-2 and CGS Report No. 2009-0171). The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 46.



**Figure 46: Plan View of Generic Geological Model 8**

##### 7.2.8.1. Geological Model

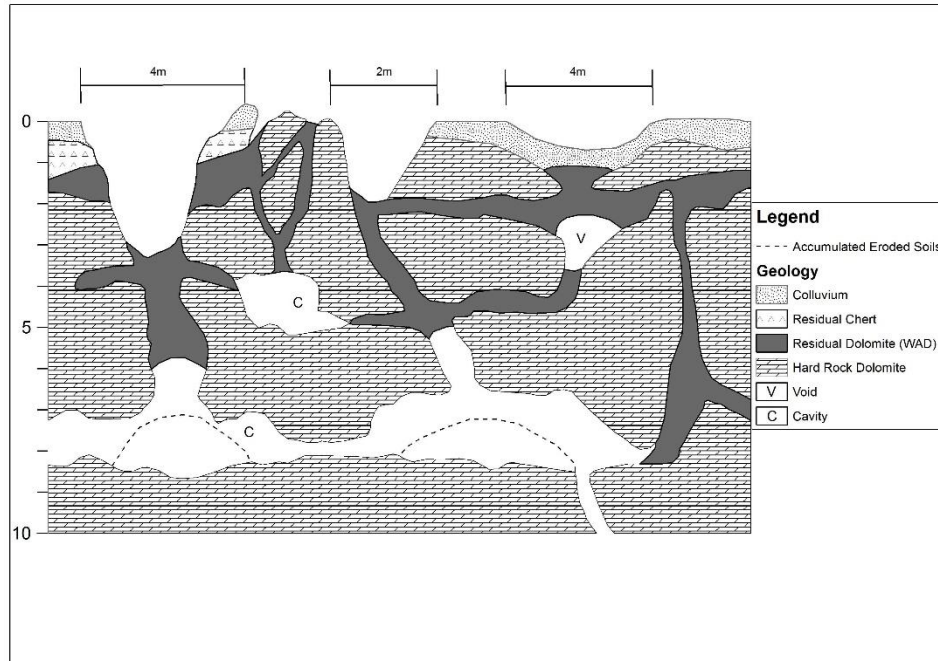
The geological model is based on a gravity survey (10 m station interval) and a total of four percussion boreholes were drilled in the area surrounding the first sinkhole (4 m diameter extending to a depth of 3 m). The boreholes located within the electrical servitude area are not displayed on the geological model illustrated in Figure 47.

- Complexity: Complex due to highly variable bedrock profile and material susceptible to subsurface erosion.
- Blanketing Layer: Comprising a horizon of colluvium (1 m) underlain by residual



chert (1 m) in sub-areas, followed at depth by a horizon of 1 m to 5 m thick residual dolomite (wad), highly susceptible to subsurface erosion or consolidation. Voids encountered.

- Dolomite bedrock: Highly jointed vertically and horizontally, joints filled with residual dolomite (wad) and interconnected cavities encountered. The dolomite bedrock appears to be at a shallow depth (1 m to 5 m), however the highly weathered bedrock profile presents dolomite bedrock at a depth of 9 m below the cavities.
- Groundwater Level: In dolomite bedrock.



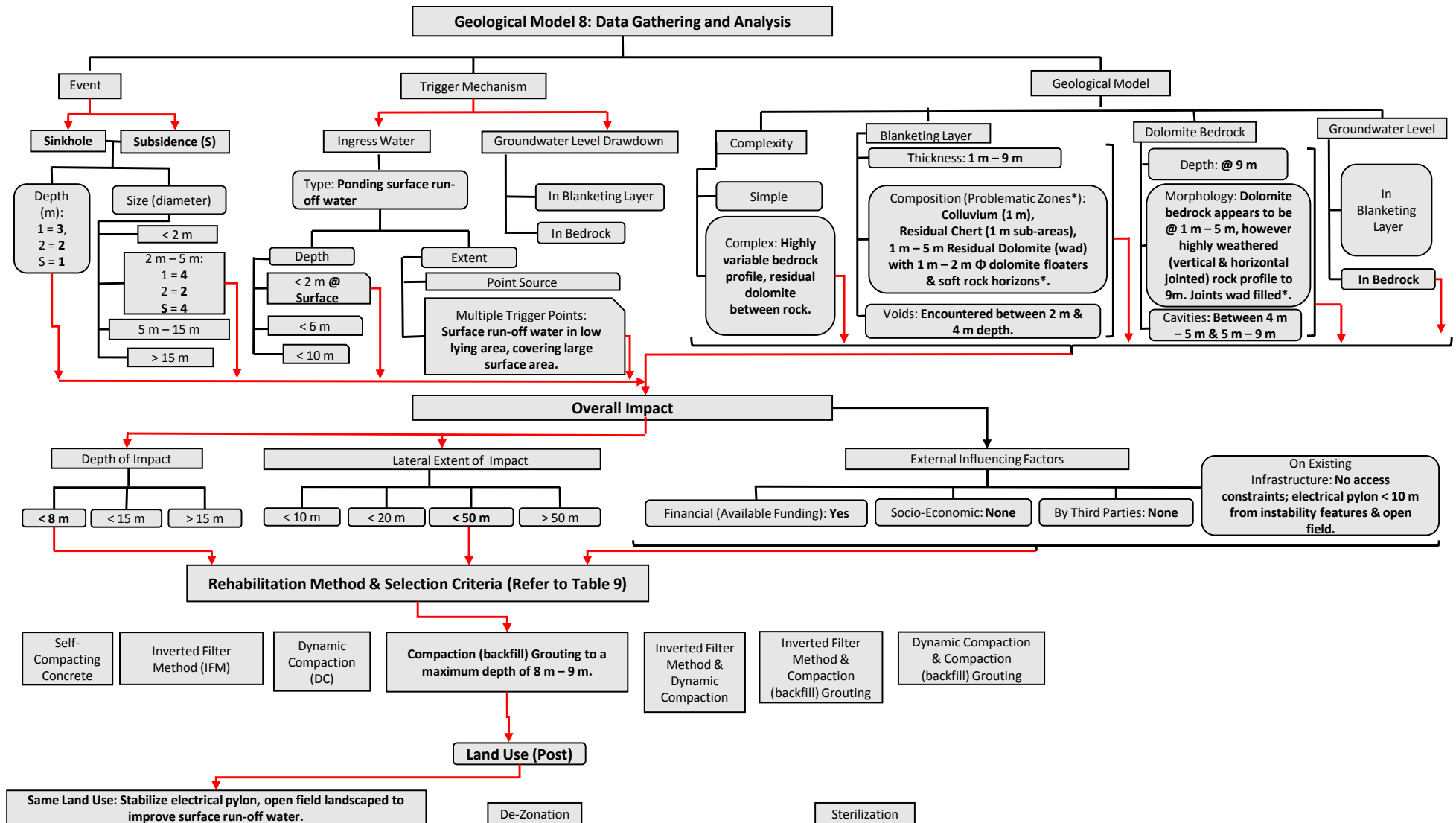
**Figure 47: Generic Geological Model 8.**

#### 7.2.8.2. Cause of sinkhole or subsidence formation

Poor surface water run-off management: Ponding of surface run-off water in low lying area. Surface run-off water flowing downwards through the highly erodible residual dolomite (wad) encountered at or near ground surface, mobilizing this material downwards into voids and cavities along vertical joints.

#### 7.2.8.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability features: 4 m diameter size sinkhole extending to a depth of 3 m; 2 m diameter size sinkhole extending to a depth of 2 m and a 4 m diameter size subsidence extending to a depth of 1 m.
- Depth and extent of triggering mechanism: At surface, large surface area.
- Impact on existing infrastructure: Electrical pylon located less than 10 m from instability features.



Flow Chart 9: Generic Geological Model 8 – Process of sinkhole and subsidence evaluation criteria and selection of rehabilitation method

#### 7.2.8.4. Recommended Rehabilitation Method

Compaction (backfill) Grouting: Refer to the Rehabilitation Model (Figure 48). Area was landscaped after rehabilitation and a v-shaped concrete channel constructed to accommodate surface water run-off away from the area.

Reason for using specific rehabilitation method:

- Even though dolomite rock appears near ground surface, residual dolomite (wad) extending to a depth of nearly 9 m above and within dolomite bedrock along joints. An excavator with a maximum reach of 6 m will only be able to remove the residual dolomite (wad) above the first dolomite rock interface. Therefore the most appropriate method to rehabilitate the sinkholes and subsidence and to improve the poor subsurface conditions extending well into dolomite bedrock is to fill the sinkholes and subsidence with boulders and soilcrete (5% cement added) compacted with excavator bucket up to ground surface and then perform a grouting programme. The upstage grouting programme including a primary and secondary stage, with a tertiary stage within areas of high grout takes observed during the primary and secondary stages.

No access constraints existed for proposed rehabilitation method. The highly susceptible dolomite profile needed to be improved by means of a grouting programme to prevent the formation of further sinkholes and subsidence and to ensure the integrity of the electrical pylon.

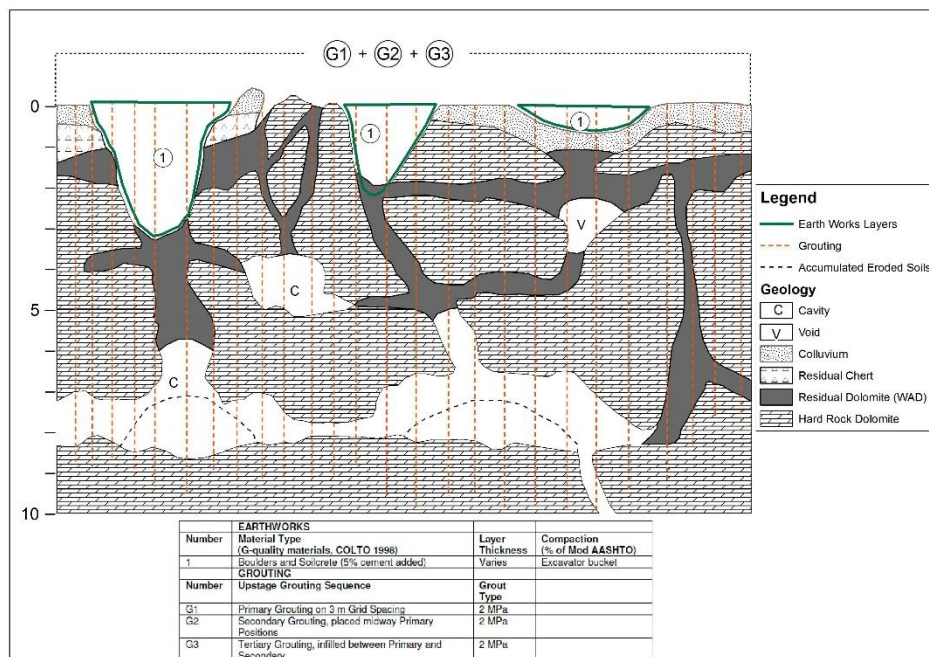


Figure 48: Rehabilitation Method Generic Geological Model 8.

#### 7.2.8.5. Land use after rehabilitation

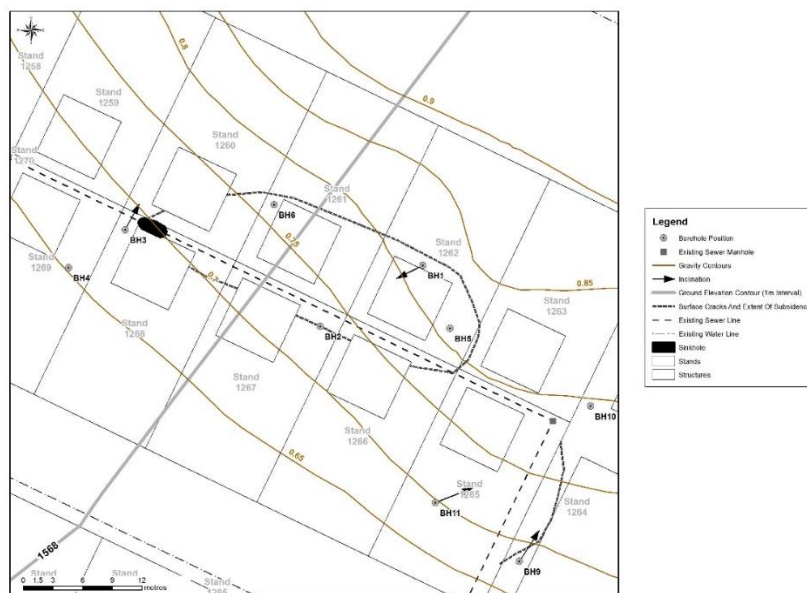
Open field, however in close proximity to an electrical pylon structure.

### 7.3 Impact to a depth of less than 15 m

Four geological models, the evaluation process (flow chart) and the most appropriate rehabilitation method for each are presented.

#### 7.3.1 Geological and Rehabilitation Model 9

Subsidence of 30 m and 1 m diameter size, both extending to a depth of 1 m occurred due to a broken mid-block sewer line, causing damage of several low cost housing structures beyond repair on various stands in Rondebult Extension 2, during August 2005 (Report No. KHH1366, KHH1378, KHH1387 and KHH1562). The affected area, existing infrastructure and boreholes are displayed in Figure 49.



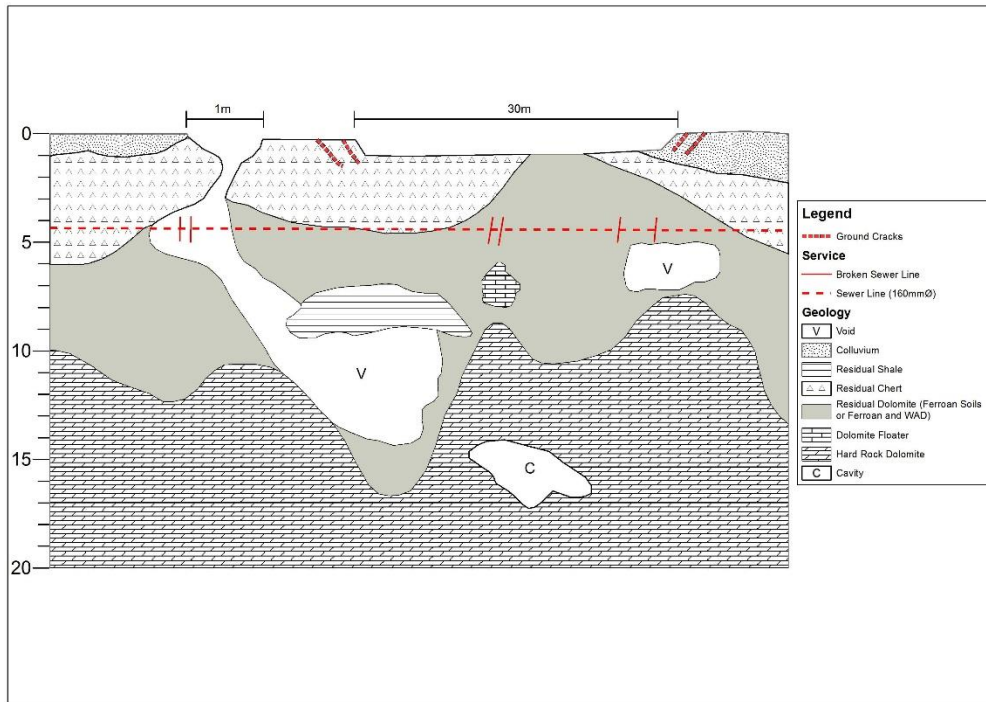
**Figure 49: Plan View of Generic Geological Model 9.**

##### 7.3.1.1. Geological Model

The geological model is based on a gravity survey (10 m station interval) and eleven percussion boreholes positioned within and around subsidence areas. The geological model is illustrated in Figure 50.

- Complexity: Complex, due to heterogenic profile.
- Blanketing Layer: Comprising a horizon of colluvium (1 m to 2 m) underlain by a horizon of residual chert (1 m to approximately 5 m thick and absent in sub-areas) followed by 2 m to 14 m residual dolomite (wad and ferroan soils) with dolomite floaters, highly susceptible to subsurface erosion or consolidation and a 1 m to 2 m thick horizon of residual shale encountered within the residual dolomite between 7 m and 9 m. Voids encountered within residual dolomite.

- Dolomite bedrock: At a variable depth of 8 m to 16 m.
- Groundwater Level: In dolomite bedrock.



**Figure 50: Generic Geological Model 9.**

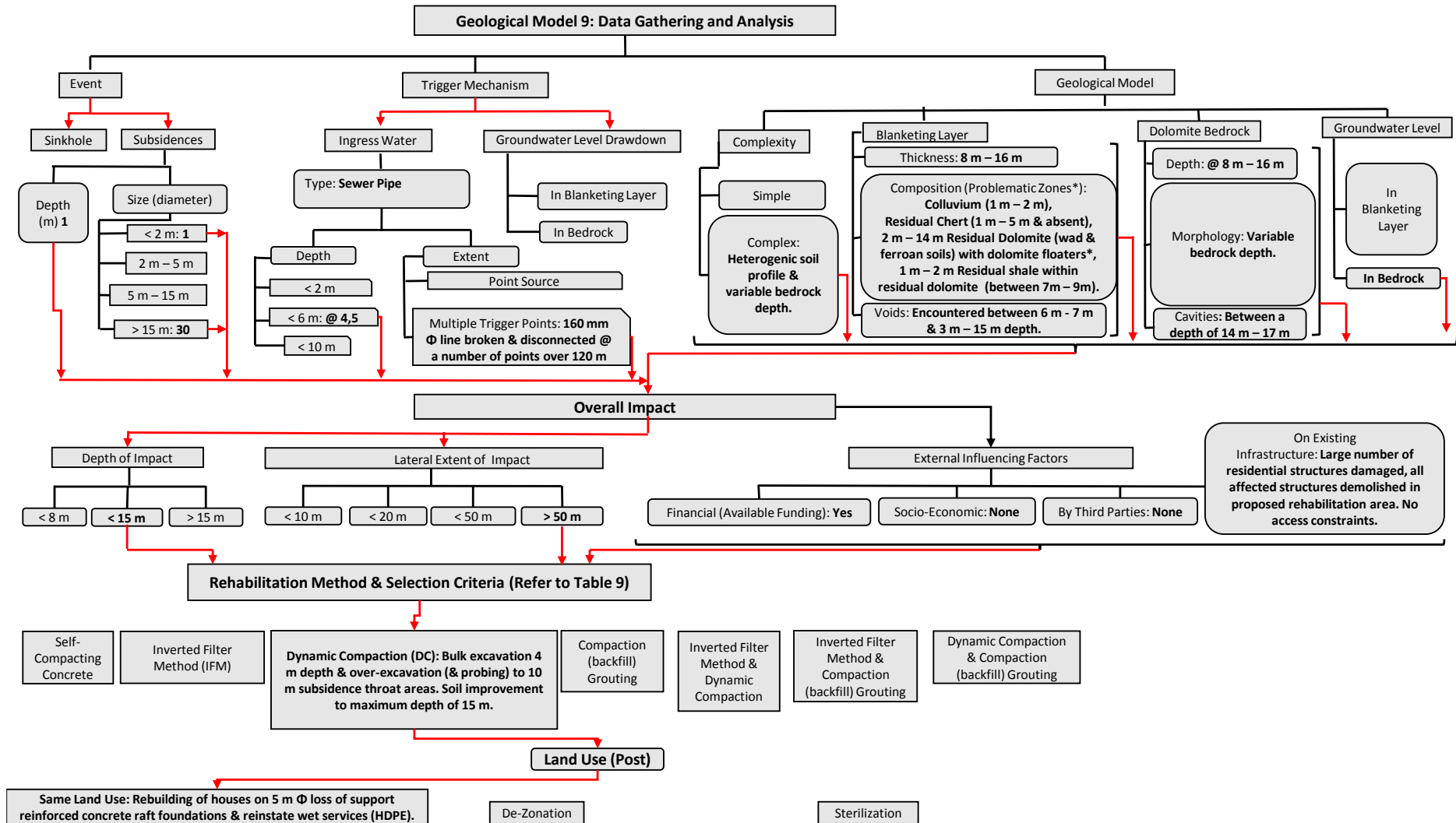
#### 7.3.1.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: A 160 mm diameter uPVC sewer line, disconnected and broken at a number of points. Sinkhole and subsidence caused due to the subsurface erosion of highly susceptible residual dolomite mobilized downwards into voids and cavities at depth.

The sewer line is located mainly within residual dolomite.

#### 7.3.1.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 30 m diameter size subsidence extending to a depth of 1 m and 1 m diameter size subsidence extending to a depth of 1 m.
- Depth and extent of triggering mechanism: At 4,5m; approximately 120 m of sewer line affected by numerous cracks and disconnected pipes.
- Impact on existing infrastructure: Large number of residential structures with structural damage and partial subsidence caused by instability features. All structures within affected area demolished before rehabilitation process.



Flow Chart 10: Generic Geological Model 9 – Process of subsidence evaluation criteria and selection of rehabilitation method

### 7.3.1.4. Recommended Rehabilitation Method

Dynamic Compaction Method: Refer to the Rehabilitation Model (Figure 51). All wet services were replaced with HDPE butt-welded pipes and manholes.

Reason for using specific rehabilitation method:

- The highly susceptible subsurface area requiring improvement is extending to a maximum depth of 16 m below ground surface, comprising a thick horizon of residual dolomite, a number of voids and cavities. The use of the Inverted Filter Method, typical applied to a maximum depth of 6 m (but up to 8 m possible) below ground surface will therefore not be suitable as rehabilitation method as the problem extends much deeper than 8 m. The recommended rehabilitation method is the Dynamic Compaction (DC) method, as this method can be used to collapse the arch of a void, densify deeper subareas typically presenting the throat of a sinkhole and densify thick layers of highly compressible residual dolomite (wad) at depths of between 10 m to 12 m as this geological model presents.

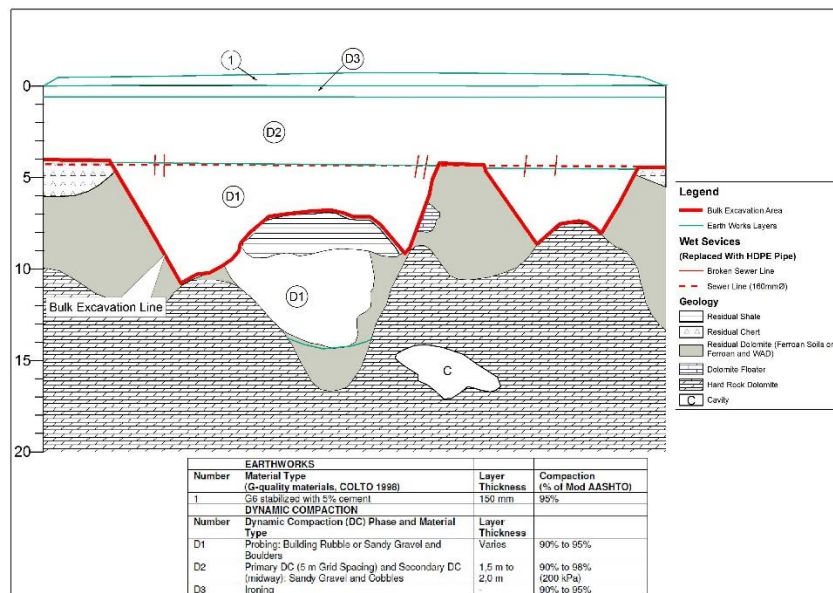


Figure 51: Rehabilitation Method Generic Geological Model 9.

Work performed:

- Number D1: In order to ensure the problematic profile is completely treated, bulk excavation of the area proposed for rehabilitation was done to a depth of 4,0 m below ground surface, followed by the over-excavation of the cavity and subsidence areas to a maximum depth of 10 m with an excavator. The DC Probing method was used to collapse the residual shale roof over the cavity, choke the deeper excavated area with building rubble and to densify thick horizons of residual dolomite;

- Number D2: Followed by DC production including a primary and secondary phase for each lift of 2,0 m (comprising sandy gravel cobbles) up to ground surface, followed by the DC Ironing Phase (Number D3).
- Number 1: The upper 0,3 m and elevated 150 mm comprising 150 mm layers of G6-quality material stabilized with 5% cement and compacted at 95% of Modified AASHTO was necessary to properly landscape the area and to densify the surficial material after the DC Ironing Phase.

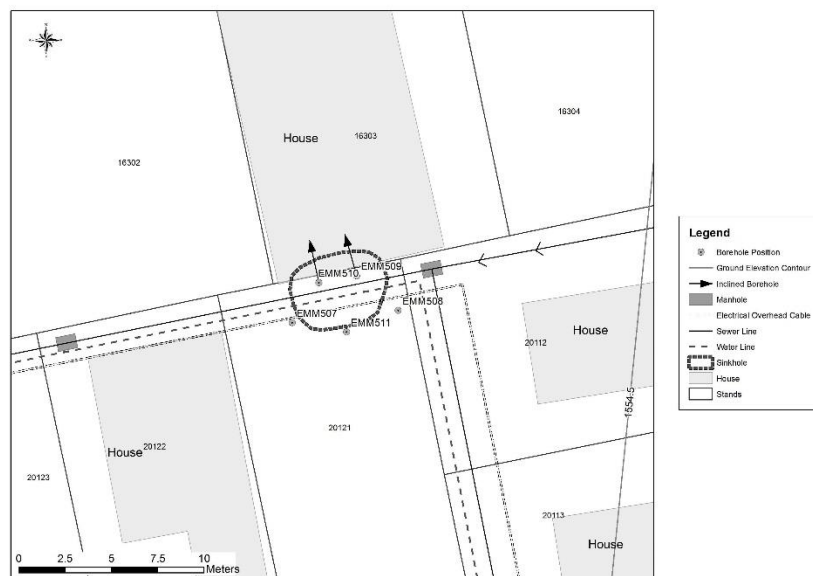
As the houses were demolished, these presented no access constraints to the recommended rehabilitation method. As the rehabilitated area is proposed for the rebuilding of houses, it was necessary to remove the problematic residual dolomite material, voids and cavities, by means of creating an engineered earth mattress with the DC method of between 4 m and 14 m.

#### 7.3.1.5. Land use after rehabilitation

Rebuilding of low cost houses each placed on a reinforced concrete raft foundation, catering for a loss of support of 5 m diameter. The treated area presents a rehabilitated profile suitable for the building of residential single storey structures. For more information related to this geological and rehabilitation model refer to Case Study 4.

#### 7.3.2 Geological and Rehabilitation Model 10

A sinkhole (dimensions of 4,5 m by 2 m extending to a depth of 2,5 m) occurred in the north-eastern corner of Stand 20121, Vosloorus Extension 30, during September 2009 (Report No. VGI3118/245/1). The sinkhole is partially extending below a double storey house. The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 52.



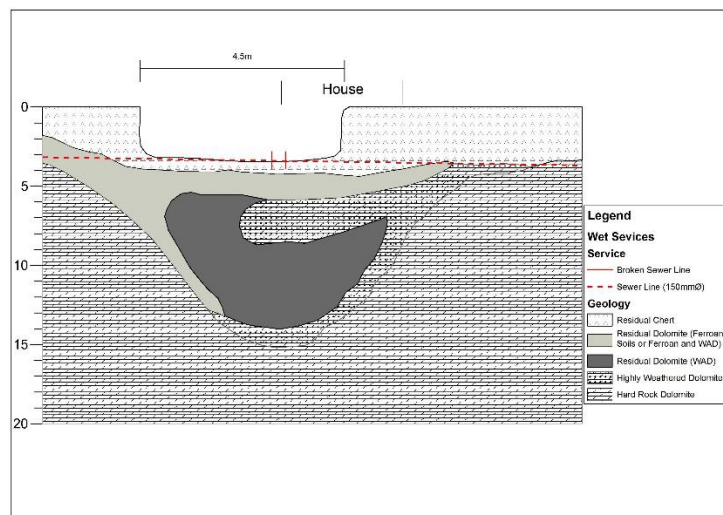
**Figure 52: Plan View of Generic Geological Model 10.**



### 7.3.2.1. Geological Model

The geological model is based on five percussion boreholes. The geological model is illustrated in Figure 53.

- Complexity: Complex, due to the presence of weathered rock above and within material susceptible to subsurface erosion.
- Blanketing Layer: Comprising a horizon of residual chert (2 m to 4 m) underlain by a horizon of residual dolomite (wad and ferroan soils) to a depth of 4 m and 14 m with a 3 m thick horizon of highly weathered soft rock dolomite between 6 m and 9 m located within the residual dolomite. No voids encountered.
- Dolomite bedrock: At a variable depth of 3 m to 15 m.
- Groundwater Level: In dolomite bedrock.



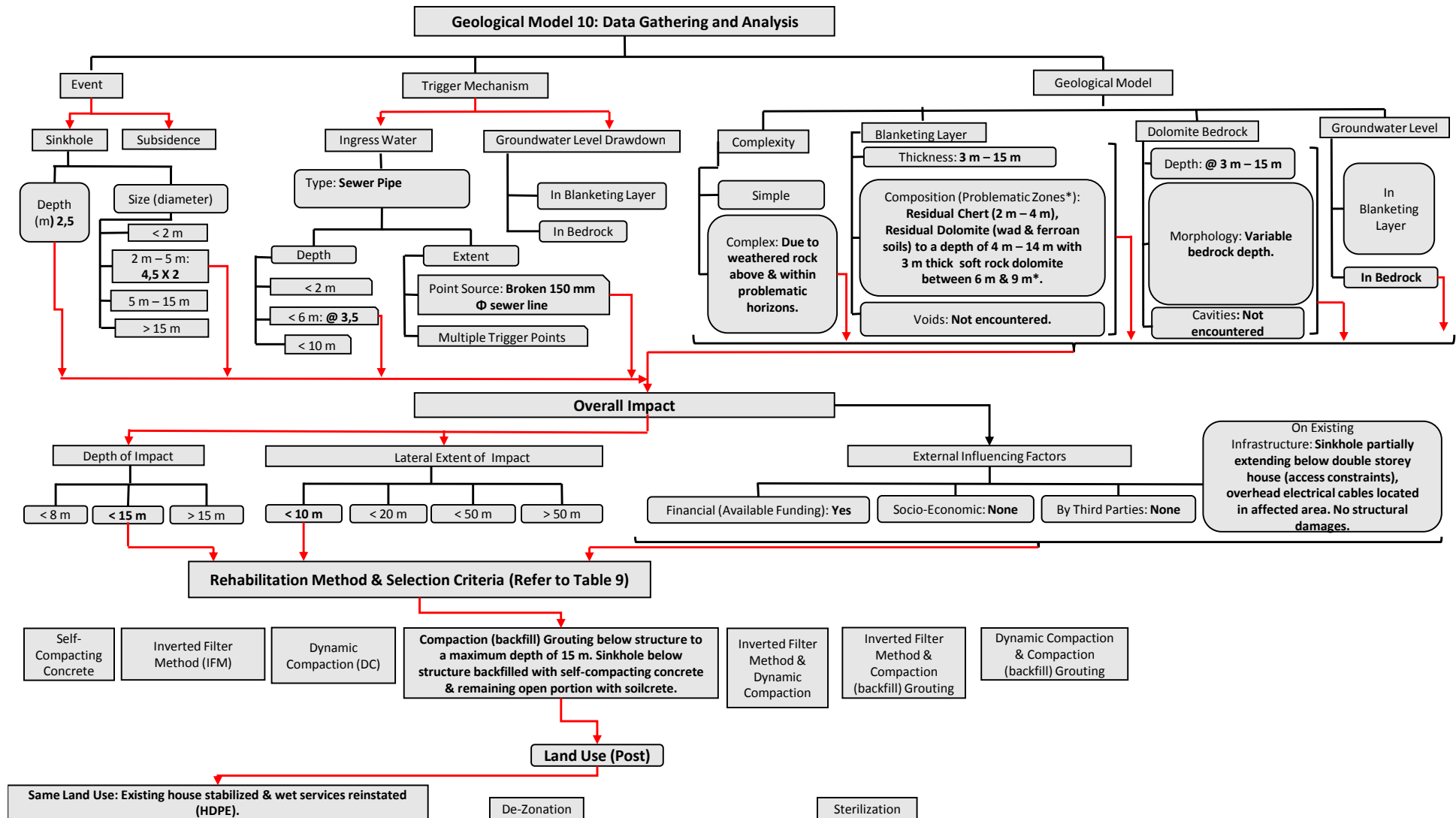
**Figure 53: Generic Geological Model 10.**

### 7.3.2.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: A broken 150 mm diameter vitrified midblock sewer line. Sinkhole caused due to the subsurface erosion of highly susceptible residual dolomite material mobilized downwards into a void or a cavity (although not encountered during drilling) at depth. The sewer line is located mainly within residual chert with subareas located in residual dolomite.

### 7.3.2.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: A sinkhole with dimensions of 4,5 m by 2 m extending to a depth of 2,5 m.
- Depth and extent of triggering mechanism: At 3,5m; point source.
- Impact on existing infrastructure: Sinkhole partially extending below a double storey residential structure; overhead electrical cables located in affected area as well as a water line. No structural damages caused to residential structure.



Flow Chart 11: Generic Geological Model 10 – Process of sinkhole evaluation criteria and selection of rehabilitation method

### 7.3.2.4. Recommended Rehabilitation Method

Compaction Grouting: Refer to the Rehabilitation Model (Figure 54). All wet services were replaced with HDPE butt-welded pipes and one new sewer manhole constructed. The sewer line was replaced by means of the pipe-jacking method, due to limited space for excavations.

Reason for using specific rehabilitation method:

- The area requiring improvement extend to a maximum depth of 15 m below ground surface, comprising a thick horizon of residual dolomite and a sinkhole partially located below a double storey structure. The use of the Inverted Filter Method, typically applied to a maximum depth of 8 m below ground surface will therefore not be suitable as rehabilitation method as the problem extends much deeper than 8 m. The Dynamic Compaction Method is also not suitable, due to the limited working space available for the size equipment used, the vibration impact caused by the DC method directly adjacent to a structure may trigger the highly susceptible dolomite profile and more sinkholes may occur and the existing overhead electrical cables that could not be relocated will pose a danger. The recommended rehabilitation method is the Compaction Grouting method, as this method can be used to fill voids or cavities at depth below the residential structure and to densify the low density compressible residual dolomite down to bedrock depth at 15 m.

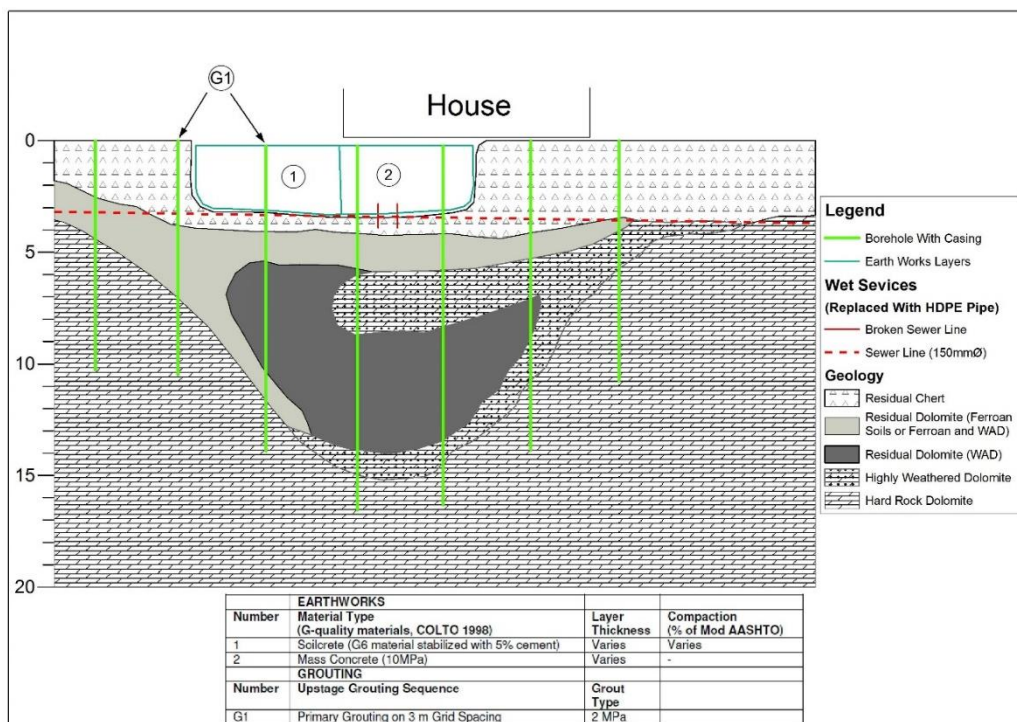


Figure 54: Rehabilitation Method Generic Geological Model 10.

Work carried out:

- The residential structure was stabilized before the grouting programme commenced by filling the sinkhole area below the structure with 10 MPa mass

concrete and the remaining open portion of the sinkhole was backfilled with soilcrete comprising G6-quality material stabilized with 5% cement, also to provide a stable platform for the drilling rig.

- Only primary grouting was conducted with some of the boreholes drilled inclined below the structure in order to densify residual dolomite or fill voids potentially located below the existing structure.

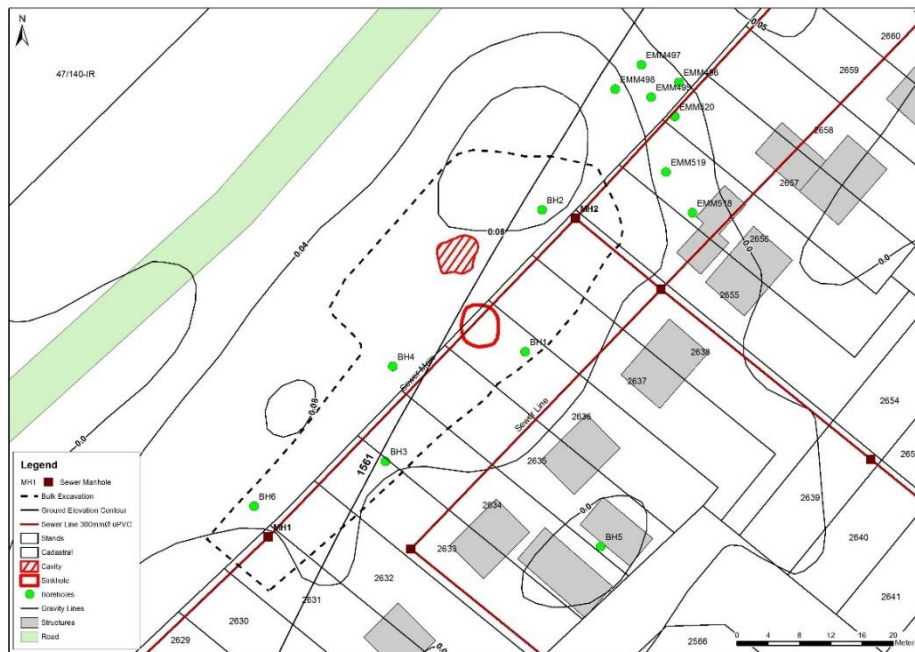
The existing houses caused access constraints for proposed and recommended rehabilitation method. To stabilize the conditions below the existing house, it was necessary to improve subsurface conditions by means of the Compaction Grouting method, including the densification of low density residual dolomite and filling of potential voids or cavities at depth below and adjacent to the house.

### 7.3.2.5. Land use after rehabilitation

Existing structure stabilized.

### 7.3.3 Geological and Rehabilitation Model 11

A sinkhole of 4 m diameter size extending to a depth of 8 m occurred on the western boundary of Stand 2636, Dragon Street, Rondebult, during January 2006 (Report No. KHH1409, KHH1465 and KHH1490). The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 55.

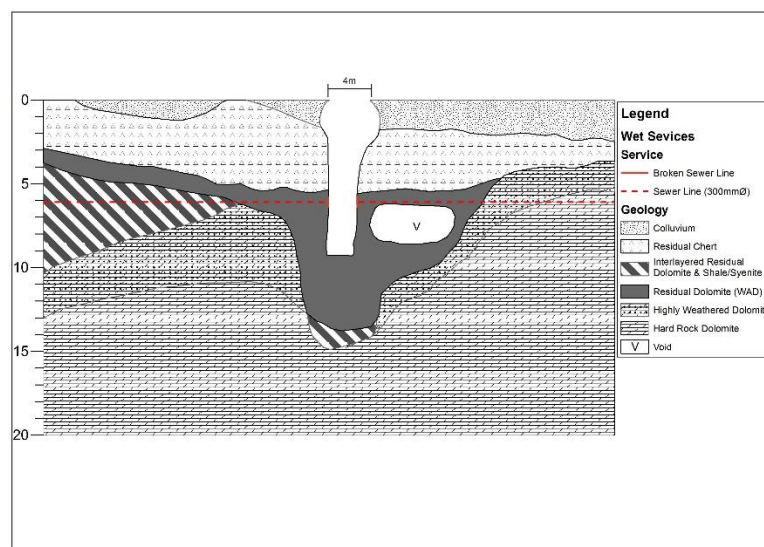


**Figure 55: Plan View of Generic Geological Model 11.**

#### 7.3.3.1. Geological Model

The geological model is based on a gravity survey (10 m station interval), six percussion boreholes and bulk excavation of the affected area. The geological model is illustrated in Figure 56.

- Complexity: Complex, heterogeneous profile.
- Blanketing Layer: Comprising a horizon of colluvium (1 m to 2 m or absent) underlain by a horizon of residual chert (1 m to approximately 5 m thick) followed by 1 m to 9 m residual dolomite (wad), highly susceptible to subsurface erosion or consolidation and at depth underlain by a 1 m to 6 m thick horizon of interlayered residual dolomite and shale or syenite encountered just above dolomite bedrock in subareas between depths of 4 m and 15 m. Void encountered within residual dolomite.
- Dolomite bedrock: At a variable depth of 6 m to 15 m.
- Groundwater Level: In dolomite bedrock.



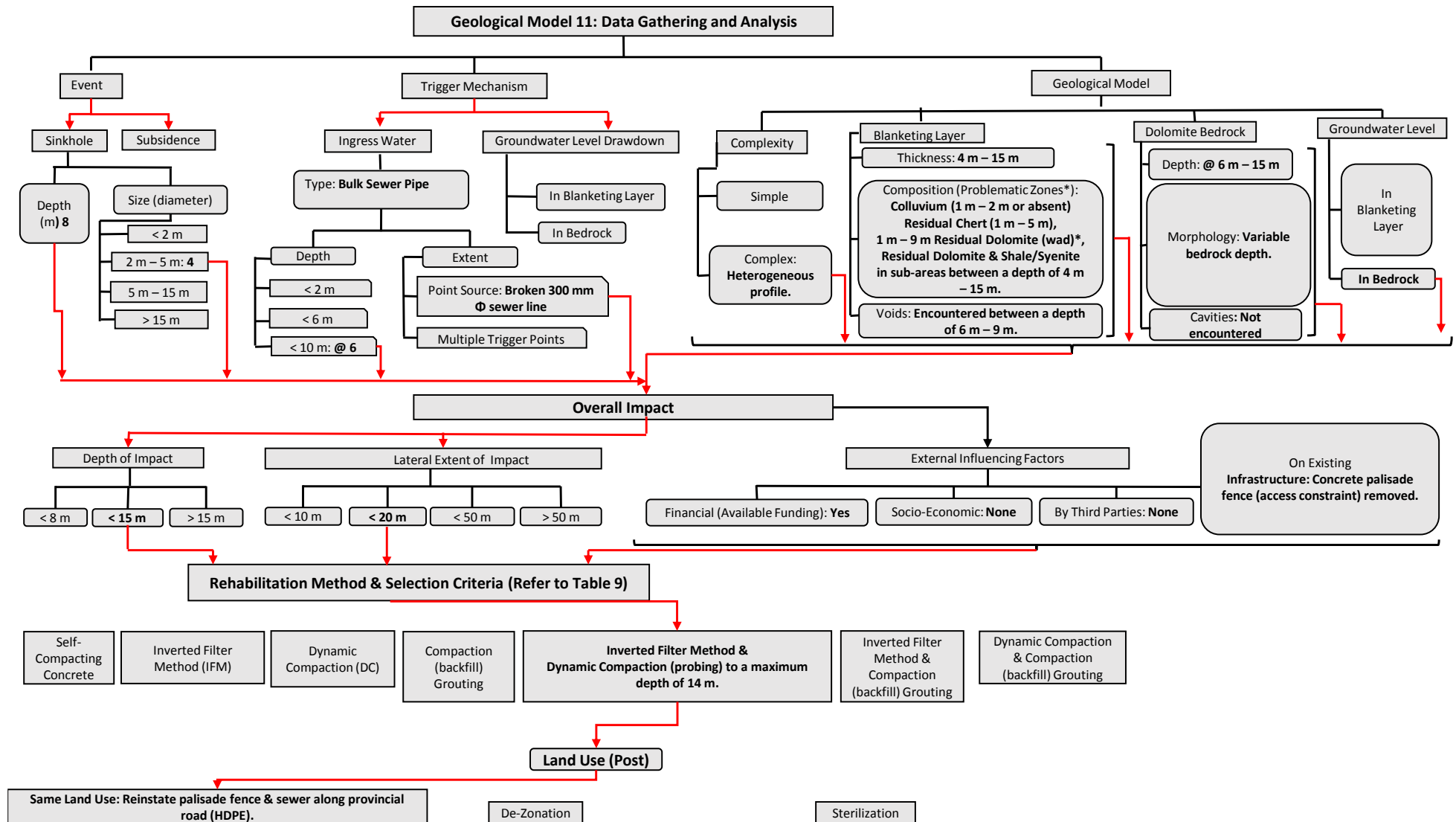
**Figure 56: Generic Geological Model 11.**

### 7.3.3.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: A 300 mm diameter uPVC broken bulk sewer line. Sinkhole caused due to the subsurface erosion of highly susceptible residual dolomite mobilized downwards into voids at depth. The sewer line is located mainly within residual dolomite.

### 7.3.3.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

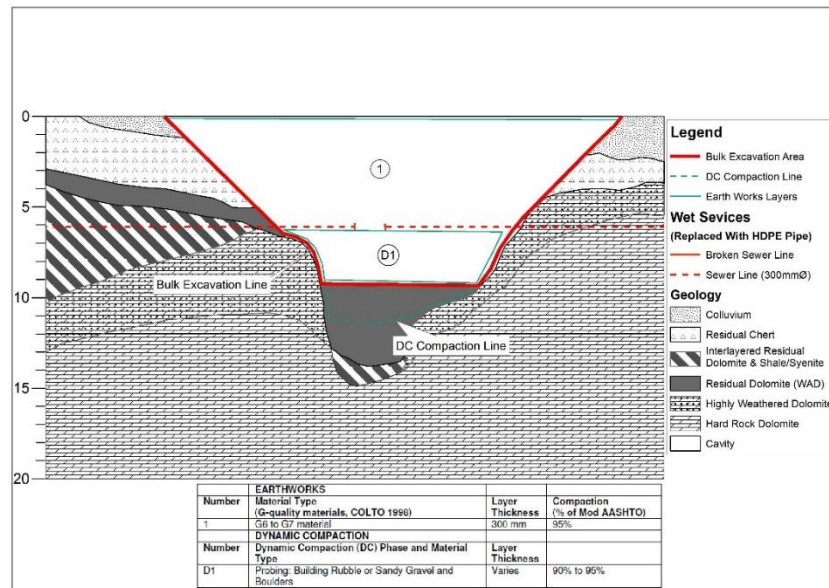
- Depth and extent of instability feature: 4 m diameter size sinkhole extending to a depth of 8 m.
- Depth and extent of triggering mechanism: At 6 m; point source.
- Impact on existing infrastructure: Concrete palisade fence subsided into sinkhole.



Flow Chart 12: Generic Geological Model 11 – Process of sinkhole evaluation criteria and selection of rehabilitation method

### 7.3.3.4. Recommended Rehabilitation Method

Combination of the Inverted Filter Method and Dynamic Compaction Method: Refer to the Rehabilitation Model (Figure 57). All wet services were replaced with HDPE butt-welded pipes and manholes.



**Figure 57: Rehabilitation Method Generic Geological Model 11.**

Reason for using specific rehabilitation method and work carried out:

- The area requiring improvement extend to a maximum depth of 14 m below ground surface, comprising a thick horizon of residual dolomite, presence of a void and a sinkhole; with the broken sewer line located at a depth of 6 m below ground surface. Bulk excavation was therefore required to a depth of 6 m below ground surface to replace this wet service. The area of the sinkhole and the void was over excavated to a depth of 10 m; choked with sandy gravel and boulders and densified by means of the DC Probing Method up to a depth of 6 m below ground surface, placing of the sewer line and the remaining area backfilled in layers of 300 mm with G6 to G7-quality material compacted to 95% Modified AASHTO.

Taking into consideration the depth of excavation in sub-areas (10 m), within highly susceptible residual dolomite (wad), the DC Method is regarded the most appropriate rehabilitation method for densification of these deeper zones. In addition, existing residential structures was located at an adequate distance away (more than 20 m) in order to perform DC without causing damages to the existing structures. No access constraints for the recommended rehabilitation method. To ensure the integrity of the newly placed sewer line, it was necessary to remove the problematic residual dolomite material and replace with more competent material, backfill and densify deeper located residual dolomite and voids, by means of the DC Method.

### 7.3.3.5. Land use after rehabilitation

Sewer servitude along a provincial road. For more information related to this geological and rehabilitation model refer to Case Study 5.

### 7.3.4 Geological and Rehabilitation Model 12

A sinkhole of 3 m diameter size extending to a depth of 2 m occurred along Msomi Street, Katlehong, during March 2009 (Report No. VGI3118R-WO39A & WO215-2). The affected area, existing infrastructure and boreholes are displayed in Figure 58.



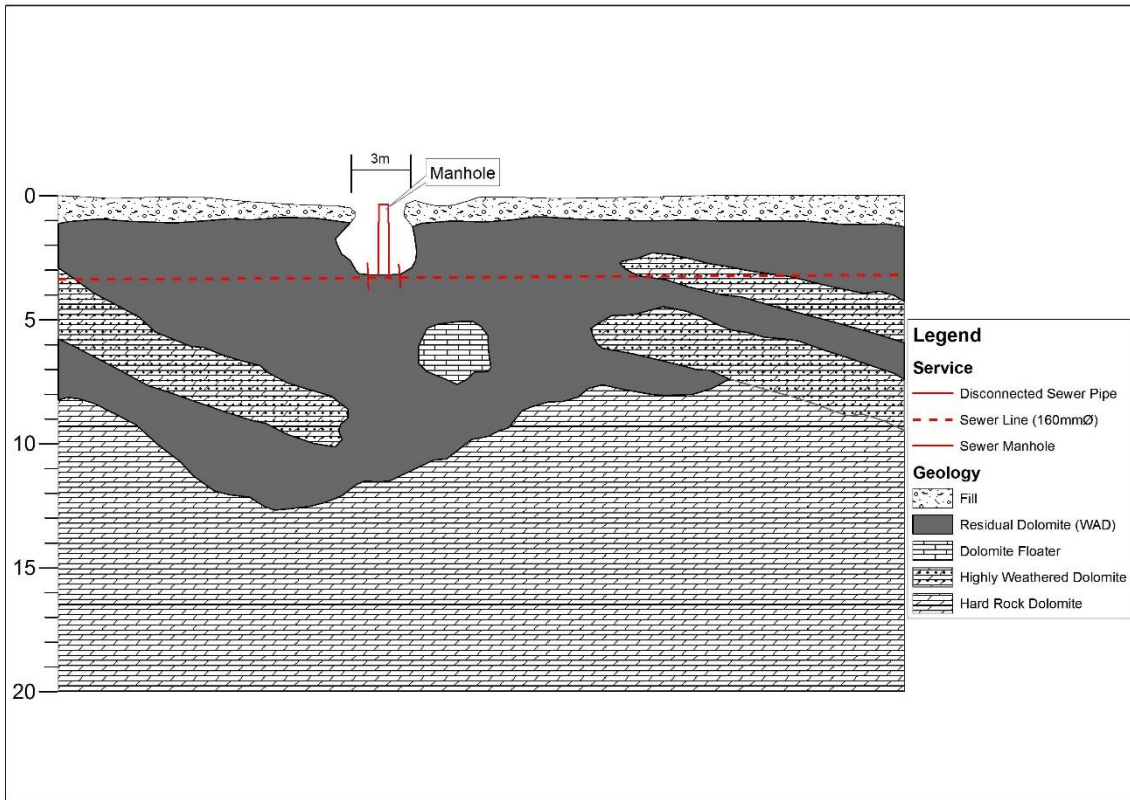
**Figure 58: Plan View of Generic Geological Model 12.**

#### 7.3.4.1. Geological Model

The geological model is based on a gravity survey (10 m station interval) and five percussion boreholes drilled in the area surrounding the sinkhole. The geological model is illustrated in Figure 59.

- Complexity: Complex, due to weathered rock and floaters located within problematic soil horizons.
- Blanketing Layer: Comprising a horizon of colluvium (1 m) underlain by a horizon of 8 m to 13 m thick residual dolomite (wad), highly susceptible to subsurface erosion or consolidation. Highly weathered soft rock dolomite horizons of 1 m to 2 m encountered within the residual dolomite (wad) between a depth of 3 m and 10 m. No voids encountered.
- Dolomite bedrock: At a depth of 8 m to 13 m. No cavities.
- Groundwater Level: In dolomite bedrock.





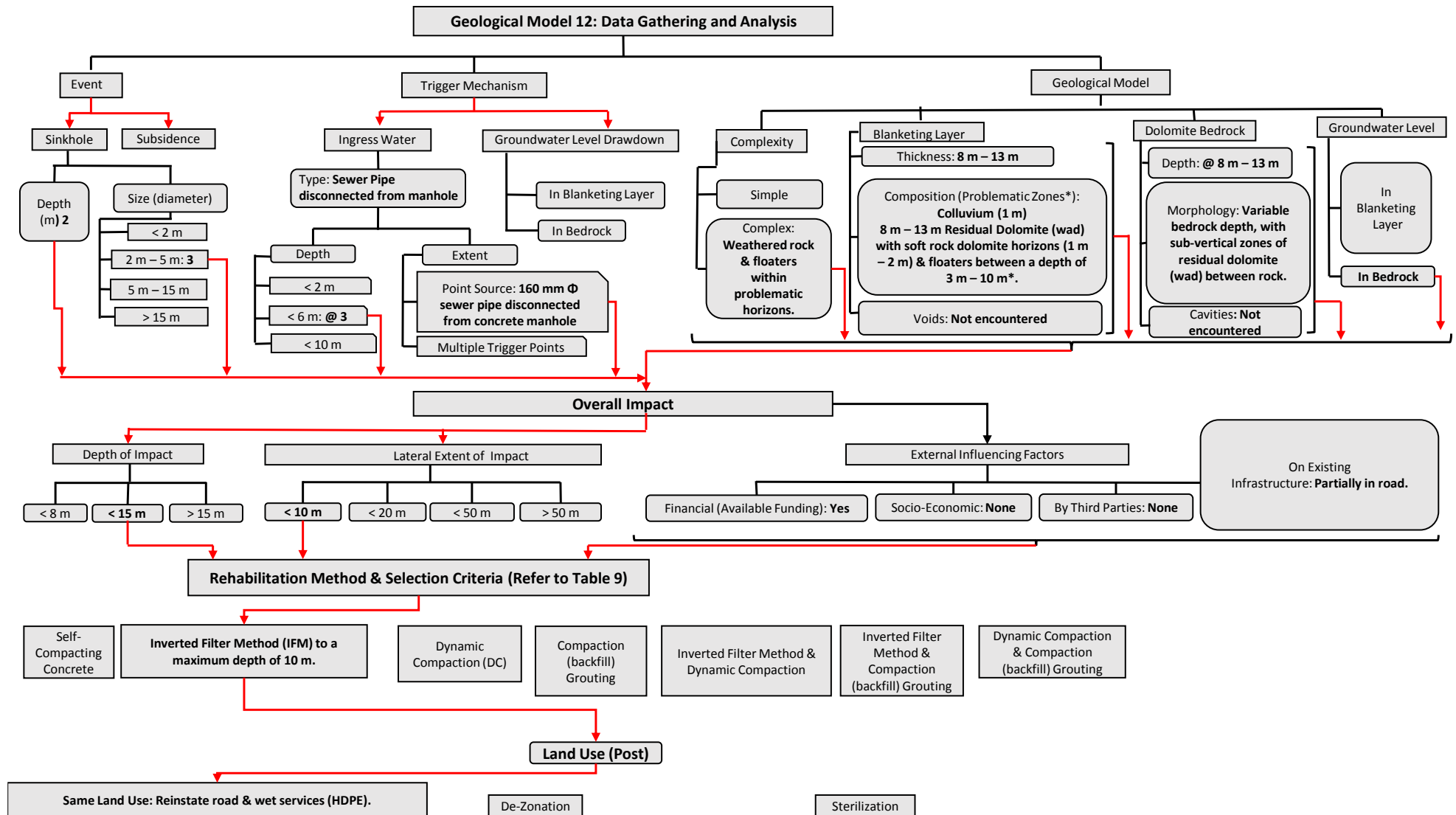
**Figure 59: Generic Geological Model 12.**

#### 7.3.4.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: A 160 mm diameter uPVC sewer line disconnected from concrete manhole. The uPVC sewer pipe and the manhole, is located within the residual dolomite (wad) horizon. Sewage from the disconnected pipe caused consolidation and possibly subsurface erosion of the residual dolomite (wad).

#### 7.3.4.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 3 m diameter size sinkhole extending to a depth of 2 m.
- Depth and extent of triggering mechanism: At a depth of 3 m, point source.
- Impact on existing infrastructure: Road.



Flow Chart 13: Generic Geological Model 12 – Process of sinkhole evaluation criteria and selection of rehabilitation method

7.3.4.4. Recommended Rehabilitation Method

Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 60). Entire sewer line replaced with HDPE butt welded pipe and two HDPE manholes from manhole to manhole over a distance of approximately 60 m. It should be noted that all HDPE pipes are placed within a 100 mm thick layer of pipe bedding material.

Reason for using specific rehabilitation method:

- The highly susceptible subsurface area requiring improvement is extending to a maximum depth of 13 m below ground surface, comprising a thick horizon of residual dolomite with some highly weathered soft rock dolomite horizons in sub-areas. As the intended land use after rehabilitation includes a road and ensuring the integrity of the newly placed sewer line and manholes, it was decided to use the Inverted Filter Method. Bulk excavation with an excavator to a maximum depth of 10 m within the area of the sinkhole.

No access constraints for proposed and recommended rehabilitation method. Remaining profile below excavated area comprising no more than 3 m highly susceptible residual dolomite (wad) material and some highly weathered soft rock dolomite horizons.

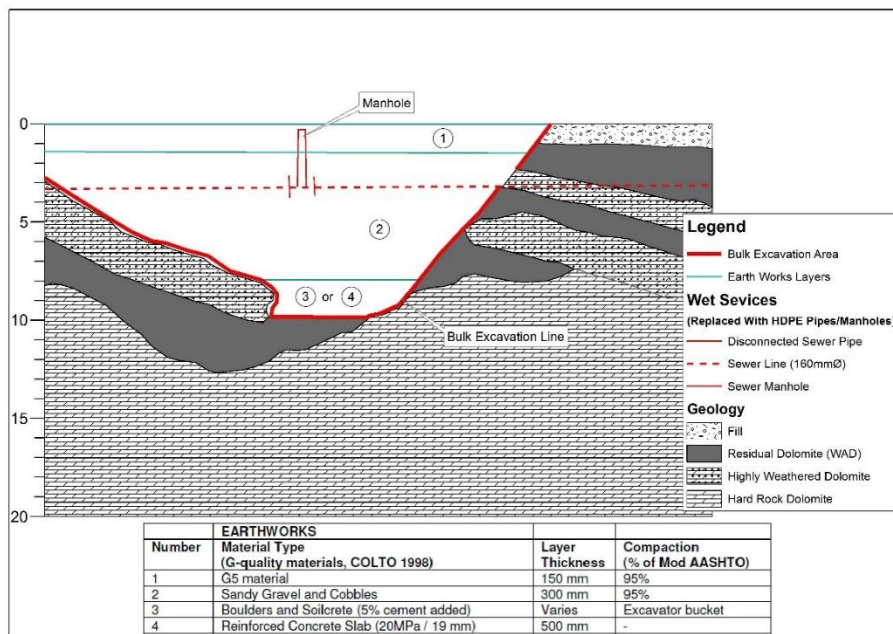


Figure 60: Rehabilitation Method Generic Geological Model 12.

Layer works:

- Number 1: The upper 1,5 m comprising 150 mm G5-quality material compacted at 95% Modified AASHTO. The upper 0,3 m were compacted to 98% compaction effort as part of the road layer works.

- Number 2: The bulk filling between a depth of 1,5 m to 8,0 m comprising sandy gravel and cobbles placed within 300 mm thick layers compacted at 95% Modified AASHTO deviates from the typical use of G8-quality material placed in layers of 200 mm compacted with a 32 Ton excavator bucket.
- Number 3 or 4: The base of the excavation was filled with 2 m of boulders and soilcrete with a 5% cement component in the soilcrete mix, compacted with excavator bucket to choke the potential throat. Alternatively a 500 mm thick reinforced concrete slab could have been constructed.

To ensure the integrity of the newly placed sewer line and the road, it was necessary to remove the problematic residual dolomite material and replace with more competent material.

#### 7.3.4.5. Land use after rehabilitation

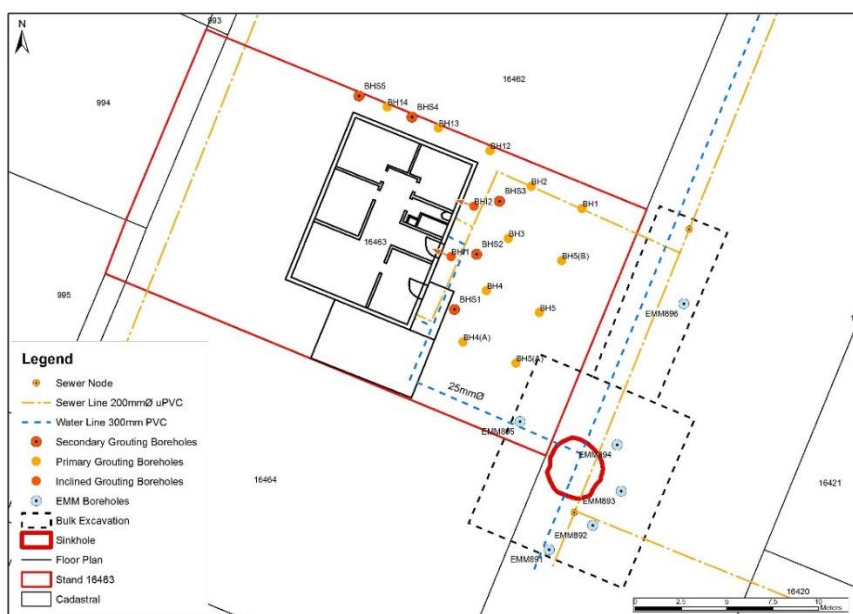
Road with servitude and large open field adjacent to it.

### 7.4 Impact to a depth of more than 15 m

Five geological models, the evaluation process (flow chart) and the most appropriate rehabilitation method for each are presented.

#### 7.4.1 Geological and Rehabilitation Model 13

A sinkhole of 3 m diameter size extending to a depth of 5 m occurred in the western servitude of Mabuya Street on the eastern boundary of Stands 16462 and 16463, on 20 Septemebr 2011 (VGI3355/WO391, VGI3355/391/1 and VGI3355 WO391-1) . A poorly constructed house located within 10 m from the sinkhole is severely cracked. The affected area, existing infrastructure and boreholes are displayed in Figure 61.

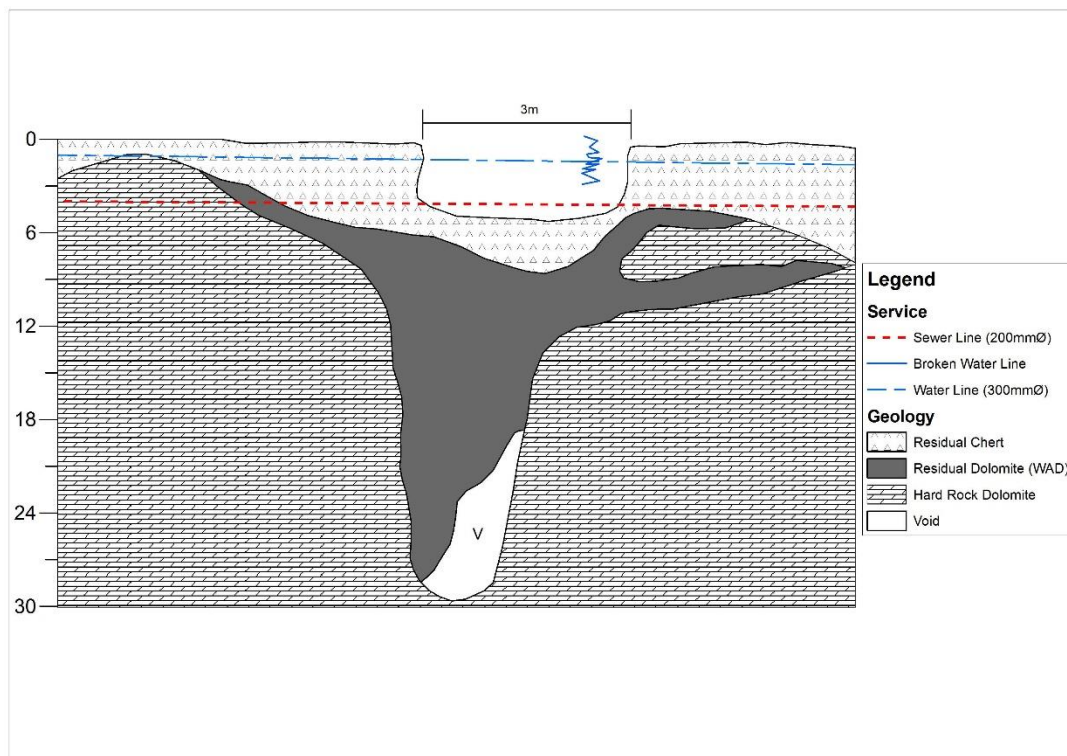


**Figure 61: Plan View of Generic Geological Model 13.**

#### 7.4.1.1. Geological Model

The geological model is based on six percussion boreholes drilled during the investigation phase, placed in the area surrounding the sinkhole and the drilling of eighteen percussion boreholes during the grouting (backfill) programme. A large number of DPSH tests were also conducted on Stand 16463 in the area between the sinkhole and the house (not indicated). The geological model is illustrated in Figure 62.

- Complexity: Complex, due to deeply weathered dolomite zone presenting gryke.
- Blanketing Layer: Comprising a horizon of residual chert (1 m to 8 m) underlain by a (1 m to 29 m thick) horizon of residual dolomite (wad) to a depth of 3 m and 29 m with a 1 m to 3 m thick horizon of highly weathered soft rock dolomite between 5 m and 8 m located within the residual dolomite in subareas. No voids encountered.
- Dolomite bedrock: At a variable depth of 1 m to 29 m, presenting a gryke.
- Groundwater Level: In dolomite bedrock.



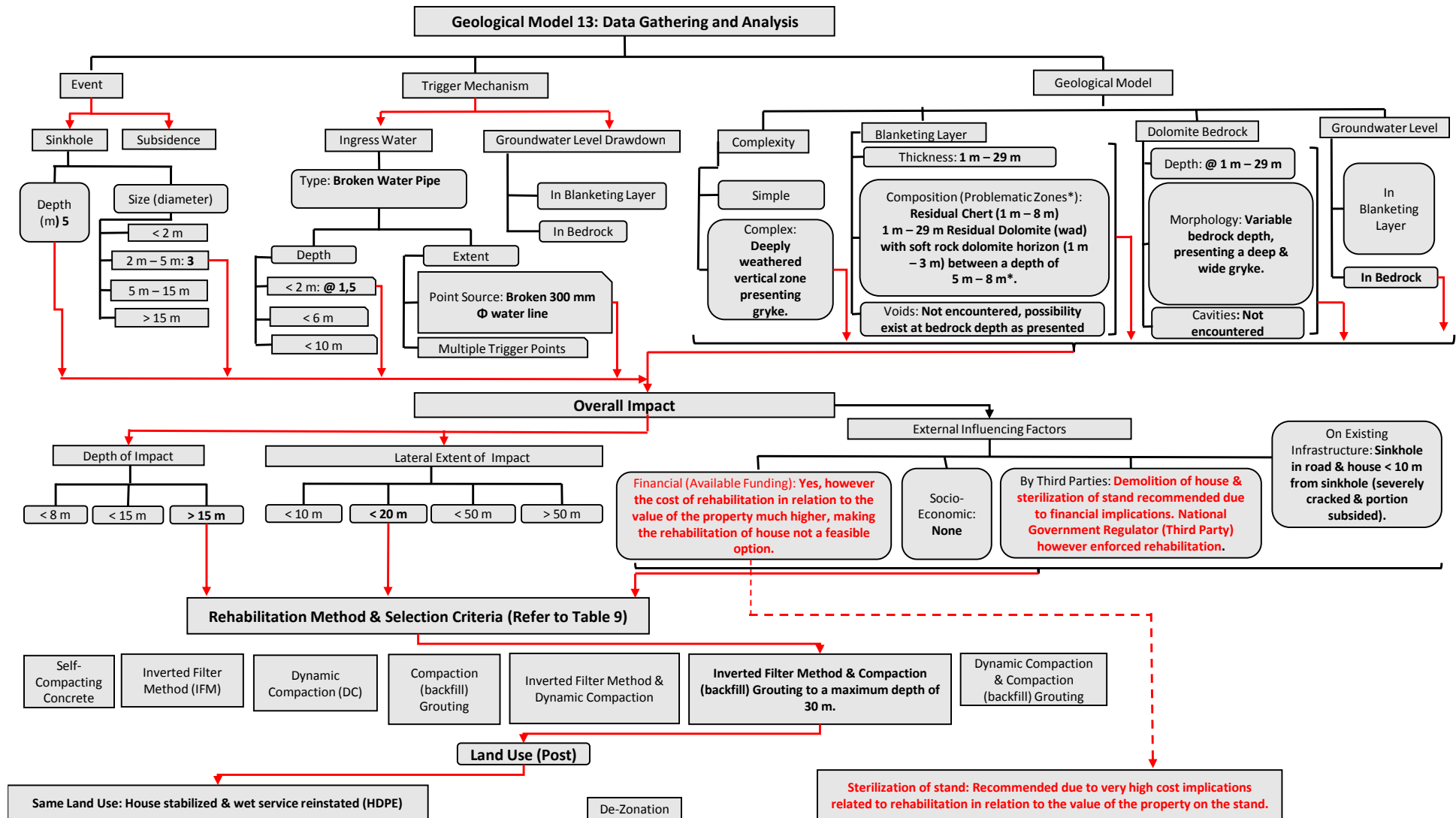
#### 7.4.1.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: A broken 300 mm diameter PVC water line. Sinkhole caused due to subsurface erosion of highly susceptible residual dolomite material mobilized downwards along the steeply gradient dolomite bedrock interface into a void or a cavity (although not encountered during drilling) at depth.

Subsurface erosion took place at depth over a lateral distance of nearly 20 m. The water line is located mainly within residual chert.

#### 7.4.1.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: A sinkhole of 3,0 m diameter size extending to a depth of 5,0 m.
- Depth and extent of triggering mechanism: Water at 1,5 m (point source); additionally a 200 mm uPVC sewer line located at a depth of approximately 4,5.
- Impact on existing infrastructure: Sinkhole partially in road and residential structure located approximately 10 m from the sinkhole, severely cracked with one portion of the structure slightly subsided.



Flow Chart 14: Generic Geological Model 13 – Process of sinkhole evaluation criteria and selection of rehabilitation method

7.4.1.4. Recommended Rehabilitation Method

Compaction Grouting and Inverted Filter Method: Refer to the Rehabilitation Model (Figure 63).

All broken and leaking wet services were replaced with HDPE butt-welded pipes and one new sewer manhole constructed within the affected area.

Reason for using specific rehabilitation method:

- As the dolomite bedrock profile presents a 29 m deep gryke (deep narrow slot) filled with highly susceptible residual dolomite (wad) and possibly also comprising voids; extending below the residential structure located 10 m away that needs soil improvement, the Inverted Filter Method typically applicable for rehabilitation of areas up to a depth of 8 m and the DC Method applicable for the rehabilitation of areas up to a depth of 12 m; will not be suitable. The Inverted Filter Method is however applicable to improve soil conditions within the area of the sinkhole and section of wet services that needed to be replaced.

The recommended rehabilitation method is the Compaction Grouting Method, as this method can be used to fill voids or cavities at depth, also below the residential structure, and to densify the low density compressible residual dolomite down to bedrock depth at 29 m.

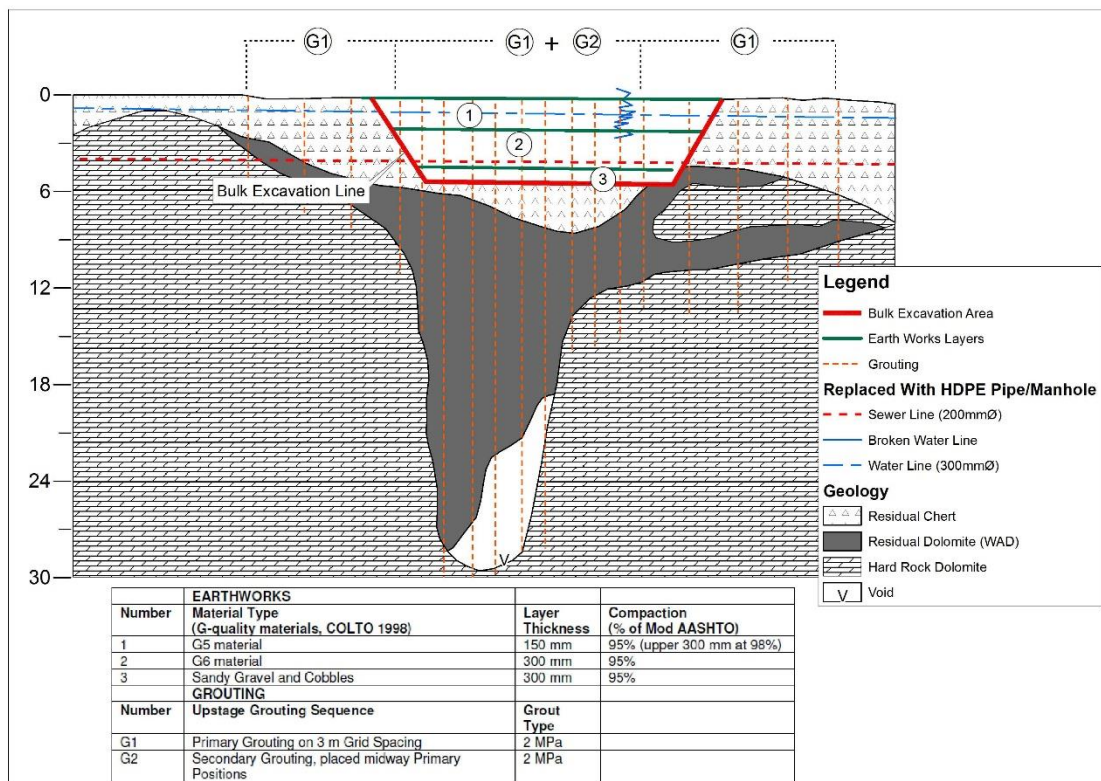


Figure 63: Rehabilitation Method Generic Geological Model 13.



Work carried out:

- The grouting programme included a primary and secondary stage in the gryke, between the sinkhole and the house and also adjacent to the structure in area of structural subsidence. Grouting below the structure was done by means of inclined boreholes. Micro-driven piles installed at a 2 m interval below the foundation was done as part of the stabilisation of the structure and a 150 mm thick reinforced concrete slab was constructed inside the house in the portion subsided.
- Conditions within the area of the sinkhole and affected wet services were improved by means of the Inverted Filter Method: Below the sewer line, placing of 300mm thick layers of sandy gravel cobbles compacted at 95% Modified AASHTO compaction; between 1,5 m and 4,5 m placing of 300 mm thick layers of G6-quality material compacted at 95% Modified AASHTO and the upper 1,5 m comprised 150 mm thick layers of G5-quality material compacted at 95% Modified AASHTO, with the upper 0,3 m compacted at 98% as part of the road layer works.

The existing houses caused access constraints for proposed and recommended rehabilitation method.

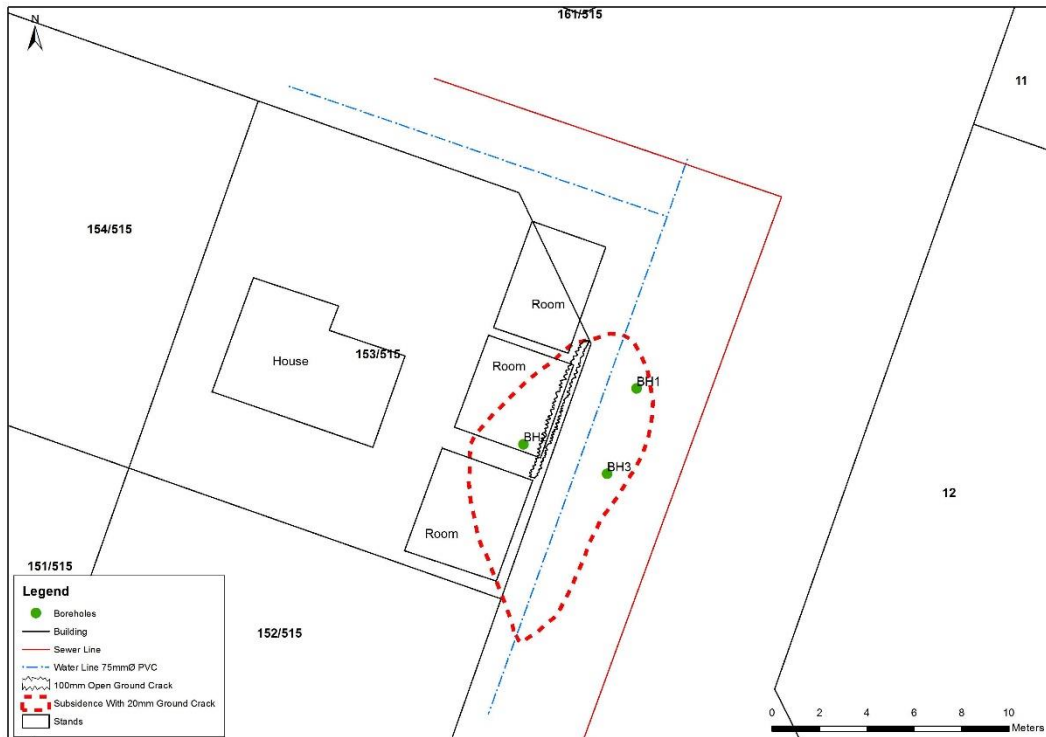
To stabilize the conditions below the existing house, it was necessary to improve subsurface conditions by means of the Compaction Grouting method, including the densification of low density residual dolomite and filling of potential voids or cavities at depth below the house and the area between the sinkhole and the house. The sinkhole and affected wet services was improved by means of the Inverted Filter Method.

#### 7.4.1.5. Land use after rehabilitation

Existing structure stabilized. For more information related to this geological and rehabilitation model refer to Case Study 8.

#### 7.4.2 Geological and Rehabilitation Model 14

An oval shaped subsidence with dimensions of 18 m by 8 m extending to a depth of 0,5 m occurred partially in Molala Road and below three informal structures (rooms) on Stand 153, Katilehong, on 18 June 2007 (Report No. KHH1643). The three informal structures were evacuated and demolished. The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 64.

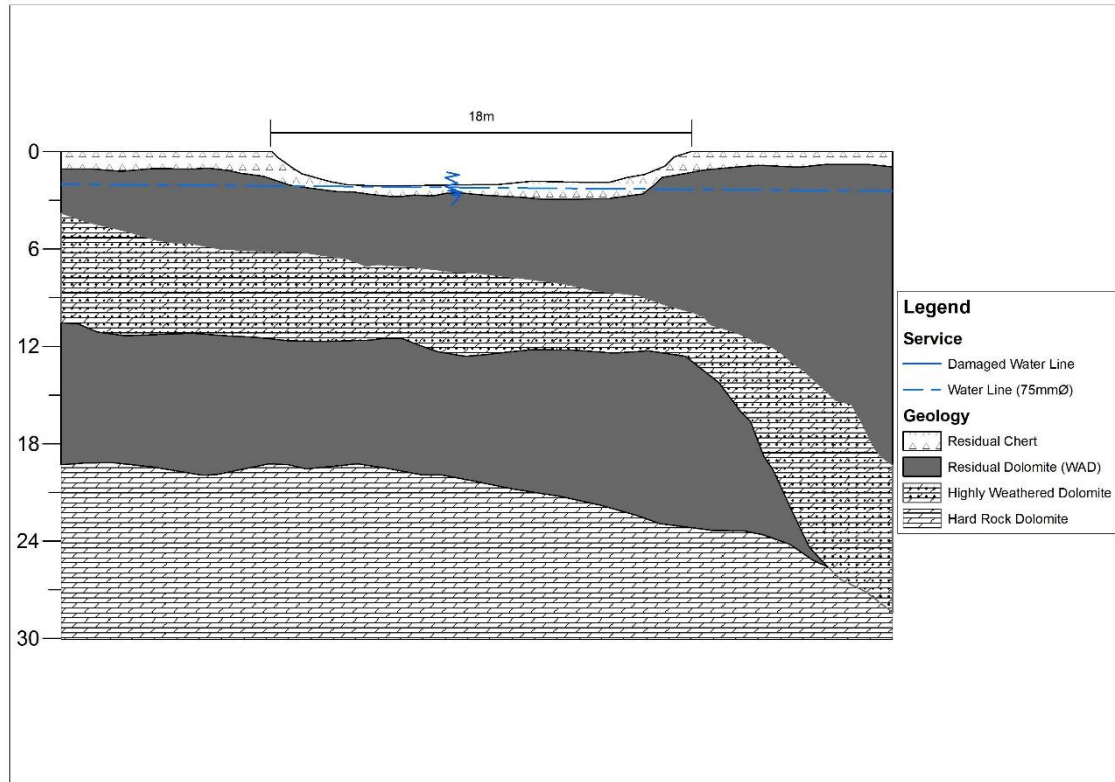


**Figure 64: Plan View of Generic Geological Model 14.**

#### 7.4.2.1. Geological Model

The geological model is based on three percussion boreholes drilled within the subsidence area. The geological model is illustrated in Figure 65.

- Complexity: Complex, weathered rock horizon within problematic soils.
- Blanketing Layer: Comprising a horizon of residual chert (1 m) underlain by a horizon of 2 m to 12 m thick residual dolomite (wad), highly susceptible to subsurface erosion or consolidation within area of subsidence, although extending to a maximum depth of 18 m in subareas; a second 1 m to 10 m thick horizon of residual dolomite (wad) occurs below a highly weathered soft rock dolomite horizon of 3 m to 6 m encountered between a depth of 4 m and 27 m. No voids encountered.
- Dolomite bedrock: At a depth of 19 m to 28 m. No cavities.
- Groundwater Level: In dolomite bedrock.



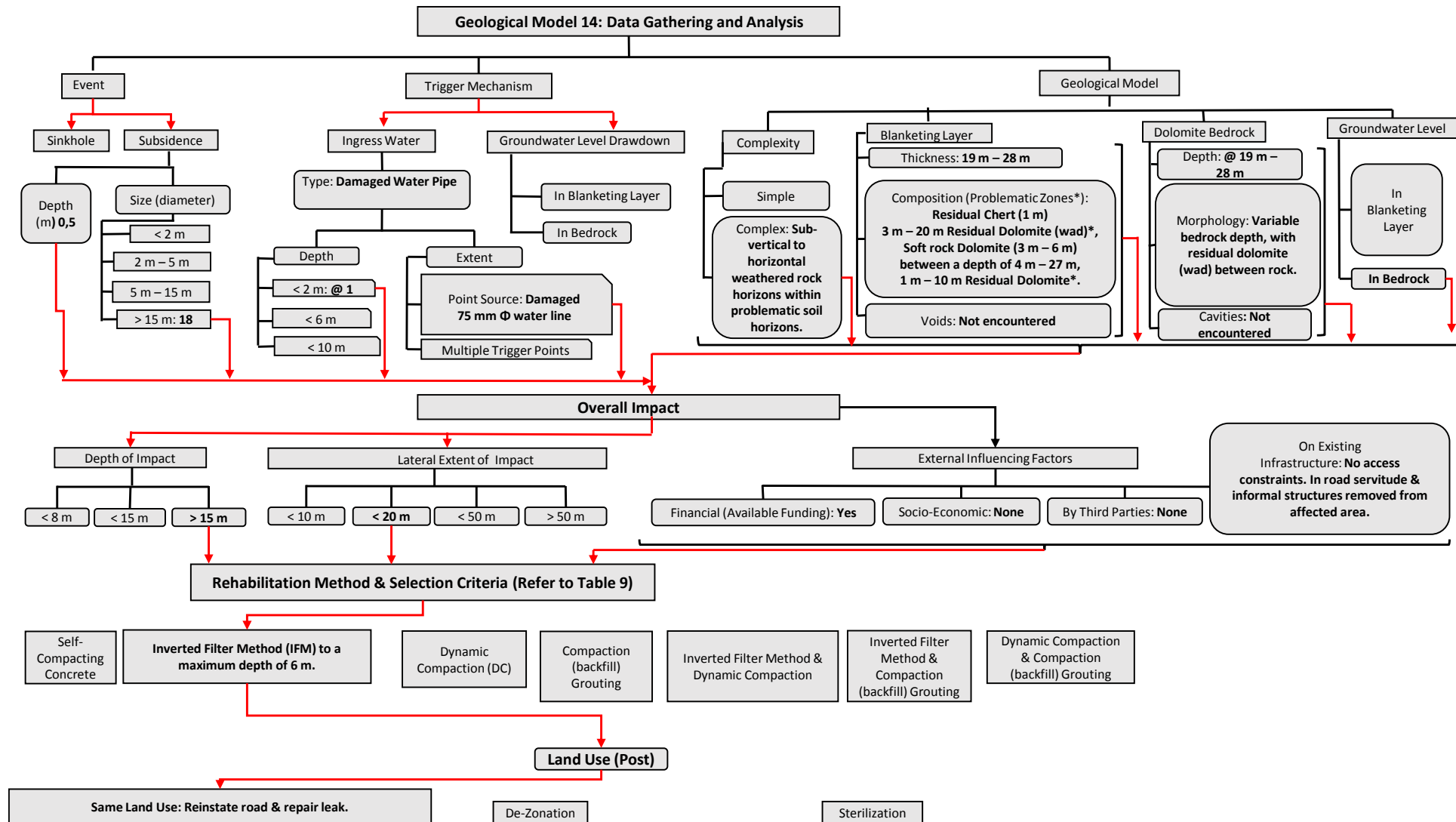
**Figure 65: Generic Geological Model 14.**

#### 7.4.2.2. Cause of sinkhole or subsidence formation

Concentrated water ingress: A damaged 75 mm diameter PVC water line, located within residual chert and residual dolomite (wad). The leak on the PVC water pipe caused consolidation and possibly subsurface erosion of the residual dolomite (wad).

#### 7.4.2.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 18 m diameter size subsidence extending to a depth of 0,5 m.
- Depth and extent of triggering mechanism: At a depth of 1 m, point source.
- Impact on existing infrastructure: Road and adjacent informal structures.



Flow Chart 15: Generic Geological Model 14 – Process of subsidence evaluation criteria and selection of rehabilitation method

#### 7.4.2.4. Recommended Rehabilitation Method

Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 66).

The leak on the damaged PVC pipe was repaired by the municipality.

Reason for using specific rehabilitation method:

- As the intended land-use after rehabilitation included a road with servitude, the Inverted Filter Method is recommended as rehabilitation process, with only the upper residual dolomite (wad) horizon considered for rehabilitation. If the same geological profile was located in close proximity to an important structure that could be affected, a grouting programme will be required down to dolomite bedrock at a depth of 19 m to 28 m to densify both the residual dolomite (wad) horizons located above and below the 3 m to 6 m thick horizon of highly weathered soft rock dolomite.

No access constraints for proposed and recommended rehabilitation method.

Remaining profile below excavated area comprising 3 m and less highly susceptible residual dolomite (wad) material, 3 m to 6 m highly weathered dolomite, followed at depth by a 10 m thick horizon of residual dolomite (wad).

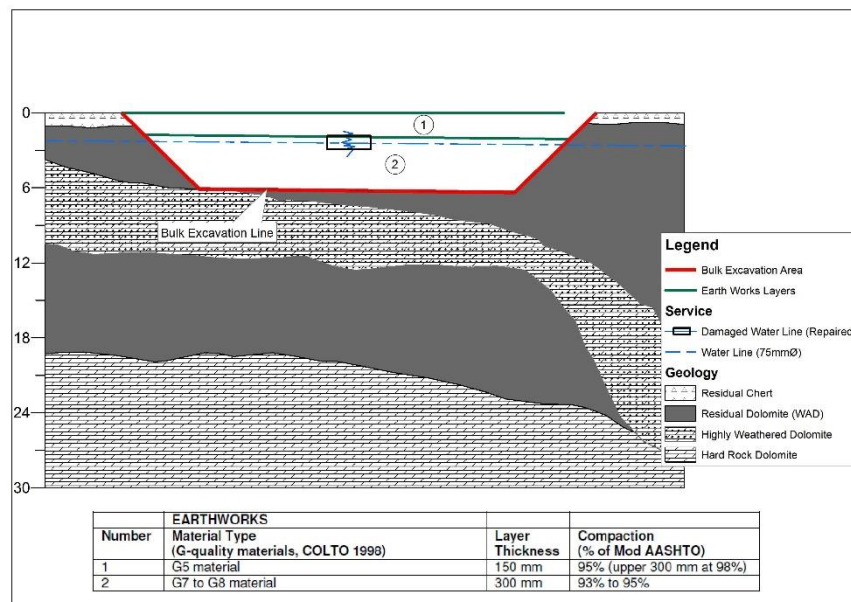


Figure 66: Rehabilitation Method Generic Geological Model 14.

Layer works:

- Number 1: The upper 1,5 m comprising 150 mm G5-quality material compacted at 95% of Modified AASHTO, however the upper 0,3 m were compacted to 98% compaction effort as part of the road layer works.
- Number 2: The base of the 6 m deep excavation up to 1,5 m below ground

surface was filled with 300 mm thick layers of G7 to G8-quality material compacted at 93% to 95% Modified AASHTO.

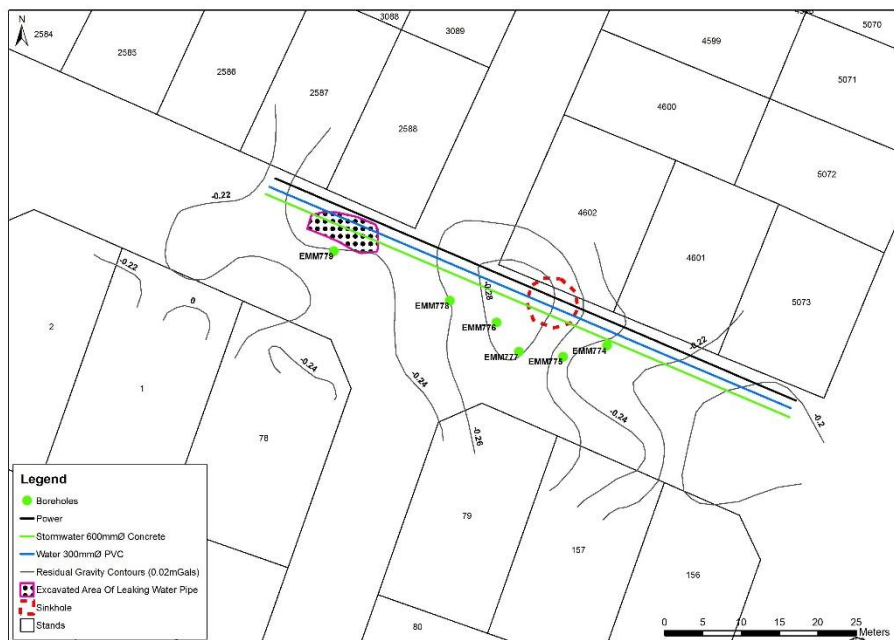
To ensure the integrity of the repaired water line and the road, it was necessary to remove the upper problematic residual dolomite material and replace with more competent material.

#### 7.4.2.5. Land use after rehabilitation

Road with servitude.

#### 7.4.3 Geological and Rehabilitation Model 15

A sinkhole of 8 m diameter size extending to a depth of 4 m occurred on the southern boundary of Stand 4602, Tshabalala Street Katlehong, during January 2011 (Report No. VGI3355 WO335). The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 67.



**Figure 67: Plan View of Generic Geological Model 15.**

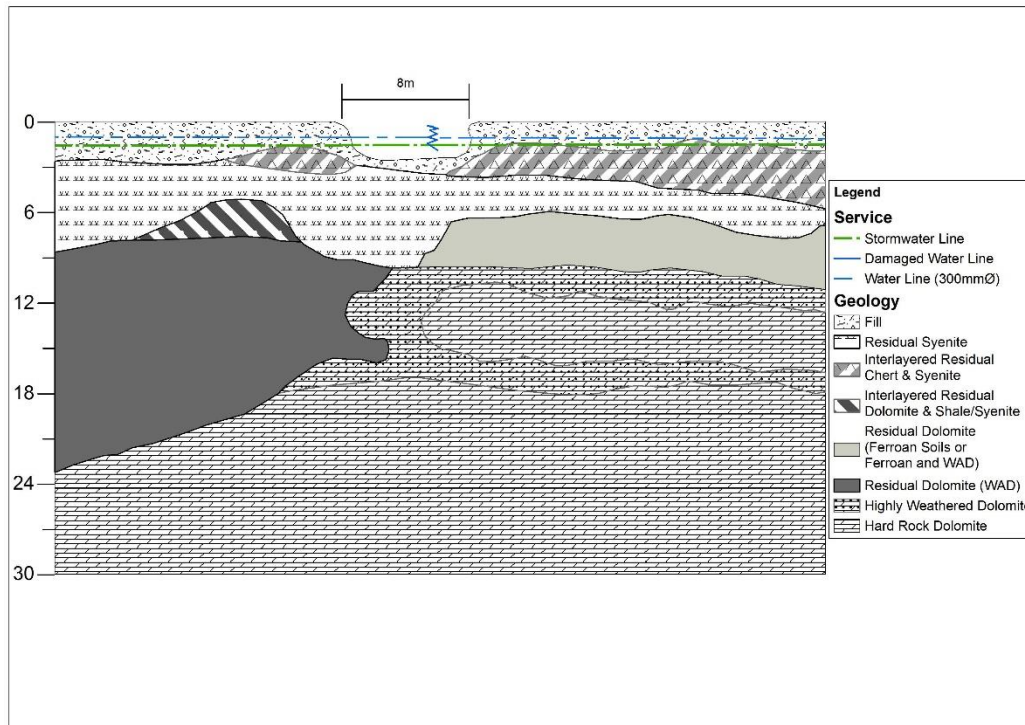
#### 7.4.3.1. Geological Model

The geological model is based on a gravity survey (10m station interval) and five percussion boreholes drilled in the surrounding area of the sinkhole and one percussion borehole in the region of the leaking water line. The geological model is illustrated in Figure 68.

- Complexity: Complex, heterogenous profile.
- Blanketing Layer: Comprising road fill (1 m to 2 m), interlayered residual chert and syenite (1 m to 3 m) in subareas, followed by residual syenite and

interlayered residual syenite and dolomite (1 m to 3 m) in sub-areas underlain by a 3 m thick horizon of residual dolomite (ferroan soils) in subareas and residual dolomite (wad) of 6 m to 14 m thick in sub-areas, highly susceptible to subsurface erosion or consolidation. Highly weathered soft rock dolomite horizon encountered between 9 m and 18 m. No voids encountered.

- Dolomite bedrock: At a depth of 18 m to 23 m. No cavities.
- Groundwater Level: In dolomite bedrock.



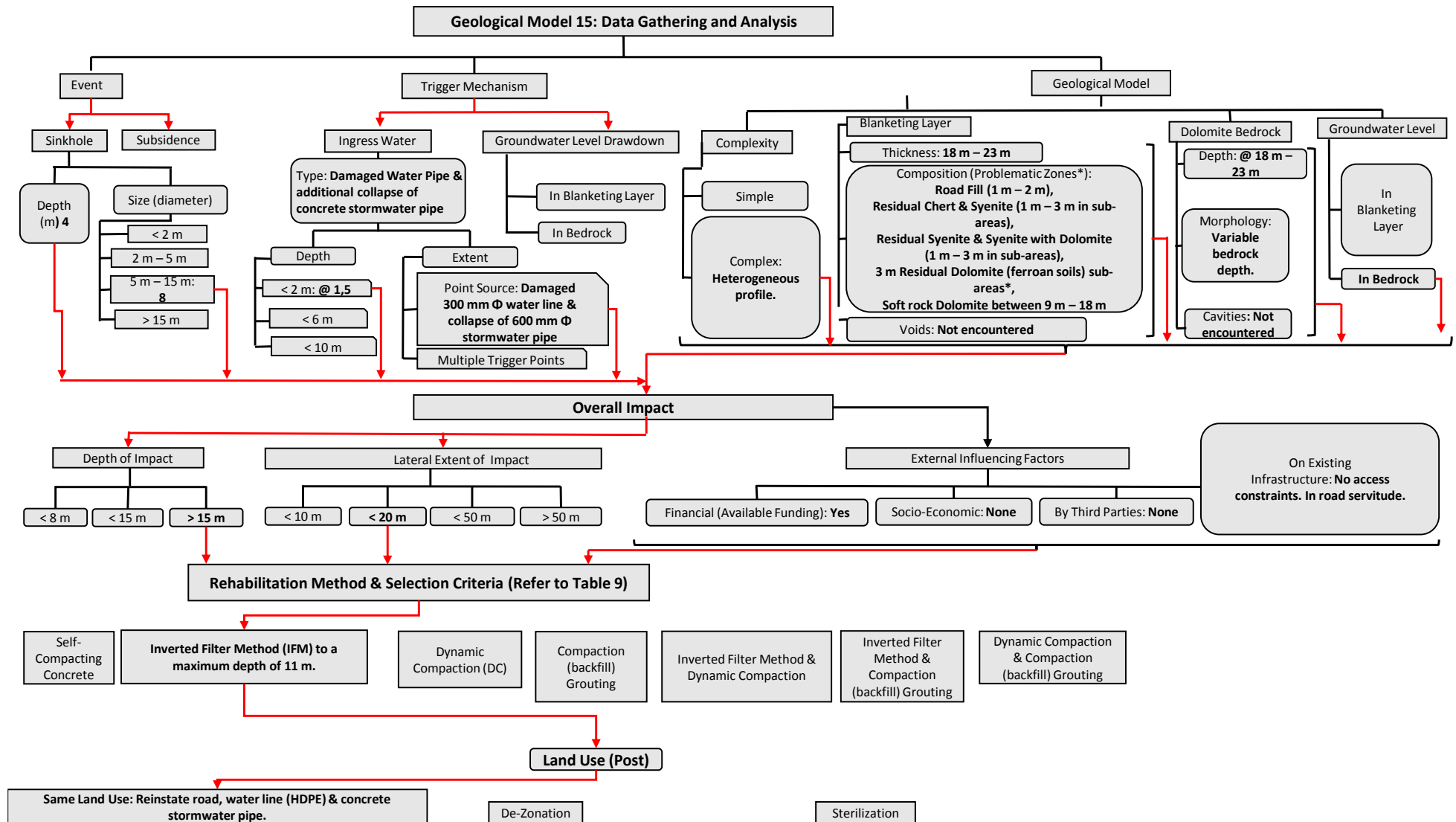
**Figure 68: Generic Geological Model 15.**

#### 7.4.3.2. Cause of sinkhole or subsidence formation

Cocentrated water ingress: A damaged 300 mm diameter PVC water pipe, located within road fill, caused subsurface erosion of the underlain residual dolomite (wad).

#### 7.4.3.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 8 m diameter size sinkhole extending to a depth of 4 m.
- Depth and extent of triggering mechanism: At a depth of 1,5 m, point source. In addition, caused the collapse of a concrete stormwater pipe located at the same depth.
- Impact on existing infrastructure: Road and servitude.



Flow Chart 16: Generic Geological Model 15 – Process of sinkhole evaluation criteria and selection of rehabilitation method



#### 7.4.3.4. Recommended Rehabilitation Method

Inverted Filter Method: Refer to the Rehabilitation Model for various earthworks layers (Figure 69).

The water line was replaced with HDPE butt welded material over a distance of 120m and the stormwater pipe replaced and properly sealed on joints; including trench sub-surface soil improvement to a maximum depth of 3,0 m below ground surface.

Reason for using specific rehabilitation method:

- As the intended land-use after rehabilitation includes a road with servitude, the Inverted Filter Method is recommended as rehabilitation process in the area of the sinkhole, including the removal of residual dolomite (wad and ferroan soils) to a depth of 9 m.

No access constraints for proposed and recommended rehabilitation method. Remaining profile below excavated area comprising highly weathered dolomite and dolomite bedrock.

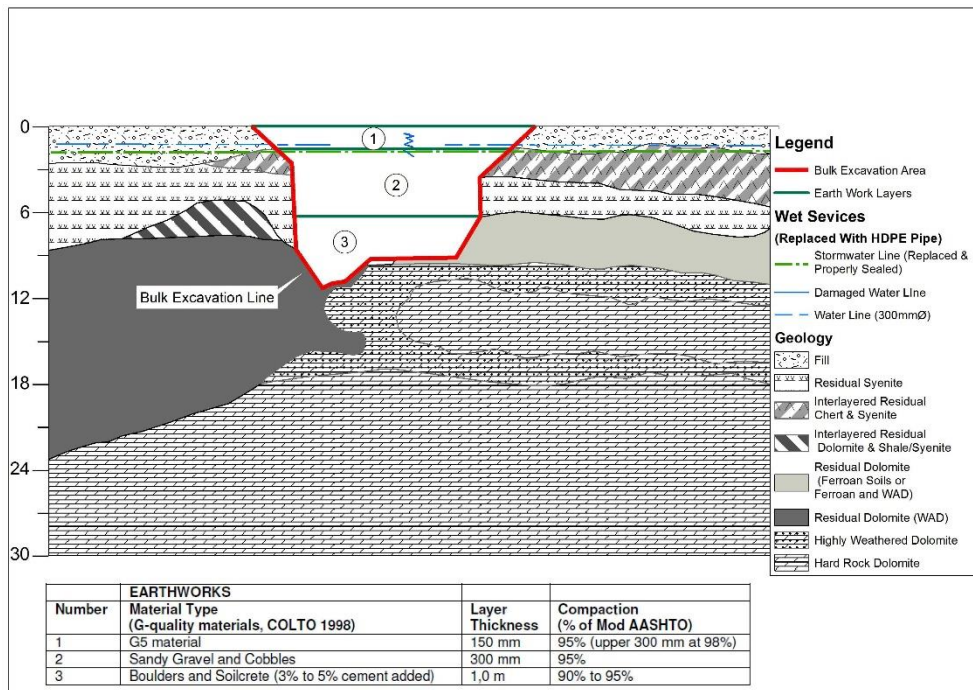


Figure 69: Rehabilitation Method Generic Geological Model 15.

Layer works:

- Number 1: The upper 1,5 m comprising 150 mm G5-quality material compacted at 95% of Modified AASHTO, with the upper 0,3 m compacted to 98% compaction effort as part of the road layer works.
- Number 2: Sandy gravel and cobbles in 300 mm thick layers compacted at 95% Modified AASHTO was placed between a depth of 1,5 m and 6 m.

- Number 3: The base of the 9 m deep excavation, with a subarea over-excavated to 10 m, up to 6 m below ground surface was filled with 1 m thick layers of boulders and soilcrete with 5% cement content.

To ensure the integrity of the new water-stormwater pipelines and road, it was necessary to remove the problematic residual dolomite material within the area of the sinkhole and replace with more competent material.

#### 7.4.3.5. Land use after rehabilitation

Road with servitude.

#### 7.4.4 Geological and Rehabilitation Model 16

A sinkhole of 50 m diameter size extending to a depth of 25 m occurred next to a road in the Bapsfontein area during January 2004. The affected area and existing infrastructure are displayed in Figure 70.



**Figure 70: Plan View Generic Geological Model 16.**

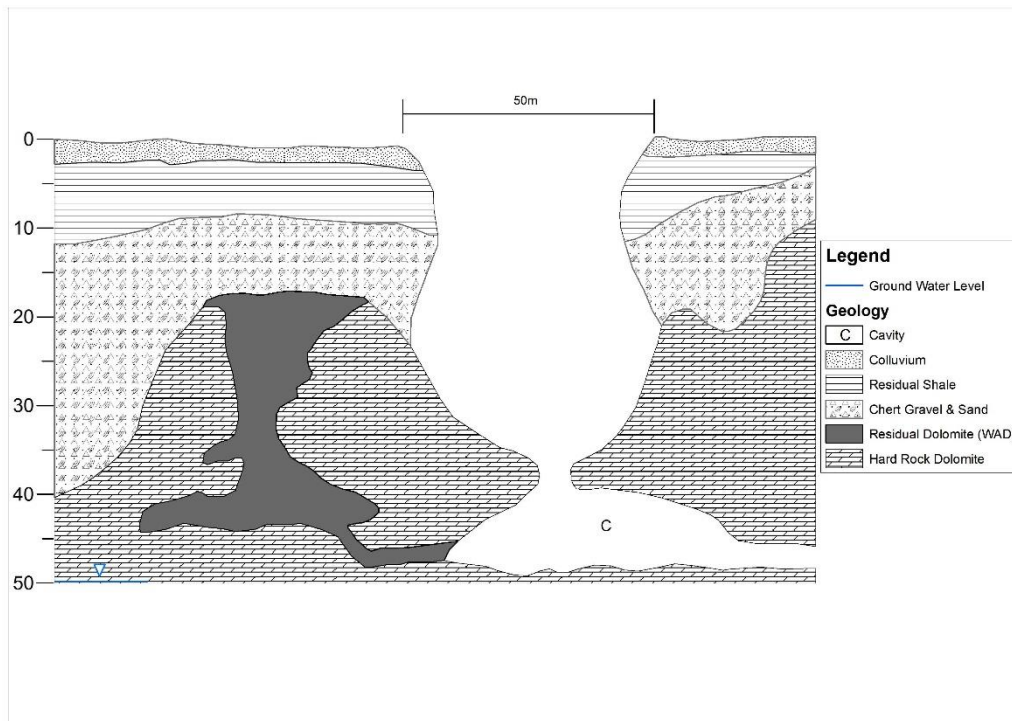
#### 7.4.4.1. Geological Model

The geological model is based on the model presented by Wagener (2009) and the extrapolation of borehole information from an investigation conducted within the informal settlement by the author (Report No. VGI3118R-WO6). The geological model is illustrated in Figure 71.

- Complexity: Complex, deep profile susceptible to instability.
- Blanketing Layer: Comprising a horizon colluvium (1 m to 3 m thick), underlain

by residual shale of the Karoo (2 m to 10 m thick) and chert gravel and sand (5 m to 27 m thick), followed at depth by residual dolomite (wad) that are absent to 25 m thick. No voids encountered.

- Dolomite bedrock: At a depth of 8 m to 40 m. Number of inter-connected cavities.
- Groundwater Level: Original groundwater level located in chert gravel and sand at 19 m, drawdown into dolomite bedrock and currently located at 50 m.



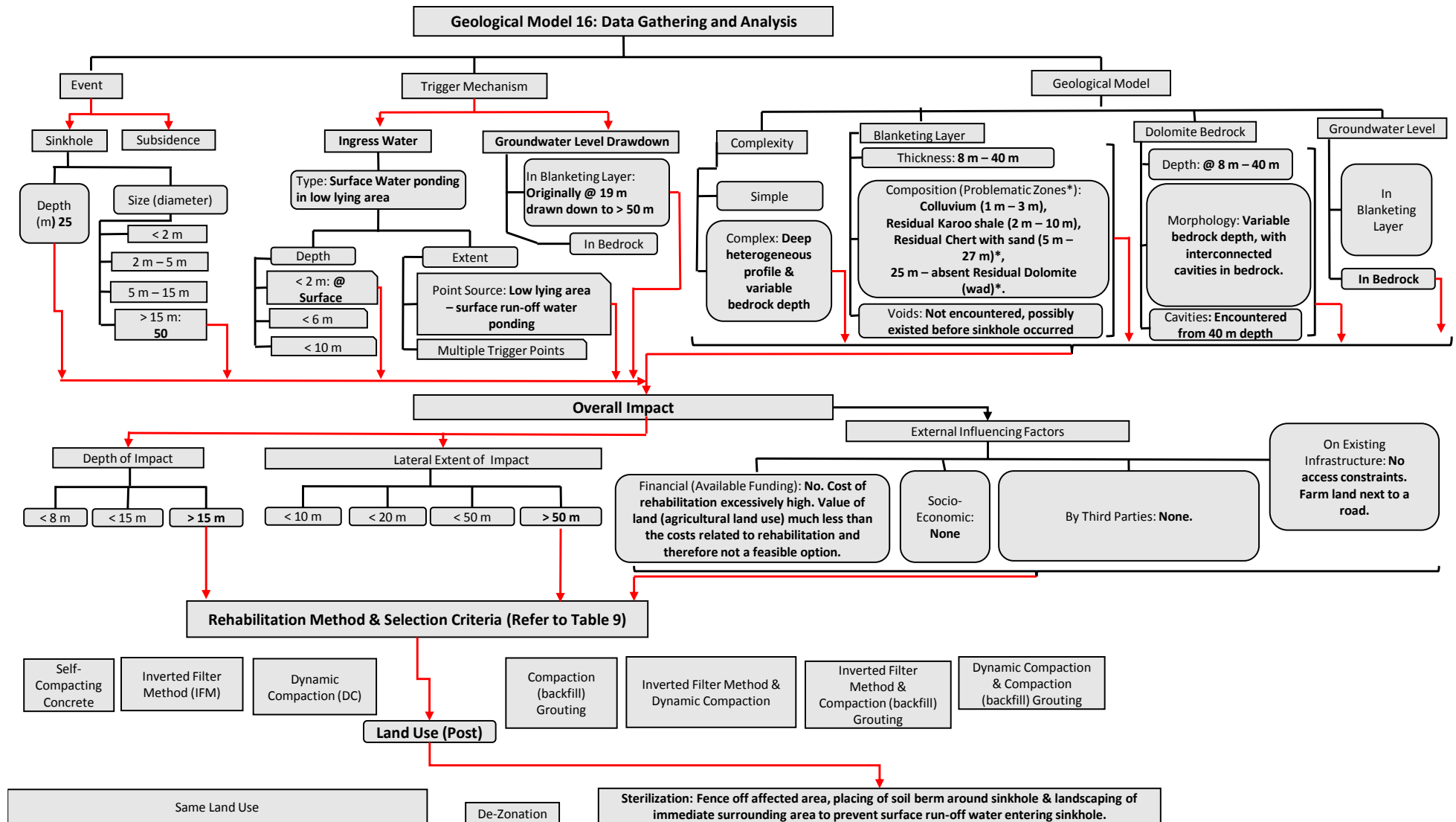
**Figure 71: Generic Geological Model 16.**

#### 7.4.4.2. Cause of sinkhole or subsidence formation

Dewatering: The original groundwater level was drawdown from 19 m to 50 m and exposed material highly susceptible to mobilization and subsurface erosion. Poor surface water drainage in the area will cause subsurface erosion of highly susceptible material mobilized downwards in large to very large cavities located in dolomite bedrock above the current water table.

#### 7.4.4.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 50 m diameter size sinkhole extending to a depth of 25 m.
- Depth and extent of triggering mechanism: Groundwater level drawdown to 50 m, exposing a deep susceptible dolomite profile, with a potential for the sinkhole diameter to increase.
- Impact on existing infrastructure: Potentially a road.



Flow Chart 17: Generic Geological Model 16 – Process of sinkhole evaluation criteria and selection of rehabilitation method

#### 7.4.4.4. Recommended Rehabilitation Method

Placing of a soil berm around the sinkhole area and landscaping of immediate surrounding areas to ensure surface water run-off away from the sinkhole. Fence off affected area to prevent access.

Reason for using specific rehabilitation method:

- The rehabilitation of instability features of this extent is costly and not economically viable to rehabilitate, especially when located on agricultural land. The long term rehabilitation measure for instability features caused by dewatering is the proper management and control of groundwater in dolomite compartments by ensuring groundwater levels are restored to their original level, thereby creating stability. Consideration can only be given to the rehabilitation of existing instability features after the groundwater level has been restored to its original or near original level, if such feature poses a risk to existing structures.

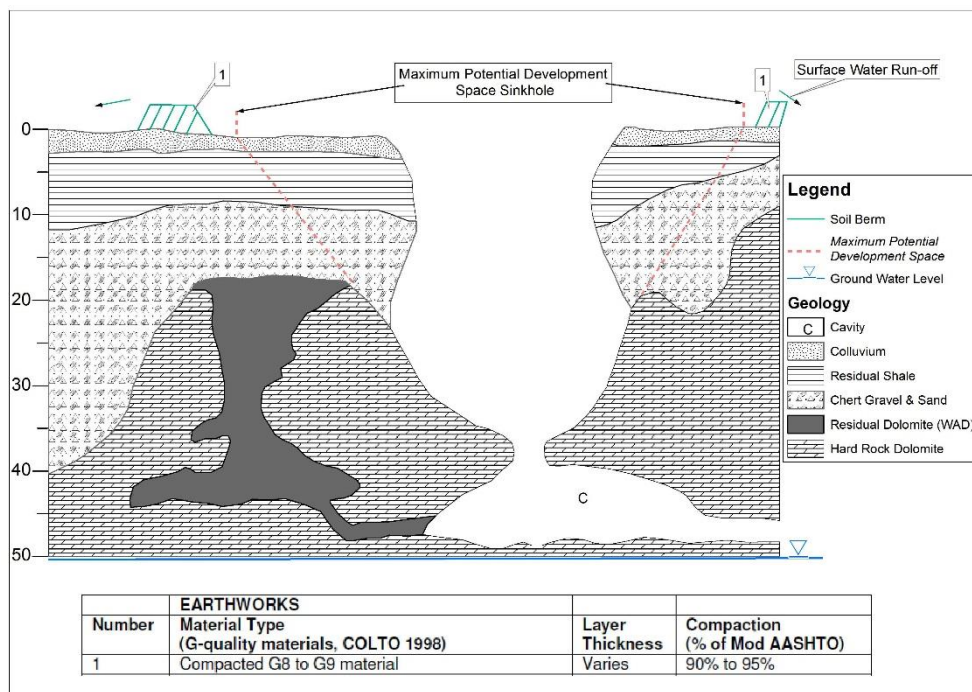


Figure 72: Rehabilitation Method Generic Geological Model 16.

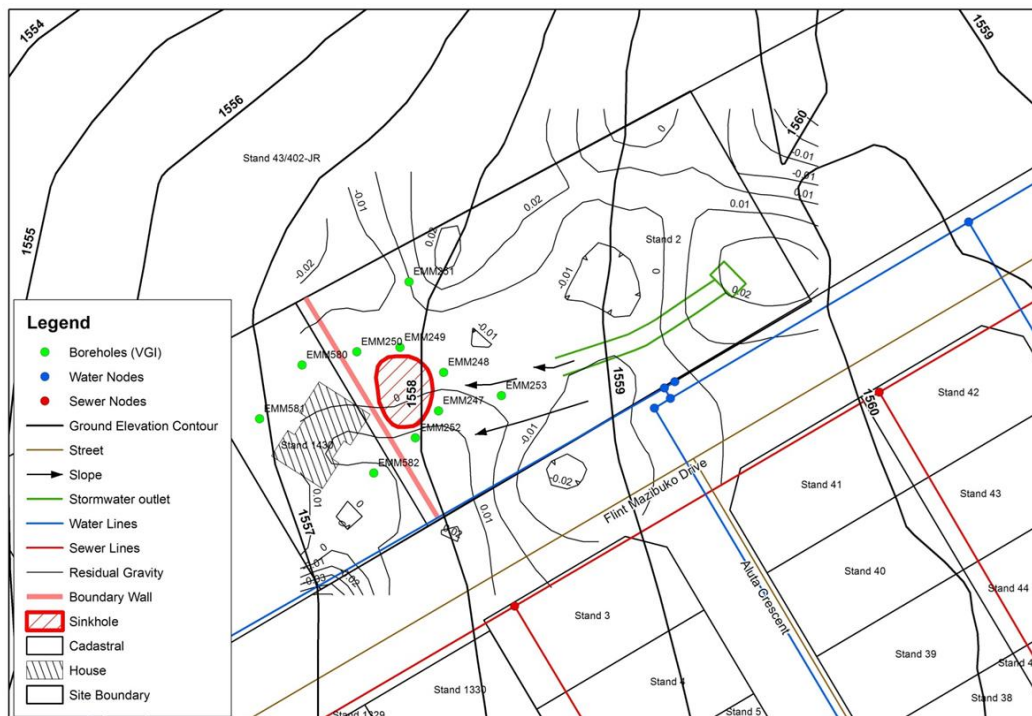
#### 7.4.4.5. Land use

Agricultural.

#### 7.4.5 Geological and Rehabilitation Model 17

A sinkhole of 7 m diameter size extending to a depth of 5 m occurred on the south-western boundary of Stand 2, Flint Mazibuko Street, Tembisa Extension 1, during

January 2009 (Report No. VGI3118/199/1 and VGI3118R-WO199-2). A house is located within 7 m from the sinkhole. The affected area, existing infrastructure and the positions of boreholes are displayed in Figure 73.

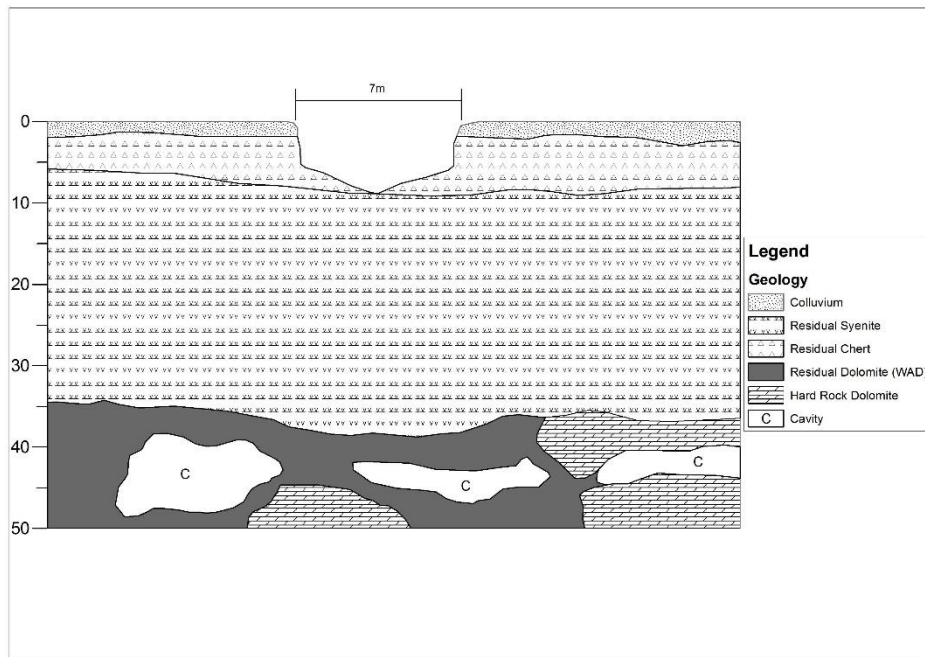


**Figure 73: Plan View of Generic Geological Model 17.**

#### 7.4.5.1. Geological Model

The geological model is based on a gravity survey (10 m station interval) and the drilling of ten percussion boreholes in the area surrounding the sinkhole. The geological model is illustrated in Figure 74.

- Complexity: Complex, thick horizon of low susceptibility material above problematic zone.
- Blanketing Layer: Comprising a horizon of colluvium (1 m) and residual chert to a depth of between 5 m and 7 m, underlain by residual syenite to a depth of 35 m to 38 m, followed at depth by 10 m to approximately 15 m thick residual dolomite (wad) highly susceptible to subsurface erosion or consolidation. Voids encountered.
- Dolomite bedrock: At a depth of 35 m to 45 m. Cavities encountered.
- Groundwater Level: In dolomite bedrock.



**Figure 74: Generic Geological Model 17.**

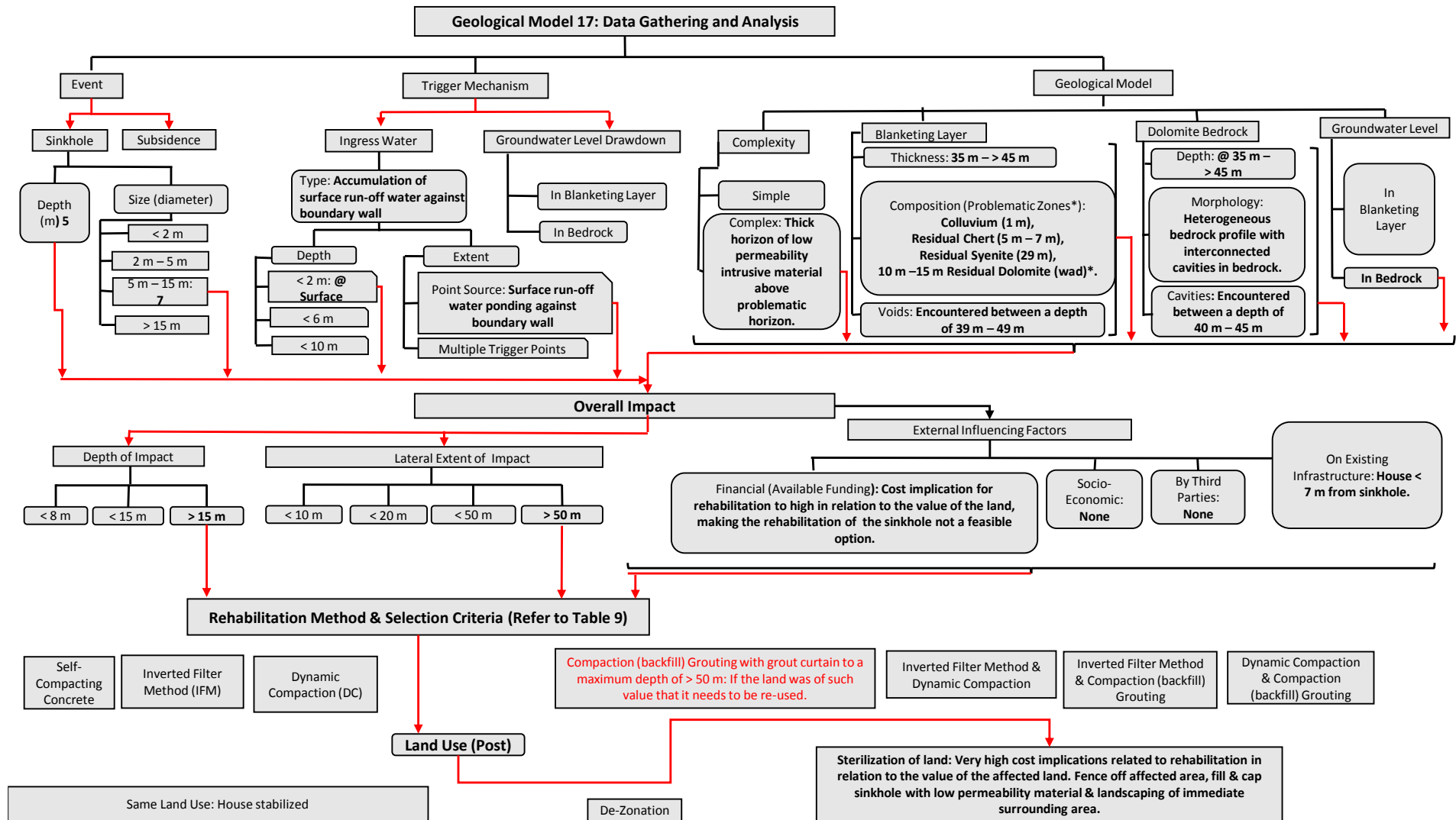
#### 7.4.5.2. Cause of sinkhole or subsidence formation

Accumulation of surface run-off water against a boundary wall.

Typically a sinkhole or a subsidence will not be associated with an area where the subsurface profile comprises a nearly homogeneous blanketing layer of nearly 40 m of low mobilisation potential material such as residual syenite; except if a fault zone is present. However the residual gravity does not reflect a fault zone within the area of the sinkhole. The alternative is that dolomite bedrock within the area directly below the sinkhole is much closer to ground surface with some residual dolomite (wad) above it, presenting a geological profile susceptible to subsurface erosion and sinkhole formation, when triggered by the accumulation of surface water.

#### 7.4.5.3. Depth and lateral extent of instability feature, triggering mechanism and impact on existing infrastructure

- Depth and extent of instability feature: 7 m diameter size sinkhole extending to a depth of 5 m.
- Depth and extent of triggering mechanism: At ground surface, point source.
- Impact on existing infrastructure: House located in close proximity to the sinkhole.



Flow Chart 18: Generic Geological Model 17 – Process of sinkhole evaluation criteria and selection of rehabilitation method



#### 7.4.5.4. Recommended Rehabilitation Method

Grouting Programme including a grout curtain or a Capping Layer of low permeability material: Refer to the Rehabilitation Model (Figure 75).

Reason for using specific rehabilitation method:

- The recommended rehabilitation method will be a grouting programme including the creation of a grout curtain around the area proposed for improvement. As the residual dolomite (wad) comprises a large number of voids and dolomite bedrock with cavities from a depth of approximately 35 m below ground surface, receptacles can readily accept mobilized material from above. The cost implications related to such a grouting programme would have amounted to more than R 20 million in 2009 and as such was not regarded as a feasible option, considering the land use (open field with one residential structure potentially affected by the sinkhole).

The alternative and more feasible option is to re-locate the residence on the stand adjacent to the sinkhole and properly fence of the affected area including the evacuated house. Construct a capping layer of bulk unconsolidated G8 to G9-quality material elevated to at least 1,5 m above natural ground level extending at least 10 m beyond the sinkhole area. Landscape the surrounding area to promote good surface water drainage away from the unconsolidated filled sinkhole.

The existing house on the adjacent stand is located less than 7 m from the sinkhole and caused access constraints during the investigation of the sinkhole. The existing house will need to be demolished after evacuation of the residence in order to facilitate the proposed rehabilitation method.

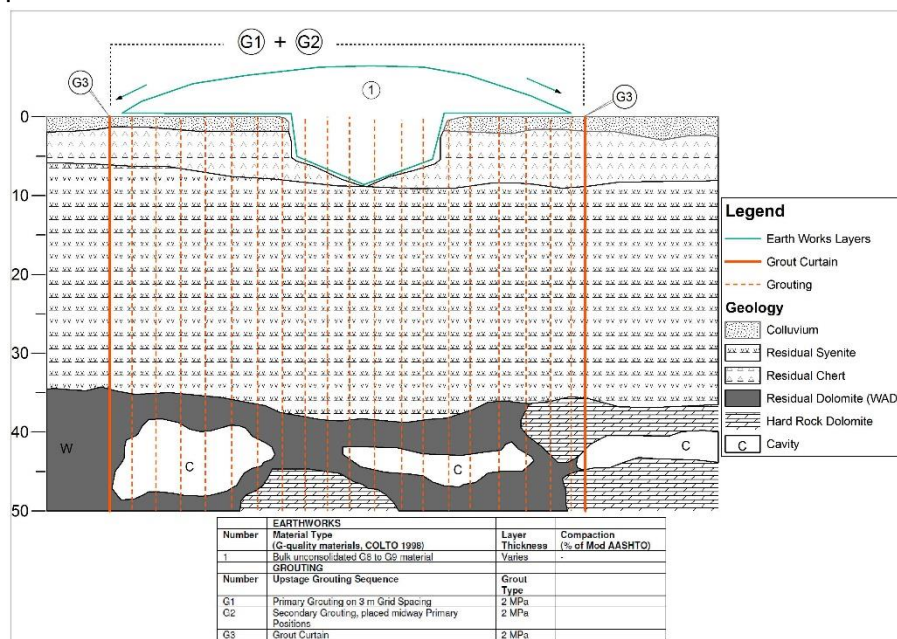


Figure 75 Rehabilitation Method Generic Geological Model 17.

#### 7.4.5.5. Land use after rehabilitation

Sterilization of land recommended, taking into consideration the cost implications related to the recommended rehabilitation method, namely compaction grouting with a grout curtain.

For more information related to this geological and rehabilitation model refer to Case Study 10.

### 7.5 Method of rehabilitation of sinkholes and subsidences in Ekurhuleni

The sinkhole and subsidence rehabilitation method mostly used in the Ekurhuleni Metropolitan Municipal area is the Inverted Filter Method, accounting for 85% of rehabilitation work, 10% for compaction grouting and 5% for the use of the Dynamic Compaction Method.

### 7.6 Conclusions

From the seventeen generic geological models presented and ten recorded case studies it is evident that each sinkhole or subsidence is unique, affected by a number of influencing factors that must be considered in the selection of the most appropriate rehabilitation method.

A site specific set of criteria for the rehabilitation of the feature must be developed to ensure proper stabilisation and safe future use of the area. The rehabilitation of sinkhole or subsidence areas and affected infrastructure should however have the same end goal, namely: To ensure the eroded area and possible voides and cavities had been properly backfilled and densified; an impervious blanket or engineering designed earth mattress created; all subsurface wet services are replaced and comply with industry standards; and ensure proper surface drainage away from the area.

The standardised flow chart developed during this research study on the process of sinkhole or subsidence evaluation to determine the best rehabilitation method for different sinkhole and subsidence scenarios is a very complex process. This is due to all the influencing factors that need to be taken into consideration, as illustrated by the representative seventeen sinkhole and subsidence generic geological and rehabilitation models with related flow charts developed for the East Rand.

Even though each sinkhole or subsidence is unique, the evaluation of the various influencing factors considered to determine the most appropriate rehabilitation method are the same, as illustrated by the various flow charts for the different models. The same approach is therefore suggested in other regions affected by sinkholes and subsidences. Similar or near similar geological scenarios may exist in other dolomite or limestone regions and the various generic geological models and rehabilitation methods developed for the East Rand may serve as a guideline to determine the most appropriate rehabilitation method in similar geological scenarios.

The seventeen representative generic geological models for the East Rand provide a broad base understanding of different dolomite environments, their susceptibility to sinkhole or subsidence formation and best practice rehabilitation as seen by the author.

As illustrated by the various flow charts, the overall impact factors, depth of impact and lateral extent of impact are determined by the following factors: Event (depth and size (diameter)), trigger mechanism (ingress water (type, depth and extent) or groundwater level drawdown) and the geological model (complexity, blanketing layer (thickness, composition (problematic zones and depth) and voids), dolomite bedrock (depth, morphology and presence of cavities) and groundwater level (in blanketing layer or in bedrock). The selection of the most appropriate rehabilitation method depends on the land use proposed after rehabilitation and the overall impact factors, including: Depth of impact, lateral extent of impact and external influencing factors. External influencing factors to consider in the selection of the rehabilitation method including: Impact on existing infrastructure (current land-use), financial (available funds), socio-economic factors and the role of third parties.

Rehabilitation methods vary and the method used will depend largely on the geological model and external influencing factors including available funding (financial) and the position of the instability feature (impact on existing infrastructure). Specifically in terms of the current and post land use, the method and materials required to rehabilitate a small sinkhole in an undeveloped rural area can be vastly different from that needed to repair a sinkhole or a subsidence under an occupied building or in the middle of a road in a highly urbanized area.

## 8. CONCLUSIONS

The following conclusions can be made from the literature survey and research:

- Sinkholes and subsidences have been reported as early as 1884 in South Africa. The formation of sinkholes and subsidences prior to 1950 occurred naturally, caused by periods of drought followed by wetter periods. Since the 1950's the cause of sinkholes and subsidences is mainly anthropogenic (related to mining and urbanisation). Dolomite groundwater compartments located above the goldbearing Witwatersrand Supergroup were dewatered and development of townships on dolomite took place, including the installation of subsurface wet services, especially in the Gauteng Province. This led to a significant increase in instability events.
- Although dolomite land occurs in the Northern Cape, North West, Limpopo and Mpumalanga, it is the dolomite of the Malmani Subgroup of the Chuniespoort Group in the Gauteng Province and the West Rand District that is notorious for sinkhole and subsidence formation. More than 3000 events are recorded within Gauteng and the West Rand District. Some of these events have resulted in major structural damage and loss of life.
- Most of the sinkholes and subsidences have been recorded in the West Rand District and in the City of Tshwane, with numerous research studies been done on sinkholes and subsidences in these two areas. However, a large number of sinkholes and subsidences have also been recorded on the East Rand in the Ekurhuleni Metropolitan Municipal area of jurisdiction, which is the focus of this study.
- The mechanism of sinkhole and subsidence formation from ingress of water and a dewatering perspective has been described in detail by Jennings *et al.* (1965) and Brink (1979). However, Buttrick (1987 and 1992) has found that if the water table is below the receptacle depth, the nature of the blanketing layer above dolomite bedrock, especially if comprising residual dolomite and gap graded materials, plays a more critical role for sinkhole or subsidence formation due to ingress of water. Ingress of water from a leaking subsurface wet service as a process of internal erosion may cause the formation of a subsurface void and a sinkhole. This process deviates from the order of events as specified by Jennings *et al.* (1965) where it is stipulated that the final contributing factor is ingress water.
- Extensive research and publication have been done on the investigation, evaluation, development and management of land underlain by dolomite to prevent the formation of sinkholes and subsidences. However, little emphasis is given to the various processes and methodologies available and applied to sinkhole or subsidence investigation and rehabilitation.
- The first priority when investigating a sinkhole or subsidence is to reduce or remove the triggering mechanism that caused the sinkhole or subsidence and to reduce the likelihood of aggravating the problem. In a built-up environment, the triggering

mechanism is typically ingress water related to leaking subsurface wet services or due to poor surface water run-off.

- Various methods of investigation, including non-intrusive and intrusive methods have been tried and tested to determine the extent of subsurface erosion within the affected sinkhole or subsidence area. The non-intrusive geophysical gravity method in association with the drilling of percussion boreholes; exposure of the affected area by means of excavation; in areas not accessible for a drilling rig where gravel, cobbles and boulders are absent in the subsurface profile the use of the Dynamic Probe Super Heavy (DPSH) test method; is the most appropriate methods for sinkhole or subsidence investigations. It should, however, be stated that the gravity method is not always successful in delineating narrow grykes in a shallow dolomite environment. The use of a specific method or methods of investigation is, however, dictated by the accessibility of a site. Accessibility constraints within a build-up area, may lead to the use of an investigation method other than what is preferred.
- The specific method, or combination of methods, used to rehabilitate a sinkhole or a subsidence will depend on available funding, current and proposed land use, the subsurface conditions, accessibility for equipment and the impact of the rehabilitation procedure on existing infrastructure.
- The various methods of sinkhole and subsidence rehabilitation used in South Africa and their applications are as follows:
  - Inverted Filter Method: Comprises the backfilling of a sinkhole including blocking of the throat of the sinkhole with rockfill and/or boulders or the use of self-compacting concrete. This is followed by layers of progressively finer material, compacted at a specific compaction effort to create an impermeable capping. The Inverted Filter Method is applicable in areas of small to very large -size sinkholes and subsidences of all sizes, extending to a maximum depth of less than 6 m or the throat of the sinkhole is visible within 8 m to 10 m from natural ground surface. This method can however also be applied to depths of up to 12 m to 16 m (with a 2 m wide terrace at 6 m) if adequate space exists for such large bulk excavations.
  - Dynamic Compaction Method: Involves the placing of selected materials typically in lifts or layers of 2 m (can vary between 1 m to 3 m), followed by dynamic compaction on a specific grid spacing, including primary and secondary points carried out for each lift (or layer), where a large weight known as a pounder is dropped from a considerable height onto the soil to be compacted and densified. Dynamic Compaction probing is where the pounder is dropped repeatedly in only one area. The Dynamic Compaction method can compact or densify poor subsurface soils such as residual dolomite (wad) or soil layers with a loose consistency at depth to a maximum of 8 m to 10 m below natural ground surface, all depending on the energy applied. A maximum depth of 12 m is specified by some authors. Dynamic Compaction probing can be used to collapse the roof of a cavity located at a depth greater

than the bulk excavated area (typically to a depth of 4 m to 6 m). It should, however, be noted, where a competent layer of chert for example is present above a compressible layer of residual dolomite (wad), most of the energy expended by the compaction effort is absorbed by the competent chert layer and the material below is not compacted. To reach the required compaction effort down to a specific depth, it is necessary to excavate through the competent layer down to the residual dolomite.

- Combination of the Dynamic Compaction and Inverted Filter Method: Comprises the collapsing of cavities at depth and the chocking of the sinkhole throat by means of the Dynamic Compaction Probing Method up to a specific depth, followed by the Inverted Filter Method including the backfilling of the excavated area by layers of progressively finer material, compacted at a specific compaction effort to create an impermeable capping. A combination of these two methods may be considered where an area proposed for rehabilitation comprises sub-areas with sinkholes and underlying deeper cavities not reachable with an excavator or sub-areas of residual dolomite (wad) is present in profile to a typical depth of 10 m below natural ground level. A combination of these two methods is regarded as a cost effective and practical rehabilitation method to improve subsurface conditions in areas affected by sinkholes to a maximum depth of between 10 m and 15 m below natural ground level.
- Compaction (backfill) Grouting Method: Is a method in which a mix of sand, cement and water is pumped under a specific pressure as determined by the investigator, into cavities at depth to fill the void or to densify poor subsurface soils; on a specific grid spacing, including primary (typically 3 m grid spacing), secondary and sometimes tertiary grouting points. Grouting is carried out either as upstage, downstage or a combination of downstage and upstage. Compaction grouting can be used to improve subsurface conditions to variable depths ranging from 2 m to more than 60 m below natural ground surface. It is, however, a very expensive soil improvement technique and is mainly considered where cavities or poor subsurface conditions exist at depths that cannot be treated by means of the Inverted Filter or Dynamic Compaction Methods. Therefore a depth factor of more than 12 m is applicable for the use of the grouting method. The grouting method may also be considered at depths shallower than 12 m in areas where subsurface conditions need to be improved close to and below existing structures that cannot be demolished due to their importance. As compaction grouting can cause ground heave when high pressures are applied to inject concrete, it can be used to raise footings of an affected structure to nearly its original level when settlement occurred. However, careful monitoring is required during the grouting process to not cause more structural damages where grout is pumped under too high pressures.
- Combination of Inverted Filter and Grouting Methods: A combination of these two methods may be considered in areas where the sinkhole or subsidence is interconnected at depth with subvertical erosion tunnels extending into

dolomite bedrock, over a distance away from the sinkhole or subsidence. The Inverted Filter Method can be used to a maximum depth of 12 m to backfill and rehabilitate the sinkhole or subsidence feature, whilst the grouting programme is undertaken in the area where the subvertical erosion tunnel was encountered in the bulk excavation area at depth. The purpose of the grouting programme is to seal off the subvertical erosion tunnel extending into bedrock by means of a grout curtain, or if sufficient funds are available also fill the cavity.

- Combination of Dynamic Compaction and Grouting Methods: A combination of these two methods may be considered in areas of major trafficking, such as roads and railway lines, where a sinkhole occurred and cavernous conditions exist at a depth greater than 10 m. Compaction grouting can be carried out to fill the cavity or cavities at depth and Dynamic Compaction conducted to create an engineered mattress providing the required bearing capacity for major transport services.
- Self-Compacting Concrete or Soil-cement Mix: Self-compacting concrete comprising a pumpable concrete mix of at least 5 MPa strength or Soil-cement mix comprising a high slump mix of soil and cementitious binder of at least 2 MPa strength may be used for chocking the throat of a sinkhole, to plug grykes, or forming a stable working platform at the base of a sinkhole, or for mass filling of cavities or runnels.
- Nearly half of the Ekurhuleni Metropolitan Municipal area is classified as dolomite land. A total of 241 ground movement incidents had been recorded, since 2005 to mid-2013. The sinkhole and subsidence rehabilitation method mostly used in the Ekurhuleni Metropolitan Municipal area is the Inverted Filter Method accounting for 85% of rehabilitation work, 10% for compaction grouting and 5% for the use of the Dynamic Compaction Method.
- The sinkhole and subsidence rehabilitation method should not be prescriptive, given the vast number of variables involved. A comprehensive understanding of the affected area is also essential for cost effective and practical rehabilitation measures.
- From the seventeen generic geological models presented and ten case studies recorded, it is evident that each sinkhole or subsidence is unique, affected by a number of influencing factors that must be considered in the selection of the most appropriate rehabilitation method. A site specific set of criteria for the rehabilitation of the feature must be developed to ensure proper stabilisation and safe future use of the area. The rehabilitation of sinkhole or subsidence areas and affected infrastructure should however have the same end goal, namely: To ensure the eroded area and possible voides and cavities had been properly backfilled and densified; an impervious blanket or engineering designed earth mattress created; all subsurface wet services are replaced and comply with industry standards; and ensure proper surface drainage away from the area.

- A number of determining factors need to be established and analysed after the occurrence of an event in order to develop the geological model, determine the impact of external influencing factors and select the most appropriate rehabilitation method. The various determining factors considered and influencing the decision making process on the most appropriate rehabilitation method include, the depth and lateral extent of impact of instability and triggering mechanism, geological model, external influencing factors (impact on existing infrastructure (current land use), financial (available funds), socio-economic factors and the role of third parties) and the proposed land use after rehabilitation.
- The sinkhole or subsidence evaluation process, selection of the rehabilitation method and related standardised flow chart, developed during this research study, are illustrated by the seventeen generic geological models developed for the East Rand. Even though each sinkhole or subsidence is unique, the evaluation of the various influencing factors considered to determine the most appropriate rehabilitation method are the same, as illustrated by the various flow charts for the different models. The same approach is therefore suggested in other regions affected by sinkholes and subsidences. Similar or near similar geological scenarios may exist in other dolomite or limestone regions and the various generic geological models and rehabilitation methods developed for the East Rand may serve as a guideline to determine the most appropriate rehabilitation method in similar geological scenarios
- The seventeen representative generic geological models, related flow charts and recommended rehabilitation methods, for the East Rand provide a broad base understanding of different dolomite environments, their susceptibility to sinkhole or subsidence formation and best practice rehabilitation, as seen by the author.
- As illustrated by the various flow charts, the overall impact factors namely, depth of impact and lateral extent of impact, are determined by the following factors: Event (depth and size (diameter)), trigger mechanism (ingress water (type, depth and extent) or groundwater level drawdown) and the geological model (complexity, blanketing layer (thickness, composition (problematic zones and depth) and voids), dolomite bedrock (depth, morphology and presence of cavities) and groundwater level (in blanketing layer or in bedrock). The selection of the most appropriate rehabilitation method depends on the land use proposed after rehabilitation and the overall impact factors, including: Depth of impact, lateral extent of impact and external influencing factors. External influencing factors to consider in the selection of the rehabilitation method including: Impact on existing infrastructure (current land-use), financial (available funds), socio-economic factors and the role of third parties.
- Rehabilitation methods vary and the method used will depend largely on the geological model and external influencing factors including available funding (financial) and the position of the instability feature (impact on existing infrastructure). Specifically in terms of the current and post land use, the method and materials required to rehabilitate a small sinkhole in an undeveloped rural



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## FIGURES RELATED TO CASE STUDIES

**Figure 76:** Locality of Case Study Areas 1 to 9 (1:50 000 scale, Alberton (2628AC) Topographic Map) and Case Study Area 10 (1:50 000 scale, Centurion (2528CC) Topographic Map).

**Figure 77:** Geology of Case Study Areas 1 to 9 (1:250 000 scale, East Rand (2628) Map) and Case Study Area 10 (1:50 000 scale, Lyttelton (2528CC) Map) on a scale of 1:100 000.

**Figure 78:** Geohydrology of Case Study Areas 1 to 9 (1:50 000 scale, Alberton (2628AC) Topographic Map) and Case Study Area 10 (1:50 000 scale, Centurion (2528CC) Topographic Map) (VGIconsult Projects Dolomite Database, 2014).

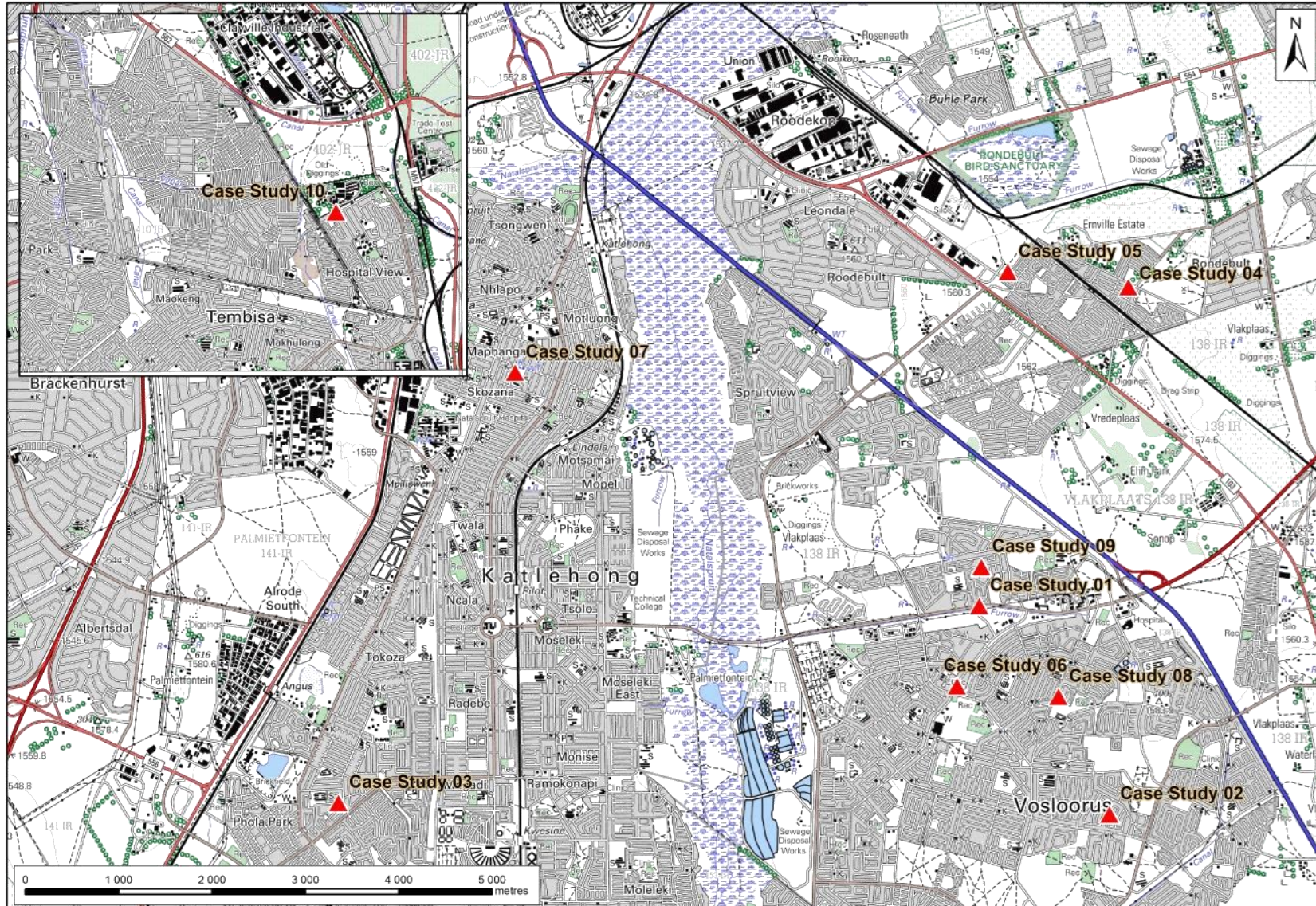


Figure 76: Locality of Case Study Areas 1 to 9 (1:50 000 scale, Alberton (2628AC) Topographic Map) and Case Study Area 10 (1:50 000 scale, Centurion (2528CC) Topographic Map).



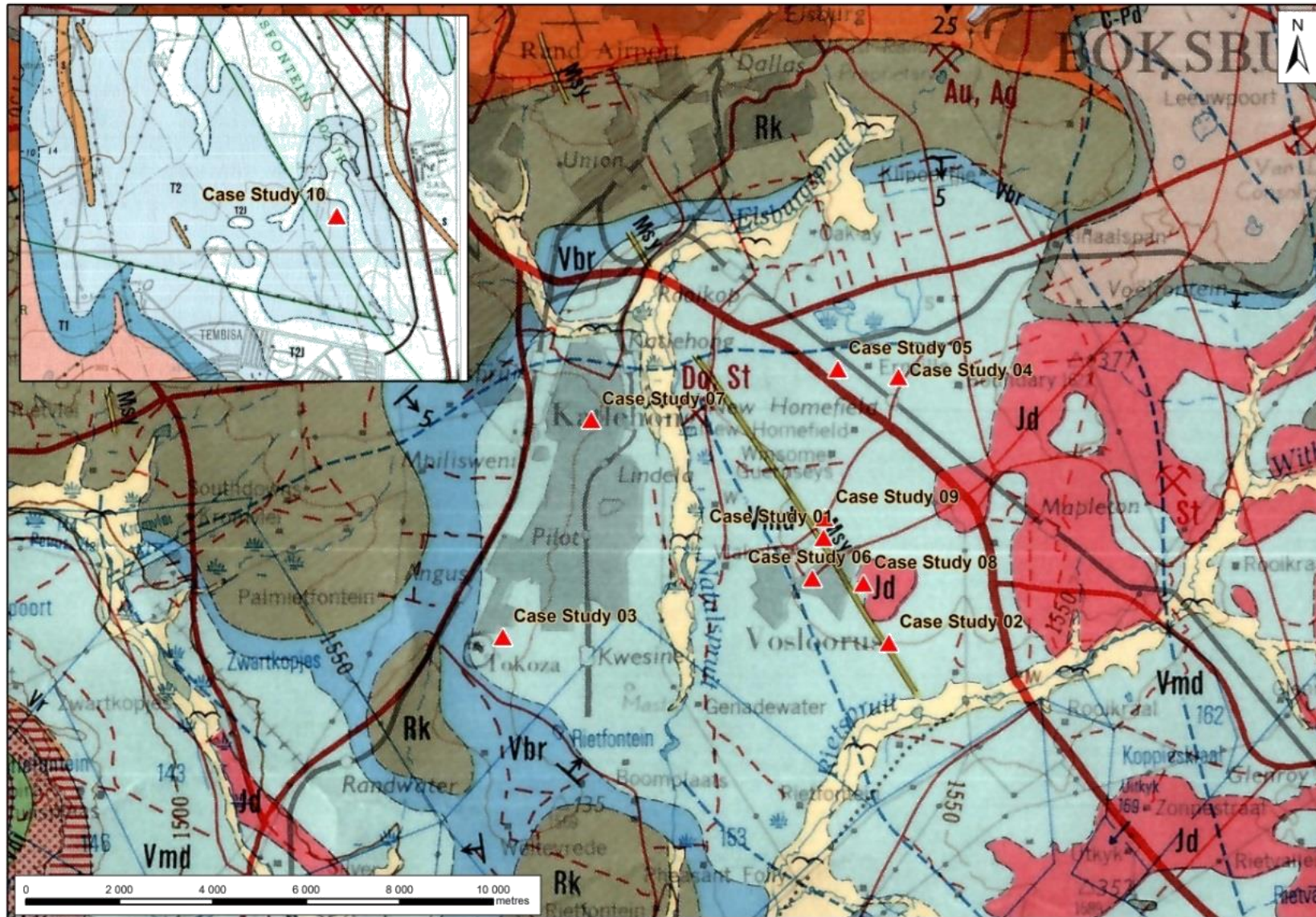


Figure 77: Geology of Case Study Areas 1 to 9 (1:250 000 scale, East Rand (2628) Map) and Case Study Area 10 (1:50 000 scale, Lyttelton (2528CC) Map) on a scale of 1:100 000.

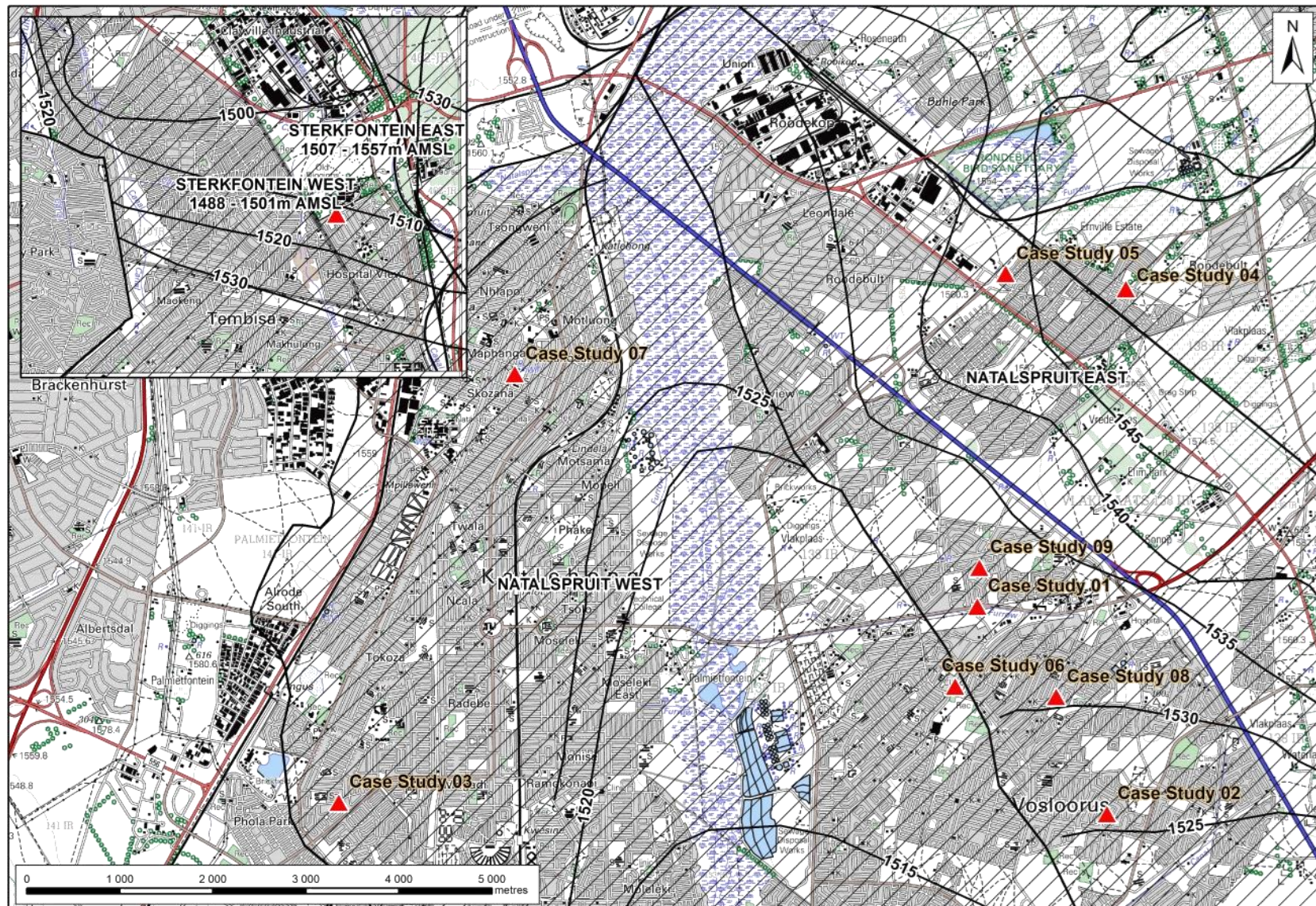


Figure 78: Geohydrology of Case Study Areas 1 to 9 (1:50 000 scale, Alberton (2628AC) Topographic Map) and Case Study Area 10 (1:50 000 scale, Centurion (2528CC) Topographic Map) (VGIconsult Projects Dolomite Database, 2014).

**APPENDIX A**

***CASE STUDY 1***

## CASE STUDY 1

### 1. INTRODUCTION

During a routine CCTV-camera inspection of an Ekurhuleni main sewer line (160 mm diameter uPVC pipe placed within a 200 mm diameter asbestos pipe), along Bierman Road, it was found that the sewage between two manholes disappears.

The CCTV-camera inspection revealed a 20 m section of a 75 m long sewer pipe between two manholes to be damaged (Figure A.1).

No visual evidence, such as surface cracks or damage to structures in the vicinity of the reported broken sewer line was observed during a site inspection on 18 August 2005 (Report Number KHH1383). However, the disappearance of sewage is an indication that subsurface erosion has already taken place and a high susceptibility exists for cavernous conditions to be present that can manifest into a sinkhole at ground surface over time. The immediate action was to shut the sewer system down and pump all the sewage away from the affected area to reduce the potential for further subsurface erosion to take place, which will increase the susceptibility for sinkhole formation.

A dolomite stability investigation including a gravity survey on a 10 m grid spacing, to provide information on the depth and morphology of the dolomite profile and the drilling of three percussion boreholes (Boreholes BH1 to BH3) within the area where the sewer line was indicated to be damaged was conducted on 6 October 2006. Accessibility was limited due to the presence of a water main (400 mm diameter steel pipe) directly south of the sewer and a pre-cast wall situated halfway between the water main/sewer and houses. Therefore two (Boreholes BH1 and BH2) of the three boreholes were drilled at a 15 degree angle from the vertical into a northern direction to ensure that no damage will occur to the water main.

The affected area (broken sewer line), existing infrastructure, residual gravity contours, the position of boreholes and DPSH tests are displayed in Figure A.1.

The gravity survey revealed the following:

- Gravity low area, situated halfway between the two manholes.
- Three distinct gravity high areas viz. in the area around manholes and 20 m west of the eastern manhole.
- The gravity low expands into a north western and south eastern direction.
- The three gravity high areas may be related to dolomite pinnacles or shallow dolomite bedrock.

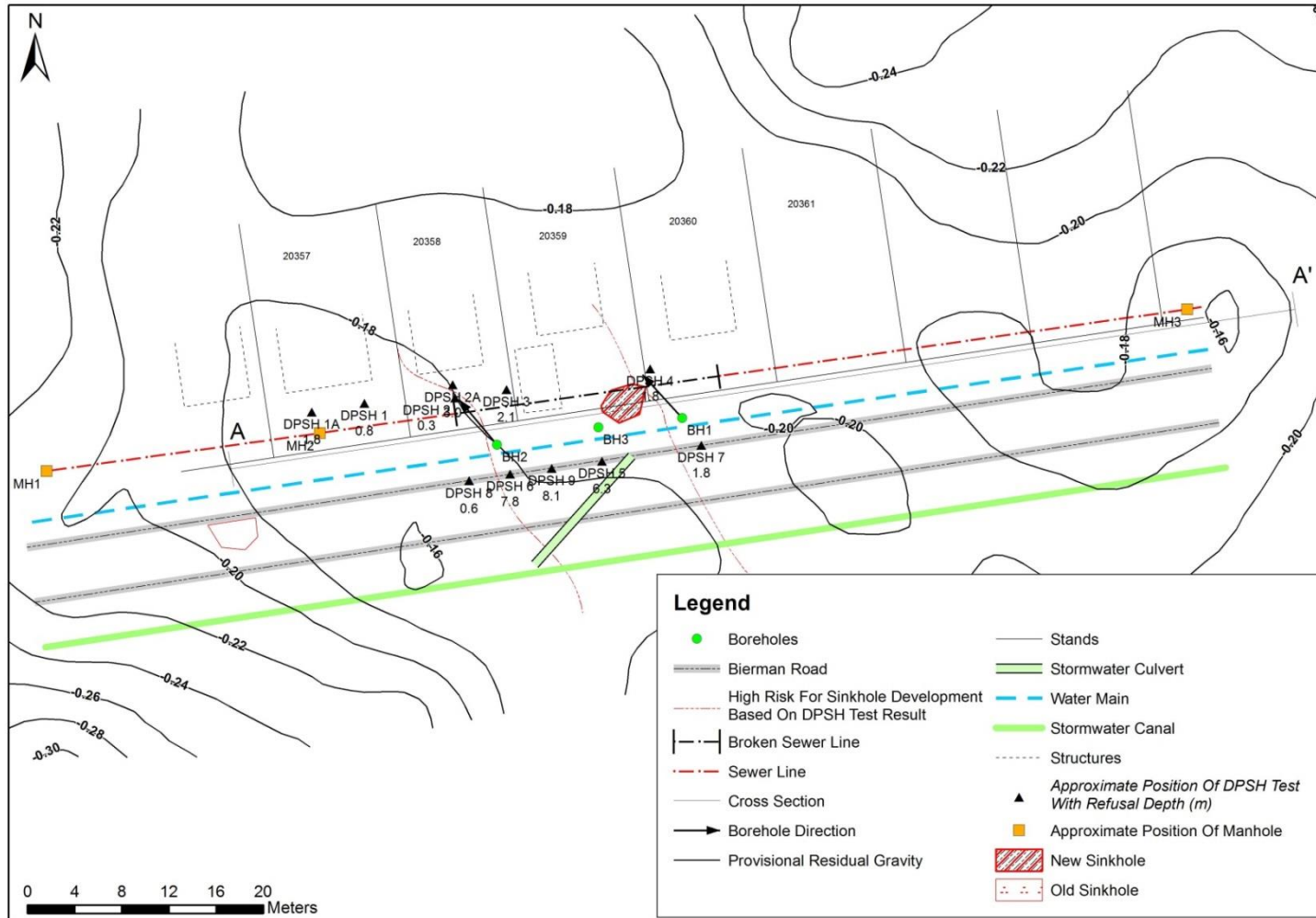


Figure A.1: Case Study 1 –Plan view of affected area, gravity contours, boreholes and DPSH test positions.

A geological cross-section presenting subsurface conditions as encountered during the drilling of Boreholes BH1 to BH3 and a postulated profile based only on gravity survey results is illustrated in Figure A.2 and represents the following subsurface profile:

- Dolomite bedrock at a depth of 8 m to 17 m. A 1 m to 3 m thick horizon of highly weathered soft rock dolomite encountered between depths of 6 m to 17 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of colluvium, followed at depth by residual chert. The surface layer is underlain by residual dolomite comprising ferroan soils (encountered between depths of 3 m to 8 m with a layer thickness varying between 1 m to 5 m or absent) and/or manganiferous (wad) soils (encountered between depths of 1 m to 16 m with a layer thickness varying between 2 m to 14 m). Rapid penetration rates, air losses and no sample return were encountered in the residual dolomite horizons encountered above dolomite bedrock during drilling.
- Cavities were intercepted between depths of 4 m and 6 m (BH2) and between 2 m to 4 m and 9 m to 12 m (BH3) within residual dolomite (wad).
- Groundwater was not intercepted in boreholes drilled. The regional groundwater level is 22 m below natural ground level within dolomite bedrock.

Based on the gravity survey and the borehole information the area is characterised by a high susceptibility for a large to very large size sinkhole or subsidence within the area of the broken sewer line and a potential exists that the sinkhole may extend below the houses situated to the north and below Bierman Road situated to the south.

Dynamic Probe Super Heavy (DPSH) tests were conducted in areas not accessible for a drilling rig, in order to quantify the extent of the erosion/soft wad, particularly below nearby houses and the road to the south. Eleven DPSH tests (DPSH 1, DPSH 1A, DPSH 2, DPSH 2A and DPSH 3 to DPSH 9) were conducted on 21 October 2005 (KHH Letter Report, dated 15 November 2005). The purpose of the DPSH testing was to determine the various consistencies associated with the soil horizons at depth and to determine if a cavity is present at depth.

The approximate positions of the DPSH tests are shown on Figure A.1. The results of the DPSH tests correlate reasonably well with the drilling results, viz. (KHH Letter Report, dated 15 November 2005):

- The DPSH tests conducted in Bierman Road, in the vicinity of Boreholes BH2 and BH3 are characterised by penetration depths of between 6 m and 8 m (DPSH5, DPSH6 and DPSH9).
- All other DPSH tests refused at a relatively shallow depth of less than 3,0 m within the upper chert gravel layer. These tests are inconclusive because the wad underlying the surface chert layer could not be reached.
- Although the DPSH tests were not fully successful in defining the extent of the subsurface erosion from the broken sewer, it did confirm that soft compressible wad extends at least to the edge of Bierman Road. DPSH tests conducted near

the houses to the north of the sewer line indicated very stiff soils from a shallow depth of 0,2 m to 0,4 m with refusal depths in chert gravel between 0,3 m and 3,0 m depth. In general firm to very stiff consistencies were encountered within the residual chert layer where refusal did not take place on chert gravel or cobbles.

- As mentioned above, these results are not conclusive with respect to sinkhole formation.

A site inspection on 14 March 2006 before commencement of rehabilitation work revealed the following:

- A sinkhole (dimensions of 4 m diameter size extending to a depth of 4 m below ground surface) developed in the south-eastern corner of Stand 20359, in the area of the section of broken EMM bulk sewer line (Plate A.1). This correlates with the subsurface conditions (cavities) encountered in Borehole 3 drilled in close proximity to the sinkhole (Figures A.1 and A.2).



**Plate A.1: Sinkhole on Stand 20359.**

- An inspection of the sewer line between Manhole 1 and Manhole 2 showed that excessive settlement of the pipe had occurred that also needed to be replaced. The settlement was caused by an old partially rehabilitated sinkhole.

Taking the existing geological conditions on site into account (e.g. depth to dolomite bedrock, presence of highly erodible and compressible residual dolomite (wad), cavities and the sinkhole) the following was originally recommended in terms of rehabilitation of the affected area (Letter Report Number KHH1468):

- Demolish illegal pre-fabricated concrete structure on Stand 20359 within the servitude area of the bulk sewer and boundary walls along sewer line to be replaced with a 200 mm diameter HDPE butt welded pipe.
- Pumping of sewage above ground via a pipe system from Manhole 3 to Manhole 1 over a distance of 100 m.
- A temporary subsurface HDPE butt welded sewer line constructed running parallel to the existing broken sewer line (to be replaced) and discharges into Manhole MH 2 to accommodate the outfall sewer pipes from residential stands. A permanent sewer pipe for house connections should be constructed directly above the main sewer line once the rehabilitation work has been completed.
- Excavate down to one metre below the invert level of the sewer (approximately 5 m below surface) between Manhole MH 1 to MH 3, i.e. a distance of approximately 100 m with an excavator.
- Remove all highly erodible and compressible residual dolomite (wad) between dolomite bedrock pinnacles.
- After inspection of the floor conditions, use of DC method to in situ compact the localised deeper weathered affected zones, while dump rock/building rubble is added to create a stone column replacement affect.
- An alternative method to DC of the localised deeply affected zones is to cover it with a 200 mm thick reinforced concrete slab (4 m wide and 20 m long reinforced with Mesh 395), at the sewer floor level. This option becomes viable if the affected area is well-defined, localised and surrounded by suitable material which can carry the loads imposed by the concrete slab and overlying backfill.
- Shut down and drain the water main to the south during the excavation process to prevent a sudden ingress of water into the excavation in the event of rupture.
- During the opening of the sewer line, the possibility of cavernous conditions extending to the north towards the houses and to the south towards Bierman Road, should also be confirmed and remedial actions then taken if necessary to prevent collapse or structural damages to the houses or the road.
- Backfilling of the sinkholes must involve blocking of the throat of the sinkhole with large stones, backfilling with low plasticity material (silty/gravelly sand) in 100 mm thick layers, each compacted to at least 95% of Modified AASHTO maximum dry density at optimum moisture content.



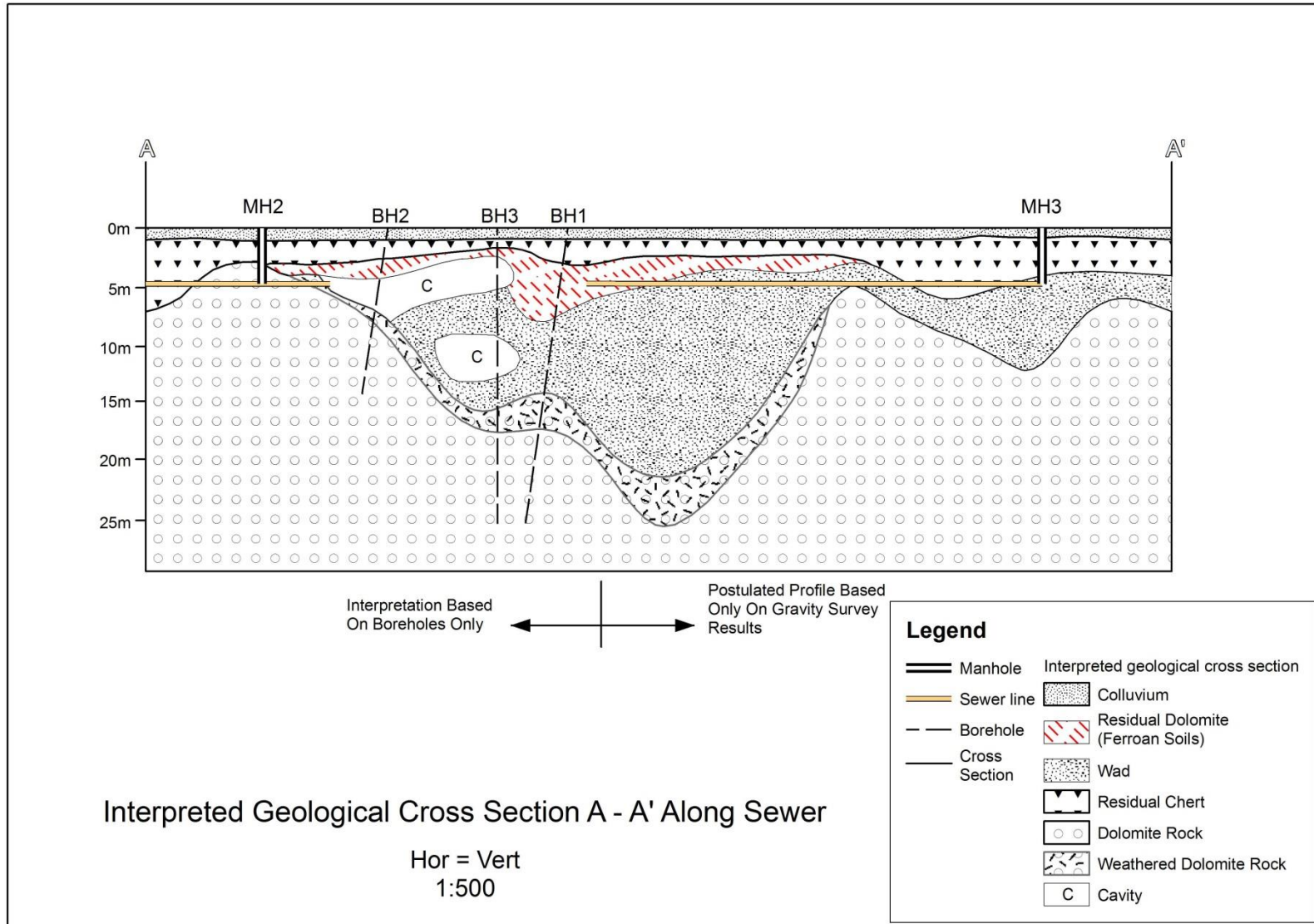


Figure A.2: Case Study 1 – Interpreted Geological Cross-Section A – A` along Sewer.

- Backfill below the sewer pipe with soilcrete compacted at 95% compaction effort. Placing of 200 mm diameter HDPE sewer line in and on a 100 mm thick layer of bedding material (river sand). Backfill the sewer trench above pipeline level with G6-quality material compacted to at least 95% of Modified AASTHO maximum dry density at optimum moisture content.
  
- Reinstate stand boundary walls.

## 2. CONSTRUCTION PHASE

### 2.1 Sewer Trench

The typical geological profile observed to a maximum depth of 4 m below natural ground level from east to west in the northern and southern sewer trench walls over an approximate distance of 100m from Manhole MH3 to MH2 and from Manhole MH2 to MH1 comprises (Figure A.3):

- Manhole MH3 to MH2:

In general the profile comprises dense to very dense clayey silty sand with 30% to 40% chert gravel and cobbles, residual chert.

Shallow dolomite bedrock pinnacles, encountered in sub-areas along the northern and southern sewer trench.

Hard rock dolomite floaters encountered in sub-areas along the southern sewer trench.

Residual dolomite (wad or manganiferous soils) was encountered in the northern and southern sewer trench walls between dolomite bedrock pinnacles and in the area of dolomite floaters.

Two cavities were intercepted in the southern sewer trench wall. Both cavities formed adjacent to dolomite bedrock pinnacles within residual dolomite (wad). Plate A.2 represents the cavity encountered in Borehole BH2 and encountered at the base of the sewer trench excavation. Plate A.3 represents the cavity encountered in Borehole BH3 encountered in the southern side wall of the sewer trench excavation.

- Manhole MH2 to MH1:

In general the profile comprises dense to very dense clayey silty sand with 30% to 40% chert gravel and cobbles, residual chert.

Shallow dolomite bedrock pinnacles, were encountered in sub-areas along the northern and southern sewer trench. Inter-layered dolomite and chert rock was encountered along the northern sewer trench in one area.



**Plate A.2: Cavity encountered in Borehole BH2 and at base of sewer trench excavation.**



**Plate A.3: Cavity encountered in Borehole BH3 and in southern side wall of sewer trench.**

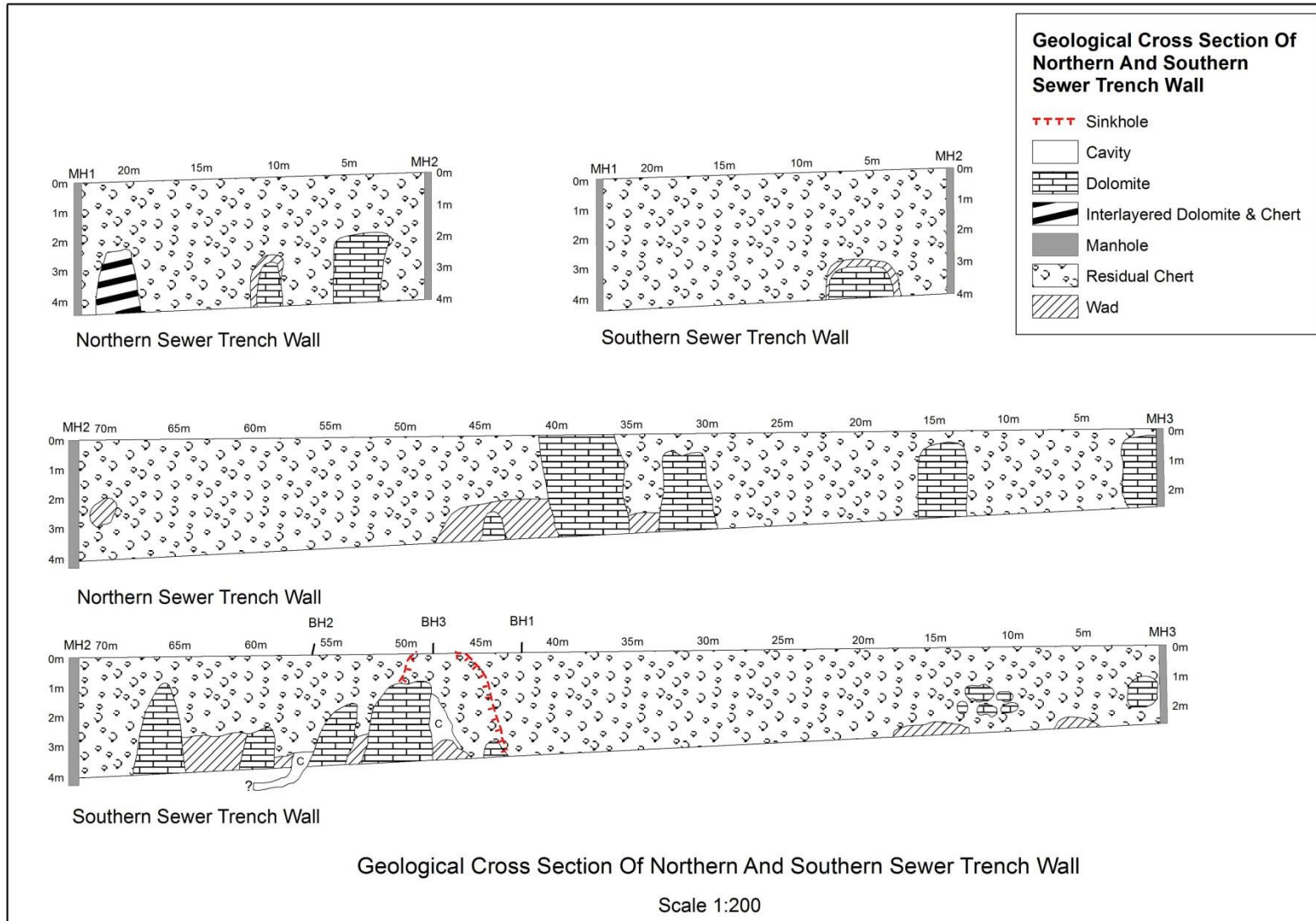


Figure A.3: Case Study 1 – Geological Cross-Section of Northern and Southern Sewer Trench Wall.

A 0,5m thick layer of residual dolomite (wad or manganiferous soils) was encountered in the northern and southern sewer trench walls around dolomite bedrock pinnacles.

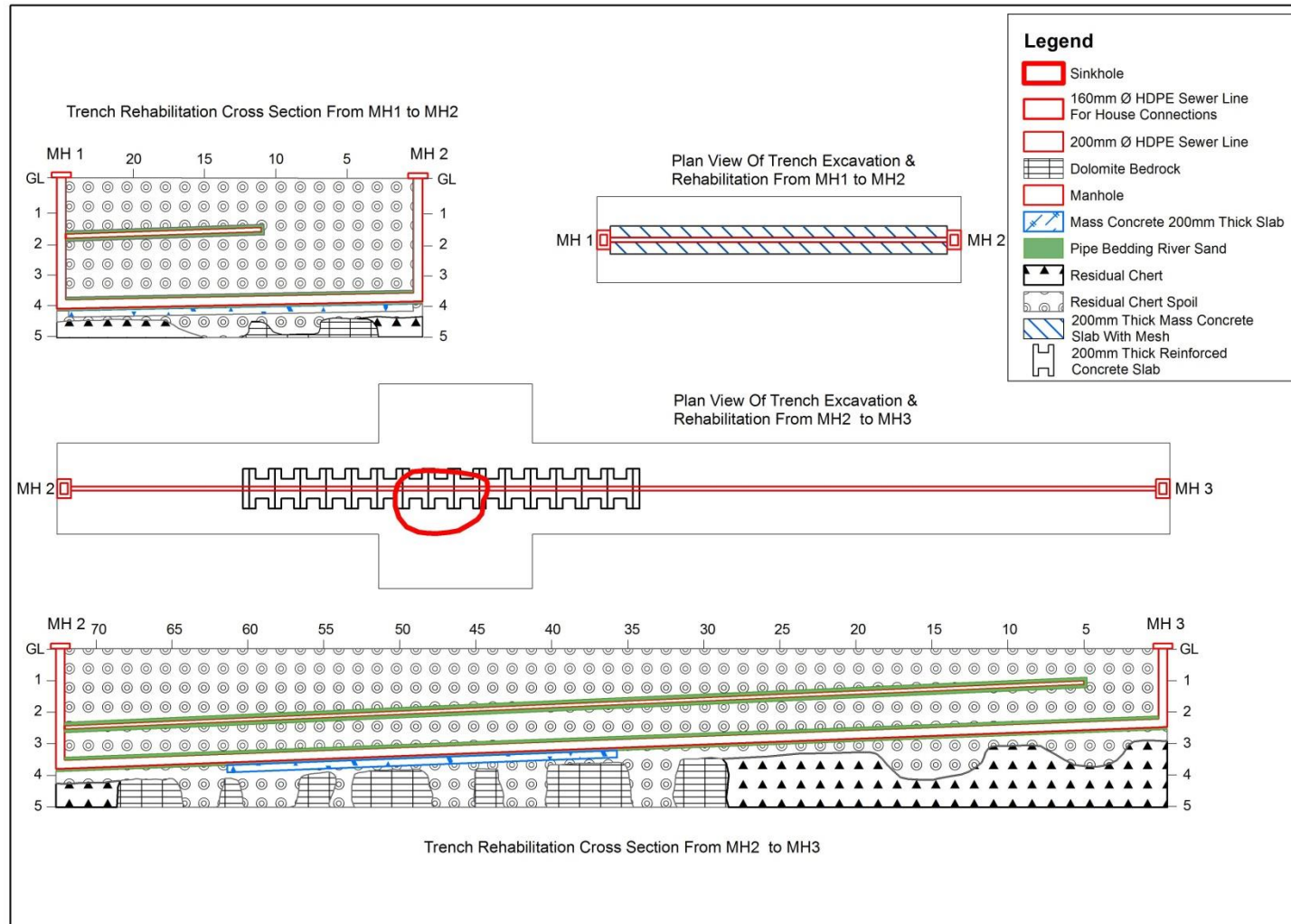
Work performed: Sewer Trench:

- Over excavate the entire sewer trench to a depth of 0,5m below the base of the pipe line (approximately 3m to 4,5m below natural ground level). In areas of poor subsurface conditions (residual dolomite wad) over excavate to a depth of 1m to 1,5m below the base of the pipe level.
- Use of soilcrete to backfill the trench and compacted to 95% Modified AASHTO to 0,1m below the base of the pipe. Placing of 100mm thick bedding material (river sand) and HDPE pipe and compacted in the excavation to the required pipe fall and placing of 100mm bedding material (river sand) all around pipe.
- In the area of the sinkhole and dolomite pinnacles, between Manhole MH2 and MH3, a 25m long by 4m wide and 200mm thick reinforced concrete slab was placed below the HDPE sewer pipeline as support.
- A reinforced concrete slab (dimensions of 25m length by 4m width and 200mm thick reinforced with mesh) was placed below the sewer pipe between Manhole MH1 to MH2 for support.
- Backfill above pipe level in 300mm thick layers of residual chert spoil classifying as G6 or C3 (stabilised) and compacted to 95% compaction effort up to the level of the 160mm diameter HDPE pipe for residential sewer connections and then backfill up to natural ground level with G6 quality material at 95% compaction effort after placing of the 160mm diameter HDPE pipe in 100mm thick bedding material.

A plan view and cross-section of the sewer trench excavation and rehabilitation work carried out between Manholes MH1 to MH3 is illustrated in Figure A.4.

## 2.2 Bierman Road

After heavy rains a subsidence of 3m diameter extending to a depth of 0,3m appeared on the northern edge of Bierman Road. The subsidence is located between Manhole MH1 and MH2. The position of the subsidence is indicated on Figure A.5. The subsidence area was opened with an excavator. A partially rehabilitated sinkhole that had previously been filled with highly decomposed domestic waste to an anticipated maximum depth of 6m was found in the area where the subsidence occurred.



**Figure A.4: Case Study 1 – Plan view and cross-section of the sewer trench excavation and rehabilitation work carried out between Manholes MH1 to MH3.**

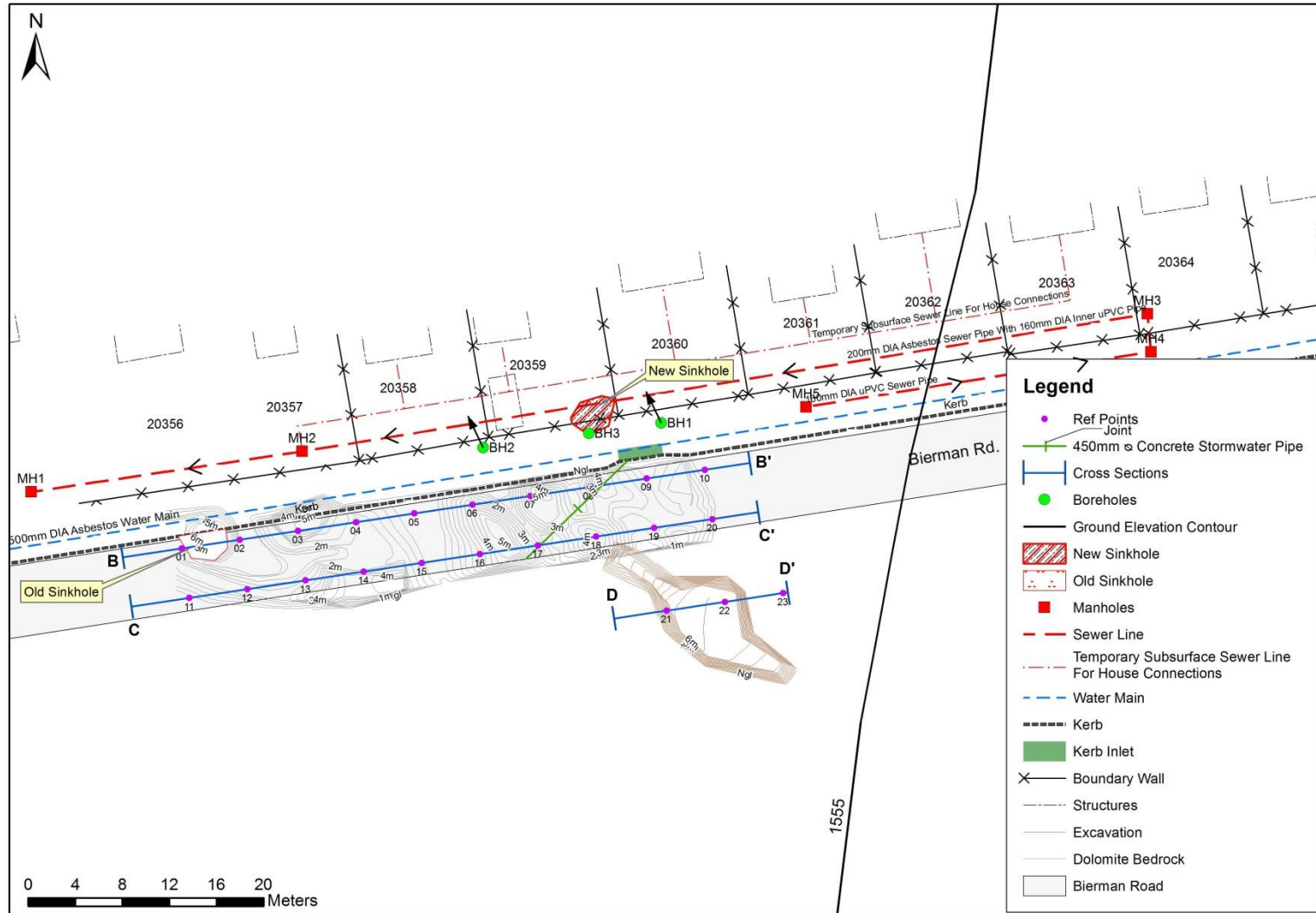


Figure A.5: Case Study 1 – Bierman Road bulk excavation and dolomite bedrock.

As a number of cavities were also encountered in the sewer trench excavation, located to the north of Bierman Road, rehabilitation work within the area of Bierman Road was recommended as the sinkhole in Bierman Road is possibly connected to the cavities and sinkhole encountered in the sewer trench.

Work performed: Bierman Road:

A plan view with contour elevations of the bulk road excavation in Bierman Road and south of Bierman Road is illustrated in Figure A.5. Two geological cross-sections, namely B-B' and C-C' through the road excavation and geological cross-section C-C' through the sinkhole to the south of Bierman Road, as encountered during the excavation, are illustrated in Figure A.6. The rehabilitation work carried out in Bierman Road and south of Bierman Road is illustrated as cross-sections in Figure A.7. A plan view of the dolomite pinnacles or shallow dolomite bedrock and troughs are illustrated in Figure A.8.

The following rehabilitation work was carried out in Bierman Road and south of Bierman Road (Letter Report Number KHH1468):

- The road section between the partially rehabilitated sinkhole and the new sinkhole (on Stand 20359) was box cut using an excavator (50m in length by 8m in width by 4,5m in depth) to determine the extent of the tunnel erosion between the two sinkholes.
- The road excavation has also revealed that a 20m long section of a 450mm diameter concrete stormwater pipe situated between a kerb inlet and the outfall had experienced excessive vertical settlement. The settlement occurred because the joints between the pipe sections were not properly sealed during the pipe installation and have leaked into the underlying highly erodible and compressible residual dolomite (wad) material. The entire 20m long pipe section was removed and replaced with a new concrete pipe with proper joint sealing.
- It was found that the road was underlain by an extensive network of dolomite bedrock pinnacles and a number of cavities (Plate A.4). The cavities formed within the troughs between the dolomite pinnacles, comprising residual dolomite (wad) at depth, causing tunnel erosion (Refer to Figure A.6).



**Plate 4:**  
**Bulk excavation Bierman Road exposing shallow dolomite bedrock, photo taken towards the east.**



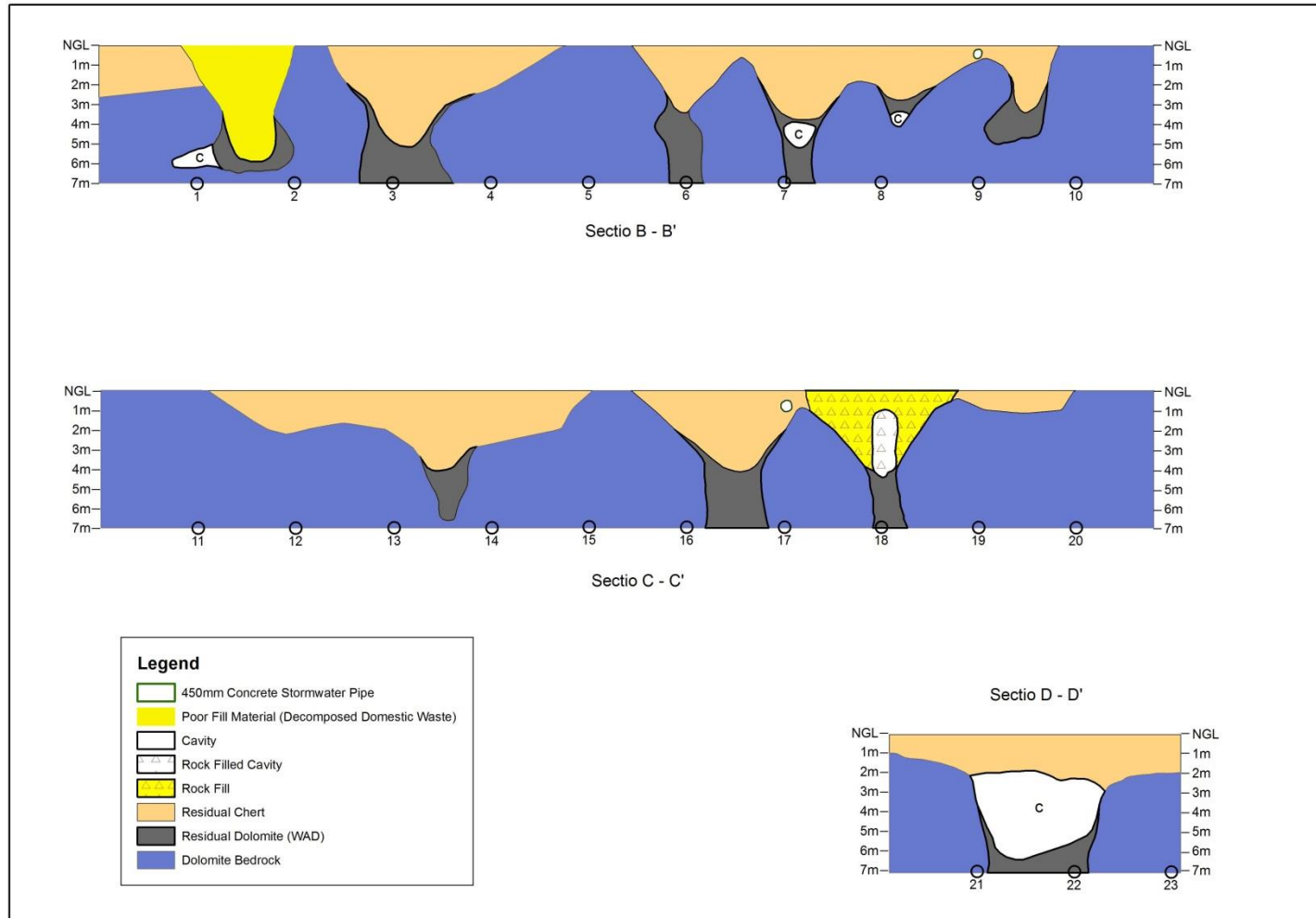


Figure A.6: Case Study 1 – Geological Cross-Sections along Bierman Road.

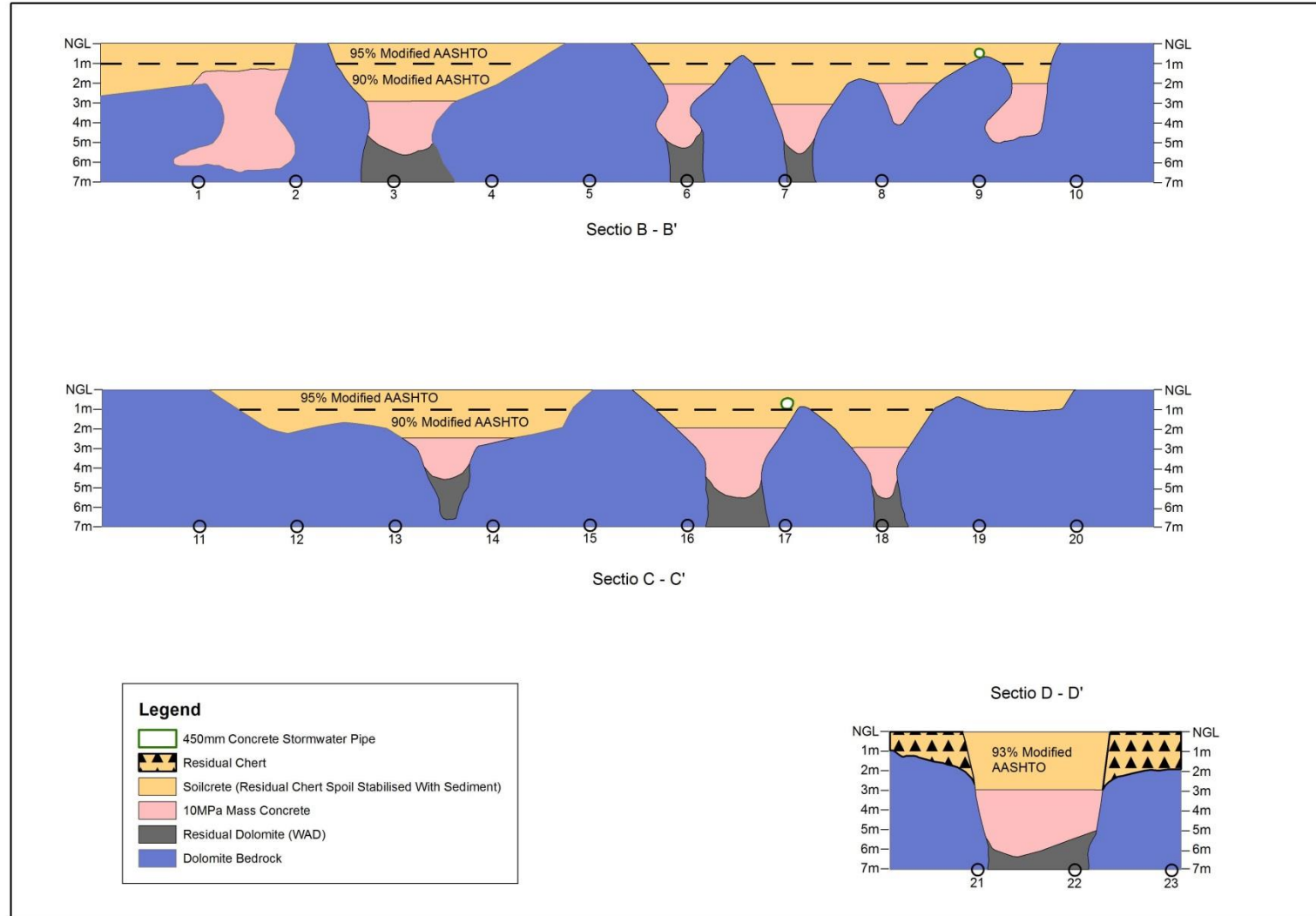


Figure A.7: Case Study 1 – Cross-Sections of Rehabilitation Work along Bierman Road.

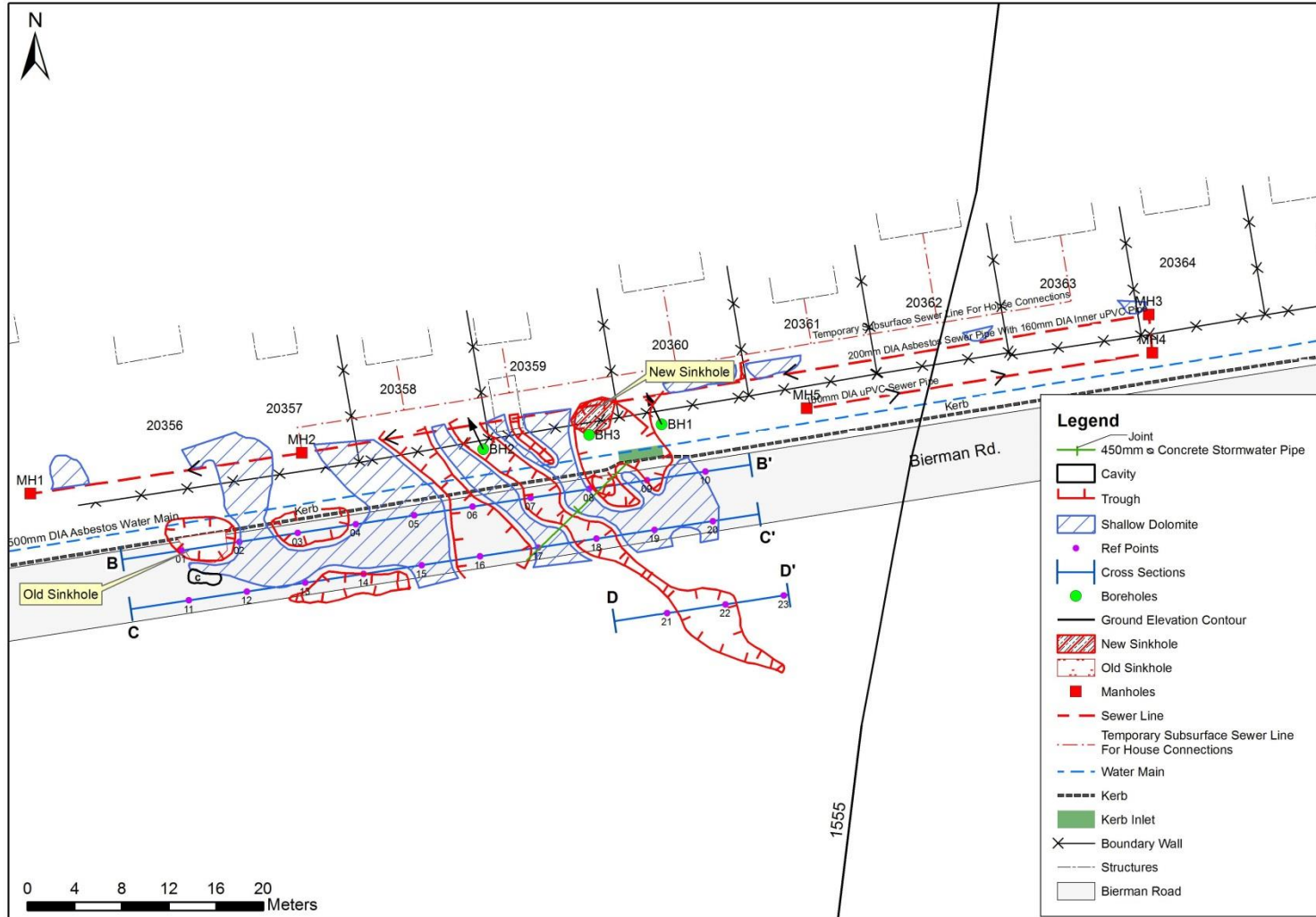
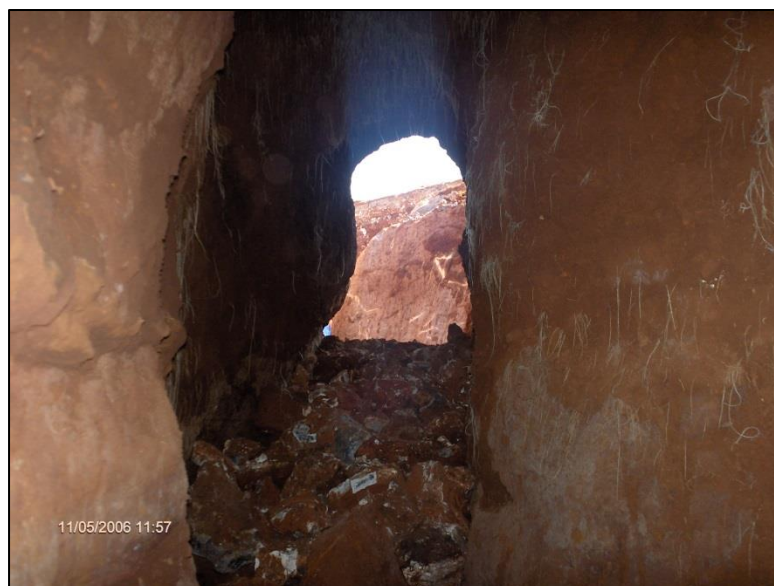


Figure A.8: Case Study 1 – Areas of shallow dolomite bedrock and troughs along Bierman Road.

- Areas of troughs were over excavated to a maximum depth of 5m to 6m below natural ground level. A 1m wide and 3m high erosion tunnel filled with rock fill was observed on the southern boundary of Bierman Road within one of the troughs (Plates A.5 and A.6).



**Plate A.5: Exposure of erosion tunnel in southern side wall of Bierman Road excavation.**



**Plate A.6: Photo taken from the inside of the erosion tunnel outwards.**

- The tunnel erosion extending towards the south was opened with an excavator discovering a large cavity 6m to the south where the erosion tunnel opened up. The cavity of approximately 5m to 6m diameter at a depth of 2m below natural ground level was also opened with the excavator down to a depth of 7m below natural ground level.
- All waste down to a depth of 6 m was removed within the area of the old partially rehabilitated sinkhole.
- The areas of troughs (forming v-shaped wedges), sinkholes and cavities were filled with 10MPa mass concrete up to 2m to 3m below natural ground level. In the area of the partially rehabilitated old sinkhole mass concrete was cast up to a level just below the 500mm diameter asbestos cement water main (1,5m below natural ground level) to support the pipe as it crosses directly over the sinkhole.
- Backfilling above the mass concrete with soilcrete (residual chert spoil classified as G6 material and 5% cement).
- In Bierman Road: The soilcrete from the base of the excavation up to 1 m below ground level must be compacted to 90% Modified ASSHTO dry density at optimum moisture content. The soilcrete backfill between 0,3 m and 1,0 m below ground level must be compacted to 95% of Modified AASHTO maximum dry density at optimum moisture content. Followed by road layer works: The road sub-base to be 150 mm thick and compacted to 98% Modified AASHTO dry density at optimum moisture content; the road base course (G2 material) to be 150 mm thick and compacted to 98% Modified AASHTO dry density at optimum moisture content; a 25 mm premix layer to be placed over the base course layer.
- In the area of the sinkhole south of Bierman Road: The soilcrete from the base of the remaining excavation up to ground level must be compacted to 93% of Modified AASHTO maximum dry density at optimum moisture content.

The subsurface conditions in the area along the affected sewer line, Bierman Road, sinkholes and cavities had been improved to a tolerable hazard. A tolerable hazard was reached by removing problematic materials such as the residual dolomite (wad) to a maximum depth of 4,5 m in the area of the sewer line, backfilling of over-excavated sections with soilcrete mix and placing of a reinforced concrete slab in areas of dolomite pinnacles at base of sewer trench floor, replace sewer line with HDPE-material and backfilling of the remaining sewer trench with suitable material properly compacted. The troughs (with cavities) encountered between shallow dolomite bedrock pinnacles excavated to 6 m to 7 m deep, along the excavated section of Bierman Road and the cavity encountered to the south of Bierman Road, was filled with 10 MPa mass concrete up to 2 m to 3 m from natural ground level. The remaining excavation areas were backfilled with soilcrete. The concrete stormwater pipe encountered in the Bierman Road excavation area was removed and replaced with a new concrete pipe with proper joint sealing.

**APPENDIX B**

***CASE STUDY 2***

## CASE STUDY 2

A sinkhole occurred on the eastern boundary between Stands 1063 and 1064 in the north-western servitude of Njakata Crescent, Vosloorus Extension 2, on 20 November 2008 (Plate B.1). The sinkhole was caused by a broken water pressure release valve used while repairing a leak on the EMM bulk water line. A site inspection of the affected area was conducted on 26 November 2008 and revealed the following (Report Number VGI3118/193/2, 2008):

- A 5 m diameter sinkhole extending to a depth of 3 m below natural ground surface, with an approximately 1m diameter erosion tunnel extending to a depth greater than 5 m towards the central eastern boundary of the house (approximately 2 m away from the sinkhole) on Stand 1064.
- The sinkhole is situated partially on Stand 1063, Stand 1064 and stretching a meter into the tar road.
- Severe damage to the boundary wall of Stand 1064 facing the street and nearly a meter subsidence of the gatepost at Stand 1063, within the affected area.
- An EMM water pressure release valve is situated within the subsided area, between the tar road and the south-eastern boundary of Stand 1063 and Stand 1064.



**Plate B.1: Sinkhole on eastern boundary of Stands 1063 and 1064, Njakata Crescent Street, Vosloorus Extension 2.**

- The water meter for Stand 1063 is situated on the boundary with Stand 1062 and the water meter for Stand 1064 is situated on the boundary with Stand 1095. Therefore no internal wet services are present within the area of the sinkhole.
- Surface water run-off originating from heavy rains, will flow in a south-eastern direction directly into the sinkhole from Stand 1063 and from the northern side of the road. Stand 1064 has proper surface water drainage (sealed off areas) and no surface run-off water originating on Stand 1064 will enter the sinkhole.
- The leaking EMM pressure release valve is 200 mm under water within the pressure release valve box. The water within the valve box lowered with at least 30 mm over a period of 3 hours.
- It is clear from the shape, depth and extent of the sinkhole, that subsurface erosion started in the area of the water release valve, causing a 1 m subsidence in the immediate area, with deeper (>3 m) subsurface erosion that took place towards the house on Stand 1064.
- The structures on Stand 1063 and Stand 1064 do not show any structural defects related to the sinkhole.

A dolomite stability investigation including the drilling of three percussion boreholes (Boreholes EMM190 to EMM192) was conducted in the area surrounding the sinkhole to determine subsurface conditions and the required soil improvements (Report Number VGI3118/193/2, 2008). Boreholes could although not be placed west of the sinkhole, as access for a drilling rig was not possible between the sinkhole and the house on Stand 1064. Two of the three boreholes (EMM190 and EMM192) were drilled 30° from vertical.

The affected area, existing infrastructure and the position of boreholes are displayed in Figure B.1.

A geological cross-section presenting subsurface conditions as encountered during the dolomite stability investigation surrounding the sinkhole on Stands 1063 and 1064 is illustrated in Figure B.2. The dolomite stability investigation revealed the following subsurface profile (Report Number VGI3118/193/2, 2008):

- Dolomite bedrock at a depth of 7 m to 13 m. Highly to moderately weathered soft rock dolomite encountered between 4 m and 7 m below residual syenite or just above hard rock dolomite.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of residual chert. The surface layer is underlain by residual syenite with a layer thickness of 1 m to 3 m. Residual dolomite (wad or manganiferous soils) was encountered below the residual syenite above dolomite rock in one borehole between a depth of 3 m and 5 m. Residual dolomite (wad) related to potential cavernous conditions, was encountered within dolomite rock between a depth of 7 m and 10 m and 7 m to 13 m. Rapid penetration rates, air and sample losses were recorded during drilling in the residual dolomite zones and in hard rock dolomite.



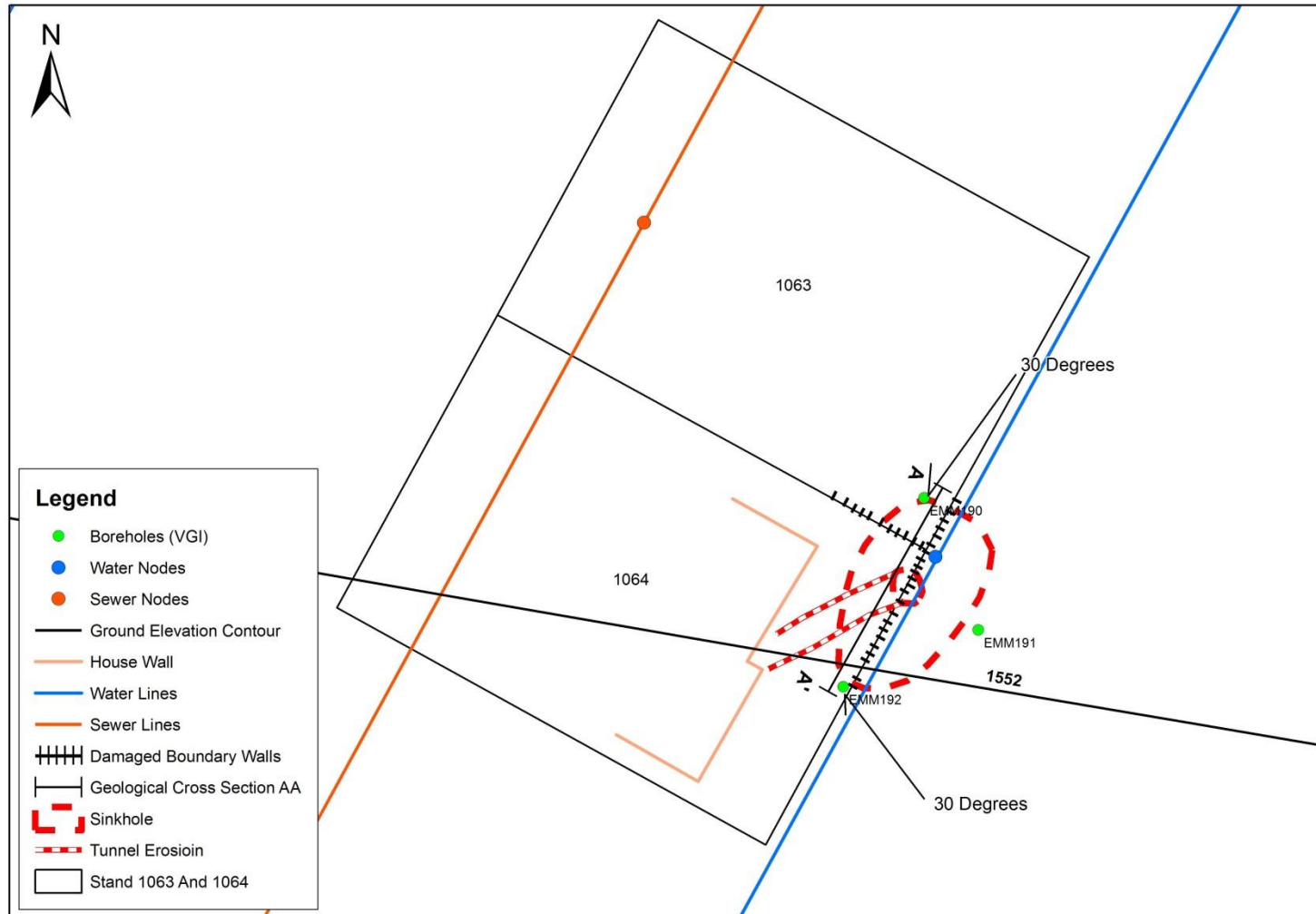


Figure B.1: Case Study 2 – Plan view of affected area and borehole positions.

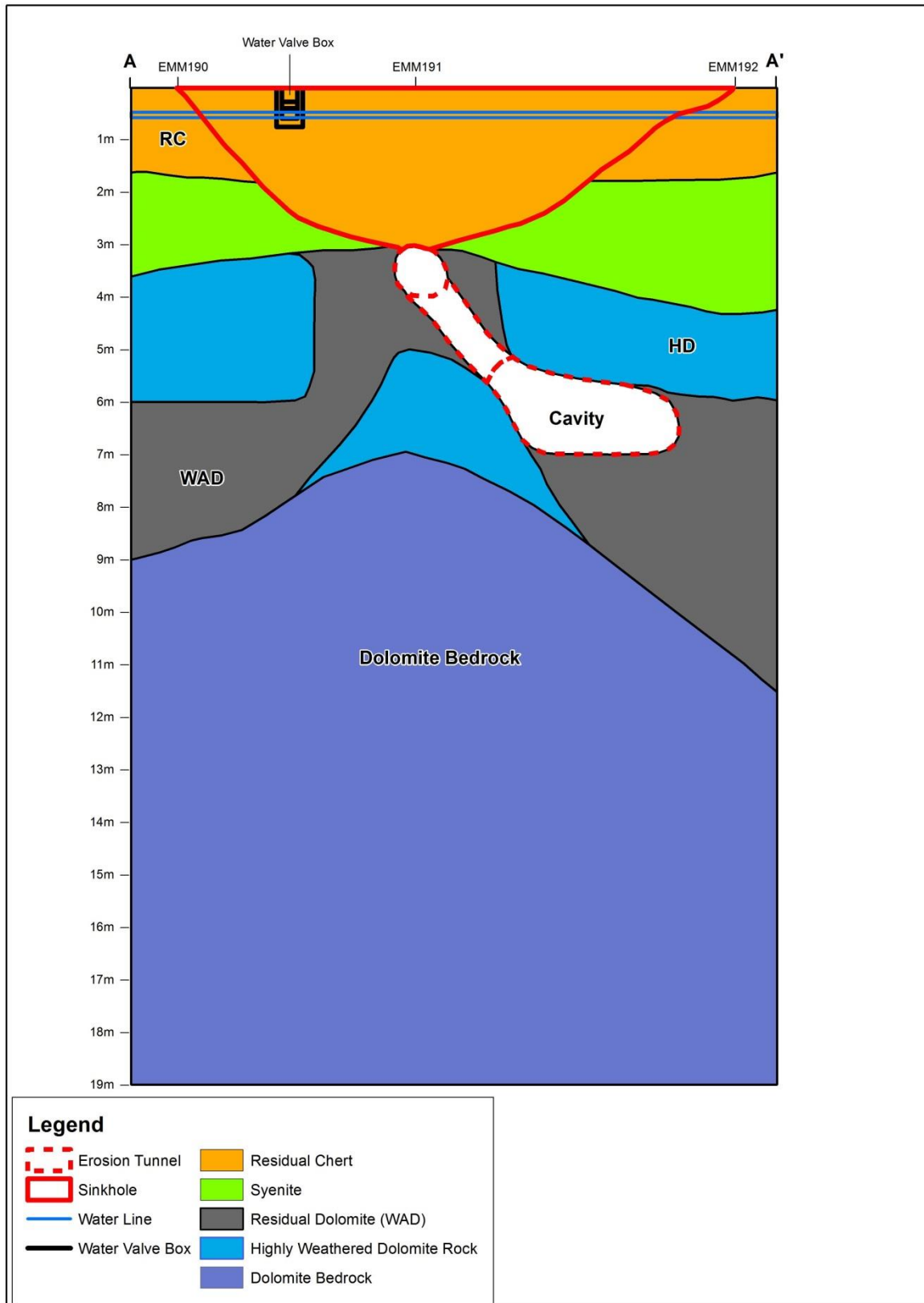


Figure B.2: Case Study 2 – Interpreted Geological Cross-Section A – A`.

- Cavities were not intercepted in any of the boreholes. Voidedness related to potential cavities was, however, recorded within the residual dolomite (wad) within two of the boreholes and a 1 m diameter erosion tunnel exists at the base of the sinkhole at a depth of 3 m below ground surface extending to a depth greater than 5 m towards the house on Stand 1064.
- Although water was intercepted at a depth of 5 m to 12 m on the contact with dolomite bedrock during drilling, all the boreholes were recorded as `dry` 24 hours after drilling. The water may have rather originated from leaking wet services. The regional groundwater level is at 1526 m AMSL (26 m below natural ground level) within dolomite bedrock.

Taking the existing geological conditions on site into account (e.g. depth to dolomite bedrock, presence of highly erodible and compressible residual dolomite (wad)), sinkhole with an erosion tunnel extending below the house on Stand 1064; improvement of the subsurface conditions required the use of the Inverted Filter Method. The area of rehabilitation is presented in Figure B.3 and a cross-section of the rehabilitation work is presented in Figure B.4. The following was carried out in terms of rehabilitation of the affected area (Report Number VGI3118/193/2, 2008):

- Placing of a 0,5 m high soil berm (comprising low permeability materials, such as clay and silt) around the affected area, especially at Stand 1063 and in the road to ensure no surface water run-off can enter the sinkhole area, which would aggravate subsurface erosion and could lead to collapse of the structure on Stand 1064, in the time before rehabilitation.
- Demolish boundary walls within area proposed for rehabilitation.
- Bulk excavation (10 m by 7 m area) to a depth of 1 m to 7 m, including the area of the water pressure release valve and water pipe over a distance of 10 m. Excavation slopes at 1:1 down to 3 m and vertical from 3 m to 7 m.
- The bulk excavated area and cavity below the house on Stand 1064 was backfilled with 10 MPa mass concrete up to 1 m below natural ground level (Plate B.2). The remaining 1 m of the excavation was backfilled with silty/gravelly sand (G5 quality) in 150 mm thick layers up to ground level, each layer compacted to 95% of Modified AASHTO maximum dry density at optimum moisture content. The upper 0,3 m was compacted at 98% of Modified AASHTO maximum dry density at optimum moisture content. The entire site was landscaped to facilitate surface water drainage away from the structure.
- The water line and water pressure valve box located at a depth of approximately 0,6 m was levelled during backfilling of the excavation.
- The boundary walls and tar road was re-instated.

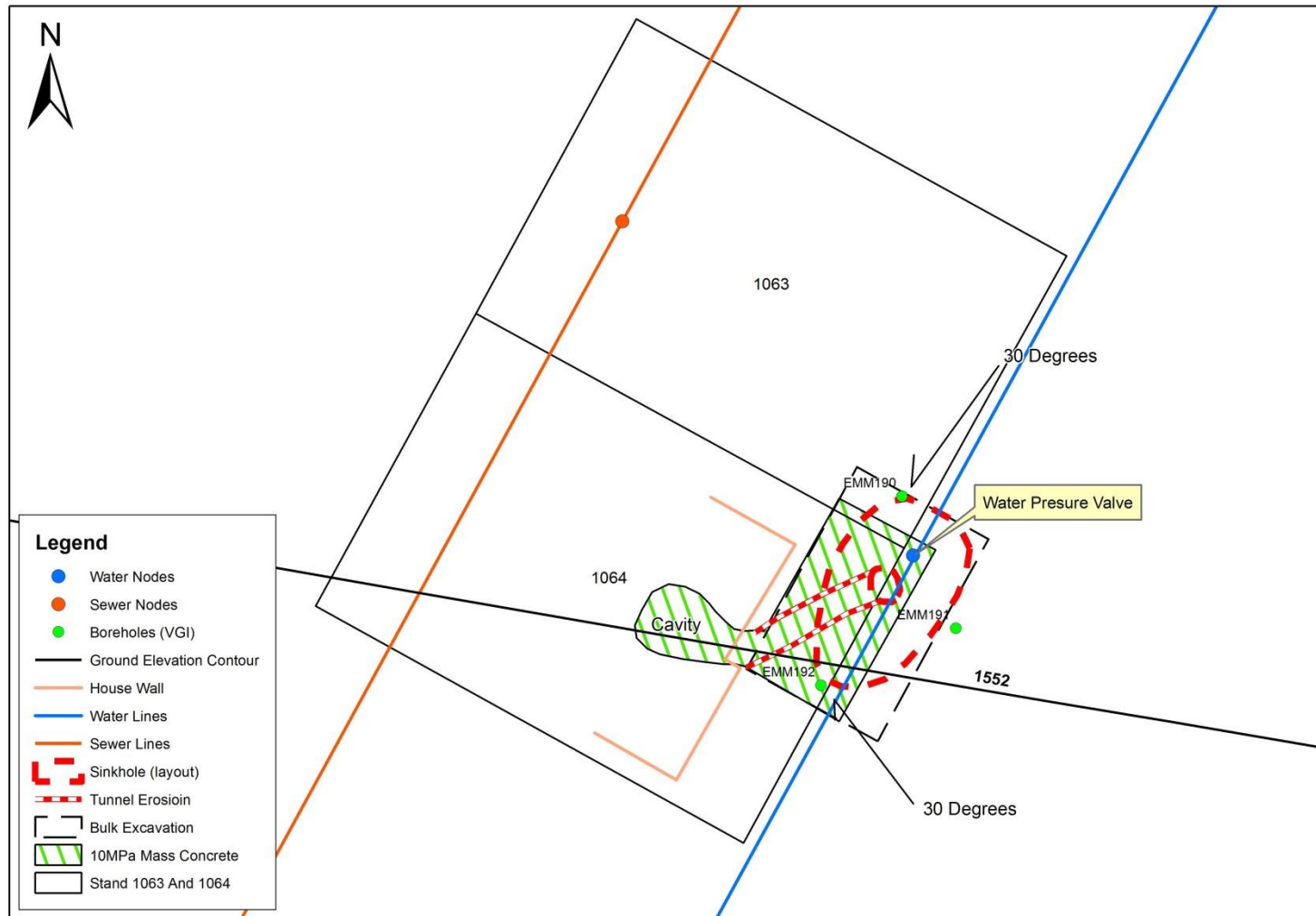


Figure B.3: Case Study 2 – Area of Rehabilitation.

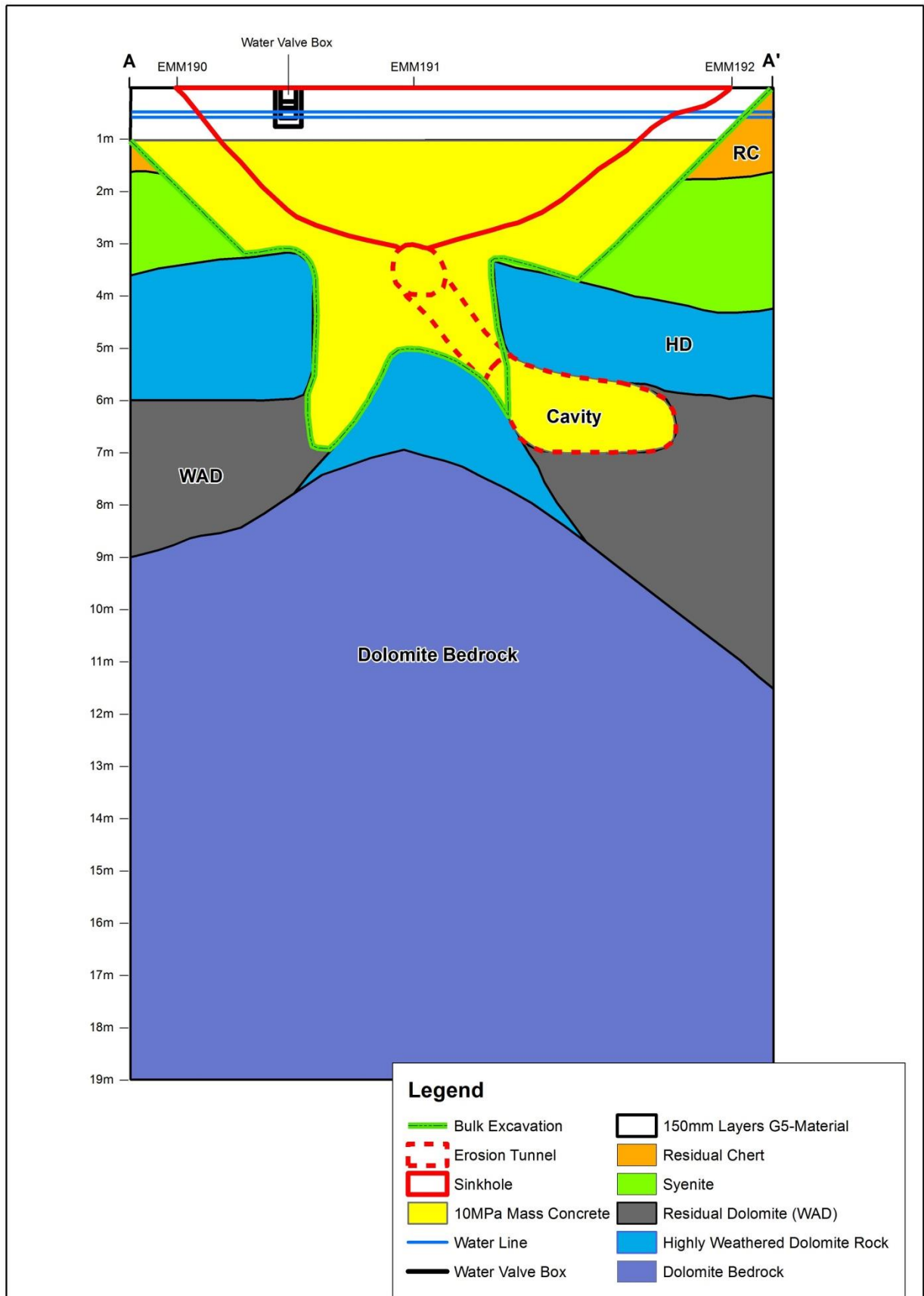


Figure B.4: Case Study 2 – Cross-Section A – A' of rehabilitation work carried out.



**Plate B.2: Bulk excavated area and cavity backfilled with 10 MPa mass concrete.**

The subsurface conditions on Stand 1064 and the sinkhole area had been improved to a tolerable hazard. A tolerable hazard was reached by removing problematic materials such as the residual dolomite (wad) to a depth of 7 m below ground surface and replacing it with mass concrete up to 1m below natural ground level with the remaining 1 m backfilled with G5-quality material creating an engineered soil mattress of 1 m thickness.

**APPENDIX C**

***CASE STUDY 3***

## CASE STUDY 3

A 15 m diameter subsidence extending to a depth of 0,5 m occurred within the street directly east of Stand 1344 in Tokoza, before 2004. This subsidence which has been rehabilitated at the end of 2011, did contribute to structural damage to the house on Stand 1344. The subsidence was triggered by a leak on the connection between the original 150 mm diameter vitrified clay sewer line and 200 mm diameter Class 6 HDPE sewer line (placed by municipal officials before 2004), causing subsurface erosion or consolidation settlement of dolomite residuum (wad). The sewer line is located at a depth of approximately 4 m below ground surface. The sewer line was replaced from Manhole MH1 to MH2 by a 200 mm diameter Class 16 HDPE butt welded and two HDPE manholes. All dolomite residuum (wad) material encountered to a depth of 7 m in boreholes drilled in the affected area was replaced by G5 to G7 quality material by means of the inverted filter method within the area of the subsidence and along the trench of the new HDPE pipe (Report Number VGI3355/89, November 2011).

It was recommended that the house on Stand 1344, which was severely damaged beyond repair, be evacuated and demolished as the affected area was extending towards the west onto Stand 1344. In addition, a cavity (3 m diameter and 1m height at a depth of 3 m) was intercepted in the west to east aligned 4 m deep trench to the south of Stand 1344 during the replacement of the sewer line with an HDPE pipe. The cavity, extending towards the house on Stand 2/1851, was backfilled with mass concrete. A dolomite stability investigation including the drilling of two percussion boreholes (Boreholes EMM1083 and EMM1084) was conducted in the footprint area of the demolished house on Stand 1344 to determine subsurface conditions and the required soil improvements (Report Number VGI3355/89-1, April 2012).

The affected area, existing infrastructure and the position of boreholes are displayed in Figure C.1. A geological cross-section presenting subsurface conditions as encountered during the dolomite stability investigation on Stand 1344 is illustrated in Figure C.2 (Report Number VGI3355/89-1, April 2012).

The dolomite stability investigation on Stand 1344 revealed the following homogeneous subsurface profile (Report Number VGI3355/89-1, April 2012):

- Dolomite bedrock at a depth of 9 m. A 1 m to 2 m thick horizon of highly weathered soft rock dolomite encountered between depths of 7 m to 9 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of ferruginised colluvium to a depth of 2 m. The surface layer is underlain by residual dolomite (wad or manganiferous soils) to a depth of 7 m. Rapid penetration rates but no air and sample losses were encountered in the boreholes in the residual dolomite zone.
- Cavities were not intercepted in any of the boreholes. Cavities can, however, be expected within the residual dolomite (wad) horizon encountered above bedrock. Voids were observed during the excavation of the affected area within the dolomite residuum (wad) horizon directly below a honeycomb ferricrete capping layer at 2 m.



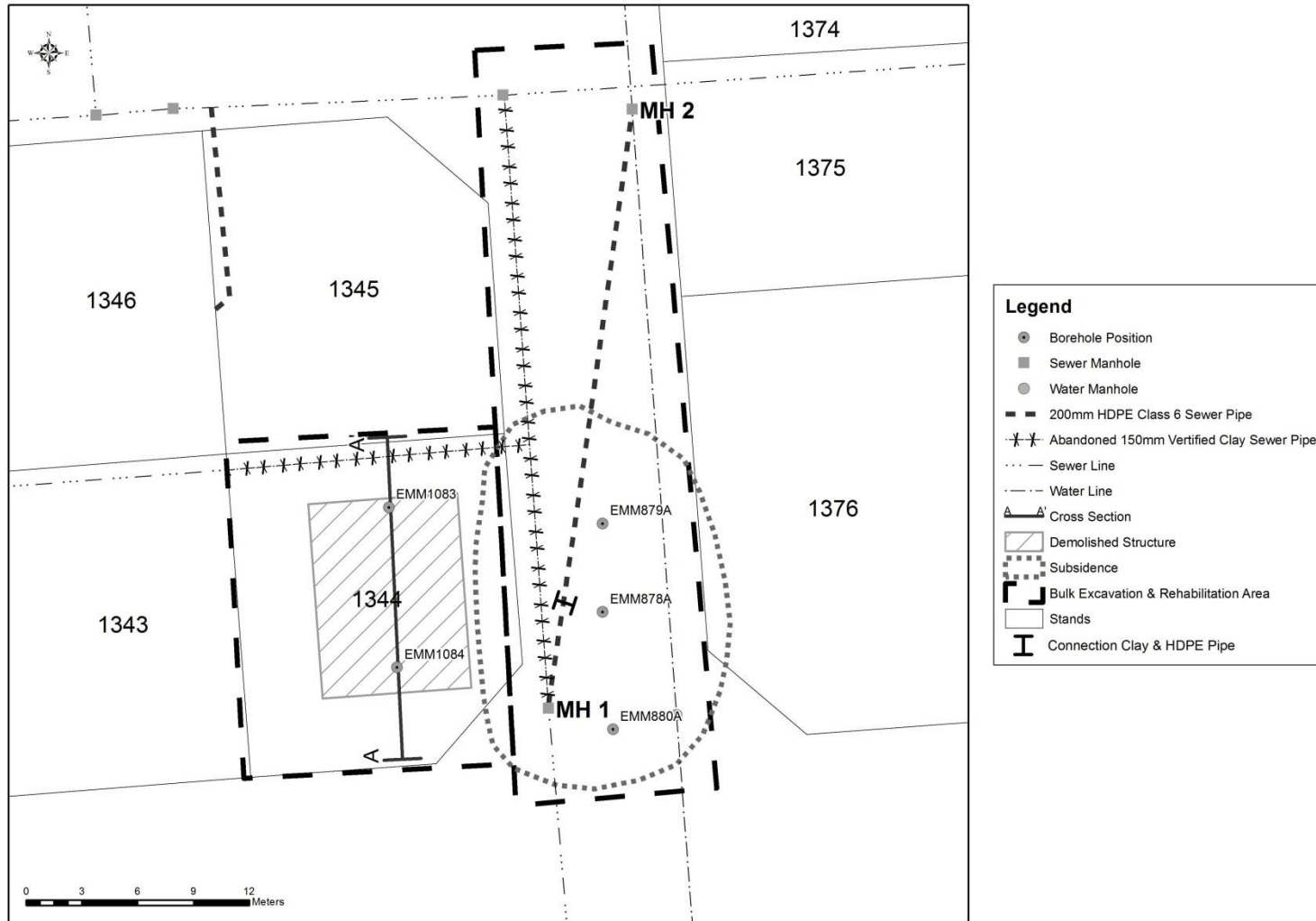


Figure C.1: Case Study 3 – Plan view indicating affected area, existing infrastructure and the position of boreholes.

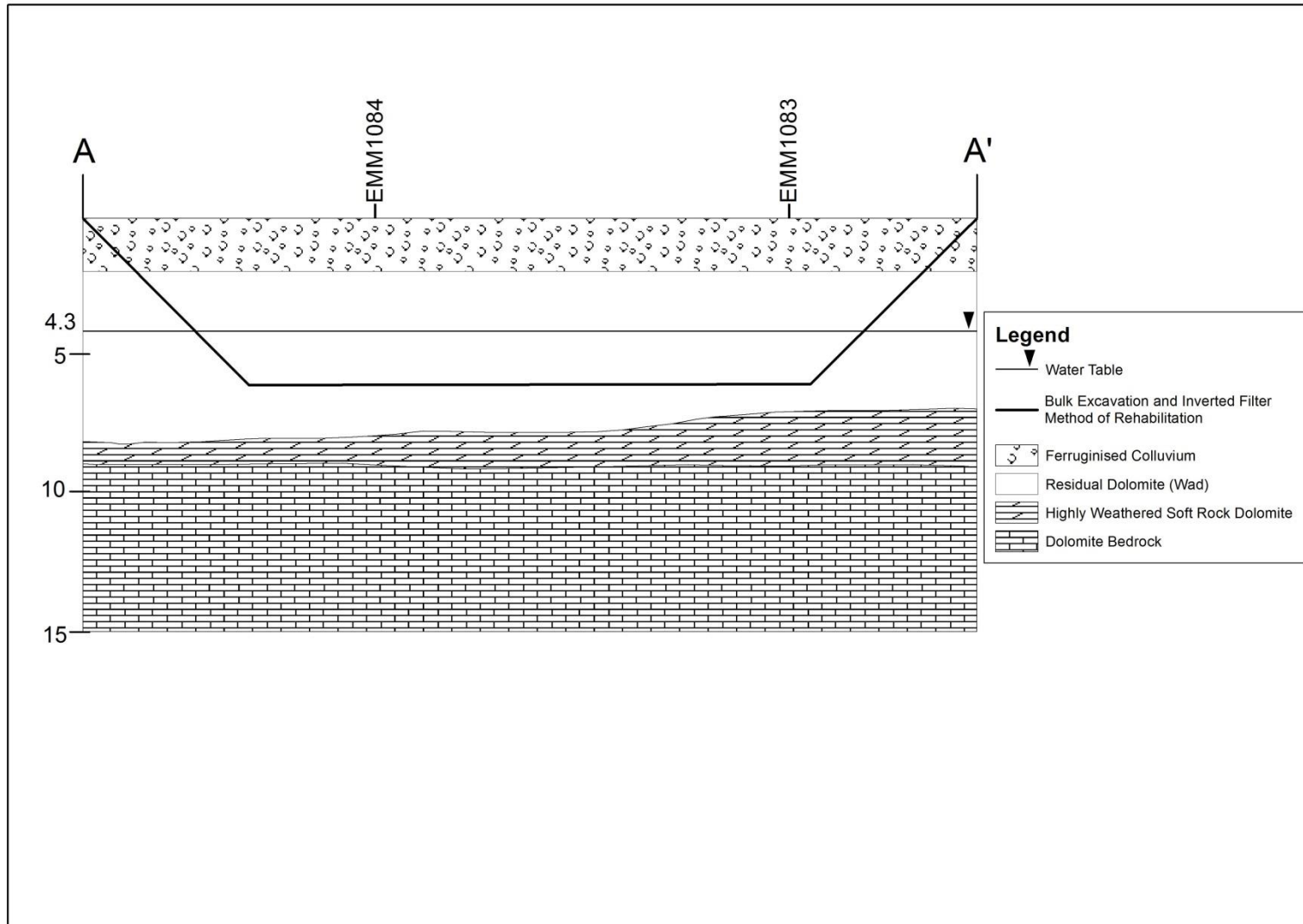


Figure C.2: Case Study 3 – Interpreted Geological Cross-Section A – A`.

- Although water was intercepted at a depth of 4,1 m and 4,3 m in boreholes drilled, these levels are not regarded as the Original Groundwater Level (OWL) and may have rather originated from leaking wet services. However, the presence of nodular and honeycomb ferricrete in profile is an indication of a potential perched water table. The regional groundwater level is at 1528 m AMSL (27 m below natural ground level) within dolomite bedrock.

Taking the existing geological conditions on site into account (e.g. depth to dolomite bedrock, presence of highly erodible and compressible residual dolomite (wad) and a perched water table) improvement of the subsurface conditions on Stand 1344 required the use of the Inverted Filter Method. The following was carried out in terms of rehabilitation of the affected area (Report Number VGI3355/89-1, April 2012):

- Blocking off and removal of all internal wet services.
- Bulk excavation (15 m by 11 m at base of excavation) to a depth of 6 m. Excavation slopes at 1:1 to 6 m depth. Care was to be taken of water within the excavation area from a depth of 4 m, as it would cause the dolomite residuum (wad) to liquefy and slope failure could occur (Plate C.1). All mandatory safety requirements pertaining to working in excavations were to be applied. A pump was available on site to drain the excavation area during works.



**Plate C.1: Bulk excavation in progress below water level causing unstable side slopes and collapse.**

- Backfilling of the excavation involved the placing of large boulders and stones in filled with soilcrete (10% cement) and compacted with an impact roller in 1 m lifts up to 3 m from ground surface (Plate C.2).



**Plate C.2: Bulk excavated area backfilled to stable level.**

This was followed by backfilling with low plasticity material: Cobbles/gravels in 300 mm thick layers up to a depth of 1,5 m below ground surface, followed with silty/gravelly sand (G5 quality) in 150 mm thick layers up to ground level. Compaction should at least be 95% of Modified AASHTO maximum dry density at optimum moisture content. The upper 1,5 m was compacted at 98% of Modified AASHTO maximum dry density at optimum moisture content. The entire site was elevated to 150 mm above the natural ground level to facilitate surface water drainage.

The subsurface conditions on Stand 1344 and the subsidence area had been improved to a tolerable hazard. A tolerable hazard was reached by removing problematic materials such as the residual dolomite (wad) to a depth of 6 m below ground surface and replacing it with an engineered soil mattress of between 6 m to 6,5 m thickness and the removal and replacement of wet services.

**APPENDIX D**

***CASE STUDY 4***

## CASE STUDY 4

During August 2005 a broken mid-block sewer situated at a depth of approximately 4,5 m below natural ground level, caused ground subsidence and cracking of several structures on various stands in Rondebult Extension 2. A site inspection on 12 August 2005 revealed the following (Letter Report Number KHH1366, August 2005):

- Sewage flowing on ground surface, possibly due to blockages in the sewer caused by subsidence-related ruptures.
- Cracks in the ground surface, defined a 30 m diameter semi-circular subsidence. The surface cracks had an approximate width of 0,1 m and extended to a depth of 1 m.
- A 1 m diameter subsidence with a depth of 1 m below ground surface, where the homeowner extended the existing structure for a bathroom.

A follow-up inspection on 5 October 2006, revealed that the subsidence had extended towards the east. In addition, a new subsidence and sinkhole formed along the sewer line and a manhole, allowing sewage to flow directly into the sub-surface (Plate D.1).



**Plate D.1: Sinkhole and subsidence in area of Borehole BH8.**

The investigation included a gravity survey on a 10 m grid spacing, to provide information on the depth and morphology of the dolomite profile. Percussion drilling was conducted in three phases, two of these phases were performed before rehabilitation and the third phase after rehabilitation. Phase 1 included the drilling of Boreholes BH1 to BH6 on 5 October 2005 within the area where the surface cracks indicated the original affected area (Report Number KHH1378, October 2005). Phase 2 included the drilling of Boreholes BH7 to BH11 on 20 October 2006 within the additional affected area (Report Number KHH1387, October 2006).

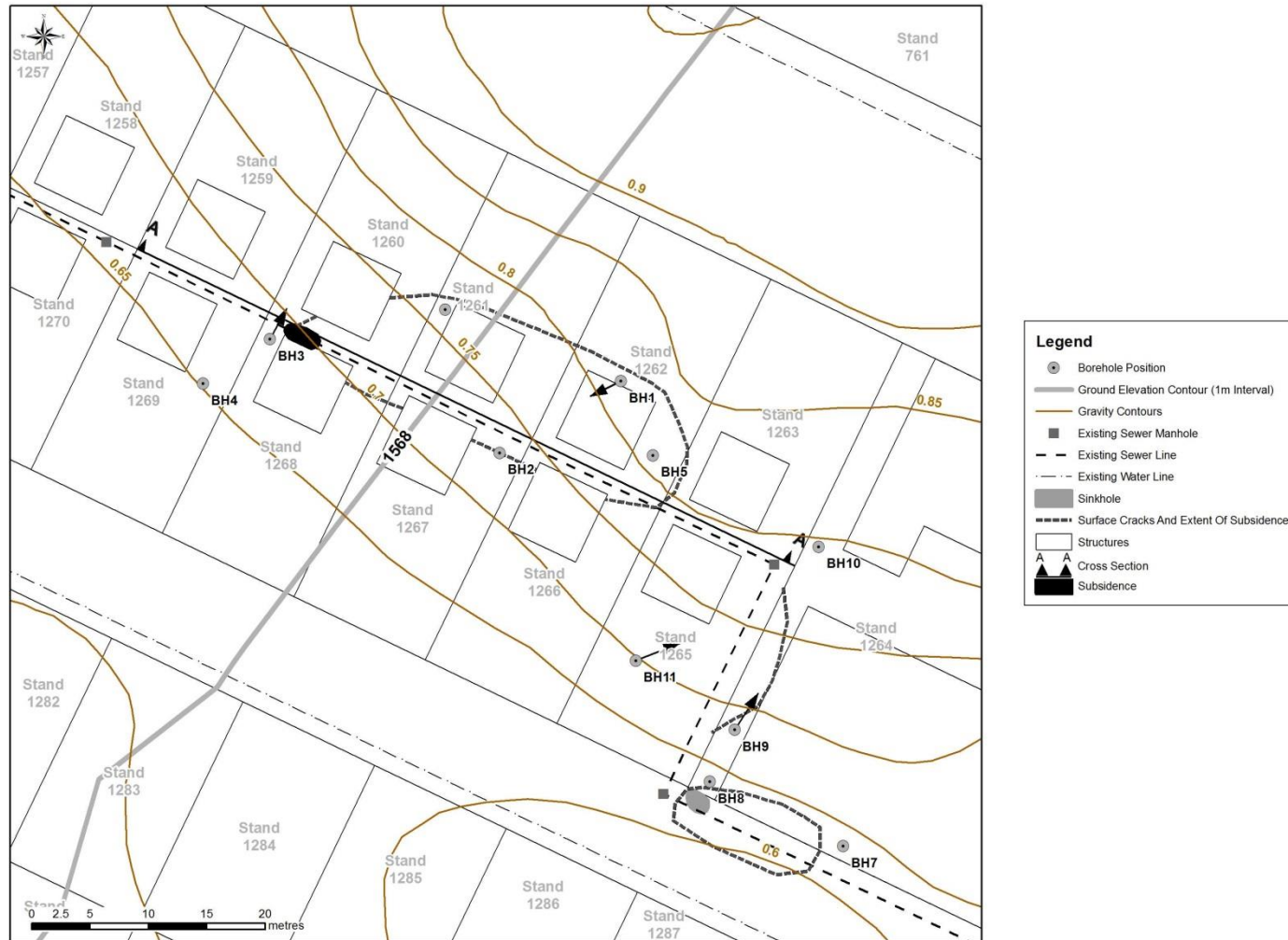
The affected area, existing infrastructure and the position of Boreholes BH1 to BH11 are displayed in Figure D.1 (Report Number KHH1378, October 2005). A geological cross-section presenting sub-surface conditions as encountered during the Phase 1 investigation is illustrated in Figure D.2 (Report Number KHH1378, October 2005).

The Phase 1 investigation revealed the following sub-surface profile as illustrated in Figure D.2 (Report Number KHH1378, October 2005):

- Dolomite bedrock at a depth ranging from 9 m to 22 m. A 1 m to 2 m thick horizon of highly weathered soft rock dolomite at variable depths ranging from 6 m to 22 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of colluvium and or residual chert to a depth of between 1 m and 6 m. The surface layer is underlain by residual dolomite comprising ferroan and manganiferous (wad) soils. The thickness of this layer varies between 3 m and 10 m. Residual shale (or syenite) was encountered in one borehole between 8 m and 11 m. Rapid penetration rates and air and sample losses were encountered in all the boreholes in the residual dolomite zones.
- Cavities were encountered within the residual dolomite (wad) between a depth of 2 m and 6 m, 4 m and 7 m and 11 m to 21 m. A cavity was also encountered within dolomite bedrock between a depth of 18 m and 21 m.
- Sewage from the broken sewer line was encountered in one borehole at a depth of 8,2 m. No groundwater was encountered and the regional groundwater level is at 1545 m AMSL (23 m below natural ground level) within dolomite bedrock.

The sub-surface conditions encountered in Boreholes BH7 to BH11 during the Phase 2 investigation is summarised below (Report Number KHH1387, October 2006):

- Dolomite bedrock at a depth ranging from 7 m to 9 m. A 1 m to 2 m thick horizon of highly weathered soft rock dolomite directly above hard rock dolomite at variable depths ranging from 4 m to 9 m in most boreholes. A 1 m thick horizon of highly weathered soft rock syenite was encountered between the highly weathered dolomite and hard rock dolomite in one borehole between 6 m and 7 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of residual chert to a depth of between 1 m and 5 m. The surface layer is underlain by inter-layered residual dolomite and syenite encountered between a depth of 3 m and 8 m. Residual dolomite (wad) was encountered in general just above highly weathered dolomite rock between 1 m to 8 m. Fast penetration rates and air and sample losses were encountered in all the boreholes in the residual dolomite zones.
- Cavities were not encountered in any of the boreholes.
- No groundwater was encountered in any of the boreholes. Sewage was encountered from a depth of 2 m to 5 m in all the boreholes drilled and is associated with the broken sewer lines. The regional groundwater level is at 1545 m AMSL (23 m below natural ground level) within dolomite bedrock.



**Figure D.1: Case Study 4 - Plan view of affected area, existing infrastructure and the position of Phase 1 and 2 boreholes.**



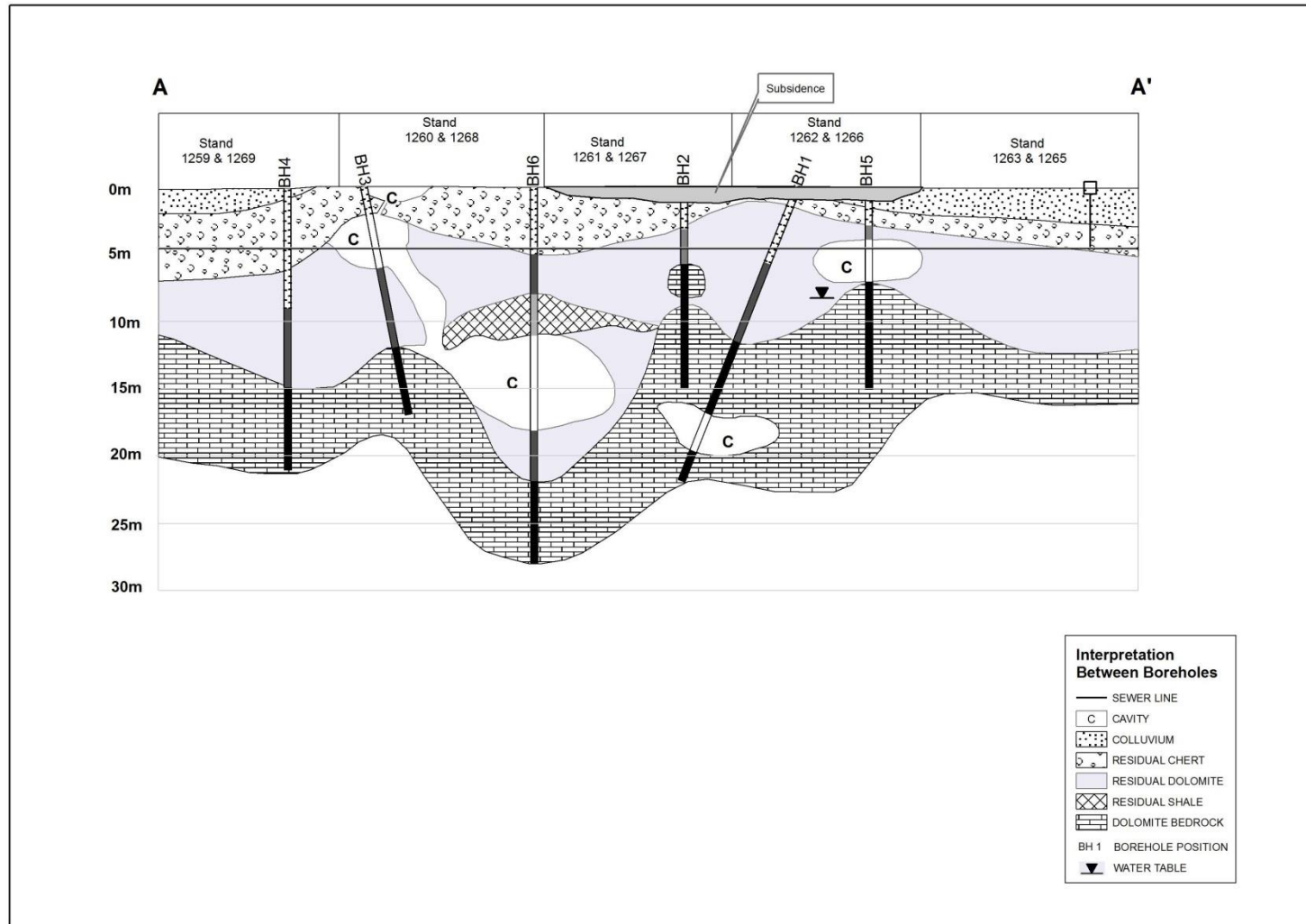


Figure D.2: Case Study 4 – Interpreted Geological Cross-Section A – A`.

Taking the existing geological conditions on site into account (e.g. depth to dolomite bedrock, depth and extent of cavities, presence of highly erodible and compressible residual dolomite (wad)) and the affected infrastructure (e.g. houses, shopping centre and broken sewer lines) the following was recommended in terms of rehabilitation of the affected area (Report Number KHH1562, April 2007):

- Demolish all structures in the affected area and stockpile the building rubble (excluding metal).
- Blocking off and removal of all subsurface wet services in the area; rerouting of the existing 4,5 m deep broken mid-block sewer line section above ground.
- Bulk excavation of the affected area (40 m by 100 m) to a depth of 4 m. The two subsidence areas were then excavated to the maximum reach of the excavator (approximately 10 m) to expose the throat of the subsidence (potential sinkhole). During excavation the cavity encountered in Borehole BH5 was exposed (Plate D.2).



**Plate D.2: Cavity exposed during bulk excavation in area of Borehole BH5.**

- Dynamic Compaction (DC) probing was first performed within the deeper exposed sections to collapse subsoil cavities, after which building rubble was used to choke the throat. This process was followed by backfilling of the excavation in 1,5 m to 2,0 m lifts with gravelly soils, compacted using DC to construct a soil raft. The deep DC consisted of primary and secondary prints on a 5 m by 5 m grid spacing with volume and blow counts recorded for quality purposes for each print position. The site was levelled and an ironing operation was conducted over the entire area to complete the shallow DC treatment. The results of the primary DC pounding were used to determine or confirm the lateral extent of the problem areas and areas of deep-seated cavities or thick compressible dolomite residuum (wad).

This procedure was followed before production pounding could commence due to safety considerations during construction. The purpose of the DC was to densify the upper 10 m of the soil profile substantially, thereby decreasing permeability and erodibility.

- The entire site was elevated to 150 mm above the natural ground level to facilitate surface water drainage and compacted with an impact roller.
- A new shallow HDPE mid-block sewer and two manholes were installed.

The area of rehabilitation, new infrastructure and the position of Boreholes BH12 to BH21 drilled after completion of rehabilitation are displayed in Figure D.3 (Report Number KHH1562, April 2007). A geological cross-section presenting subsurface conditions as encountered after rehabilitation is illustrated in Figure D.4 (Report Number KHH1562, April 2007). It is clear from the illustration in Figure D.4 that the affected area has been improved to a tolerable hazard. A tolerable hazard was reached by removing and replacing problematic materials such as the residual dolomite (wad), collapse and backfilling of cavities, with an engineered soil mattress of between 4 m to 12 m thickness and the removal and replacement of wet services.

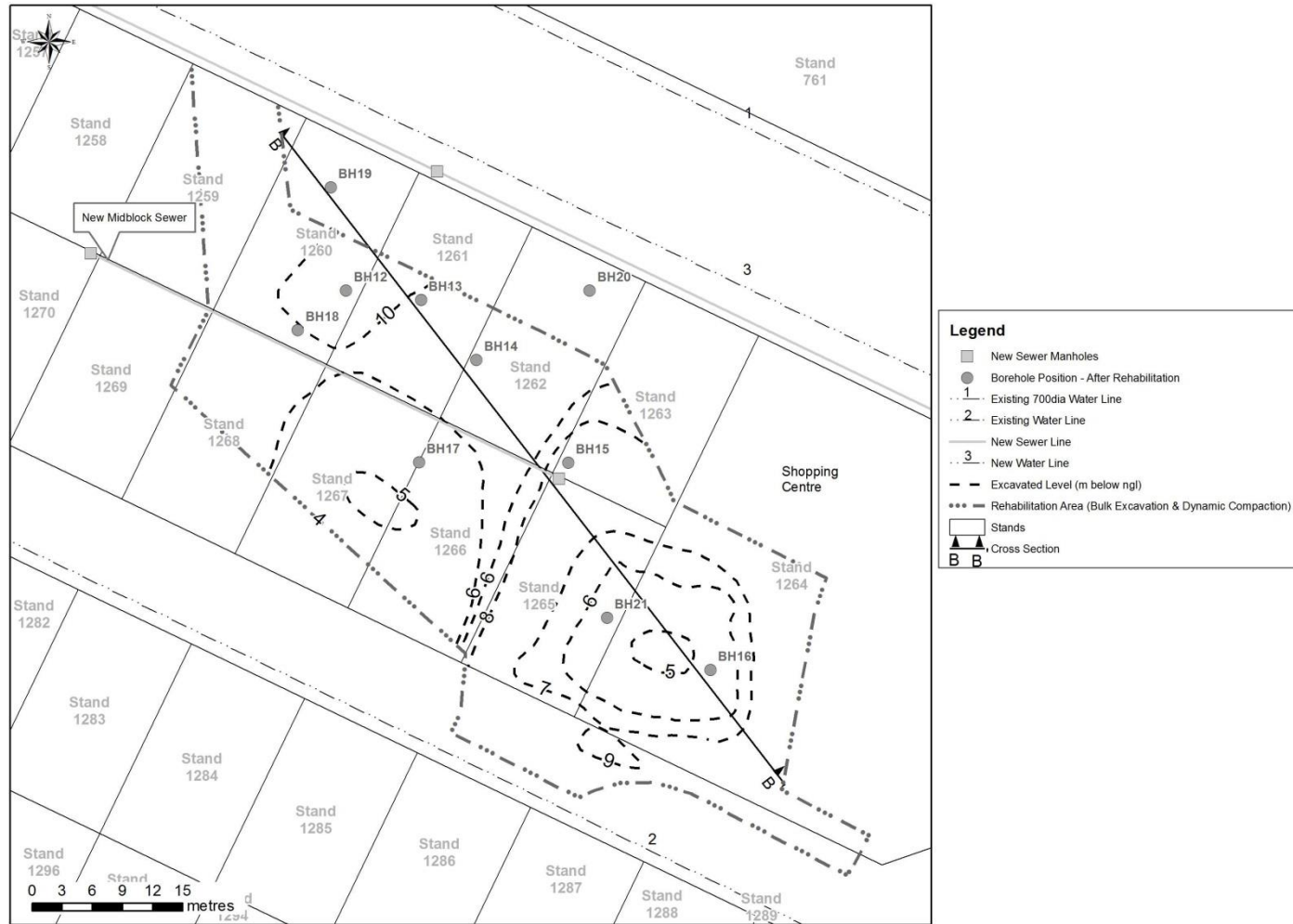


Figure D.3: Case Study 4 – Area of Rehabilitation

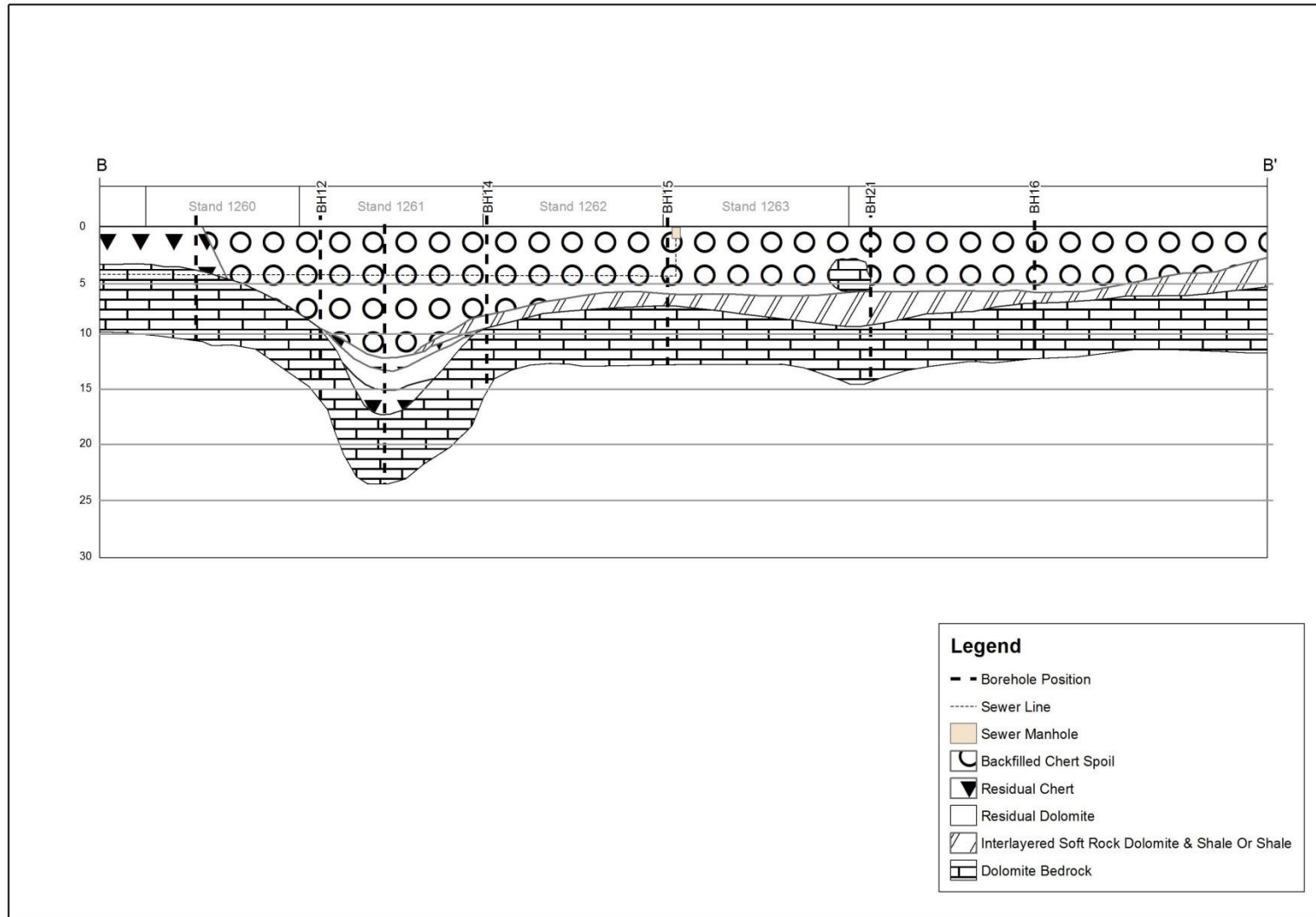


Figure D.4: Case Study 4 – Geological Cross-Section B – B' after rehabilitation.

# **APPENDIX E**

## ***CASE STUDY 5***

## CASE STUDY 5

### 1. INTRODUCTION

During the night of 27 January 2010 a sinkhole of 5 m diameter size extending to a depth of approximately 7 m formed on the north-western boundary of Stand 2656, Daffodil Street, Rondebult. The sinkhole enlarged in size during early morning on the 28<sup>th</sup> of January 2010 with partial collapse of the palisade fence.

A sinkhole was previously reported approximately 40 m to the south-west of the current sinkhole, during January 2006. This sinkhole of 4 m diameter extending to a depth of approximately 8 m formed on the western boundary of Stand 2636, due to a broken bulk sewer line (300 mm diameter uPVC). The new sinkhole reported on 28 January 2010 is located just outside the area previously rehabilitated to the south on the same sewer line.

A site inspection during January 2006 on the sinkhole that occurred at Stand 2636, Dragon Street, Rondebult revealed the following (Report Number KHH1409, February 2006):

- A sinkhole of 4 m diameter size extending to a depth of more than 8 m below natural ground surface, opened up down to the sewer line depth on the western boundary of Stand 2636 (Plate E.1).



**Plate E.1: Sinkhole on western boundary of Stand 2636.** A sewer manhole is situated 18 m north-east of the sinkhole.

- A mid-block sewer line (160 mm diameter uPVC) for all house connections is located less than 5 m from the houses and running 15 m to the east parallel to the bulk EMM 300 mm uPVC sewer.

- A broken sewer line with fast flowing effluent entering the subsurface ground profile causing subsurface erosion was observed within the sinkhole area (Plate E.2).



**Plate E.2: Broken sewer with fast flowing effluent causing subsurface erosion.**

- House sewer connections were blocked and overflowing.
- Immediate actions to be taken included the fencing off of the sinkhole area and the pumping of sewage via a line at ground surface from the manhole located to the north-east of the sinkhole towards the manhole located to the south-west of the sinkhole to reduce the potential for the sinkhole to become bigger, until the investigation including a gravity survey and the drilling of a number of boreholes had been completed and rehabilitation work undertaken.

A site inspection on 28 January 2010 of the new sinkhole at Stand 2656 revealed the following (Report Number VGI3118/270/1, January 2010):

- A 5 m diameter size sinkhole extending to a depth of approximately 7 m below natural ground surface, located on the north-western boundary of Stand 2656 in an area of a south-west to north-east aligned 300mm diameter uPVC EMM bulk sewer line (Plate E.3).
- A section of the palisade fence has fallen into the sinkhole.
- No structural damages to houses observed, situated approximately 15m to the south-east of the sinkhole.





**Plate E.3: Sinkhole at north-western boundary of Stand 2656.**

- Immediate actions to be taken included the fencing off of the sinkhole area, placing of a soil berm of 0,5m height around the sinkhole to prevent ingress of surface water run-off into the affected area. Sewage pumped via a line at ground surface from the manhole located to the north-east of the sinkhole towards the manhole located to the south-west of the sinkhole to reduce the potential for the sinkhole to become bigger, until the investigation had been completed and rehabilitation had been undertaken.

In the period awaiting the award of the tender to a rehabilitation contractor, a second sinkhole formed 6 m to the south-east of the existing sinkhole on the boundary of Stands 2656 and 2657 on 7 April 2010. A site inspection on 8 April 2010 revealed the following:

- An elongated sinkhole of 6 m long, 4 m wide and 4 m deep on the boundary between Stands 2656 and 2657 in close proximity to a north-east to south-west aligned 160 mm diameter uPVC midblock sewer line located at a depth of approximately 1,5 m below natural ground level.
- The boundary wall between Stands 2656 and 2657 collapsed into the sinkhole.
- The houses on Stands 2656 and 2657 are located approximately 3 m to the south-east of the newly formed sinkhole. Structural damages to illegal additions to the houses on Stands 2656 and 2657, built over the midblock sewer line.

A gravity survey on a 10 m station interval was conducted during February 2006 as part of the investigation of the sinkhole that occurred on the western boundary of Stand 2636 in January 2006 (Report Number KHH1465, May 2006). A total of seven percussion boreholes (BH1 to BH7) were drilled along the area where the bulk sewer

line was damaged and on gravity anomalies and gradients to determine the dolomite bedrock profile in March 2006 (Report Number KHH1465, May 2006). Accessibility for the drilling rig was limited due to a palisade fence situated 1 m to the north-west of the sewer main and houses built too close to each other to the south-east. One of the boreholes (BH2) was drilled at a 30 degree angle from the vertical towards the sewer, close to the manhole within an area where limited surface subsidence had already occurred.

The gravity survey and some of the boreholes drilled during the sinkhole investigation in 2006 was incorporated into the sinkhole study during 2010. Percussion drilling in 2010 was carried out in two phases: Phase 1 included the drilling of Boreholes EMM495 to EMM498 on 1 February 2010 placed around the sinkhole that occurred on 28 January 2010 (Report Number VGI3118-WO270-2, February 2010). Phase 2 included the drilling of Boreholes EMM518 to EMM521 on 22 April 2010 within the additional affected sinkhole area.

The affected area, existing infrastructure, gravity survey and the position of Boreholes BH1 to BH7, EMM495 to EMM498 and EMM518 to EMM521 are displayed in Figure E.1. Three geological cross-sections (A-A', B-B' and C-C') presenting sub-surface conditions as encountered during the various stages of investigations are illustrated in Figures E.2 to E.4.

The gravity survey revealed the following (Report Number KHH1465, May 2006):

- Two distinct gravity high areas: The first is located as a north-east to south-west trending ridge located between Leondale Road and the sewer main; the second is located east of the structures on Stands 2656 to 2660.
- Two gravity low areas: Both situated to the south-west and north-east of the distinct gravity high areas.
- A third intermediate gravity low area is situated to the south-east within the gravity high area on Stands 2633 and 2634.

The sinkhole investigation during 2006 revealed the following sub-surface profile in the area of the sinkhole as illustrated by the Geological Cross-Section A-A' from Manhole MH1 to Manhole MH2 in Figure E.2:

- Dolomite bedrock at a depth ranging from 6 m to 14 m. A 1 m to 4 m thick horizon of highly weathered soft rock dolomite at variable depths ranging from 4 m to 11 m. Interlayered highly weathered soft rock dolomite and shale was encountered in one borehole between a depth of 13 m and 14 m just above dolomite bedrock.

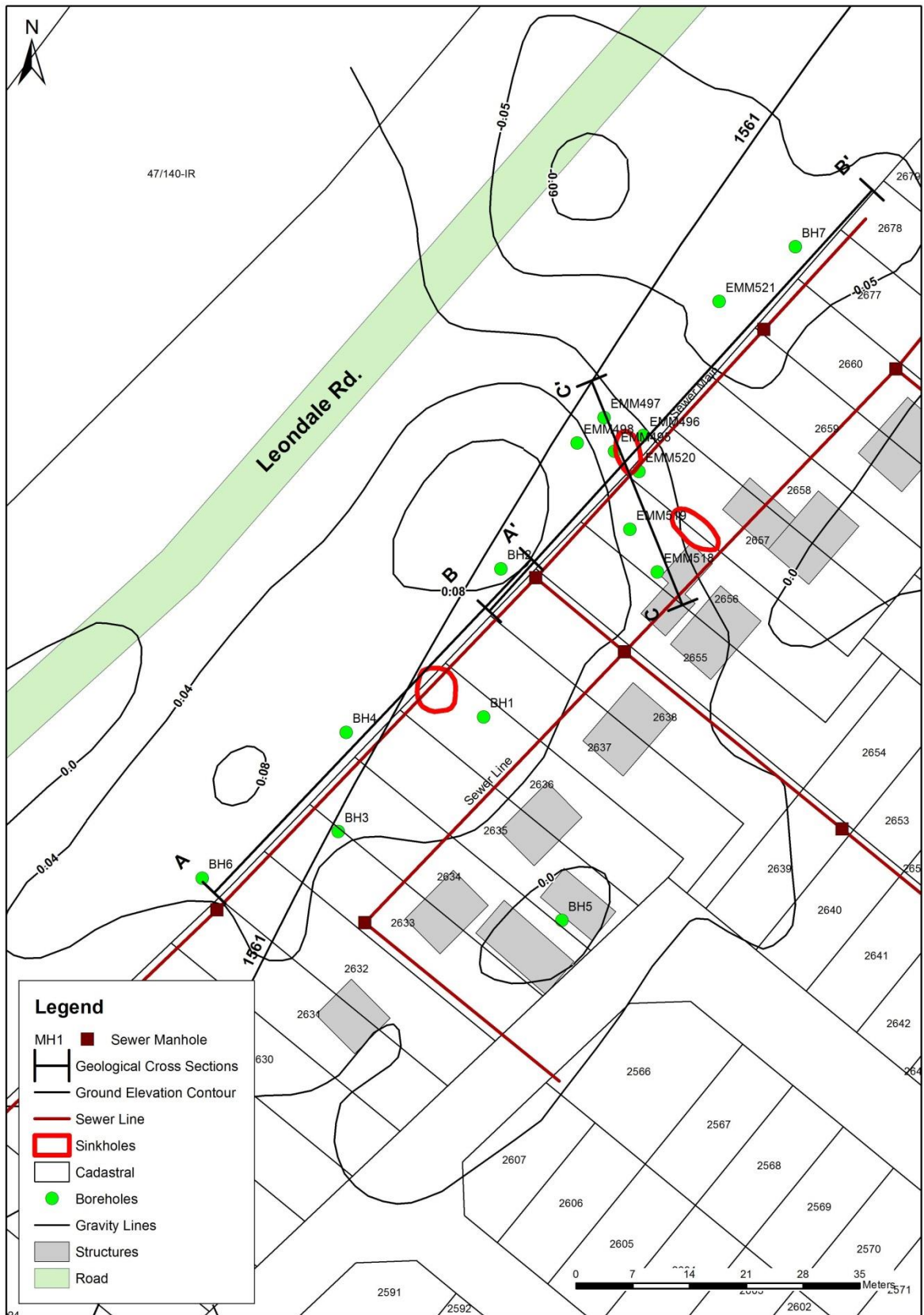


Figure E.1: Case Study 5 – Plan view of affected area, existing infrastructure, gravity contours and the position of boreholes.

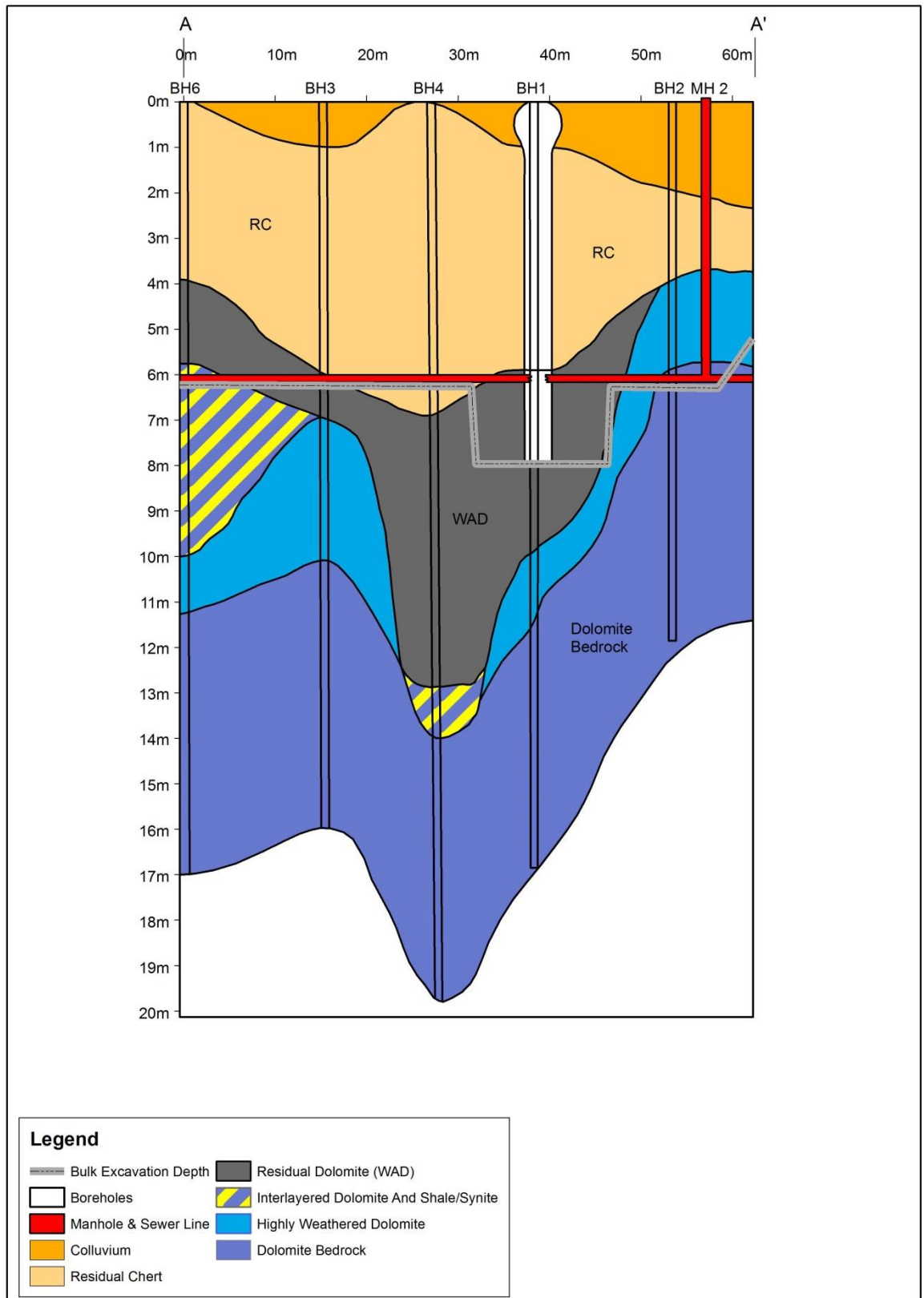


Figure E.2: Case Study 5 – Interpreted Geological Cross-Section A – A` from Manhole MH1 to MH2.

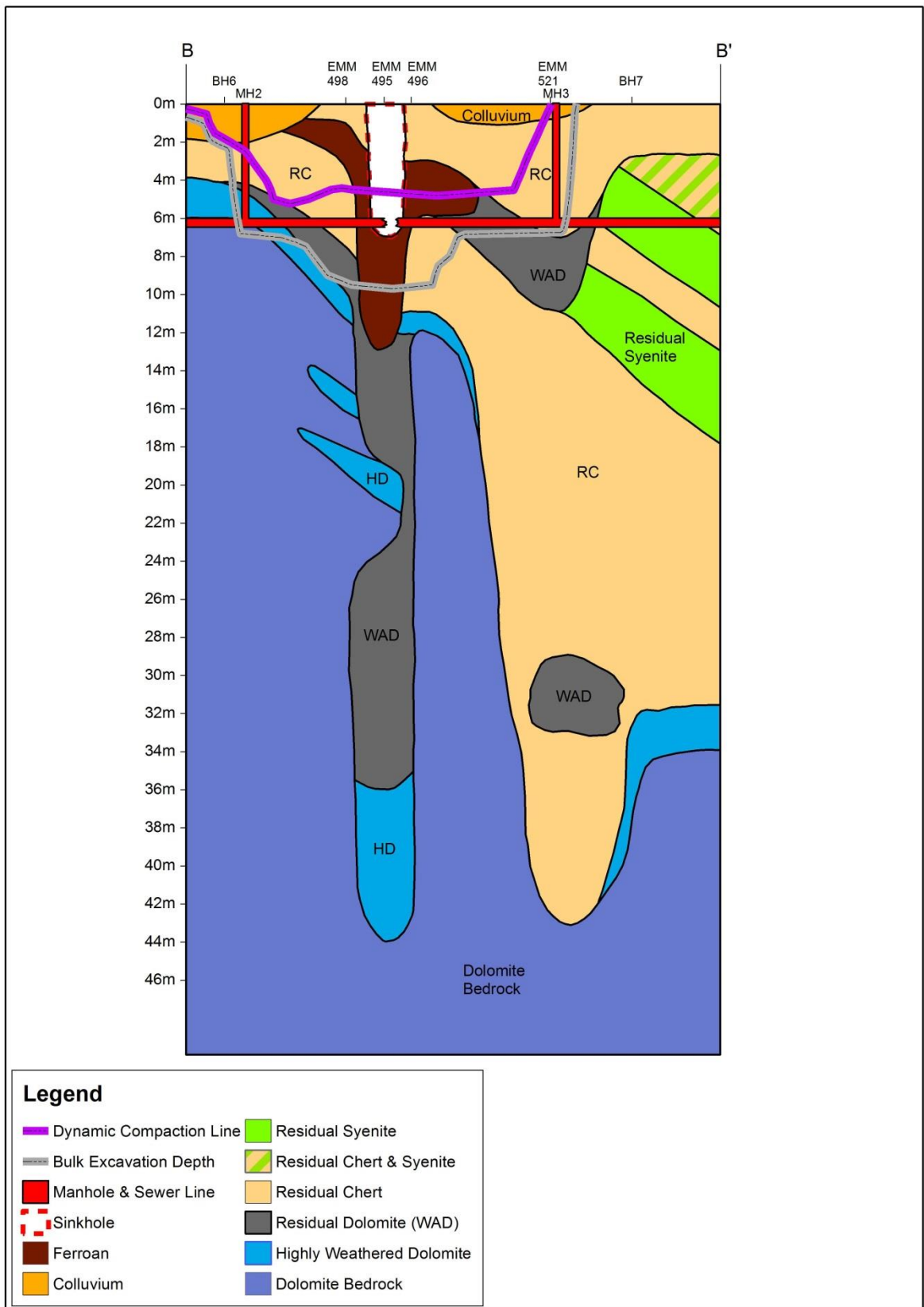


Figure E.3: Case Study 5 – Interpreted Geological Cross-Section B – B'.

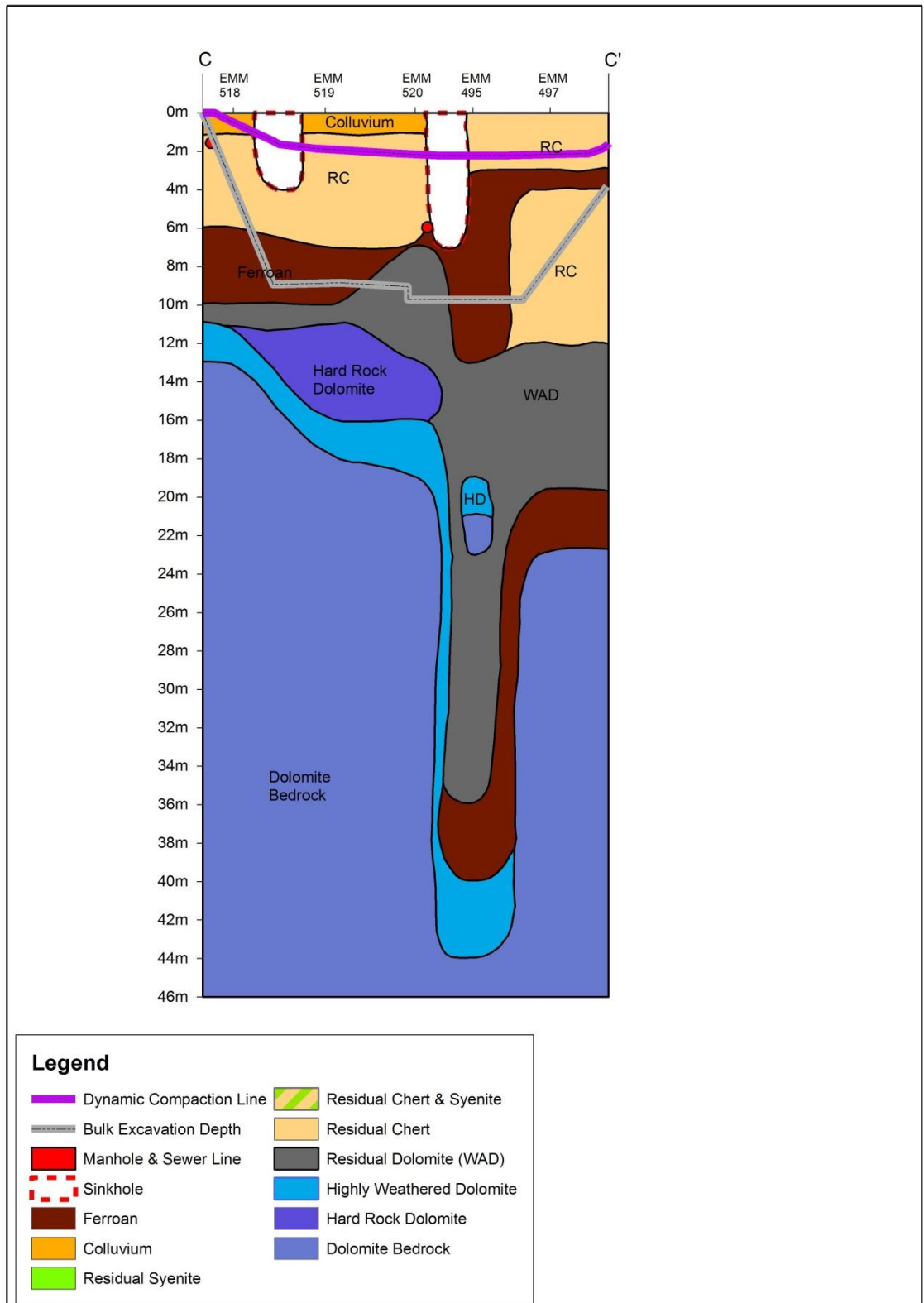


Figure E.4: Case Study 5 – Interpreted Geological Cross-Section C – C`.

- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of colluvium and or residual chert to a depth of between 4 m and 7 m. The surface layer is underlain by residual dolomite comprising ferroan and manganiferous (wad) soils. The residual dolomite (ferroan soils) was encountered in one borehole between a depth of 4 m and 6 m. The thickness of the residual dolomite (wad) layer varies between 1 m and 6 m and was encountered between a depth of 4 m and 13 m. Interlayered residual dolomite (wad) and residual shale (or syenite) was encountered in one borehole between 6 m and 10 m. Rapid penetration rates and air and sample losses were encountered in the boreholes drilled the closest to the sinkhole in the residual dolomite zones.
- No cavities were, however, encountered in boreholes during the drilling process.
- No groundwater was encountered and the regional groundwater level is at 1545 m AMSL (16 m below natural ground level) within dolomite bedrock. A sewage odour was although detected during the drilling of the boreholes, especially at the hard rock dolomite interface.
- The sinkhole is located in a gravity high area.

A geological cross-section B-B` presenting sub-surface conditions as encountered during the dolomite stability investigation parallel to the broken sewer line and through the sinkhole area that occurred in January 2010 is illustrated in Figure 48 and revealed the following:

- Dolomite bedrock at a depth ranging from 6 m to 44 m. A 1 m to 8 m thick (or absent) horizon of highly weathered soft rock dolomite at variable depths ranging from 4 m to 44 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of colluvium and or residual chert to a depth of between 1 m and 7 m. The surface layer is underlain by residual dolomite comprising ferroan and manganiferous (wad) soils. The thickness of the residual dolomite (ferroan soils) varies between 2 m and 10 m and was encountered between a depth of 1 m and 13 m in the area of the sinkhole. The thickness of the residual dolomite (wad) layer varied between 3 m and 23 m and was encountered between a variable depth of 7 m and 36 m.

A second and third layer of residual chert varying in thickness from 2 m to 16 m was intercepted between a depth of 8 m and 43 m in two of the boreholes drilled in the northern half of the cross-section. Interlayered residual chert and syenite was encountered in one borehole also in the northern half of the cross-section between a depth of 3 m and 4 m. Residual syenite (or shale) was encountered in one borehole between 4 m and 8 m and again between 10 m and 15 m in the northern half of the cross-section. Rapid penetration rates and air and sample losses were encountered in most of the boreholes in the residual dolomite, highly weathered soft rock dolomite and hard rock dolomite.

- Cavities were, however, not encountered within any of the boreholes drilled.

- A groundwater rest level was recorded in most of the boreholes drilled at a depth of between 8,9 m and 15,2 m (or 1545,8 m AMSL to 1552,1 m AMSL) within residual dolomite and residual chert. The regional groundwater level is anticipated at a depth of 1545 m AMSL (16 m below natural ground level) above and within dolomite bedrock. It is difficult to determine if the groundwater levels intercepted in boreholes can be regarded as the OWL or did the water originated from the broken sewer line located at a depth of approximately 8 m below natural ground level.
- The sinkhole is located on a gravity gradient area.

A geological cross-section C-C` presenting sub-surface conditions as encountered during the dolomite stability investigation through both sinkhole areas that occurred in 2010 is illustrated in Figure E.4 and revealed the following:

- Dolomite bedrock at a depth ranging from 13 m to 44 m. A 2 m to 4 m thick horizon of highly weathered soft rock dolomite directly above hard rock dolomite at variable depths ranging from 11 m to 44 m in most boreholes. A 3 m to 5 m thick horizon of hard rock dolomite was encountered between a depth of 11 m and 16 m above highly weathered soft rock dolomite in the eastern half of the cross-section and a dolomite floater within residual dolomite (wad) between a depth of 19 m and 23 m in the central to western portion of the cross-section.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of colluvium and or residual chert to a depth of between 6 m and 12 m. The surface layer is underlain by residual dolomite (ferroan and wad soils). A residual dolomite (ferroan soils) layer of 1 m to 10 m thickness was encountered at a depth of between 3 m and 40 m. Residual dolomite (wad) of 1 m to 23 m thickness was encountered in general just above highly weathered dolomite rock between a depth of 7 m and 36 m. Fast penetration rates and air and sample losses were encountered in all the boreholes in the residual dolomite, highly weathered soft rock dolomite and hard rock dolomite.
- Cavities were not encountered in any of the boreholes.
- A groundwater rest level was recorded in most of the boreholes drilled at a depth of between 8,7 m and 15,2 m (or 1545,8 m AMSL to 1552,3 m AMSL) within residual dolomite and residual chert. The regional groundwater level is anticipated at a depth of 1545 m AMSL (16 m below natural ground level) above and within dolomite bedrock.

It is difficult to determine if the groundwater levels intercepted in boreholes can be regarded as the OWL or did the water originated from the broken sewer line located at a depth of approximately 8m below natural ground level.

- The sinkhole is located on a gravity gradient area.



Taking the existing geological conditions on site into account (e.g. depth to dolomite bedrock, depth and extent of sinkholes, presence of highly erodible and compressible residual dolomite (wad)) and the affected infrastructure (e.g. houses and broken sewer lines) the following was recommended in terms of rehabilitation of the affected area:

## **2. CONSTRUCTION PHASE**

### **2.1 Rehabilitation of Sinkhole on Stand 2636**

Apart from replacing the existing leaking bulk sewer line with HDPE material from manhole to manhole; based on the subsurface conditions outlined above, improvement of the subsurface conditions required the use of the Inverted Filter Method. However, during the trench excavation a large cavity was encountered at a depth of 6m below natural ground level in the sidewall of the trench and the Dynamic Compaction method was additionally required in the area of the cavity (Report Number KHH1490, August 2006). The area of rehabilitation and bulk excavation are indicated on Figure E.5. The following rehabilitation work was carried out:

- Remove the 2,1m high concrete palisade fence, situated 1 m to the north-west of the sewer line, from Manhole MH1 to Manhole MH2.
- Block off the sewer between Manholes MH1 and MH2. Pumping of sewage in a temporary pipe at ground surface from one manhole to the other over a distance of 60 m, during the construction phase. The inverts at the manholes shall be properly plugged to prevent any sewage spillage in the area of construction.
- Bulk excavation (70 m by 16 m) down to one metre below the invert level of the sewer (confirmed at 6 m below natural ground surface) between Manholes MH1 and MH2. Minimum width of the floor of the excavation must be 2 m. The side slopes should be excavated at 1V:1H.
- Remove and discard the existing sewer between Manholes MH1 and MH2.
- The sinkhole area was then over-excavated to a depth of 8 m below natural ground level over a distance of 15 m to expose the throat of the sinkhole and backfilled with dump rock and granular soil compacted to 95% of Modified AASHTO maximum dry density at optimum moisture content. All excavated dolomite residuum (wad) material was discarded and removed off site.

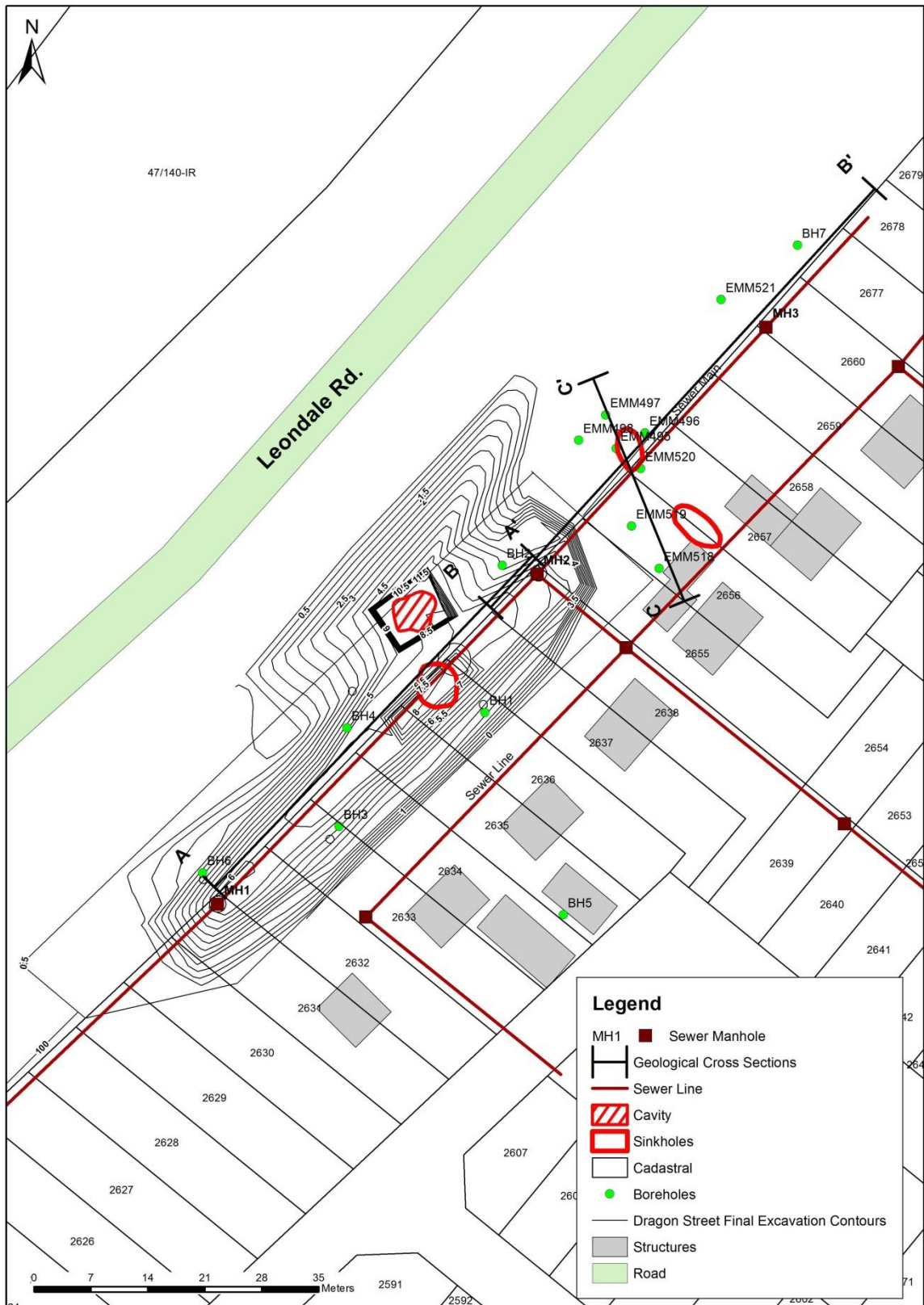


Figure E.5: Case Study 5 – Area of rehabilitation and bulk excavation at Dragon Street.

- The remainder of the trench floor area at a depth of approximately 6 m to 7 m below natural ground surface was compacted to 95% of Modified AASHTO maximum dry density at optimum moisture. A 1 m thick and 1 m wide engineered earth mattress comprising G6/G7 quality trench spoil material was constructed as 150 mm thick layers, each compacted to at least 95% compaction effort, along the entire length of the sewer to 0,1 m below the required bedding layer level. The new 300 mm HDPE pipe was placed on and within a 0,1 m thick layer of bedding material and tied in with the existing system. The sewer trench was then backfilled in 300 mm thick layers of trench spoil compacted to at least 95% compaction effort.
- During the trench excavation to replace the broken sewer line between Manholes MH1 and MH2 a cavity (2 m height and 7 m diameter in size between 6 m and 8 m below ground level) was encountered at the base of the excavation in the north-western side wall of the trench excavation in the area where the sinkhole was over-excavated to a depth of 8 m (Plate E.4). All material above the cavity was removed with an excavator and the cavity was excavated down to a depth of 12 m below natural ground level. Dynamic Compaction (DC) probing was performed within the deeper exposed section to collapse potential additional subsoil cavities, after which dump rock and granular soil was used to choke the throat. This process was followed by backfilling of the excavation in 1,5 m to 2,0 m lifts with gravelly soils, compacted using DC to construct a soil raft. The site was levelled and an ironing operation was conducted over the entire area to complete the shallow DC treatment. The purpose of the DC was to densify the upper 12 m of the soil profile substantially within the area where the cavity was encountered, thereby decreasing permeability and erodibility.



**Plate E.4: Cavity exposed during bulk excavation of sewer and sinkhole north-west of Stand 2636.**

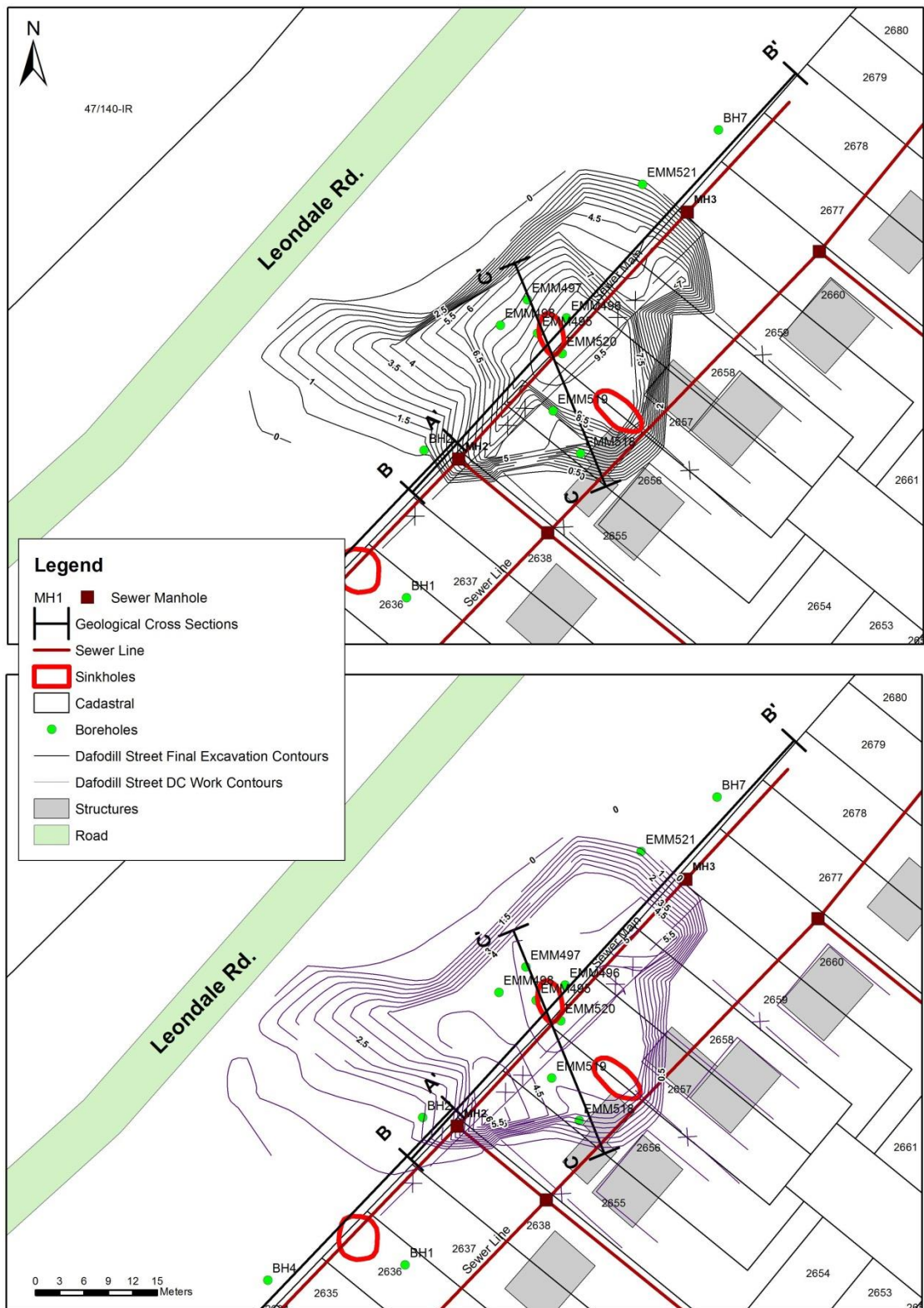
## 2.2 Rehabilitation of Sinkholes on Stands 2656 and 2657

Apart from replacing the existing leaking bulk sewer line with HDPE material; based on the subsurface conditions outlined above, improvement of the subsurface conditions required the undertaking of a Dynamic Compaction programme combined with the Inverted Filter Method (Report Number VGI3118R-WO270-2, February 2010). The area of rehabilitation, bulk excavation and Dynamic Compaction contours are indicated on Figure E.6. The following rehabilitation work was carried out:

- Remove the 2,1 m high concrete palisade fence over a distance of approximately 40 m, demolish boundary wall between Stands 2656 and 2657 and illegal temporary structures on Stands 2655, 2656 and 2657, situated within the area of bulk excavation.
- Block off the sewer between Manholes MH2 and MH3 (newly constructed to reduce costs). Pumping of sewage in a temporary pipe at ground surface from one manhole to the other over a distance of 40 m, during the construction phase. The inverts at the manholes shall be properly plugged to prevent any sewage spillage in the area of construction.
- Bulk excavation of the affected area (40 m by 30 m) to a depth of approximately 6 m below natural ground level. The two sinkhole areas were then deeper excavated to a maximum depth of 10 m below natural ground level to expose the throat of the sinkholes.
- Remove and discard the existing 300 mm diameter uPVC bulk sewer between Manholes MH2 and MH3. The broken 160 mm diameter uPVC mid-block sewer line was temporarily repaired in the area of the second sinkhole on the boundary between Stands 2656 and 2657 during the construction phase.

A crack survey was conducted on all structures in close proximity of the area proposed for rehabilitation before the Dynamic Compaction programme and after the Dynamic Compaction programme.

Dynamic Compaction (DC) probing was first performed within the deeper exposed sinkhole sections to collapse potential subsoil cavities and to densify residual dolomite (wad) at depth, after which dump rock and gravelly soils was used to choke the throat. This process was followed by backfilling of the excavation in 1,5 m to 2,0 m lifts with gravelly soils, compacted using DC to construct a soil raft to a depth of approximately 5 m below natural ground level. The deep DC consisted of primary and secondary prints on a 5 m by 5 m grid spacing with volume and blow counts recorded for quality purposes for each print position. The purpose of the DC was to densify the soil profile to a depth of 5 m below natural ground level substantially, thereby decreasing permeability and erodibility (Plate E.5).



**Figure E.6: Case study 5 – Area of rehabilitation, bulk excavation and Dynamic Compaction contours at Dafodill Street.**



**Plate E.5: Dynamic Compaction in progress in affected area at Stands 2655 to 2657.**

- A new 300 mm diameter HDPE bulk sewer line was placed between Manhole MH2 to MH3 at a depth of approximately 6 m within a 0,1 m bedding layer. Thus required the re-excitation of 1 m in the upper DC layer. The bulk excavation area was then backfilled in 300 m thick layers of gravelly excavation spoil (G6/G7 quality) compacted to at least 95% compaction effort.
- A new 160 mm diameter shallow HDPE mid-block sewer at a depth of approximately 1,5 m and three manholes were also installed from Stand 2633 to Stand 2638 and from Stand 2655 to Stand 2660 during the end of 2010.

The affected areas have been improved to a tolerable hazard. A tolerable hazard was reached by densifying or removing and replacing problematic materials such as the residual dolomite (wad), collapse and backfilling of cavities, with an engineered soil mattress of between 6 m to 12 m thickness by means of the Dynamic Compaction method or by conventional backfilling methods and the removal and replacement of wet services.

**APPENDIX F**

***CASE STUDY 6***

## CASE STUDY 6

### 1. INTRODUCTION

During March 2006 a trench, located on the south-eastern shoulder of M.C. Botha Road, extending to a maximum depth of approximately 1,0 m below natural ground level, that was left open for a long period of time caused the formation of a sinkhole after heavy rains. Structural damages (cracks) to the south-eastern perimeter wall of the Vosloorus Library, located to the opposite of the sinkhole in the road, also started to appear a few weeks after the formation of the sinkhole. A site inspection on 10 April 2006 and follow-up inspection on 18 May 2006 revealed the following (Report Number KHH1474, May 2006):

- An oval shaped sinkhole, 20 m long, 6 m wide (defined by 0,5 m wide surface cracks extending to a depth of at least 1m in the tar road) extending to a depth of 2 m. Located within the south-eastern servitude of M.C. Botha Road along an open trench excavation (Plate F.1). The sinkhole extending below M.C. Botha Road westwards to the Vosloorus Library and Vosloorus Civic Centre.



**Plate F.1: Sinkhole in south-eastern servitude of M.C. Botha Road.**

- 11 kV Electrical cables perpendicular to M.C. Botha Road exposed within the sinkhole area.
- A bulk water line (steel 200 mm diameter) running parallel to M.C. Botha located in the north-western road servitude at a depth of between 1 m and 1,5 m. A 110 mm and 160 mm diameter PVC water line running parallel to M.C. Botha located in the south-eastern road servitude and the 110 mm PVC line



crossing M.C. Botha perpendicular to connect to the bulk water line located in the north-western road servitude.

- The sinkhole is partially filled with large chert boulders and soil with cavernous conditions (air filled voids) visible (Plate F.2). The disappearance of backfill material placed in the sinkhole area by Municipal officials indicated that subsurface erosion was taking place with a high risk for a very large sinkhole to develop.



**Plate F.2: Cavernous conditions visible between chert boulders in sinkhole area.**

- At the Vosloorus Library: Structural cracks (i.e. vertical and horizontal) of up to 40 mm width observed at the south-eastern perimeter wall, within an area of subsurface wet services including sewer, water and stormwater pipes. The Vosloorus Library site is slope as such that surface water cannot freely drain away from the building, therefore water is accumulating next to the structure, especially on the eastern and southern side of the building, in the area where structural cracks were observed and partial subsidence had taken place. Additionally to the above, flower beds and fountains are situated directly next to the building to the east and south, providing a high risk for the development of sinkholes.

The investigation included a gravity survey conducted on a 2,5 m grid spacing at the Vosloorus Library and three 10 m spaced lines on a 2,5 m station interval at M.C. Botha Road, to provide information on the depth and morphology of the dolomite profile. Percussion drilling was conducted in three phases, two of these phases were performed before rehabilitation and the third phase after the original rehabilitation. Phase 1 included the drilling of Boreholes BH1 to BH12 on 24 May 2006 within M.C. Botha Road around the sinkhole area and two of these boreholes were

drilled on the eastern side of the Vosloorus Library in close proximity to where structural damage was observed. Phase 2 included the drilling of Boreholes BH13 to BH18 on 26 October 2006 placed according to gravity features not drilled during the first phase investigation. Three of the boreholes (BH13 to BH15) were drilled at a 20 to 30 degree angle from vertical to evaluate subsurface conditions below the Vosloorus Library, especially in the area showing ongoing structural deterioration. Phase 3 included the drilling of Boreholes BH19 to BH31 on 9 July 2007 within the north-western road servitude of M.C. Botha Road. The purpose of the Phase 3 investigation was to determine the extent of a large cavity that was discovered during the bulk excavation of the area to be rehabilitated in M.C. Botha Road.

The affected area, existing infrastructure, gravity survey and the position of Boreholes BH1 to BH31 are displayed in Figure F.1 (Report Number KHH1516, November 2006).

The gravity survey revealed the following (Report Number KHH1516, November 2006):

- Two gravity low areas: The first occurs as a north to south trending gryke feature in M.C. Botha Road extending towards the Vosloorus Civic Centre and the second is situated below the south-eastern portion of the Vosloorus Library in the area of structural damage and deterioration.
- Two distinct gravity high areas are present on both sides of the gravity low area that represents a gryke, viz. in the area of the shopping centre situated on the eastern boundary of M.C. Botha and the second appears as a ridge, situated to the east of the Vosloorus Library building.
- A third gravity high area is present within the gravity low area that represents a gryke.

## **2. GEOLOGICAL CROSS-SECTIONS**

The boreholes drilled during the Phase 1 to Phase 3 investigations revealed the following sub-surface profiles as illustrated in the geological cross sections Figure F.2 to Figure F.5 (Report Number KHH1516, November 2006):

### **2.1 Phase 1 and Phase 2 Dolomite Stability Investigations**

Figure F.2 and Figure F.3 provides four interpreted geological cross-sections (A - A' to D - D'), based on the borehole information and gravity survey as obtained during the Phase 1 and Phase 2 dolomite stability investigations. The boreholes revealed the following subsurface profiles:

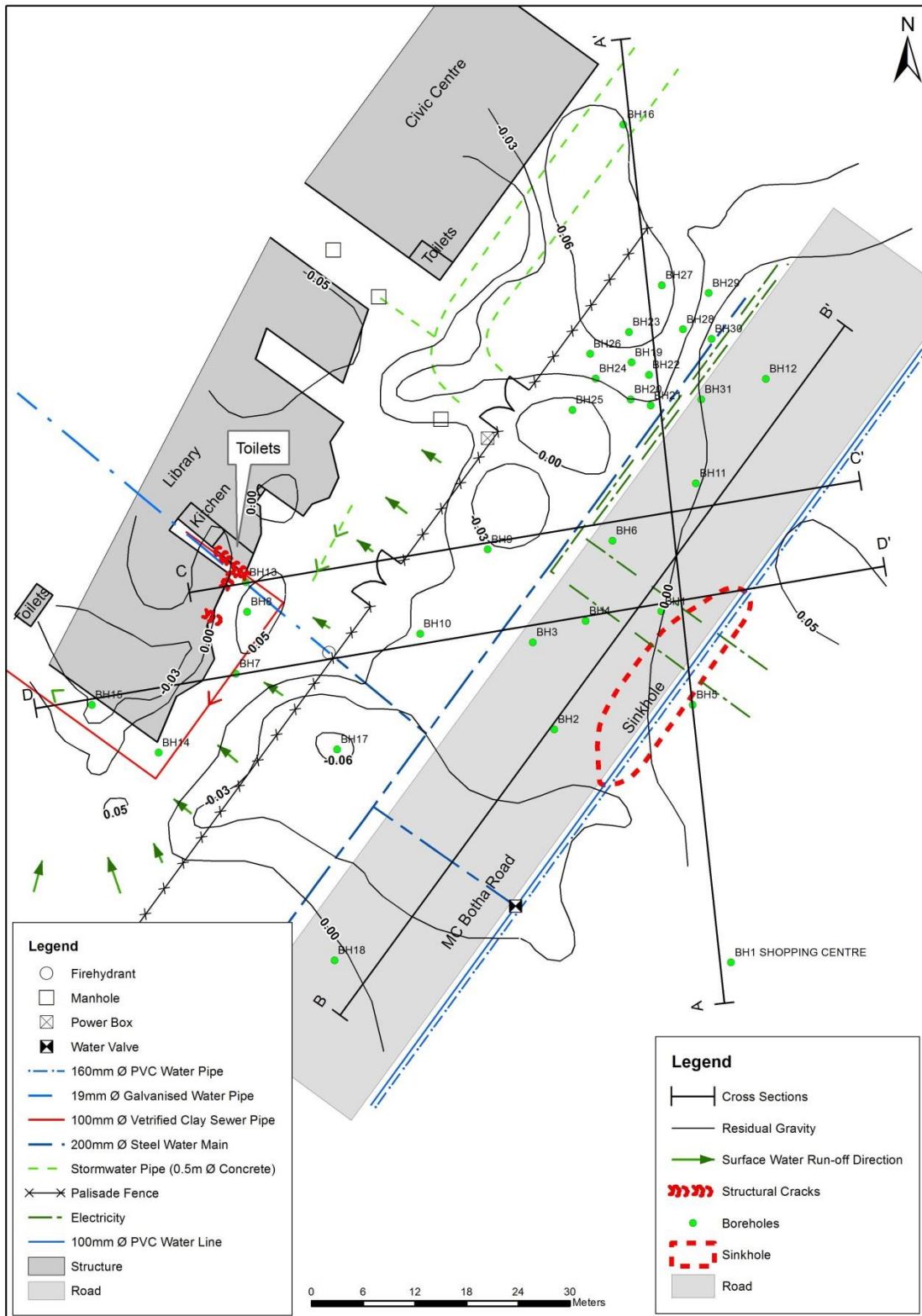


Figure F.1: Case Study 6 – Plan view of affected area, existing infrastructure, gravity contours and position of boreholes.

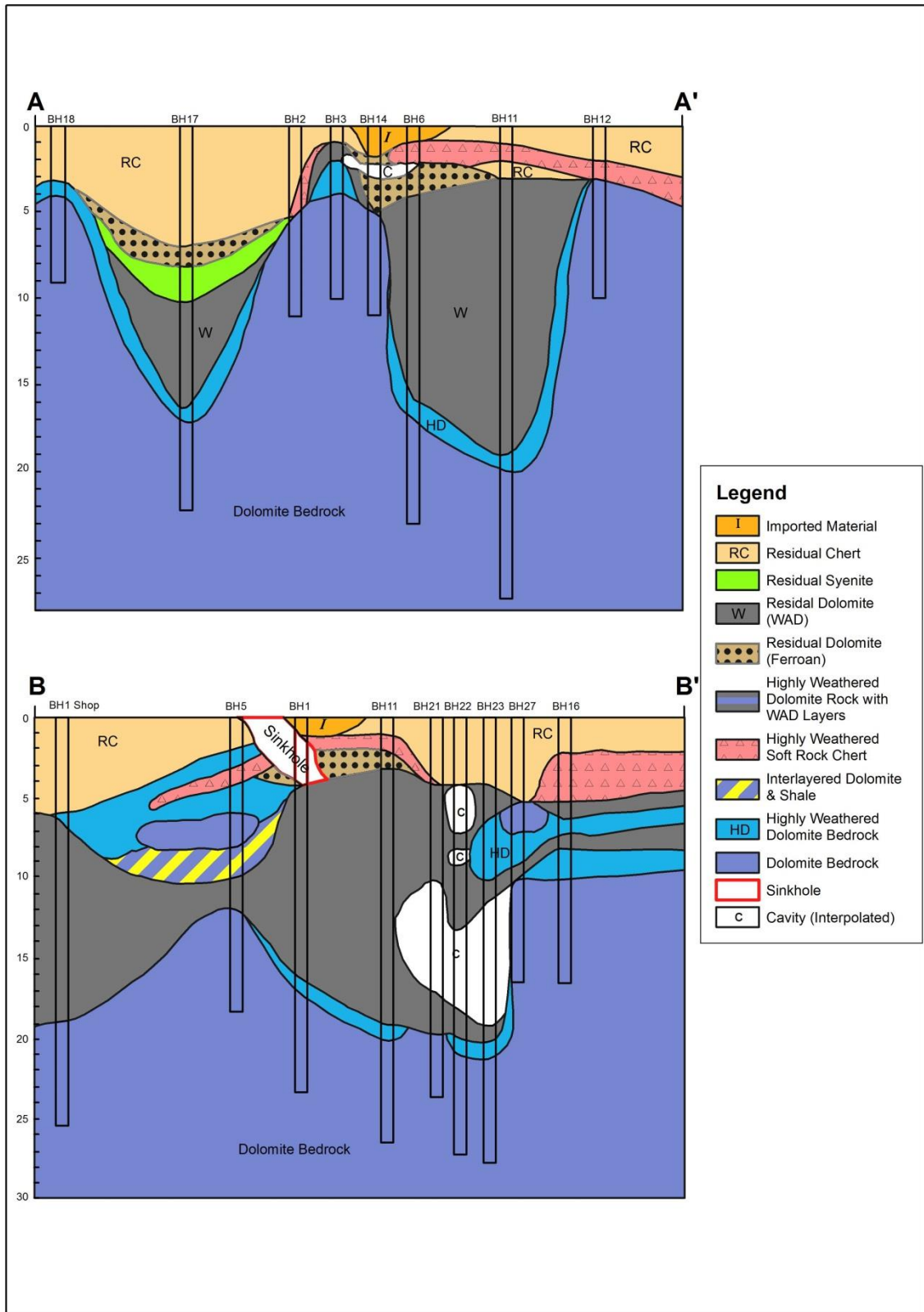


Figure F.2: Case Study 6 – Interpreted Geological Cross-Section A – A` and B – B`.

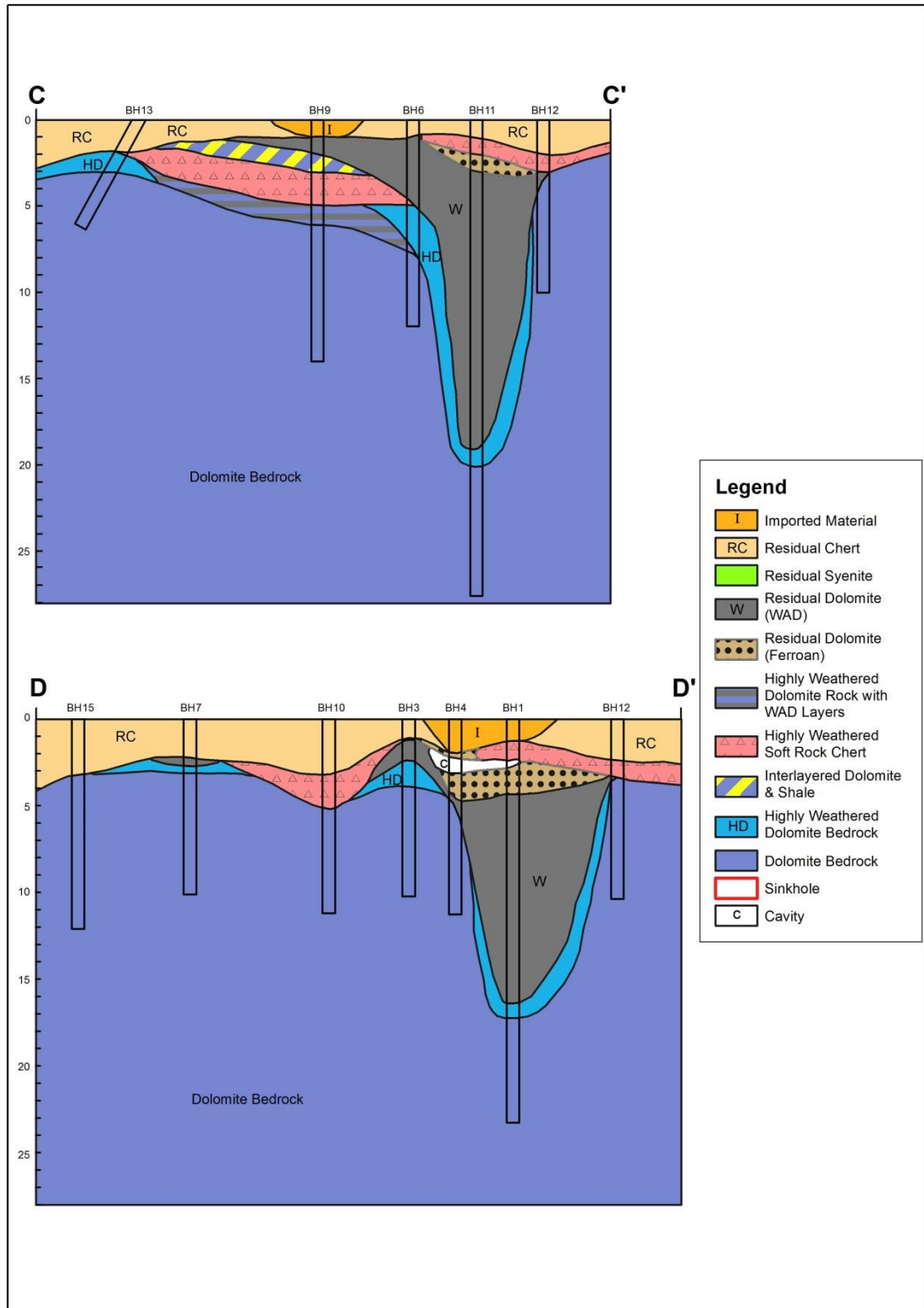


Figure F.3: Case Study 6 – Interpreted Geological Cross-Section C – C' and D – D'.

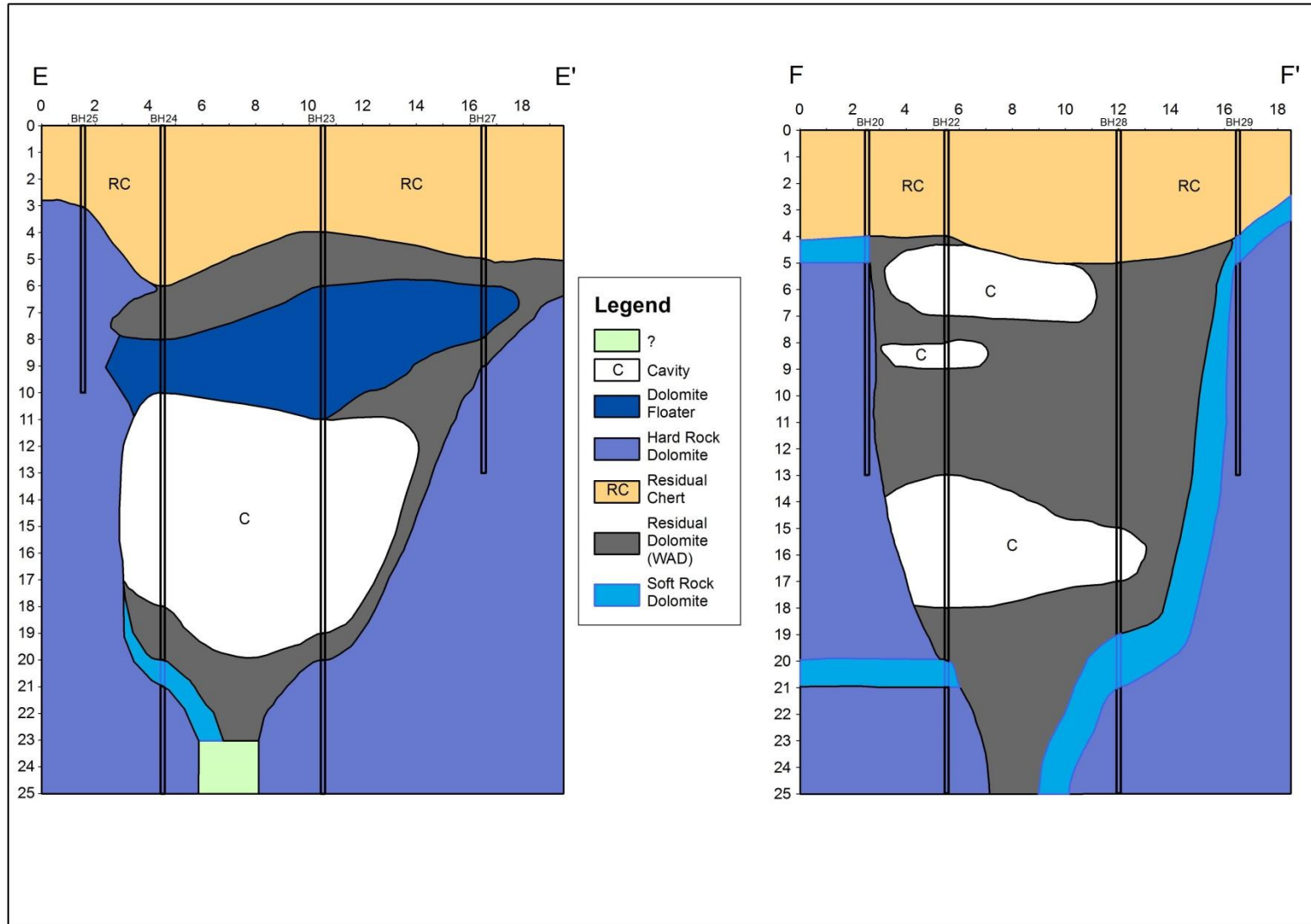


Figure F.4: Case Study 6 – Interpreted Geological Cross-Section E – E` and F – F`.

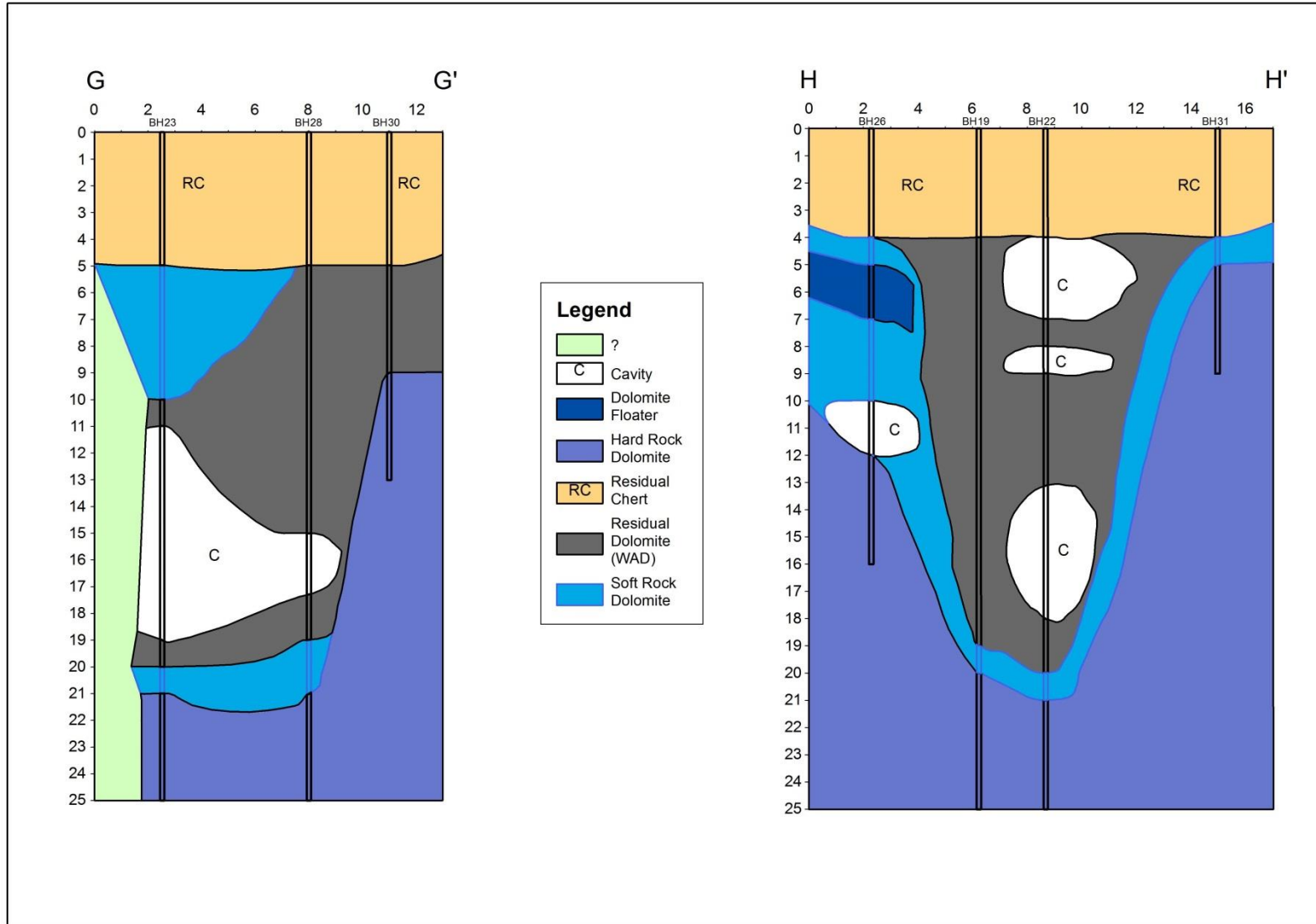


Figure F.5: Case Study 6 – Interpreted Geological Cross-Section G – G` and H – H`.

### 2.1.1 Geological Cross-Section A-A'

- The interpreted geological cross-section A - A' is located along the centre line of M.C. Botha road.
- Dolomite bedrock at a depth ranging from 3 m to 20 m, presenting two deep zones bordered by shallow dolomite bedrock on both sides. A 1 m to 2 m (or absent) thick horizon of highly weathered soft rock dolomite at variable depths ranging from 2 m to 20 m.
- The blanketing layer above dolomite bedrock comprises: A 1 m to 2 m thick horizon of imported fill material only encountered within the area of the sinkhole. The remaining surficial layer comprises residual chert from ground surface extending to a depth of 1 m to 7 m. In the northern and central half of the cross-section the residual chert is underlain by a 1 m thick highly weathered soft rock chert capping layer between a depth of 1 m and 5 m. The residual chert and chert capping layer is underlain by residual dolomite comprising ferroan and manganiferous (wad) soils. The 1 m to 3 m thick residual dolomite (ferroan soils) were encountered between depths of 1 m and 5 m in the northern portion of the cross-section and between a depth of 4 m and 8 m in the southern portion of the cross-section. The 6 m to 16 m thick horizon of residual dolomite (wad) was encountered between depths of 1 m and 19 m in the central and northern portion of the cross-section and between 10 m and 16 m in the southern portion of the cross-section. Residual syenite was encountered in one borehole between 8 m and 10 m above residual dolomite (wad).
- An interpolated cavity is shown in the central portion of the cross-section within the area of the sinkhole between depths of 2 m and 3 m.
- The highly weathered soft rock chert and residual syenite both forms a supporting arch above the residual dolomite (wad) and cavities at depth.
- No groundwater was encountered and the regional groundwater level is at 1518 m AMSL (33 m below natural ground level) within dolomite bedrock.

### 2.1.2 Geological Cross-Section B-B'

- The interpreted geological cross-section B - B' (Refer to Figure F.2) is located along the gravity low area that represents a gryke-type feature (deeply weathered zone typically filled with residual dolomite (Plate F.3).
- Dolomite bedrock at a depth ranging from 9 m to 21 m. Hard rock dolomite was also encountered in two boreholes between a depth of 5 m and 8 m. A 1 m thick (or absent) horizon of highly weathered soft rock dolomite just above dolomite bedrock between 13 m and 21 m. A 1 m to 4 m (or absent) thick horizon of highly weathered soft rock dolomite is encountered within the blanketing layer at variable depths ranging from 2 m to 10 m in four boreholes. Interlayered soft rock dolomite and shale encountered between a depth of 8 m and 11 m comprising a little wad between a depth of 10 m and 11 m in one borehole.





**Plate F.3: Photo of gryke taken towards the south with soft rock dolomite capping removed over cavity in area of east-west aligned cables.**

- The blanketing layer above dolomite bedrock comprises: A 1 m thick horizon of imported fill material only encountered within the area of the sinkhole. The remaining surficial layer comprises residual chert from ground surface extending to a depth of 1 m to 6 m. In sub-areas the residual chert is underlain by a 1 m to 3 m thick highly weathered soft rock chert capping layer between a depth of 1 m and 5 m. The residual chert and chert capping layer is underlain by residual dolomite comprising ferroan and manganiferous (wad) soils. The 1 m to 2 m thick residual dolomite (ferroan soils) were encountered between depths of 2 m and 4 m in the central portion of the cross-section in the same area as the sinkhole. The 1 m to 16 m thick horizon of residual dolomite (wad) was encountered between depths of 3 m and 20 m.
- Cavities were encountered within the residual dolomite (wad) between a depth of 4 m and 7 m, 8 m and 9 m and 10 m to 19 m.
- The highly weathered soft rock dolomite and chert encountered in sub-areas both forms a supporting arch above the residual dolomite (wad) and cavities at depth.
- No groundwater was encountered and the regional groundwater level is at 1518 m AMSL (33 m below natural ground level) within dolomite bedrock.

### 2.1.3 Geological Cross-Section C - C':

- The interpreted geological cross-section C - C' (refer to Figure F.3) is perpendicular to the gryke-type feature along the gravity low area, presenting a nearly 30 m wide and 19 m deep gryke (deeply weathered zone) typically filled with residual dolomite.

- Dolomite bedrock at a depth of 19 m within the gryke and bordered by dolomite bedrock at a depth of 3 m on both sides of the gryke. A 1 m to 3 m thick (or absent) horizon of highly weathered soft rock dolomite just above dolomite bedrock between 2 m and 20 m. In one borehole interlayered highly weathered soft rock dolomite with shale was encountered between a depth of 2 m and 3 m and highly weathered soft rock dolomite with wad layers was encountered between a depth of 5 m and 6 m.
- The blanketing layer above dolomite bedrock comprises: A 1 m thick horizon of imported fill material only encountered in one borehole in close proximity to the sinkhole. The remaining surficial layer comprises residual chert from ground surface extending to a depth of 1 m to 2 m. In sub-areas the residual chert is underlain by a 1 m to 2 m thick highly weathered soft rock chert capping layer between a depth of 1 m and 5 m. The residual chert and chert capping layer is underlain by residual dolomite comprising ferroan and manganiferous (wad) soils. The 1 m thick residual dolomite (ferroan soils) was encountered in one borehole between a depth of 2 m and 3 m in the central portion of the cross-section in the same area as the sinkhole. The 1 m to 16 m thick horizon of residual dolomite (wad) was encountered between depths of 3 m and 19 m.
- Cavities were not encountered.
- The highly weathered soft rock chert encountered in sub-areas forms a partially supporting arch above the residual dolomite (wad) and potential cavities at depth.
- No groundwater was encountered and the regional groundwater level is at 1518 m AMSL (33 m below natural ground level) within dolomite bedrock.

#### 2.1.4 Geological Cross-Section D - D':

- The interpreted geological cross-section D-D' (refer to Figure F.3) is perpendicular to the gryke-type feature along the gravity low area and parallel to geological cross-section C-C', presenting a nearly 30 m wide and 16 m deep gryke (deeply weathered zone) typically filled with residual dolomite.
- Dolomite bedrock at a depth of 17 m within the gryke and bordered by dolomite bedrock at a depth of 3 m to 4 m on both sides of the gryke. A 1 m to 2 m thick (or absent) horizon of highly weathered soft rock dolomite just above dolomite bedrock between 2 m and 17 m.
- The blanketing layer above dolomite bedrock comprises: A 1 m to 2 m thick horizon of imported fill material only encountered in two boreholes in close proximity to the sinkhole. The remaining surficial layer comprises residual chert from ground surface extending to a depth of 1 m to 3 m. The residual chert is typically underlain by a 1 m to 2 m thick highly weathered soft rock chert capping layer between a depth of 1 m and 5 m. The residual chert and chert capping layer is underlain by residual dolomite comprising ferroan and manganiferous (wad) soils. The 1 m to 3 m thick residual dolomite (ferroan soils) was encountered in two boreholes between a depth of 1 m and 5 m in the same area as the sinkhole. The 1 m to 12 m thick horizon of residual dolomite (wad) was encountered between depths of 1 m and 16 m in most of the boreholes.

- An interpolated cavity within residual dolomite is shown between a depth of 2 m and 3 m in the area of the sinkhole.
- The highly weathered soft rock chert encountered in most of the boreholes forms a supporting arch above the residual dolomite (wad) and potential cavities at depth.
- No groundwater was encountered and the regional groundwater level is at 1518 m AMSL (33 m below natural ground level) within dolomite bedrock.

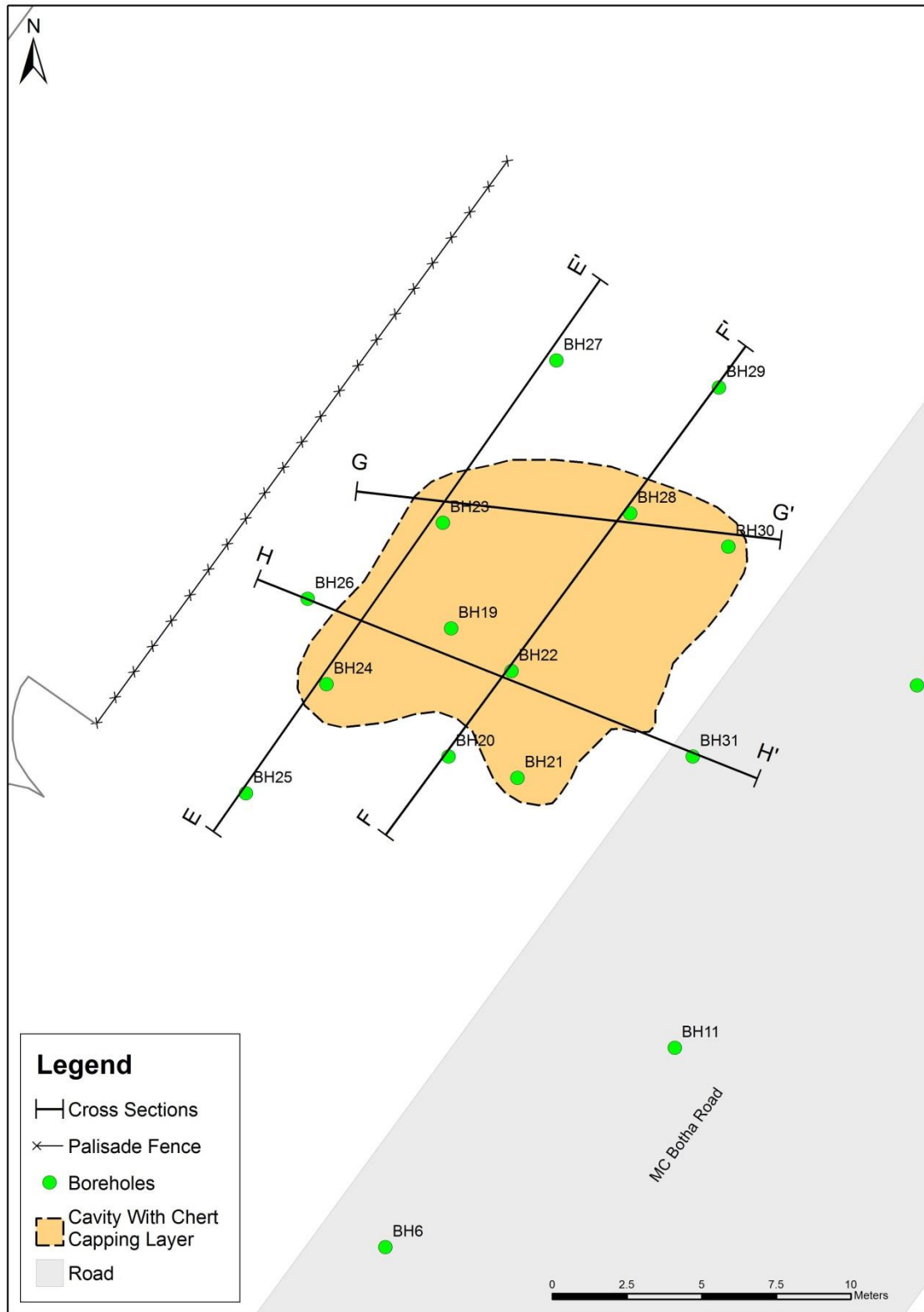
## 2.2 Phase 3 Dolomite Stability Investigations

Figure F.4 and Figure F.5 provide four interpreted geological cross-sections (E - E' to H - H'), based on the borehole information and gravity survey obtained during the Phase 3 dolomite stability investigation. Geological cross-sections E - E' to H - H' are within the area of the cavity encountered in the northern corner of the bulk excavation side wall during the bulk excavation as part of the rehabilitation procedures.

The positions of the Geological Cross-Sections E – E` to H – H` in relation to the cavity with chert capping, are illustrated in Figure F.6. The boreholes revealed the following subsurface profiles:

### 2.2.1 Geological Cross-Section E - E'

- Dolomite bedrock at a depth of 20 m to 21 m within the gryke and bordered by dolomite bedrock at a depth of 3 m to 6 m on both sides of the gryke. A 1 m thick (or absent) horizon of highly weathered soft rock dolomite just above dolomite bedrock between 20 m and 21 m in sub-areas. A 2 m to 5 m thick horizon of highly weathered soft rock dolomite was also encountered within residual dolomite (wad) between a depth of 6 m and 11 m in most boreholes.
- The blanketing layer above dolomite bedrock comprises: A surficial layer of 3 m to 6 m thick residual chert. The residual chert capping layer is underlain by residual dolomite (wad). The 1 m to 10 m thick horizon of residual dolomite (wad) was encountered between depths of 4 m and 20 m in all boreholes with the exception of one.
- A large cavity was encountered within residual dolomite (wad), below a highly weathered soft rock dolomite horizon, between a depth of 10 m and 20 m.
- The residual chert and highly weathered soft rock dolomite forms a supporting arch above the residual dolomite (wad) and large cavity at depth.
- No groundwater was encountered and the regional groundwater level is at 1518 m AMSL (33 m below natural ground level) within dolomite bedrock.



**Figure F.6: Case Study 6 – Position of Interpreted Geological Cross-Sections E – E' to H – H' in relation to the cavity with chert capping.**

### 2.2.2 Geological Cross-Section F - F'

- Dolomite bedrock at a depth of 21 m within the gryke and bordered by dolomite bedrock at a depth of 5 m on both sides of the gryke. A 1 m to 2 m thick (or absent) horizon of highly weathered soft rock dolomite just above dolomite bedrock between a depth of 4 m and 21 m and within dolomite bedrock between 20 m and 21 m.
- The blanketing layer above dolomite bedrock comprises: A surficial layer of 4 m to 5 m thick residual chert. The residual chert is underlain by highly weathered soft rock chert in Borehole 29 between a depth of 1 m and 4 m. The residual chert and soft rock chert (in subareas) capping layer is underlain by residual dolomite (wad). The 14 m to 16 m thick horizon of residual dolomite (wad) was encountered between a depth of 4 m and 20 m within the gryke zone.
- Three cavities were encountered within residual dolomite (wad), between a depth of 4 m to 7 m, 8 m to 9 m and 13 m to 18 m.
- The residual chert and soft rock chert (in sub-areas) forms a supporting arch above the residual dolomite (wad) and three cavities at depth.
- No groundwater was encountered and the regional groundwater level is at 1518 m AMSL (33 m below natural ground level) within dolomite bedrock.

### 2.2.3 Geological Cross-Section G - G'

Dolomite bedrock at a depth of 21 m within the gryke and bordered by dolomite bedrock at a depth of 9 m on one side of the gryke. A 1 m to 2 m thick (or absent) horizon of highly weathered soft rock dolomite just above dolomite bedrock between a depth of 19 m and 21 m and at a shallower depth above residual dolomite (wad) between 5 m and 10 m.

- The blanketing layer above dolomite bedrock comprises: A surficial layer of 5 m thick residual chert, with highly weathered soft rock chert encountered in Borehole BH30 between 2 m and 3 m within the residual chert. The residual chert, soft rock chert (in subareas) and soft rock dolomite (in subareas) capping layers are underlain by residual dolomite (wad). The 4 m to 14 m thick horizon of residual dolomite (wad) was encountered between a depth of 5 m and 20 m within the gryke zone.
- One cavity was encountered within residual dolomite (wad), between a depth of 11 m and 19 m.
- The residual chert, soft rock chert (in sub-areas) and soft rock dolomite forms a supporting arch above the residual dolomite (wad) and cavity at depth.
- No groundwater was encountered and the regional groundwater level is at 1518 m AMSL (33 m below natural ground level) within dolomite bedrock.

#### 2.2.4 Geological Cross-Section H - H'

- Dolomite bedrock at a depth of 20 m to 21 m within the gryke and bordered by dolomite bedrock at a depth of 5 m and 12 m on the side of the gryke. Hard rock dolomite was also encountered within highly weathered soft rock dolomite between a depth of 5 m and 7 m. A 1 m to 3 m thick (or absent) horizon of highly weathered soft rock dolomite just above dolomite bedrock between a depth of 4 m and 21 m.
- The blanketing layer above dolomite bedrock comprises: A surficial layer of 4 m thick residual chert. The residual chert is underlain by residual dolomite (wad). The 15 m to 16 m thick horizon of residual dolomite (wad) was encountered between a depth of 4 m and 20 m within the gryke zone.
- Three cavities were encountered within residual dolomite (wad), between a depth of 4 m to 7 m, 8 m to 9 m and 13 m to 18 m. A cavity was also encountered within highly weathered soft rock dolomite between a depth of 10 m and 12 m.
- The residual chert forms a supporting arch above the residual dolomite (wad) and cavities at depth.
- No groundwater was encountered and the regional groundwater level is at 1518 m AMSL (33 m below natural ground level) within dolomite bedrock.

### 3. REHABILITATION OF AFFECTED AREAS

Taking the existing geological conditions on site into account (e.g. depth to dolomite bedrock, depth and extent of cavities, presence of thick horizons of highly erodible and compressible residual dolomite (wad)) and the affected infrastructure (e.g. structural cracks at Vosloorus Library) the following was carried out in terms of rehabilitation of the affected area (Report Number KHH1516, November 2006):

#### 3.1 M.C. Botha Road

The area of rehabilitation and rehabilitation work carried out in M.C. Botha Road is represented in Figure F.7.

- Bulk excavation of the affected area (20 m by 100 m) typically to a depth of 4 m to 5 m below natural ground level. In the area of the north to south aligned gryke and sinkhole, excavations extended to depth of 6 m to 7 m to expose the throat of the sinkhole. A second deeply weathered zone comprising thick residual dolomite (wad), located in the south-western portion of the bulk excavation area, was excavated down to a maximum depth of 9 m.

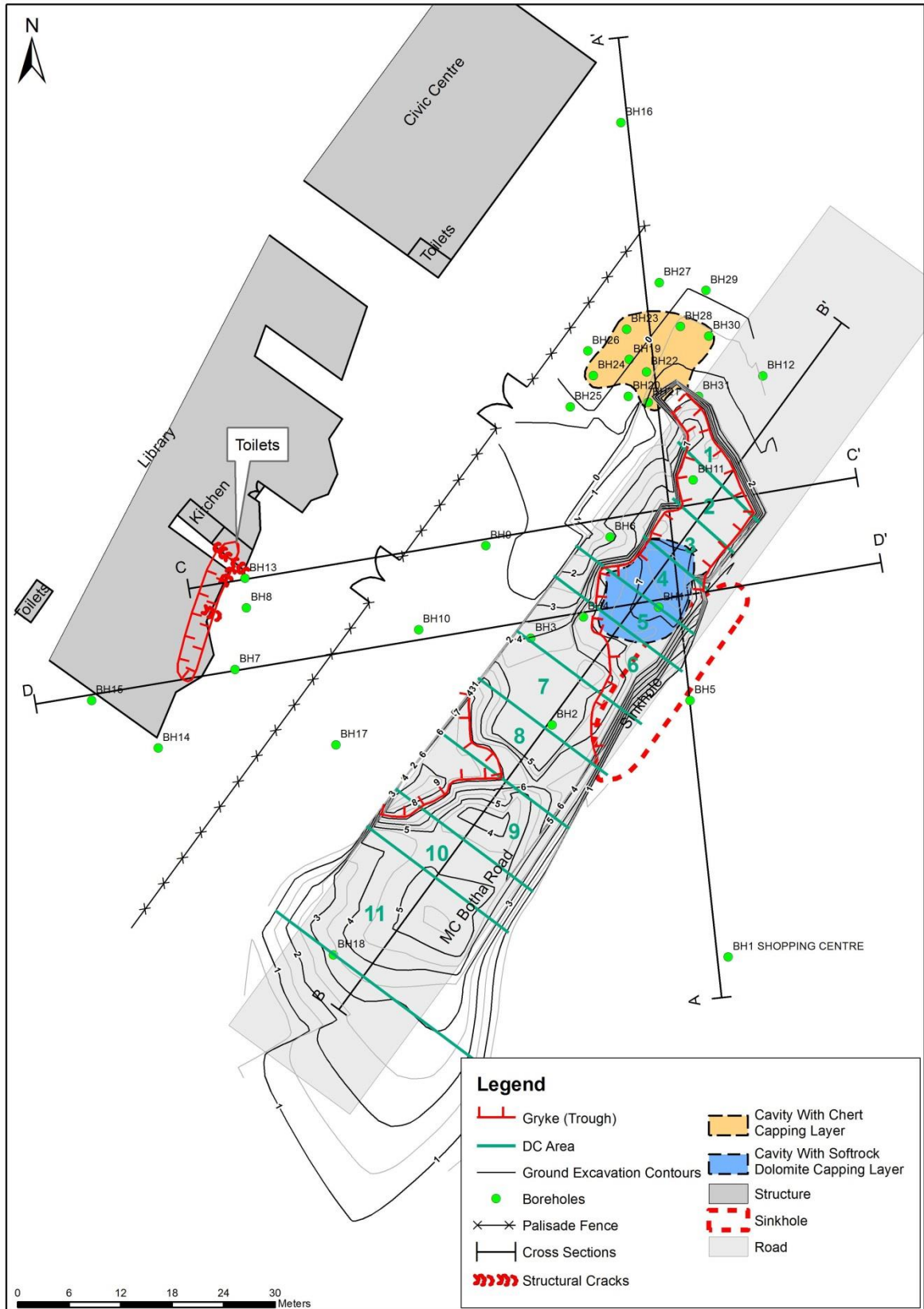


Figure F.7: Case Study 6 - Area of rehabilitation and rehabilitation work carried out in M.C. Botha Road.

During the bulk excavation a cavity of approximately 10 m diameter and 1 m high with a 1 m to 1,8 m thick highly weathered soft rock dolomite roof was encountered within the gryke area directly adjacent to the sinkhole at an approximate depth of between 4 m and 5 m (Plate F.4). The cavity is connected to the sinkhole. The roof of the cavity was removed by drilling and blasting (Plate F.20). A second cavity of approximately 11 m diameter and 3m high with a 4 m thick highly weathered soft rock chert roof was encountered at a depth of 4 m to 7 m below natural ground level within the northern corner of the bulk excavation area (Plate F.5).



**Plate F.4: Soft rock dolomite roof over a 1 m high and 10 m diameter cavity.**



**Plate F.5: Cavity exposed in northern corner of bulk excavation area with soft rock chert roof.**



- The 110 mm and 160 mm PVC water lines located within the area proposed for DC work was rerouted. The 11kV electrical cables could not be removed and was supported during the rehabilitation work.
- Dynamic Compaction probing was conducted in stages of eleven sections (DC Section 1 to DC Section 11) within the bulk excavated area. A section approach was required taking into consideration the water line and electrical cables crossing the bulk excavation area.
- The filling and consolidation of the material within each of the eleven sections during the DC process was done in a number of layers varying in thickness from 1,5 m to 3 m. The results of the DC probing for each section and its related layers are given in the table below.

**Table 5: Dynamic Compaction Layer Works.**

Dynamic Compaction Section	Fill Layer Number	Fill Layer Thickness (m)	Number of Blows Refusal	Consolidation after DC (m)
Section 1	No Fill	-	91	-
	Layer 1	1,5	185	1,5
	Layer 2	1,5	269	1
	Layer 3	3,0	233	0,5
Section 2	No Fill	-	97	1,5
	Layer 1	2,0	133	1
	Layer 2	2,0	132	0,5
	Layer 3	3,0	166	0,5
Section 3	No Fill	-	71	0,8
	Layer 1	1,5	241	0,8
	Layer 2	2,0	287	0,5
Section 4	No Fill	-	98	1
	Layer 1	1,5	133	0,5
	Layer 2	2	152	0,5
Section 5	No Fill	-	102	1
	Layer 1	2	173	1
	Layer 2	3	185	0,5
Section 6	No Fill	-	124	1
	Layer 1	2	180	1
	Layer 2	2	220	0,5
Section 7	No Fill	-	89	1
	Layer 1	1,5	123	1
	Layer 2	2	319	0,8
Section 8	No Fill	-	123	1
	Layer 1	1,5	179	1
	Layer 2	2	230	0,5
Section 9	No Fill	-	193	1,5
	Layer 1	2	180	1
	Layer 2	2	222	1
	Layer 3	3	330	1
Section 10	No Fill	-	180	1
	Layer 1	2	191	1
	Layer 2	2	228	0,8
Section 11	No Fill	-	220	1
	Layer 1	1,5	290	1
	Layer 2	2	333	1

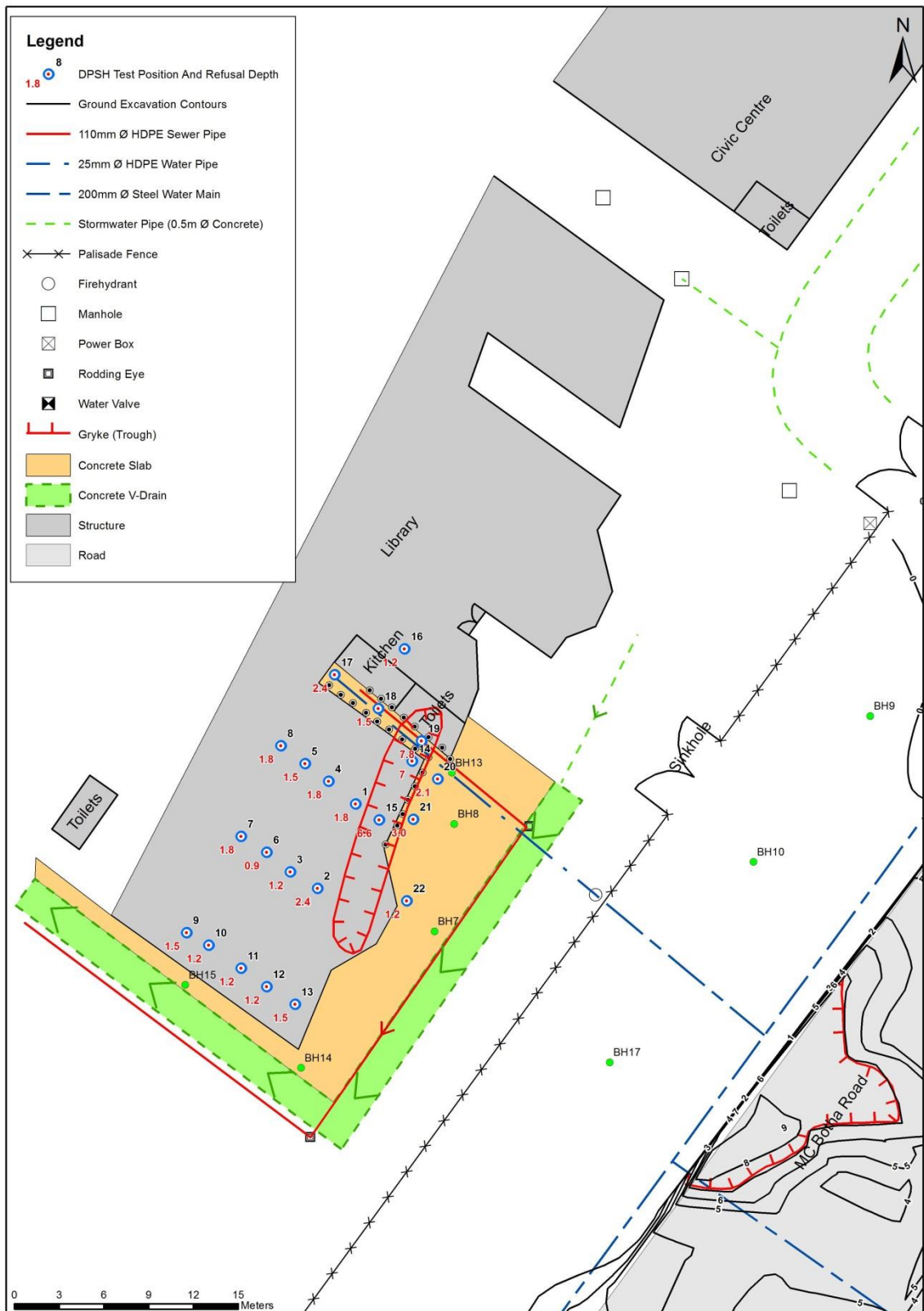
- Dynamic Compaction (DC) probing was first performed without the placing of any materials, to collapse subsoil cavities and to densify thick residual dolomite (wad) at depth. After which chert spoil (i.e. boulders, cobbles, gravel and soil) stockpiled from the excavated area was used to choke the throat areas. The number of blows recorded until visual refusal was reached varied between 71 and 124 for Section 1 to Section 8 and varied between 180 to 220 blows for Section 9 to Section 11 with 0,8 m to 1,5 m consolidation achieved after compaction. This process was followed by backfilling of the excavation in each of the eleven sections in 1,5 m to 3,0 m lifts (fill layers) with chert boulders, cobbles and gravelly soils, compacted using DC to construct a soil/rock fill raft.
- Layer 1: A 1,5 m to 2,0 m thick layer of fill was placed and driven with a penetration pounder until visual refusal was reached. The number of blows recorded until visual refusal was reached varied between 123 and 290 for Section 1 to Section 11 with 0,5 m to 1,5 m consolidation achieved after compaction.
- Layer 2: A 1,5 m to 2,0 m thick layer of fill (exception is Section 5 where the fill layer is 3 m) was placed and driven with a penetration pounder until visual refusal was reached. The number of blows recorded until refusal was reached varied between 132 and 333 for Section 1 to Section 11 with 0,5 m to 1,0 m consolidation achieved after compaction.
- Layer 3 (only conducted in DC Section 1, 2 and 9): A 3,0 m thick layer of fill was placed and driven with a penetration pounder until refusal was reached. The number of blows recorded until visual refusal was reached varied between 166 and 330 with 0,5 m to 1,0 m consolidation achieved after compaction.
- The site was levelled and an ironing operation was conducted over the entire area to complete the shallow DC treatment at a depth of approximately 0,5 m below natural ground level. The purpose of the DC was to densify the upper 8 m to 10 m of the soil profile substantially, thereby decreasing permeability and erodibility.
- After DC the road was reinstated comprising a 150 mm thick sub-grade layer of G7 material compacted to 98% Modified AASHTO at optimum moisture content, a 150 mm thick sub-base layer of G5 material compacted to 98% Modified AASHTO at optimum moisture content, a 150 mm thick base layer of G2 material compacted to 98% Modified AASHTO at optimum moisture content and a 40 mm thick asphalt layer.
- The 110 mm diameter PVC water line crossing the rehabilitation area and running parallel with the 160 mm diameter PVC water line to MC Botha Road in the eastern road servitude was replaced with HDPE pipes. The 200 mm steel bulk water line located in the western road servitude of M.C. Botha Road was replaced with a new steel pipe. The bulk steel water line was not replaced with HDPE as the distance over which this line needed to be replaced up to the position of valves was far beyond the rehabilitation area. In addition, a connection between a steel pipe and a HDPE pipe for water under pressure is difficult and leakages may originate from the connection point. The 11 kV electrical cables within MC Botha Road were sleeved.

3.1.1 Vosloorus Library (Report Number KHH1519, November 2006)

The area of rehabilitation and rehabilitation work carried out at the Vosloorus Library is presented in Figure F.8.

- The five boreholes drilled to the south and east of the Vosloorus Library where structural damages were observed, did not provide adequate information to determine the cause of structural damage and settlement of the one corner of the Vosloorus Library. During the rehabilitation work a total of 22 Dynamic Probe Super Heavy (DPSH) tests were conducted additionally within the library building and to the east of it in the area of structural damage. The purpose of the DPSH tests was to determine the possible existence of a gryke in the affected area causing settlement of the building and the related structural cracks, as the gravity survey did reveal the possibility of a deeper weathered dolomite zone that could not be reached by means of drilling. The approximate positions of the DPSH tests are shown on Figure F.8. The DPSH tests revealed the following:
  - Refusal depths of between 6,6 m and 7,8 m in DPSH tests 14, 15 and 19 conducted in the area of structural damage, presenting a gryke type feature. All other DPSH tests refused at a relatively shallow depth of between 0,9 m and 2,4 m, possibly on highly weathered soft rock dolomite.
  - The corner of the Vosloorus Library where structural damages and settlement took place the foundation was underpinned by micro driven piles on a 1 metre spacing. The foundation of the building was then jacked up to a level as close as possible to its original position. The remaining cracks filled and plastered and the building repainted.
  - All subsurface wet service (sewer, water and stormwater) was exposed by hand excavation and replaced with HDPE pipes and wet services placed below the footprint of the structure were discarded.
  - A 2 m to 4 m wide sealed surface (i.e. concrete slab and paving in places) was placed all around the structure with a v-shaped drain to the east and south to accommodate surface water run-off away from the structure. The ground immediately against the buildings or sealed surface was shaped to fall in excess of 75 mm over the first 2 m beyond the perimeter of the building, from where it drains freely away from the structure into a lined canal or on lawn graded as such to facilitate drainage.

The affected area has been improved to a tolerable hazard. A tolerable hazard was reached by removing and replacing problematic materials such as the residual dolomite (wad), collapse and backfilling of cavities, with a densified engineered soil mattress, by means of Dynamic Compaction, of between 4 m to 10 m thickness and the removal and replacement of wet services. The cavity with a 4 m thick chert capping encountered in the northern corner of the rehabilitation area in MC Botha Road was not backfilled. A number of casings were left open after the Phase 3 investigation of the cavity, in order to inject grout into the cavity as soon as any instability is start showing at ground surface. The 4 m chert capping over the cavity is providing adequate support at this stage and monitoring of the situation is required.



**Figure F.8: Case Study 6 - Area of rehabilitation and rehabilitation work carried out at the Vosloorus Library.**

The area where structural damages occurred at the Vosloorus Library was successfully remediated by means of underpinning of the building by means of micro driven piles and jacking of the corner of the building where settlement occurred. All wet services were replaced by HDPE pipes and the area surrounding the building was sealed by a concrete slab with all other areas shape to ensure surface water run-off away from structures.

**APPENDIX G**

***CASE STUDY 7***

## CASE STUDY 7

A sinkhole occurred 2 m to the west of the Credi Reservoir located on Stand 321, Katlehong during September 2010. The sinkhole was caused by excessive water spillage in a 1,5 m deep trench during the installation of a new pipe. A site inspection of the affected area was conducted on 6 September 2010 and revealed the following (Report Number VGI3355/WO305/1, September 2010):

- A sinkhole (dimensions of 2 m diameter extending to a depth of 2 m) occurred west of the Credi Reservoir, in a 1,5 m deep trench excavated for a proposed new 400 mm diameter PVC water line (Plate G.1).



**Plate G.1: Sinkhole in trench excavation for a proposed water line.**

- Residual dolomite (wad with chert gravel) observed at the lower 0,5 m of the trench in the western side wall and residual syenite within the cavity with an erosion tunnel extending towards the west at depth (Plate G.2).
- No structural damages to the reservoir due to the formation of the sinkhole.
- A north-east to south-west aligned 500 mm diameter steel bulk water line connected to the Credi Reservoir is located approximately 3 m to the south of the sinkhole. A leak on the steel line approximately 1 m before it connects to the Credi Reservoir was repaired with a clamp, with water still running from the area repaired.
- A north-east to south-west aligned 110 mm diameter PVC water line located within the area of the trench and sinkhole.



**Plate G.2: Residual syenite visible in sinkhole sidewall and erosion tunnel.**

A gravity survey was not conducted on the site and no existing surveys covering the area are available. Two boreholes (EMM643 and EMM644) were drilled to the west of the sinkhole in the area towards where the erosion tunnel was going on 14 October 2010. The seven boreholes (BH K to BH N, BH P, BH R and BH S) drilled by Geoconsult within the footprint of the Credi Reservoir during June 1991 are incorporated into the current study for a better understanding of subsurface conditions surrounding the sinkhole area. The position of the sinkhole, cavity, wet services and boreholes are displayed in Figure G.1. The subsurface profile in the area of the Credi Reservoir, trench with sinkhole and to the west of it is illustrated by the interpreted Geological Cross-Section A - A' in Figure G.2 (Report Number VGI3355 WO305, May 2011):

- Dolomite bedrock at a depth ranging from 6 m to 32 m. A 1 m to 3 m thick horizon of highly weathered soft rock dolomite at variable depths ranging from 9 m to 32 m. Interlayered highly weathered soft rock dolomite and chert of 2,5 m to 5 m thickness was encountered in the area below the Credi Reservoir between a depth of 3,5 m and 21 m just above dolomite bedrock.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of residual chert to a depth of between 1 m and 3 m. The surface layer is underlain by interlayered residual syenite and residual dolomite (wad). The first layer of residual syenite was encountered from a depth of 1,5 m to 5,5 m with a layer thickness varying between 2 m and 3,5 m and the second layer of residual syenite was encountered from a depth of 1,5 m to 10 m with a layer thickness varying between 1 m to 8,5 m.



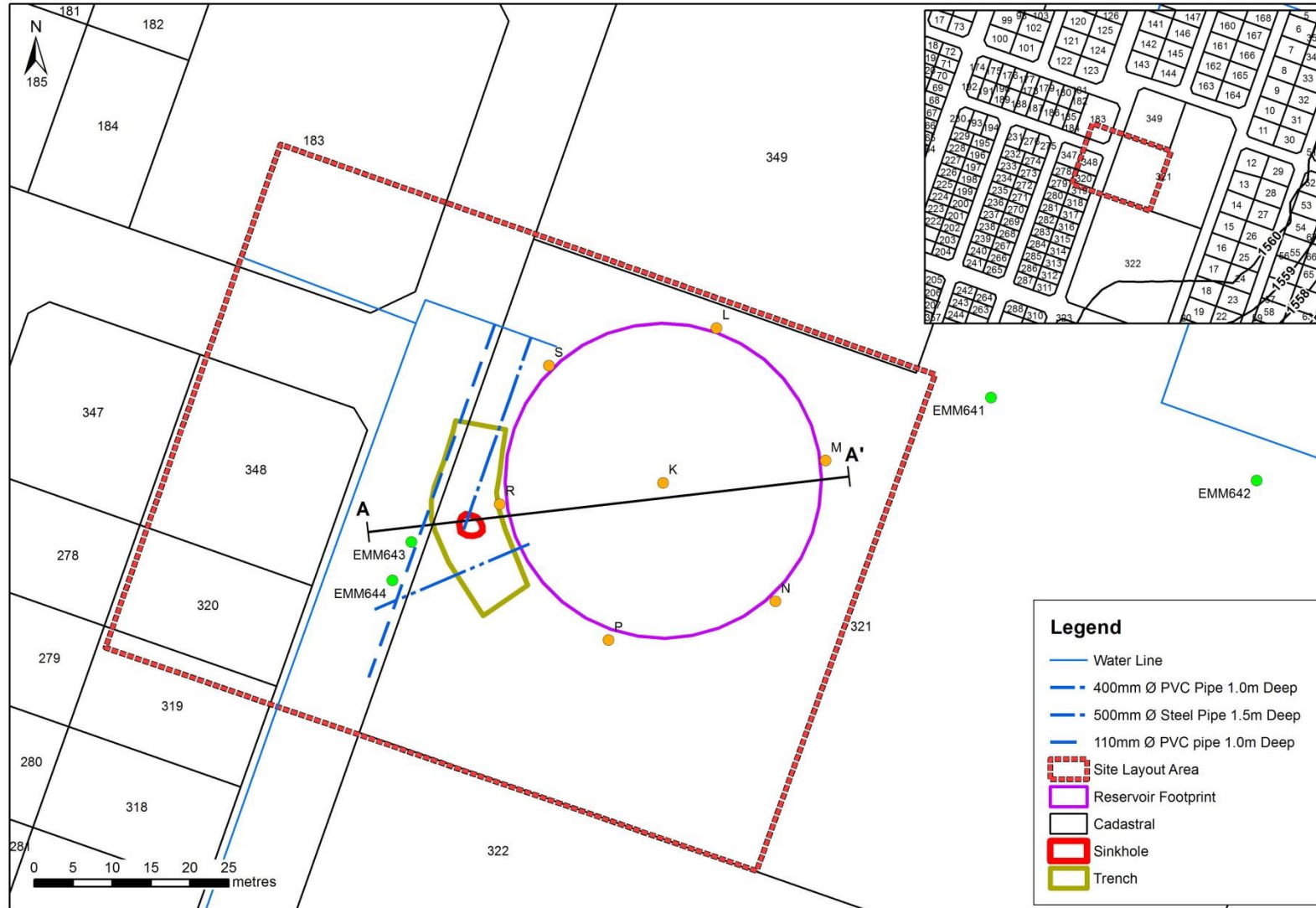
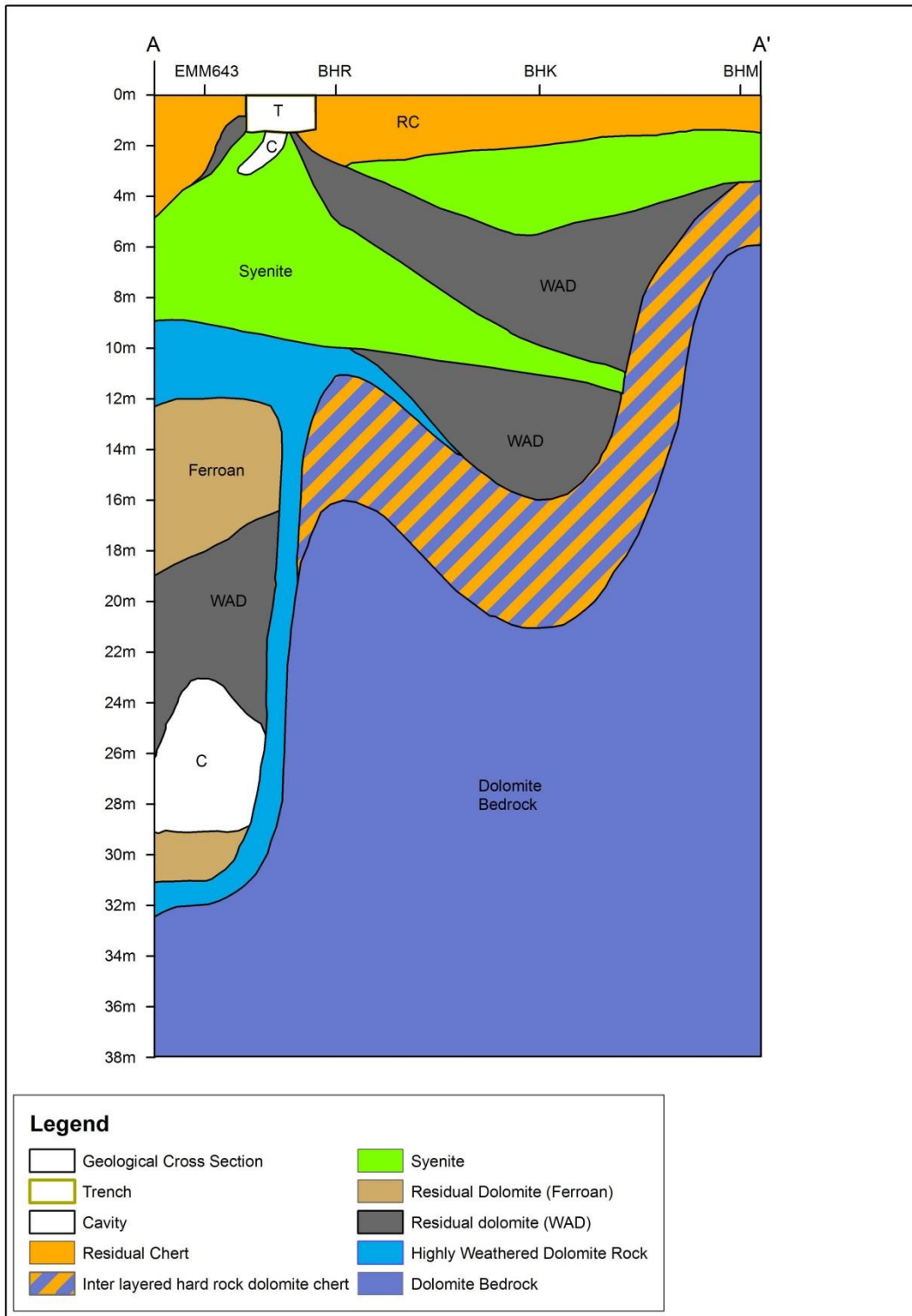


Figure G.1: Case Study 7 – Plan view of sinkhole, wet services and boreholes.



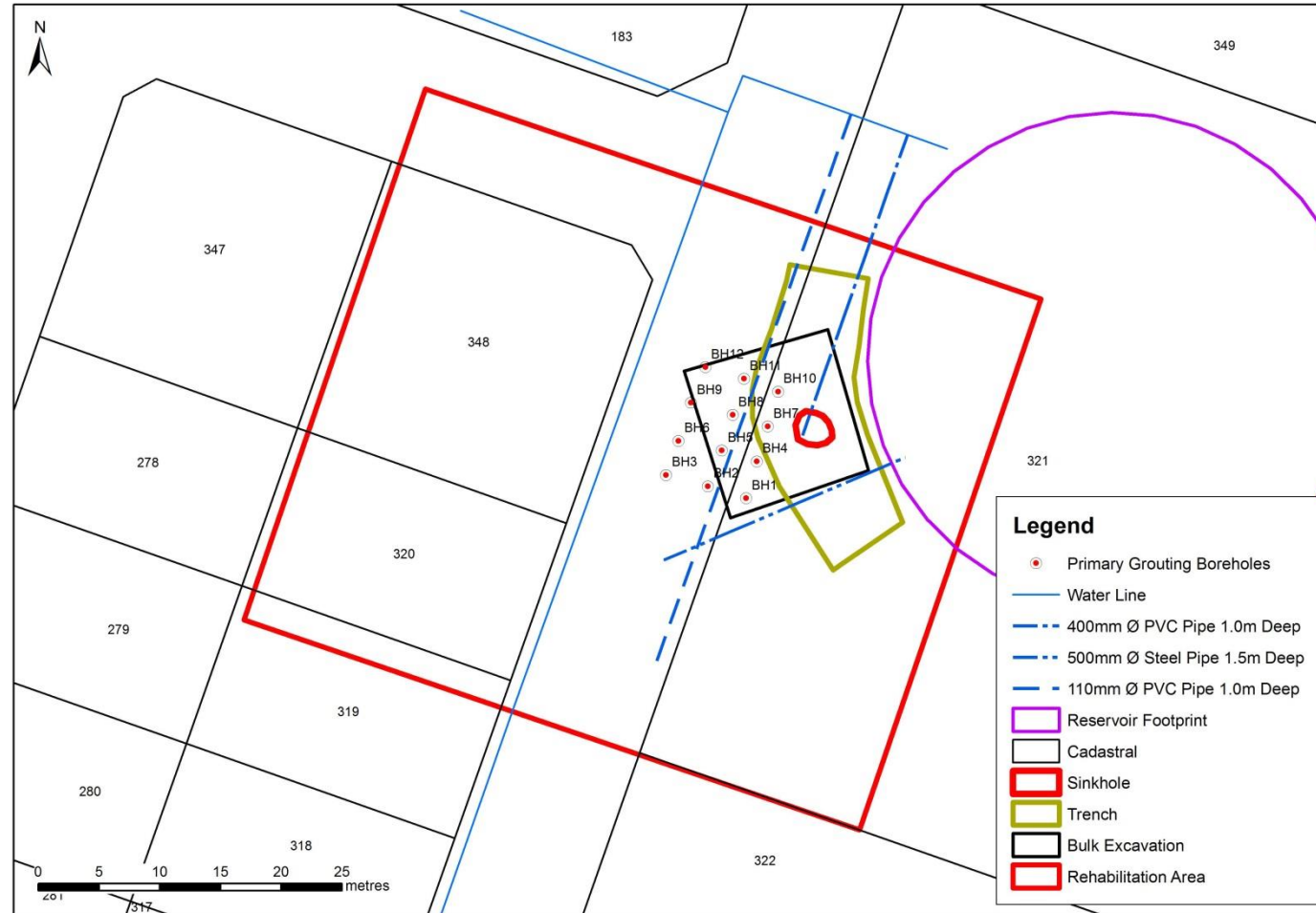
**Figure G.2: Case Study 7 – Interpreted Geological Cross-Section A – A`.**

The first layer of residual dolomite (wad) was encountered between 1 m and 10 m with a layer thickness varying between 0,5 m to 4,5 m; a second layer of residual dolomite (wad) is encountered in the eastern half of the cross-section between depths of 11 m and 16 m in one borehole. Residual dolomite (wad) was also encountered in the western half of the cross-section between a depth of 18 m and 23 m. Residual dolomite comprising ferroan soils was encountered in one borehole drilled to the west of the sinkhole between a depth of 12 m to 18 m and 29 m to 31 m. Rapid penetration rates and air and sample losses were recorded in the boreholes drilled to the west of the sinkhole in the residual dolomite zones and dolomite bedrock.

- A cavity was encountered between a depth of 23 m and 29 m in the borehole drilled to the west of the sinkhole.
- No groundwater was encountered and the regional groundwater level is anticipated at 1528 m AMSL (32 m below natural ground level) within dolomite bedrock.

Taking the above conditions into account (e.g. position of Credi Reservoir and wet services in correlation to the sinkhole) a combination of the Inverted Filter Method and a Grouting Programme was recommended in terms of rehabilitation of the affected area. The area of rehabilitation is given in Figure G.3. The following was carried out in terms of the rehabilitation work (Report Number VGI3355 WO305, May 2011):

- Remove the existing 400 mm PVC water line over a distance of approximately 20 m within the borders of Stand 321 within the affected area.
- Bulk excavation of the affected area (12 m by 12 m) typically to a depth of 6 m below natural ground level. Excavation started from the sinkhole extending towards Borehole EMM643. Excavation slopes from ground surface to 5m depth was 1:1 and from 5m to 6m vertical.
- Remove all highly erodible and compressible dolomite residuum (wad) material, expected from a depth of 1 m to 5 m.
- During the bulk excavation precaution should be taken to close the erosion tunnel potentially connecting the sinkhole with the cavity intercepted in Borehole EMM 643. It was recommended that if the erosion tunnel at a depth of 6 m is still visible, it be widened to 4 m and excavated down to 10 m with an excavator. The sinkhole did, however, only extend to a depth of 5 m below natural ground level with only residual syenite and highly weathered soft rock syenite encountered in the bulk excavated area at depth.
- Backfilling of the 6 m deep excavation involved: Cobbles/gravels in 300mm thick layers up to a depth of 1,5 m below natural ground surface, followed with silty/gravelly sand in 150 mm thick layers up to 1 m (base of proposed water line) below ground level and placing of a new 400 mm diameter HDPE butt welded water line. Continue with backfilling of the bulk excavated area up to ground surface within 150 mm thick layers. Each layer compacted to at least 95% of Modified AASHTO maximum dry density at optimum moisture content.
- Compact the excavated trench area for the new 400 mm diameter HDPE butt welded pipe to 95% of Modified AASHTO maximum dry density at optimum moisture content. The new 400 mm diameter HDPE water line was placed within and on a 0,1 m thick layer of bedding material (river sand).



**Figure G.3: Case Study 7 – Area of rehabilitation, including bulk excavation area, existing infrastructure and position of grouting boreholes.**

- A concrete valve box in accordance with PW344 standards should be constructed where the above mentioned HDPE water line will be connected onto the 500 mm diameter steel line. Backfill the trench in 150 mm to 300 mm thick layers with silty gravelly sand at 93% of Modified AASHTO maximum dry density at optimum moisture content up to 0,3 m below natural ground level. The upper last two 150 mm layers should be compacted at least at 98% of Modified AASHTO maximum dry density at optimum moisture content and 1 m beyond the excavated area up to natural ground level.

Percussion boreholes for compaction grouting purposes were drilled during the period of 20 July 2011 to 5 August 2011 and consisted of the drilling of twelve boreholes (Boreholes BH1 to BH12). The primary grouting boreholes were placed in and around the area where a cavity was encountered during the dolomite stability investigation in Borehole EMM 643. Boreholes were placed 3 m from each other within the affected area. The area of rehabilitation, including the bulk excavation area, existing infrastructure and the position of the primary grouting boreholes (Boreholes BH1 to BH12) are displayed in Figure G.3. The grouting boreholes, with the geological profile encountered during drilling, grout volumes injected and pressure applied at depth for each section is illustrated in Figure G.4. The grouting boreholes revealed the following subsurface profile:

- Dolomite bedrock at a depth ranging from 20 m to 30 m. Dolomite bedrock was not encountered in two of the twelve boreholes drilled. Hard rock dolomite was also encountered in half of the boreholes drilled, between a depth of 9 m and 20 m with a layer thickness varying between 2 m and 5 m. A 1 m to 11 m thick horizon of highly weathered soft rock dolomite at variable depths ranging from 5 m to 30 m.

The blanketing layer above dolomite bedrock comprises: A surface layer consisting of fill to a depth of 2 m encountered only in two boreholes and or residual chert to a depth of between 3 m and 9 m encountered in six of the boreholes drilled or interlayered residual chert and syenite to a depth of 4 m and 9 m encountered in four of the boreholes drilled. The surface layer is directly underlain by residual syenite (encountered between 3 m and 9 m in four boreholes with a layer thickness varying between 1 m to 4 m) or followed by residual dolomite (ferroan soils and wad) encountered above and within bedrock. The residual dolomite (ferroan soils) was encountered in six of the boreholes between variable depths of 4 m and 20 m with a layer thickness of between 1 m and 5 m. Residual dolomite (wad) was encountered in all the boreholes with the exception of one between variable depths of 5 m and 30 m with a layer thickness of between 1 m and 10 m. Interlayered residual dolomite (wad) and residual syenite was encountered in two boreholes between depths of 4 m to 8 m and between 13 m to 15 m. Rapid penetration rates, sample and air losses were encountered in the residual dolomite horizons, highly weathered soft rock dolomite and in dolomite bedrock. Slight sample and air losses were also recorded in some boreholes in the residual chert and the residual syenite.

- No cavities were encountered in any of the grouting boreholes. Cavities can, however, be expected within the residual dolomite, highly weathered soft rock dolomite and dolomite bedrock, taking into consideration total air and sample losses recorded in these zones.
- No groundwater was encountered and the regional groundwater level is anticipated at 1528 m AMSL (32 m below natural ground level) within dolomite bedrock.

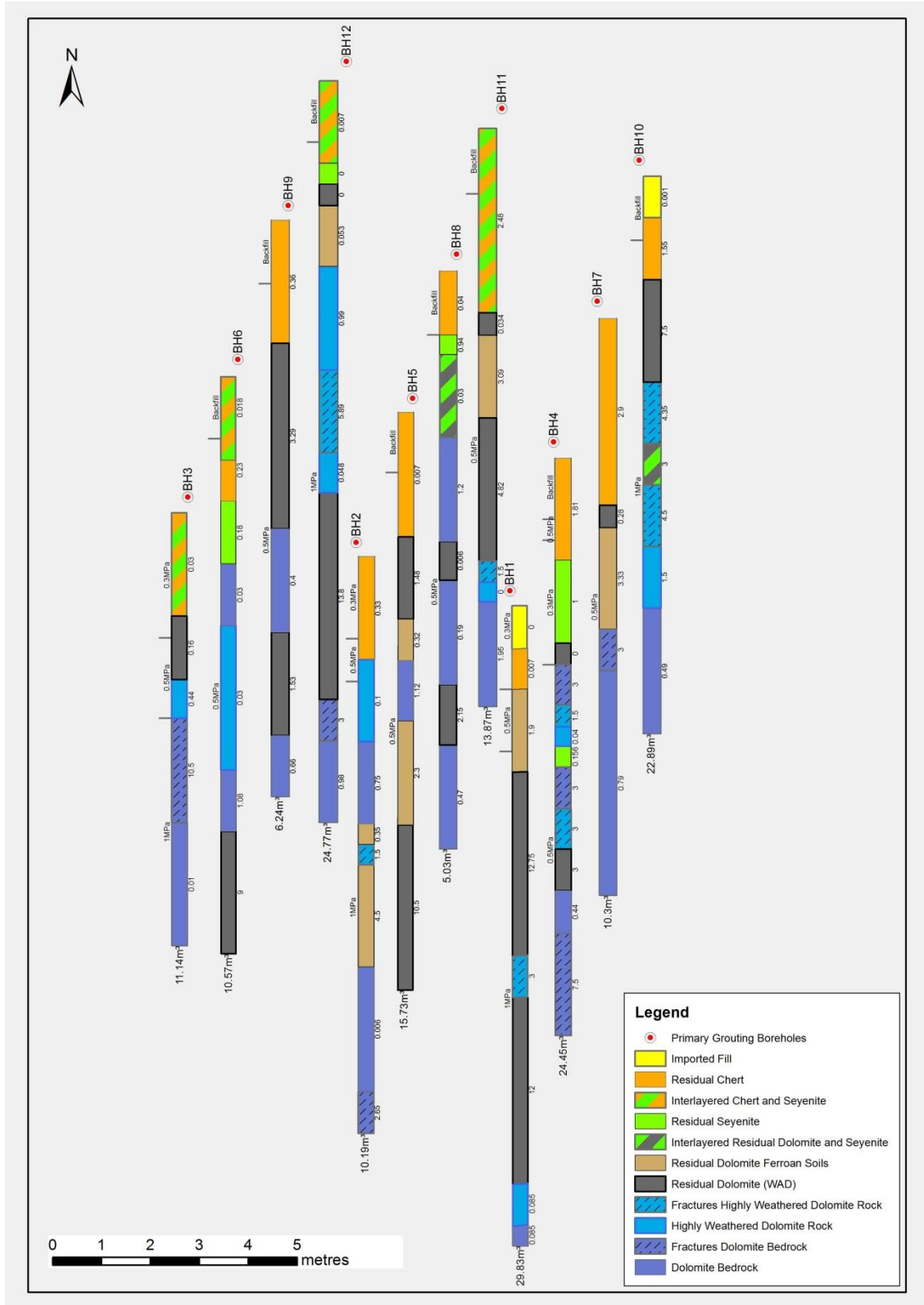


Figure G.4: Case Study 7 – Grouting boreholes with geological profile, grout volumes and pressure applied at depth.

The upstage grouting conducted only at primary points on a 3 m spacing did not need to meet any strength requirements as the objective was not to form a structural element in the ground but to backfill voids and compact problematic zones.

Only twelve primary grouting boreholes (BH1 to BH12) were drilled. As illustrated in Figure G.3 and Figure G.4. The upper 3 m to 5 m of boreholes were backfilled under gravity flow or grout injected under a maximum pressure of 0,3 MPa to prevent heave of the surficial soils, Borehole BH4 is the exception where a 0,3 MPa grout pressure was applied to a maximum depth of 10 m. A grout pressure of 0,5 MPa to 1 MPa was applied at a depth greater than 3 m to 5 m (or 10 m for BH4) to the end of the boreholes (between 21 m and 31 m).

The volume of grout injected per metre as recorded by the grouting contractor varied between 0 m<sup>3</sup> to 1,54 m<sup>3</sup>. A grout volume of 0 m<sup>3</sup> is not possible taking into consideration a drilling bit diameter of 0,114 m was used, therefore the minimum volume of grout in m<sup>3</sup> per meter (applying no pressure) should be equal to the following:

$$\begin{aligned}
 \text{Volume} &= \pi r^2 h \\
 &= (3,141592654) (0,057)^2 (1 \text{ m}) \\
 &= 0,01 \text{ m}^3 \text{ per metre}
 \end{aligned}$$

The volume of grout injected per metre per specific geological horizon is given in the table below. As specified above a 0 m<sup>3</sup> per metre grout volume or less than 0,01 m<sup>3</sup> per metre grout volume is not possible and as such where the grouting contractor did record a value of less than the specified minimum of 0,01 m<sup>3</sup> volume of grout per metre (refer to Figure G.4) the minimum value is adjusted and indicated with a (c) beyond the given value in the table below:

**Table G.1: Volume of grout injected per metre per specific geological horizon.**

<b>Geological Horizon</b>	<b>Minimum (m<sup>3</sup>/m)</b>	<b>Maximum (m<sup>3</sup>/m)</b>	<b>Average (m<sup>3</sup>/m)</b>
Fill Material	0,01 (c)	0,01 (c)	0,01 (c)
Residual Chert	0,01 (c)	1,02	0,14
Residual Chert and Syenite	0,01 (c)	0,021	0,01
Residual Syenite	0,01 (c)	0,942	0,32
Residual Dolomite (ferroan soils)	0,01 (c)	1,5	0,48
Residual Dolomite (wad)	0,01 (c)	1,54	0,70
Interlayered Residual Dolomite (wad) and Residual Syenite	0,01 (c)	1,5	0,76
Highly weathered dolomite	0,01 (c)	0,96	0,12
Highly weathered dolomite (fractured)	1,35	1,5	1,49
Hard rock dolomite	0,01 (c)	1,11	0,15
Hard rock dolomite (fractured)	1,157	1,5	1,47

High grout volumes were recorded in each borehole as follows:

- Borehole BH1: Grout volumes per metre of  $0,75 \text{ m}^3$  to  $1,53 \text{ m}^3$  injected at 1 MPa were recorded between a depth of 7 m and 27 m. Within residual dolomite (ferroan soils) between 7 m and 8 m, residual dolomite (wad) between 8 m to 17 m and 19 m to 28 m and within highly fractured soft rock dolomite between 17 m and 19 m.
- Borehole BH2: Grout volumes per metre of  $1,32 \text{ m}^3$  to  $1,5 \text{ m}^3$  injected at 1 MPa were recorded between a depth of 14 m to 18 m and 26 m to 28 m. Within residual dolomite (ferroan soils) between 15 m and 18 m, within highly fractured soft rock dolomite between 14 m and 15 m and in fractured hard rock dolomite between 26 m and 28 m.
- Borehole BH3: Grout volumes per metre of  $1,5 \text{ m}^3$  injected at 0,5 MPa were recorded between a depth of 10 m and 17 m, within fractured hard rock dolomite.
- Borehole BH4: Grout volumes per metre of  $1,5 \text{ m}^3$  injected at 0,5 MPa were recorded between a depth of 10 m and 28 m. Within residual dolomite (wad) between 19 m and 21 m, within highly fractured soft rock dolomite between 12 m to 13 m and 17 m to 19 m and within hard rock dolomite between 10 m to 12 m, 15 m to 17 m and 23 m to 28 m.
- Borehole BH5: Grout volumes per metre of  $1,03 \text{ m}^3$  to  $1,5 \text{ m}^3$  injected at 0,5 MPa were recorded between a depth of 8 m and 28 m. Within residual dolomite (wad) between 8 m to 9 m, 20 m to 21 m and 22 m to 28 m, within residual dolomite (ferroan soils) between 19 m and 20 m and within hard rock dolomite between 12 m and 13 m.
- Borehole BH6: Grout volumes per metre of  $1,5 \text{ m}^3$  injected at 0,5 MPa were recorded between a depth of 22 m and 28 m, within residual dolomite (wad).
- Borehole BH7: Grout volumes per metre of  $1,5 \text{ m}^3$  injected at 0,5 MPa were recorded between a depth of 10 m to 11 m and 14 m to 17 m. Within residual dolomite (ferroan soils) between 10 m to 11 m and 14 m to 15 m and within highly fractured hard rock dolomite between 15 m and 17 m.
- Borehole BH8: Grout volumes per metre of  $1,5 \text{ m}^3$  injected at 0,5 MPa were recorded between a depth of 21 m and 22 m, within residual dolomite (wad).
- Borehole BH9: Grout volumes per metre of  $1,5 \text{ m}^3$  injected at 0,5 MPa were recorded between a depth of 21 m and 22 m, within residual dolomite (wad).
- Borehole BH10: Grout volumes per metre of  $1,35 \text{ m}^3$  to  $1,5 \text{ m}^3$  injected at 1 MPa were recorded between a depth of 4 m and 21 m. Within residual chert between 4 m and 5 m, in residual dolomite (wad) between 5 m and 10 m, in interlayered residual dolomite and syenite between 13 m and 15 m and within highly fractured soft rock dolomite between 10 m to 13 m and 20 m to 21 m.
- Borehole BH11: Grout volumes per metre of  $1,5 \text{ m}^3$  injected at 0,5 MPa were recorded between a depth of 5 m and 28 m. Within interlayered residual chert and syenite between 5 m and 6 m, in residual dolomite (ferroan soils) between 13 m and 14 m, in residual dolomite (wad) between 14 m to 15 m and 19 m to 21 m, within highly fractured soft rock dolomite between 21 m and 22 m and within hard rock dolomite between 27 m and 28 m.
- Borehole BH12: Grout volumes per metre of  $1,39 \text{ m}^3$  to  $1,5 \text{ m}^3$  injected at 1 MPa were recorded between a depth of 14 m and 32 m. Within residual dolomite (wad) between 21 m and 30 m, within highly fractured soft rock dolomite between 14 m and 18 m and within hard rock dolomite between 30 m and 32 m.



The total volume of grout injected per borehole is given in the table below.

**Table G.2: Total volume of grout injected per specific borehole.**

<b>Borehole Number</b>	<b>Grouting Date</b>	<b>Grouting Order (First to last)</b>	<b>Total Volume of Grout (m<sup>3</sup>)</b>
BH1	22/07/2011	2	29,83
BH2	02/08/2011	4	10,19
BH3	27/07/2011	3	11,14
BH4	04/08/2011	6	24,45
BH5	05/08/2011	7	15,73
BH6	03/08/2011	5	10,57
BH7	02/08/2011	4	10,3
BH8	08/08/2011	8	5,03
BH9	02/08/2011	4	6,24
BH10	15/07/2011	1	22,89
BH11	03/08/2011	5	13,87
BH12	27/07/2011	3	24,77

It can be seen from the above mentioned that the boreholes (BH1, BH4 and BH10) drilled the closest to the sinkhole and grouted first typically has the highest grout takes. Borehole BH12 the furthest away from the sinkhole, however, also has a high grout take. The high grout takes are associated with thick dolomite residuum (ferroan and wad) zones; highly weathered soft rock fractured dolomite and fractured hard rock dolomite zones.

**APPENDIX H**

***CASE STUDY 8***

## CASE STUDY 8

### 1. INTRODUCTION

A sinkhole occurred in the western servitude of Mabuya Street on the eastern boundary of Stands 16463 and 16464, on 20 September 2011. The sinkhole is attributed to damage caused to the 300mm diameter PVC EMM bulk water line, during repairs of the internal water line of Stand 16463, located in the western servitude of Mabuya Street, Vosloorus. A site inspection of the affected area was conducted on 20 September 2011 and revealed the following (Report Number VGI3355/391/1, September 2011):

- A 3 m diameter sinkhole to a depth of 5 m, located on the eastern boundary of Stand 16463 and Stand 16464.
- A northeast – southwest aligned broken and leaking 300 mm diameter PVC bulk EMM water line, located at a depth of approximately 1,5 m within the area of the sinkhole.
- A 200 mm diameter uPVC sewer line located at a depth of more than 2 m below ground surface within the area of the sinkhole, with the same orientation as the bulk EMM water line.
- A 25 mm diameter PVC internal water line running perpendicular to the EMM bulk water and sewer line, located at a depth of less than 1m below ground surface.
- Large volumes of water from the displaced 300 mm diameter waterline disappearing along a 1 m diameter size sub-surface erosion tunnel into a northerly direction, at the base of the sinkhole (Plate H.1). All leaks on the waterlines internal and bulk were repaired immediately by the Vosloorus Water Department and the affected area barricaded. The leak on the bulk water line was repaired with a steel clump. However, the bulk EMM water line started to leak within the same area where it was repaired, on 14 February 2012 and again on 18 March 2012. On both occasions the Vosloorus Water Department was informed about the leak and requested to repair the leak.

A dolomite stability investigation was conducted on 28 September 2011. Six boreholes (EMM891 to EMM896) were drilled in the area surrounding the sinkhole (Report Number VGI3355 WO391, November 2011). Inaccessibility for a drilling rig prevented the drilling of boreholes to the west on Stand 16464. The affected area (sinkhole, broken water line), existing infrastructure and the position of boreholes are displayed in Figure H.1. An interpreted Geological Cross-Section A - A' presenting subsurface conditions as encountered during the dolomite stability investigation of the sinkhole is illustrated in Figure H.2 and revealed the following (Report Number VGI3355 WO391, November 2011):



**Plate H.1: Water from broken water line disappearing along a subsurface erosion tunnel in a northerly direction.**

- Dolomite bedrock at a depth of 4 m to 14 m. A 1 m to 2 m thick horizon of highly weathered soft rock dolomite encountered at variable depths of between 1 m to 14 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of residual chert to a maximum depth of 1 m to 4 m, followed at depth by residual dolomite (ferroan soils and wad) to a depth of 4 m to 13 m. The residual dolomite comprising ferroan soils was encountered between a depth of 3 m and 13 m with a layer thickness varying between 1 m and 3 m or absent. Residual dolomite (wad) was encountered between a depth of 2 m and 5 m with a layer thickness varying between 1 m and 3 m. Rapid penetration rates, air losses and no sample return were encountered in the residual dolomite and dolomite bedrock.
- No cavities were intercepted in any of the boreholes drilled.
- Groundwater was not intercepted in boreholes drilled. The regional groundwater level is at 1530 m AMSL (36 m below natural ground level) within dolomite bedrock.

Taking the above conditions into account the Inverted Filter Method was recommended in terms of rehabilitation of the affected sinkhole area. The following was carried out in terms of the rehabilitation work (Report Number VGI3355 WO391, November 2011):

- Bulk excavation of the sinkhole area (10 m by 10 m) typically to a depth of 5 m below natural ground level. A trench excavation (10 m long and 4 m wide) up to the manhole located on the north-eastern boundary of Stand 16463.

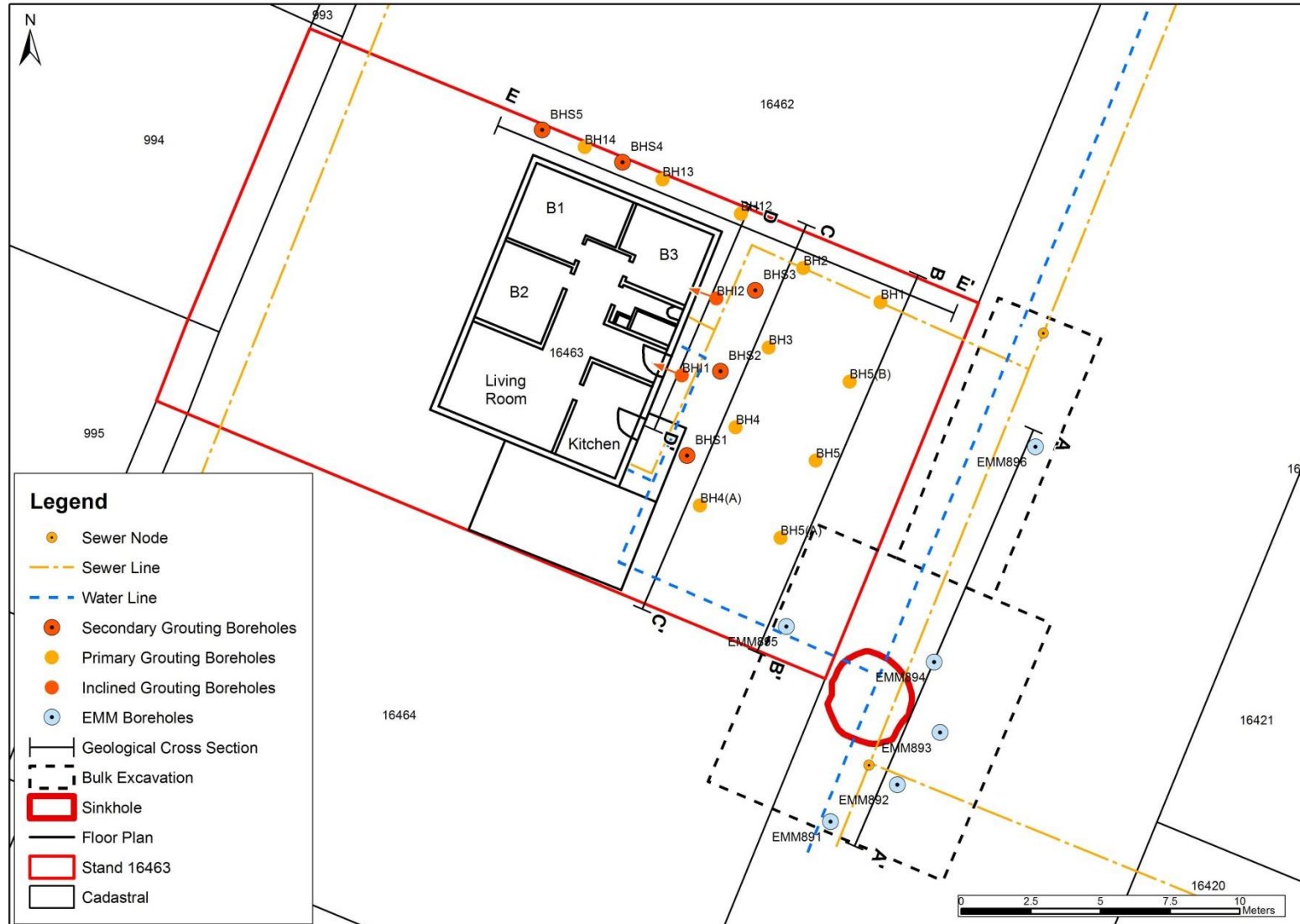


Figure H.1: Case Study 8 – Plan view of affected area, existing infrastructure and the position of boreholes.

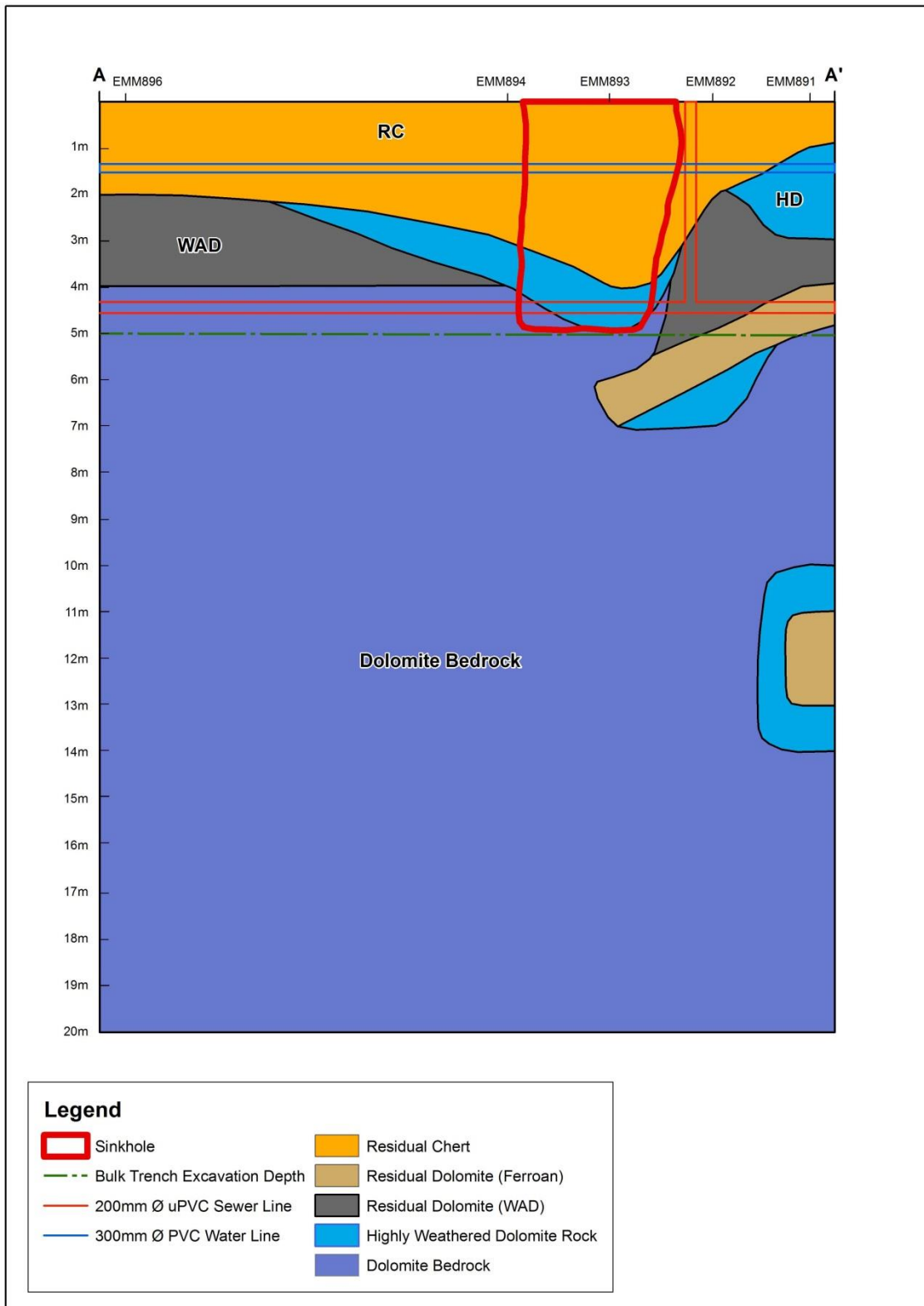


Figure H.2: Case Study 8 – Interpreted Geological Cross-Section A – A`.

- As no cavities were encountered during the investigation of the sinkhole, the rehabilitation contractor was instructed to expose the bulk 300 mm diameter PVC water line at a depth of 1,5 m and the 200 mm diameter uPVC sewer line at a depth of 4,5 m, located in the western servitude of Mabuya Street in front of Stands 16463 and 16464. The pipelines were to be exposed over a maximum distance of 20 m in the affected area, to 0,5 m below the base of the sewer line.
- The purpose of the excavation down to a depth of 5 m was to determine if any sub-surface erosion had occurred at depth below the water line located at an invert level of 1,5 m below ground surface and secondly to inspect if the EMM bulk sewer line was still in good working order.
- During the exposure of the 200 mm uPVC sewer line it was found that the manhole located on the north-eastern corner of Stand 16463 was damaged at a depth between 4 m and 4,5 m and the first 1 m section of the sewer line extending towards the south-west was also damaged. The broken sewer line section was replaced with HDPE material and the manhole was repaired. The remainder of the exposed 200 mm diameter uPVC sewer line was in a good working condition.
- The sewer line was temporarily disconnected between the manhole located on the north-eastern corner of Stand 16463 and the manhole located on the south-eastern corner of Stand 16463 over a distance of approximately 11 m and sewage pumped above ground via a pipe. The water line was supported during this time period.
- Remove all highly erodible and compressible residual dolomite (wad) material, expected at variable depths, but down to a depth of 5 m within the sinkhole rehabilitation area.
- Backfilling of the 5 m deep sinkhole bulk excavation area and the trench excavation area involved: Cobbles/gravels in 300 mm thick layers up to a depth of 4,5 m below natural ground surface compacted to 95% compaction effort; placing of the 200 mm diameter sewer line within and on a 0,1 m thick layer of bedding material (river sand); followed with silty/gravelly sand in 300 mm thick layers compacted to 95% compaction effort up to 1,5 m (base of proposed water line) below ground level and placing of a new 300 mm diameter HDPE butt welded water pipe over a distance of 15 m within and on a 0,1 m thick layer of bedding material (river sand). Continue with backfilling of the bulk and trench excavated area with silty/gravelly sand compacted to 95% Modified AASHTO maximum dry density at optimum moisture content up to 0,3 m below natural ground surface within 150 mm thick layers. The upper two 150 mm layers (up to natural ground level) compacted at least at 98% of Modified AASHTO maximum dry density at optimum moisture content, creating a lip of 1 m beyond the made earth/virgin soil boundary to protect the contact.

A complaint was received in June 2012 from the home-owner on Stand 16463 of structural damage to his house. The complainant indicated that the damage was caused by the leaking EMM bulk water line and sinkhole that occurred on 20 September 2011 on the south-eastern boundary of Stand 16463 that was rehabilitated in the beginning of 2012.

Additional investigations were then required to determine if poor subsoil conditions or erosion extends below the house on Stand 16463 and if the structural damage to the house was caused by the leaking EMM bulk water line and sinkhole. The following additional investigations were conducted on Stand 16463 (Report Number VGI3355 WO391-1, March 2013):

- An audit on internal wet services on Stand 16463 was conducted to determine if there are any leakages on internal wet services that could have contributed to the situation, during June 2012.
- Dynamic Probe Super Heavy (DPSH) tests were conducted on Stands 16463 and 16462, during June 2012. The purpose of the DPSH tests was to determine the consistencies of the various soil horizons at depth and to determine if cavities are present at depth.
- One test pit excavated by hand down to a depth of 1,5 m on the north-eastern corner of the house on Stand 16463.
- A structural engineer was appointed to do an inspection on the house on Stand 16463 in November 2012. The purpose of the inspection was to establish the extent and severity of the alleged damage and the probable cause of such damage and to provide recommendations on the house repairs. A crack survey and the monitoring of cracks at the house on Stand 16463 were conducted from June 2012 to October 2012. The purpose of the monitoring was to determine if subsurface settlement related to dolomite instability is taking place below the structure.
- A grouting programme was undertaken in the northern and eastern portions of Stand 16464 to improve subsurface conditions, during 18 October 2012 to 1 November 2012.

The audit on the internal wet services on Stand 16463 revealed the following:

- No leaks were recorded on the internal wet services (110 mm diameter uPVC sewer line and 25 mm diameter PVC water line).
- Poor surface run-off with water ponding on the eastern side of the house.

The positions of the seventeen DPSH tests (DPSH1 to DPSH17) and the one Test Pit (TP1) are indicated on Figure H.3. The DPSH tests conducted over the site revealed the following subsoil conditions (Report Number VGI3355 WO391-1, March 2013):

- Alternating soil layers of very soft, soft, firm, stiff and very stiff consistency encountered at depth at the various DPSH test positions.



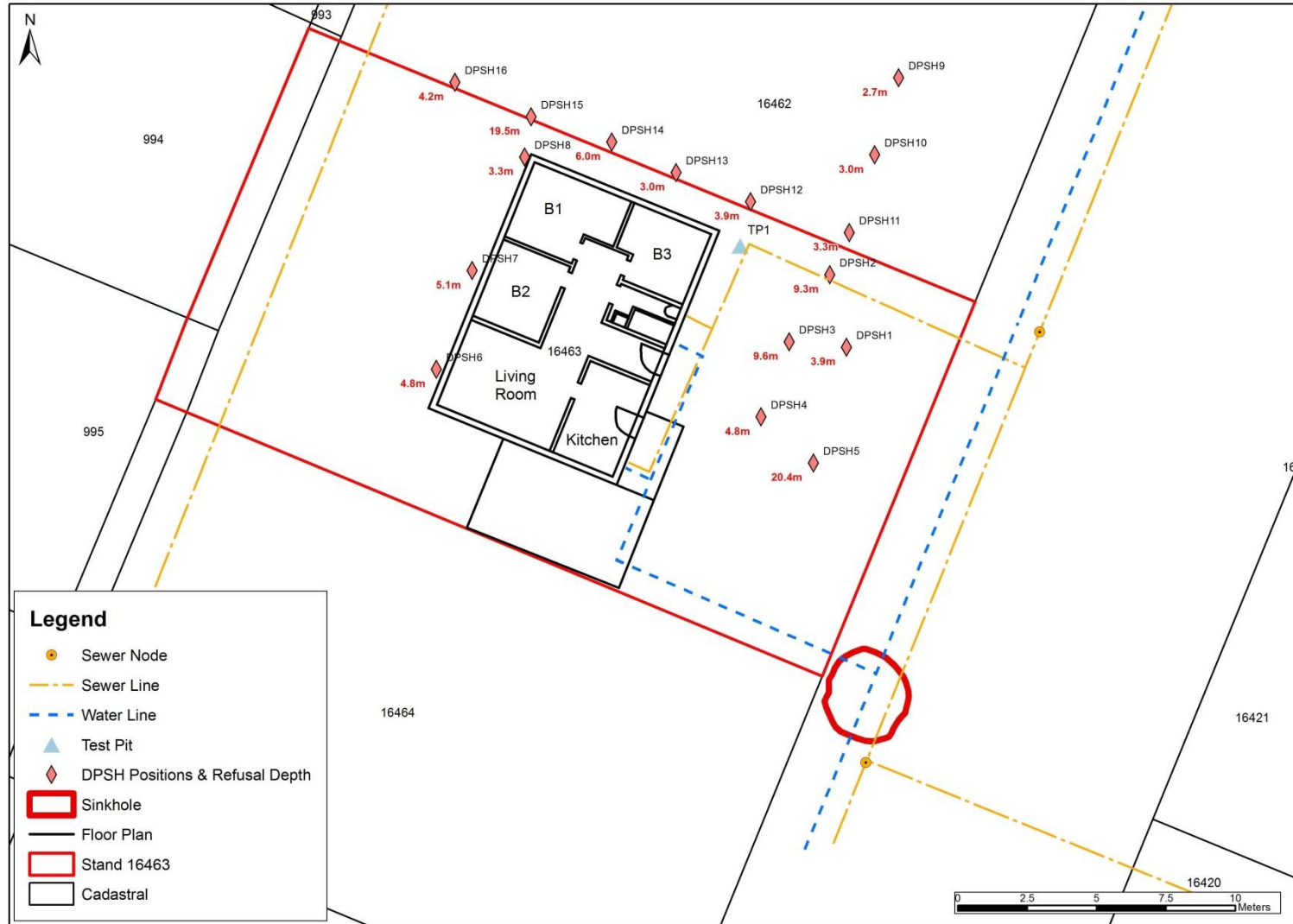


Figure H.3: Case Study 8 – Test Pit and DPSH test positions.

- Refusal at variable, but generally shallow to intermediate depths of 2,7 m to 9,6 m. The exceptions are DPSH tests D5 and D15 where refusal was encountered at depths of 19,5 m and more than 20,4 m. Refusal of the DPSH tests are possibly on highly weathered dolomite rock or hard rock dolomite.
- A variable bedrock profile as expected in a dolomite environment observed from the refusal depths, with the deeper zone occurring in the eastern half of the house on Stand 16463, in line with the crack through the foundation floor.
- Soil layers of very soft to soft consistency, representing problematic zones associated with large settlements were encountered at all the DPSH test positions at variable depths and of variable thickness on Stand 16463 and the adjacent Stand 16462.
- The very soft to soft soil consistencies are associated with poorly compacted imported fill or colluvium within 1 m from ground surface with zones deeper than 1 m associated typically with highly compressible and erodible residual dolomite (wad) and in some instances with residual chert.
- Based on the DPSH information problematic conditions including very soft or soft soil consistencies not suitable for the placing of a structure or representative of a compacted soil raft were encountered at most of the DPSH test positions.
- Problematic soil zones (including soil horizons with a very soft to soft consistency) encountered at each DPSH test position, the depth and thickness of these layers within the profile and DPSH refusal depths is given in the Table H.1

**Table H.1: DPSH Test Results.**

DPSH Test No.	Problem Zone (very soft-soft consistency) (m)-(m)	Thickness of layer (m)	Total Thickness of Problematic Zone (m)	Refusal Depth (m)
D1	1,8-2,4	0,6	0,6	3,9
D2	0,6-1,5 3,3-4,2 4,5-8,1	0,9 0,9 3,6	5,4	9,3
D3	0,3-1,8 2,1-8,7	1,5 6,6	8,1	9,6
D4	0,3-3,0	2,7	2,7	4,8
<b>D5</b>	1,2-9,3 9,6-20,4 (Maximum rods)	8,1 10,8	<b>18,9</b>	20,4 (Maximum)
D6	1,2-1,5 1,8-2,1 2,7-3,6	0,3 0,3 0,9	1,5	4,8
D7	-	-	-	5,1
D8	1,5-1,8	0,3	0,3	3,3
D9	0,9-1,2	0,3	0,3	2,7

DPSH Test No.	Problem Zone (very soft-soft consistency) (m)-(m)	Thickness of layer (m)	Total Thickness of Problematic Zone (m)	Refusal Depth (m)
D10	1,2-1,5	0,3	0,3	3,0
D11	0,9-1,2 1,8-2,1	0,3 0,3	0,6	3,3
D12	0,9-1,2 1,5-1,8 3,0-3,6	0,3 0,3 0,6	1,2	3,9
D13	1,8-2,1	0,3	0,3	3,0
D14	5,1-5,7	0,6	0,6	6,0
<b>D15</b>	0,3-1,8 2,4-2,7 3,9-4,2 8,1-8,7	1,5 0,3 0,3 0,6	<b>2,7</b>	19,5
D16	0,9-1,2 1,5-2,7	0,3 1,2	1,5	4,2
D17	0-0,3 1,8-2,1 3,6-3,9	0,3 0,3 0,3	0,9	4,2

- The most problematic area is around DPSH 5, where very soft to soft soil consistencies were encountered between 1,2 m to 9,3 m and 9,6 m to 20,4 m. DPSH 2, DPSH 3 and DPSH 15 are also regarded as problematic.

The soil profile encountered in the test pit on site, hand excavated to a depth of 1,5 m and its related geotechnical properties can be summarised as follows (Report Number VG13355 WO391-1, March 2013):

- A layer of fill, comprising firm clayey silt. This layer is encountered from ground surface to a maximum depth of 1,0 m.
- A layer of residual dolomite, comprising soft, with firm patches, clayey silt with 10% to 20% chert gravel and traces of wad. This layer is encountered from a minimum depth of 1m extending to an anticipated maximum depth in the test pit of 1,5 m.
- It is anticipated that both the imported fill and residual dolomite has a low potential expansiveness (<7,5 mm). Settlements may take place if a structure is placed on or within the residual dolomite layer under loads as low as 50 kPa (single storey residential structure). The layer of fill extending to a maximum depth of 1 m and possibly serving as a soil raft below the structure on Stand 16463 does not consist of material suitable to be used as a soil raft below structures, due to the low percentage of gravel (10% to 20%) and the anticipated moderate to high Plasticity Index values of the clayey silt material.

A description of the damage to the structure (house on Stand 16463) and the cause as observed by the structural engineer appointed in November 2012, prior to the commencement of repair work to the structure and further inspections during repairs, includes (Report Number VGI3355 WO391-1, March 2013):

- External walls built with a single skin of 140 mm thick cement bricks laid in stretcher bond, with no sign of any bed joint reinforcement observed in the walls.
- Decorative gables at each end of the house appear to be not correctly bonded into the main brick walls, possibly due to the form factor of the 140 mm brick.

### **1.1 Cracking of External Walls**

- A primary crack in excess of 6 mm wide was noted in the gable end wall (Bedroom 1), attempts have previously been made to repair this crack. The shape and position of this crack indicates settlement of the corner of the house in this area.
- A number of high level cracks (<6 mm wide) in the external walls of the structure above windows of Bedroom 1, 2 and 3, the bathroom and the entrance door.

### **1.2 Cracking of Internal Walls**

- Severe cracking in the wall at the end of passage and in the common internal wall between the bedrooms; these cracks have been previously repaired.
- Severe cracking (> 6mm) observed behind the tiles in the bathroom walls, it was noted that the tiles over and above the cracks are undamaged indicating that they were installed after the crack had occurred. High level crack observed at door of Bedroom 2, noted irregular reflections of paint next to door indicating a previous repair to this crack.
- These cracks may be related to the settlement of the house, but are exacerbated by the lack of any foundations, or floor thickening under the internal walls. The internal walls are built directly on the 5 cm thick floor slab. There are no strip footings to these walls.

### **1.3 Cracking in Floor**

- A significant crack was observed in the floor of Bedroom 1 and the passage. This crack is related to the crack in the gable end wall. The shape of the associated floor crack indicates settlement of the north-western corner of the house, taking into account the apparent lack of any mesh reinforcement in the floor of 50 mm thickness.
- The floor slab is constructed directly on top of soft residual dolomite (wad) with some harder spots of medium dense residual chert. The support of the floor slab is therefore uneven.

## 1.4 Age of Cracks

- Most of the cracks are not recent, as the cracks were repaired prior to the application of the current high gloss enamel wall finish, estimated to be 3 to 6 years old. In addition, it is apparent from the lack of damage to the bathroom tiles that the occurrence of these cracks pre-dates the fixing of these wall tiles.

## 1.5 Conclusions

- The cracking of the walls happened several years ago.
- The shape and position of the cracks is consistent with subsidence or settlement of soils under the northern most corner of the house.
- It is considered unlikely that the formation of any dolomitic sinkhole feature to the south or east of the house could create the pattern of cracks observed. Further, it appears that these cracks pre-date the recent dolomitic event.
- It appears that the original construction of the internal walls (specifically the lack of foundations or floor thickening) did not satisfy the requirements of the deemed-to-satisfy rules set out in SANS 10400.
- All structural cracks are also indicated on Figure H.4.
- It should be noted that all the existing cracks remained the same during the period of monitoring between June 2012 and October 2012 and did not become larger.

Based on the subsurface conditions encountered during the DPSH testing, a variable bedrock profile is observed, with a northwest – southeast aligned area presenting deeper dolomite bedrock (i.e. gryke – deep narrow slot) below the north-eastern portion of the house on Stand 16463, correlating with the crack in the floor slab. Improvement of the subsurface conditions required undertaking a grouting programme in the northern and eastern portions of Stand 16463.

The grouting programme included the drilling of thirteen primary grouting boreholes on a 3 m grid spacing. Two of the primary grouting boreholes (BH I1 and BH I2) were drilled at an angle of 30 degrees from vertical below the house to a depth of 8 m (7 m vertically and extending 4 m horizontally below foundation floor area). This process was followed by the drilling of five secondary grouting boreholes, positioned midway between the primary points within problematic areas. The grouting of each borehole was carried out from the bottom up, which is referred to as upstage grouting. The grouting mixture generally used, with a slump of between 25 mm and 75 mm, does not have to meet any strength requirements as the objective is not to form a structural element in the ground but to compact problematic zones and backfill potential voids missed by drilling.

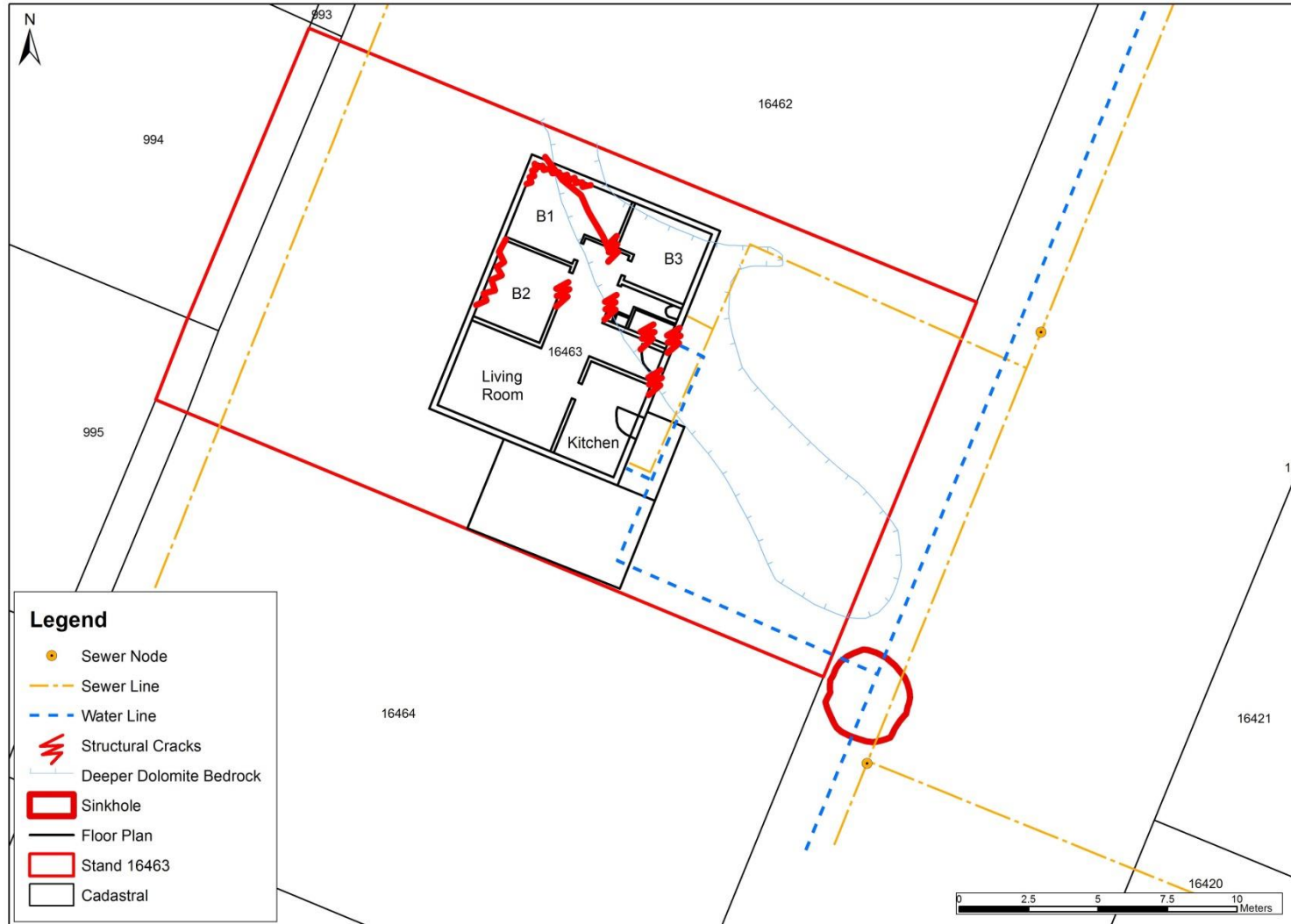
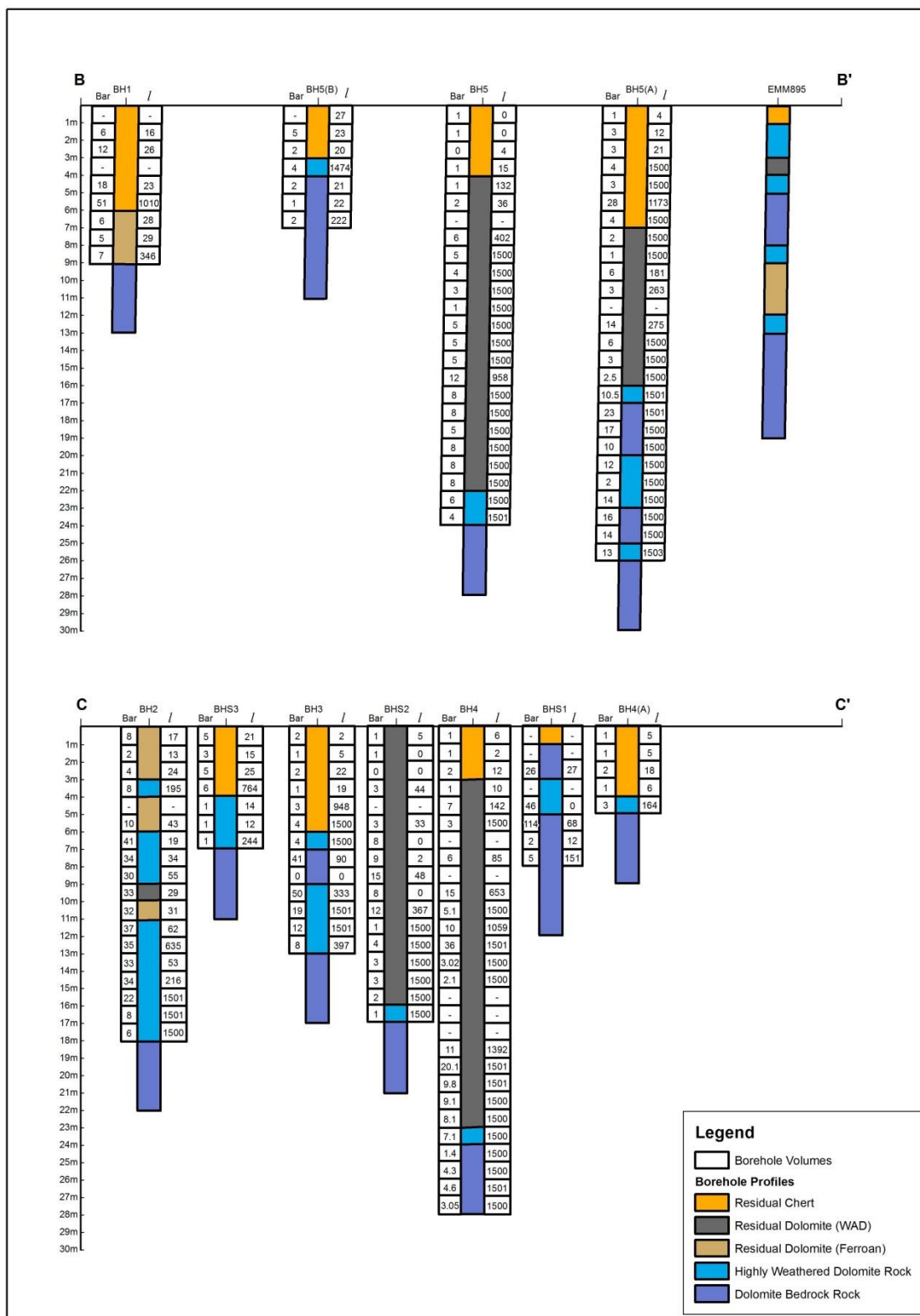


Figure H.4: Case Study 8 – Structural damage and deeper dolomite bedrock area.

The existing infrastructure and the position of grouting boreholes are displayed in Figure H.1 (Report Number VGI3355 WO391-1, March 2013). Four geological cross-sections (B - B', C - C', D - D' and E - E') presenting geological subsurface conditions as encountered during drilling, grout volumes injected (litre/metre) and pressure applied per meter (bar) at depth at each grouting point are illustrated in Figure H.5 and Figure H.6. The boreholes revealed the following subsurface geological profile (Report Number VGI3355 WO391-1, March 2013):

- Dolomite bedrock at a depth ranging from 4 m to 26 m, presenting a gryke feature. Hard rock dolomite of 2 m to 3 m thickness was also encountered closer to ground surface in sub-areas between variable depths of 1 m and 25 m typically between highly weathered soft rock dolomite horizons. A 1 m to 7 m thick horizon of highly weathered soft rock dolomite at variable depths ranging from 1 m to 26 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of residual chert to a depth of between 1 m and 7 m or residual dolomite (ferroan soils) to a depth of between 3 m and 8 m. Residual dolomite (wad) was encountered in one borehole from ground surface extending to a depth of 16 m. Residual dolomite (ferroan soils) of 1 m and 3 m thickness was also encountered lower down the profile below residual chert or between highly weathered soft rock dolomite between a variable depth of 4 m and 12 m. Residual dolomite (wad) of 1 m to 20 m thickness was also encountered below residual chert or between highly weathered soft rock dolomite between a variable depth of 3 m and 23 m. Rapid penetration rates air losses and no sample return were encountered during the drilling programme in the residual chert, residual dolomite and dolomite bedrock.
- Cavities were not encountered in any of the boreholes. Cavities can, however, be expected within the residual dolomite (wad) horizons encountered above bedrock.
- No groundwater was encountered and the regional groundwater level is at 1530 m AMSL (36 m below natural ground level) within dolomite bedrock.

The area presenting deeper dolomite bedrock (i.e. gryke –deep narrow slot), based on the DPSH test results and the grouting boreholes is illustrated in Figure H.4. The width of the gryke is estimated at 2 m to 4 m and occurs below the eastern half of the house on Stand 16463 in the same area as the floor crack through the foundation floor and where consolidation settlement of the foundation took place. The gryke (17 m to 26 m deep) is surrounded by shallower dolomite bedrock encountered at depths from 4 m to 13 m. The blanketing layer above the dolomite bedrock within the gryke area comprises thin to intermediate thick horizons (8 m to 20 m) of very soft to soft, low density compressible residual dolomite.



**Figure H.5: Case Study 8 – Cross-Section B – B` and C – C` of grouting boreholes with geological profile, grout volumes and pressure applied.**



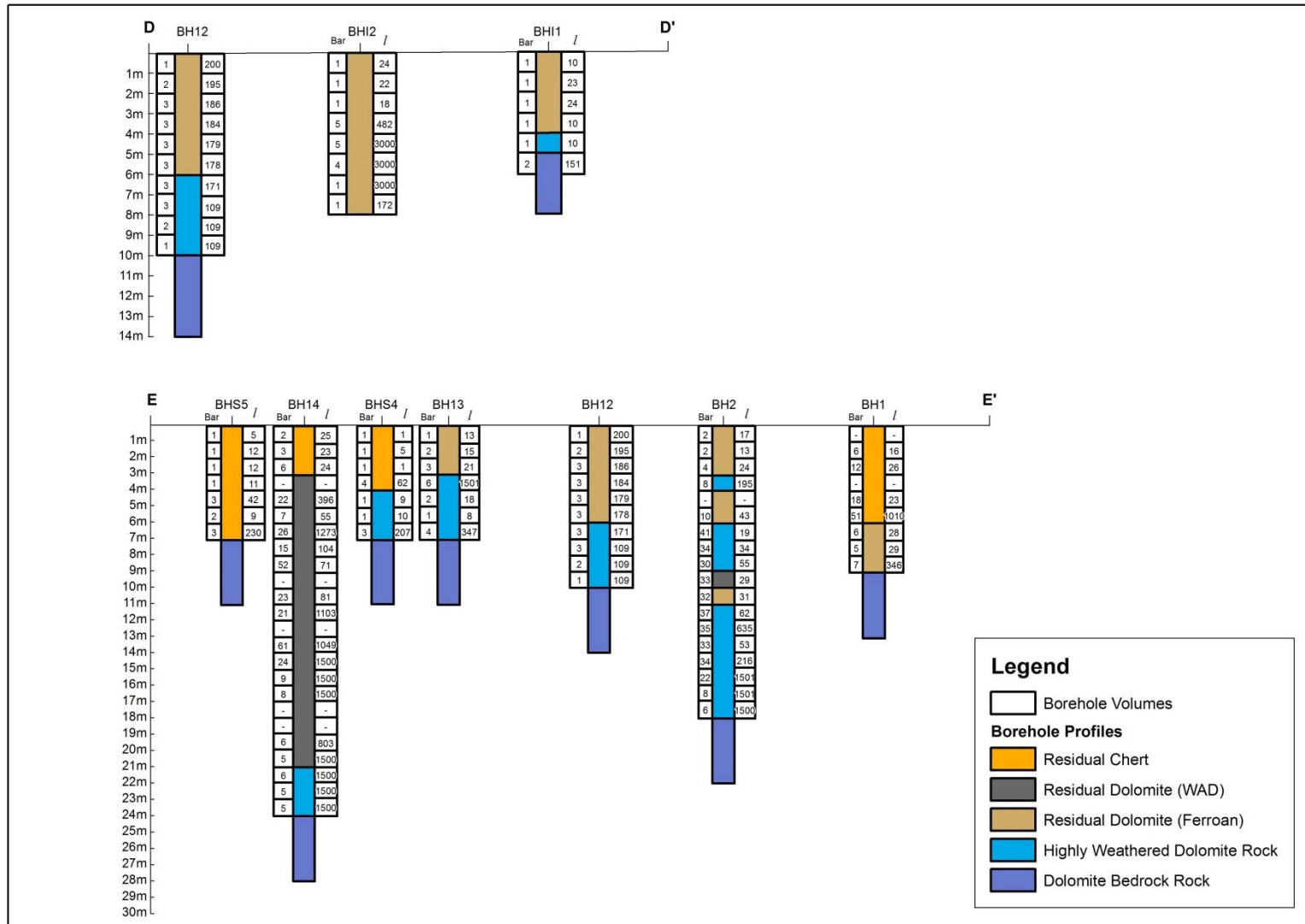


Figure H.6: Case Study 8 – Cross-Section D – D' and E – E' of grouting boreholes with geological profile, grout volumes and pressure applied.

As illustrated in Figure H.5 and Figure H.6, variable grout pressures were applied to inject the grout below ground surface ranging between 0,1 MPa (or 1 Bar) to 5,2 MPa (or 52 Bar).

Based on the field records as received from the contractor grout volumes of more than 52 Bar were recorded in two boreholes, in Borehole BHS 1, 114 Bar has been recorded between a depth of 5 m and 6 m; and in Borehole BH14, 61 Bar has been recorded between 13 m and 14 m. The maximum pressure that can be applied by the specific contractor's equipment is 60 Bar, and as such these two values are not correct and were ignored.

To prevent fracturing of the overburden resulting in ground heave, very low pressures (1 to 3 Bar or 0,1 to 0,3 MPa) were applied within the upper 3 m of the grout profile. The volume of grout injected per metre varied between 0,029 m<sup>3</sup> to 1,215 m<sup>3</sup>.

The total volume of grout injected per borehole, litre of grout per metre and the volume of grout (m<sup>3</sup>) per metre is given in the table below.

**Table H.2: Total volume of grout injected per borehole, litre of grout per metre and the volume of grout (m<sup>3</sup>) per metre.**

Borehole Number	Total Volume of Grout (m <sup>3</sup> )	Volume of Grout (l per m)	Volume of Grout (m <sup>3</sup> per m)
<b>Primary</b>			
BH1	1478	164	0,164
BH2	5928	329	0,329
BH3	7818	601	0,601
BH4	24365	870	0,870
BH4(A)	188	38	0,038
BH5	24048	1002	1,002
BH5(A)	28916	1112	1,112
BH5(B)	1809	258	0,258
BH12			
BH13	1923	275	0,275
BH14	15507	646	0,646
<b>Primary Inclined</b>			
BHI 1	228	28,5	0,029
BHI 2	9718	1215	1,215
<b>Secondary</b>			
BHS 1	258	32	0,032
BHS 2	9499	559	0,559
BHS 3	1095	156	0,156
BHS 4	295	42	0,042
BHS 5	321	46	0,046

It is illustrated in the below mentioned table that the highest grout volumes of between 0,870 m<sup>3</sup>/m to 1,215 m<sup>3</sup>/m were encountered within the area presenting the deeper

dolomite bedrock (i.e. gryke) area, comprising thin to intermediate thick horizons (8 m to 20 m) of residual dolomite.

Low to intermediate grout volumes of between 0,029 m<sup>3</sup>/m to 0,329 m<sup>3</sup>/m were encountered in all other boreholes where shallower dolomite bedrock was encountered with thin layers of residual dolomite or no residual dolomite.

## **2. STRUCTURAL AND FINISHING TOUCHES**

### **2.1 Additional Repairs and Improvements**

The following additional repairs and improvements were carried out to the house and surrounding area on Stand 16463 (Report Number VGI3355 WO391-1, March 2013):

- The portions of external and internal walls where cracks were observed were demolished and reconstructed with reinforcement and plastered.
- The 5 cm floor slab in Room 1, Room 3, half of the passage and a metre into the bathroom (including the area of the crack in the floor slab) was removed. The soft residual dolomite and residual chert material encountered below the removed concrete floor slab was removed down to a depth of 0,4 m and replaced by 100mm thick layers (X3) of G5-quality cement stabilised material compacted at 98% of Modified AASHTO Maximum Dry Density at Optimum Moisture Content. A new 15 mm thick reinforced (with Y20 reinforcement) concrete slab was constructed within this area. Slots were cut below the internal walls within this area to ensure a continuous reinforced slab and in addition ensure that the internal walls are underpinned in the area of the concrete slab.
- All the tiles of the roof were displaced towards the northern subsided portion of the house. The tiles were correctly placed and all broken ceilings replaced.
- A new boundary wall was constructed towards the north of the house.
- Finishing Touches: the entire house was painted externally and internally. The passage and the bathroom were retiled, and vinyl flooring placed in rooms.

### **2.2. Micro Driven Piles**

- To prevent fracturing of the overburden resulting in ground heave, very low pressures (1 to 3 Bar) were applied within the upper 3 m of the grout profile and as such the upper 3 m of the soil profile (that may still present problematic soils such as collapsible/compressible soils or expansive soils) will potentially not be compacted as well as the deeper areas in profile where much higher pressures were used to inject the grout.
- As part of the stabilisation of the structure a total of eighteen micro piles were installed at a 2 m interval below the foundation of the external wall of the house on Stand 16463. Steel sleeves (piles) were driven in to a point of refusal. The piles were then cast with 25 MPa concrete with Y16 reinforcing. The piles have a load

capacity of 180 kPa. The piles were installed after the grouting programme has been completed.

- Refusal depths of the micro driven piles varied between 1 m and 4 m.

The position of the reinforced concrete slab and positions of piles with the refusal depth at each is indicated in Figure H.7.

### **2.3 Internal Water and Sewer Lines and Surface Water Run-Off**

- The internal sewer and water lines on Stand 16463 were replaced with HDPE butt-welded material and connected to the bulk water and sewer line of Ekurhuleni.
- The garden area on Stand 16463 was landscaped and a concrete canal constructed to ensure surface water run-off is taking place away from the area. The position of the concrete canal and upgrade on all wet service is indicated in Figure H.8.

## **3. CAUSES OF STRUCTURAL DAMAGES TO THE HOUSE ON STAND 16463 AND REHABILITATION**

### **3.1 Primary Cause of Structural Damage**

- Based on the subsurface conditions encountered during the DPSH testing and drilling of the grouting boreholes on Stand 16463 very poor subsurface dolomitic conditions including thick horizons of residual dolomite (wad) was encountered, not suitable for a residential structure.
- In addition, the structure appears to be founded on a poorly compacted soil raft, consisting of some layers of residual dolomite (wad) of soft consistency, placed on natural occurring soils comprising very soft to soft compressible material (residual dolomite) extending to variable depths but up to 16m to 23m within the are presenting deeper dolomite bedrock (gryke).
- Foundation design: The current foundation (i.e. normal strip footings) cannot withstand a sinkhole or a subsidence of a minimal diameter of 5 metres to greater than 15 metres. Ground instability (i.e. sinkhole or subsidence formation) triggered by ingress of water (i.e. leaking wet services including water and/or sewer or ponding surface water) will impact negatively on the integrity of the structure. The most appropriate design would have been a reinforced concrete raft foundation catering for a 5 m diameter size sinkhole, placed on a 1,5 m thick engineered earth mattress.

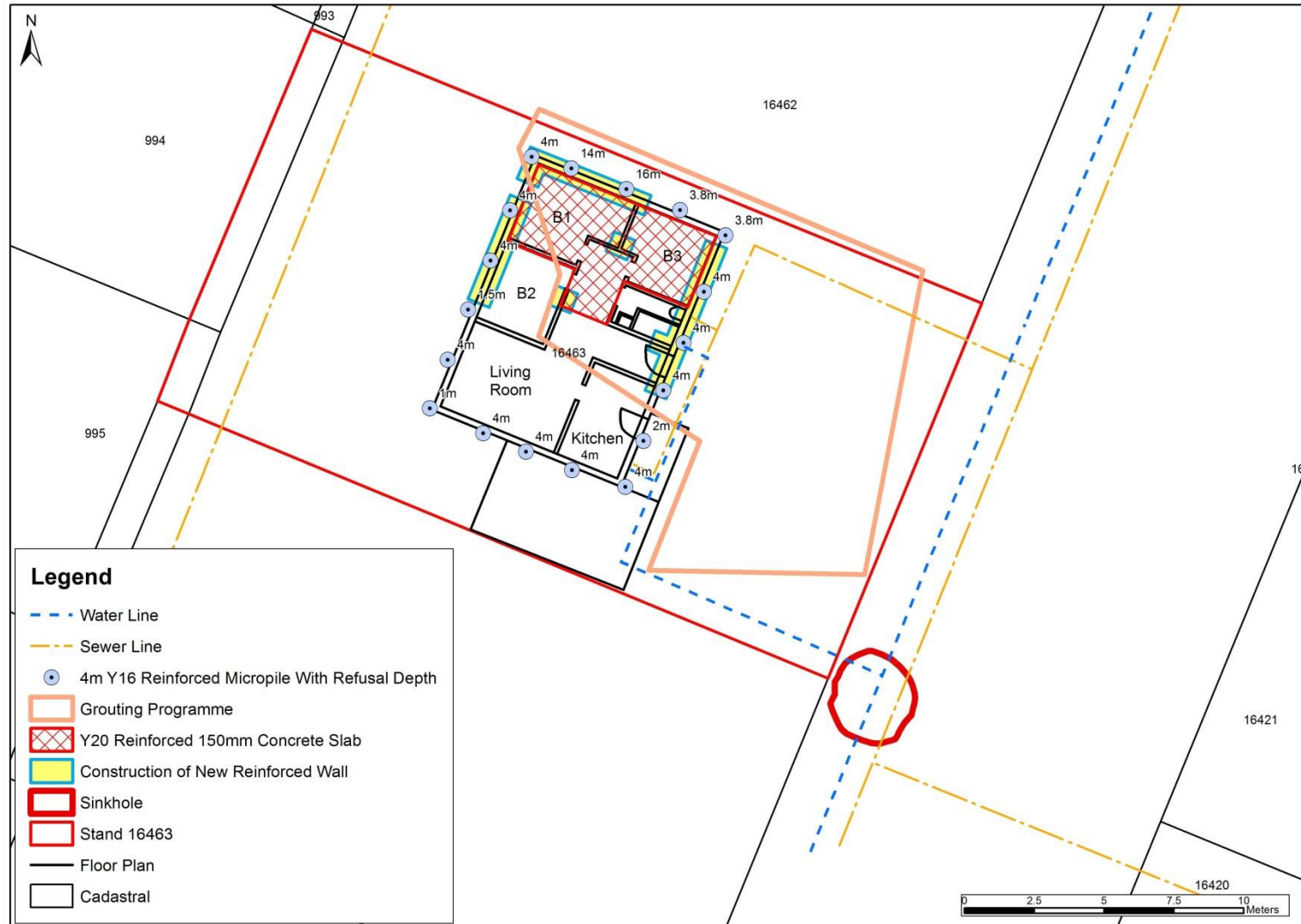


Figure H.7: Case Study 8 – Structural repairs and improvements to the house on Stand 16463.

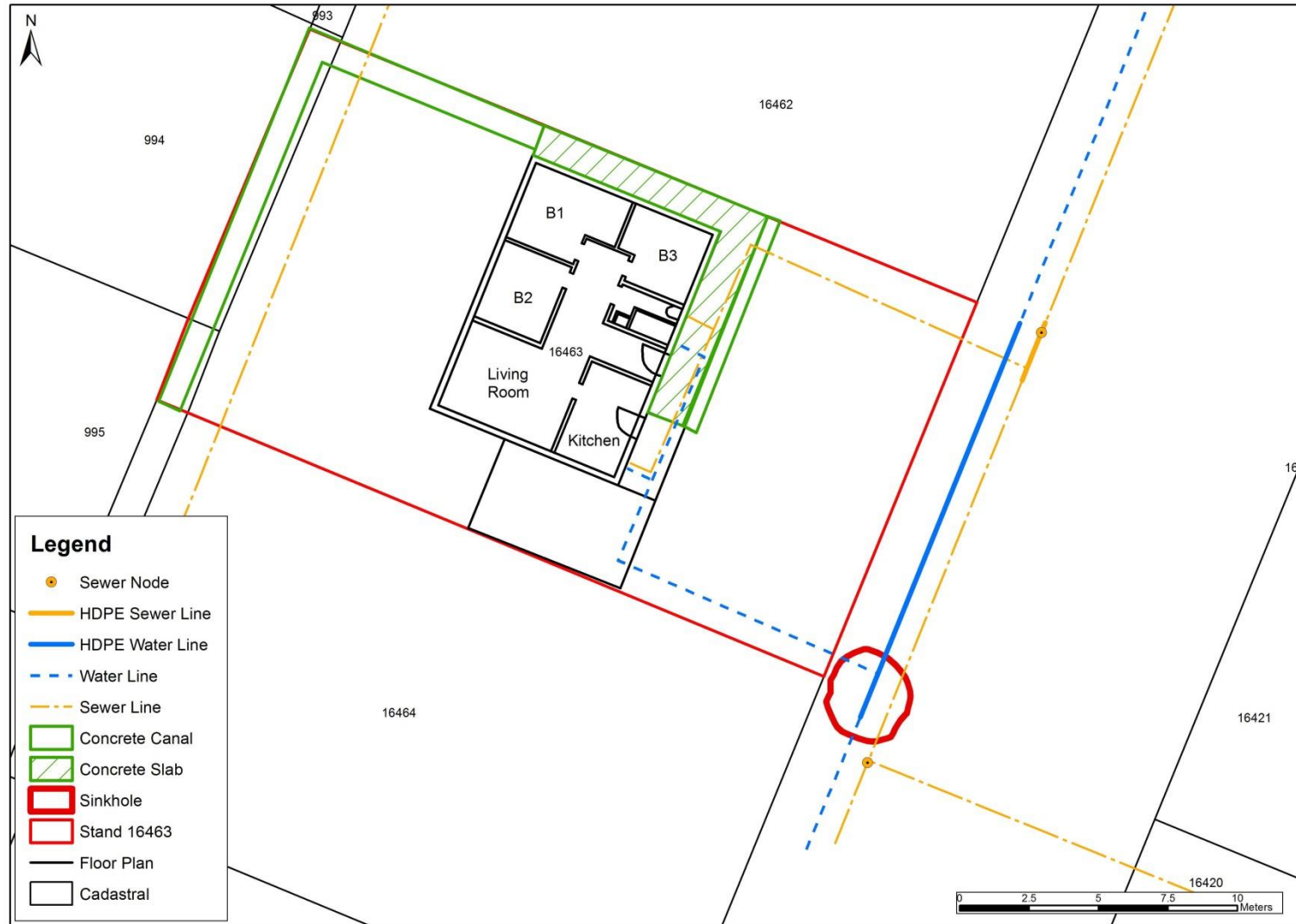


Figure H.8: Case Study 8 – Wet services and surface water runoff upgrade.

- Based on the finding of the structural engineer, the cracking of the walls occurred several years ago. The shape and position of the cracks is consistent with subsidence or settlement of soils under the northern-most corner of the house, within the deeper dolomite bedrock zone. It is considered unlikely that the formation of any dolomitic sinkhole feature to the south or east of the house could create the pattern of cracks observed. Furthermore, it appears that these cracks pre-date the recent dolomite stability event.
- It appears that the original construction of the internal walls (specifically the lack of foundations or floor thickening) did not satisfy the requirements of the deemed-to-satisfy rules set out in SANS 10400.

### **3.2 Secondary Contributing Factor:**

- The leak on the 300 m diameter PVC bulk EMM water line located within the western servitude of Mabuya Street may potentially have contributed to the re-opening of the already existing cracks in the house, as settlement took place of highly compressible residual dolomite (wad) material within the area presenting deeper dolomite bedrock conditions.
- An additional contributing factor is the ponding of run-off surface water. The topographic gradient on Stand 16463 is from east to west and as such all surface water to the east of the house on stand 16463 is draining towards the house.

### **3.3 Rehabilitation of foundation and soil improvements to the house on Stand 16463:**

- Adequate measures were taken to stabilise the compressible residual dolomite (wad) material below and adjacent to the structure within problematic areas by means of a grouting programme. In addition as part of the stabilisation of the structure reinforced micro piles were installed at 2 m intervals below the foundation of the external walls of the house extending to refusal depths, thereby displacing the foundation load to stable conditions. All external and internal walls with cracks was demolished and reconstructed with reinforcement. The affected floor area with the crack was removed and replaced by a 150 mm reinforced concrete raft foundation placed on a 0,3 m thick compacted soil mattress. Slots were cut below the internal walls so that reinforcement can go through presenting a continuous concrete slab that also underpins internal walls in that area.

# **APPENDIX I**

## ***CASE STUDY 9***



## CASE STUDY 9

A sinkhole occurred in the north-eastern corner of Stand 20121 Vosloorus on 2 September 2009. The sinkhole, extending below a double storey house was caused by a leaking mid-block sewer line (Plate I.1). A sinkhole previously occurred on Stand 20121, due to a leaking internal sewer line in 2001 and the residential structure was demolished. The exact position and the rehabilitation process followed on the sinkhole that occurred during 2001, are unknown. A site inspection of the affected area was conducted on 3 September 2009 and revealed the following (Report Number VGI3118/245/1, September 2009):



**Plate I.1: Sinkhole in north-eastern corner of Stand 20121, Vosloorus Extension 30.**

- A sinkhole (dimensions of 4,5 m by 2 m extending to a depth of 2,5 m) occurred on the northern boundary of Stand 20121 and extended below the house on Stand 16303 (Plate I.2).
- East to west aligned wet services, including sewer and water were located within the area of the sinkhole. A sewer manhole is located directly east of the sinkhole.
- An east to west aligned overhead electrical cable is also located in the area of the sinkhole.
- Very recent additions (as observed from aerial photos) to the house on Stand 16303 including a double storey structure extending over the building line and wet services servitude area. The additions are not according to Building Regulations.
- No structural damage was observed to the house located partially on the sinkhole.



**Plate I.2: Close-up view of sinkhole on Stand 20121 Vosloorus Extension 30.**

Taking the above conditions into account (e.g. position of existing double storey structure and wet services in correlation to the sinkhole) the following was carried out in terms of rehabilitation of the affected area:

- To stabilise the house, the cavity below the house was filled with 10 MPa mass concrete up to the boundary wall. The remaining portion of the sinkhole south of the northern boundary wall in the area of subsurface wet services was backfilled in 300 mm thick layers of gravelly soil and each layer compacted to 93% of Modified AASHTO maximum dry density at optimum moisture content. The backfilling of the sinkhole was also required to provide access for a drilling rig in the affected area.
- A new HDPE manhole was constructed to a depth of approximately 3,5 m in the north-western corner of the adjacent stand to the west. The existing broken vitrified clay sewer line was replaced by a HDPE butt-welded pipe by means of pipe cracking, from the existing sewer manhole located east of the sinkhole to the newly constructed manhole. The existing water line was also replaced with a HDPE butt welded pipe.
- Percussion boreholes for compaction grouting purposes were drilled during the period of 4 December 2009 to 10 December 2009 and consisted of the drilling of five percussion boreholes (Boreholes EMM507 to EMM511). Two of the five boreholes were drilled at a 20 degree inclination below the affected house.
- Boreholes were placed as best as possible 2,5 m to 3 m from each other within the affected area.

The affected area, existing infrastructure and the position of Boreholes EMM507 to EMM511 are displayed in Figure I.1. A geological cross-section presenting subsurface conditions as encountered during drilling, grout volumes injected and pressure applied at depth for each section is illustrated in Figure I.2. The boreholes revealed the following subsurface profile:

- Dolomite bedrock at a depth ranging from 5 m to 18 m. A 1 m to 2 m thick horizon of highly weathered soft rock dolomite at variable depths ranging from 5 m to 18 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of residual chert to a depth of between 3 m and 5 m. The surface layer is underlain by residual dolomite comprising ferroan soils (layer thickness between 1 m to 2 m) or manganese (wad) soils. Rapid penetration rates and no sample return were encountered in the residual dolomite (wad) horizon encountered above bedrock.
- Cavities were not encountered in any of the boreholes. Cavities can, however, be expected within the residual dolomite (wad) horizon encountered above bedrock.
- No groundwater was encountered and the regional groundwater level is at 1533 m AMSL (21 m below natural ground level) within dolomite bedrock.

The upstage grouting conducted only at primary points on a 2,5 m to 3 m spacing did not need to meet any strength requirements as the objective was not to form a structural element in the ground but to backfill voids and compact problematic zones. When a grouting programme is considered as a soil improvement method, multi stage grouting is normally done in a series of primary and secondary points, with the possibility of a tertiary stage. All the primary points are drilled first on a 3 m grid spacing, followed by the secondary points some days later. The secondary points are positioned midway between the primary points.

The site conditions, however, only allowed for primary points. As illustrated in Figure I.2 a grout pressure of 10 Bar (or 1 MPa) was used between a depth of 5 m to 20 m below ground surface, With a grout pressure of between 5 to 8 Bar (or 0,5 MPa to 0,8 MPa) applied from ground surface to an average depth of 5 m. The volume of grout injected per metre varied between 0,18 m<sup>3</sup> to 2,4 m<sup>3</sup>.

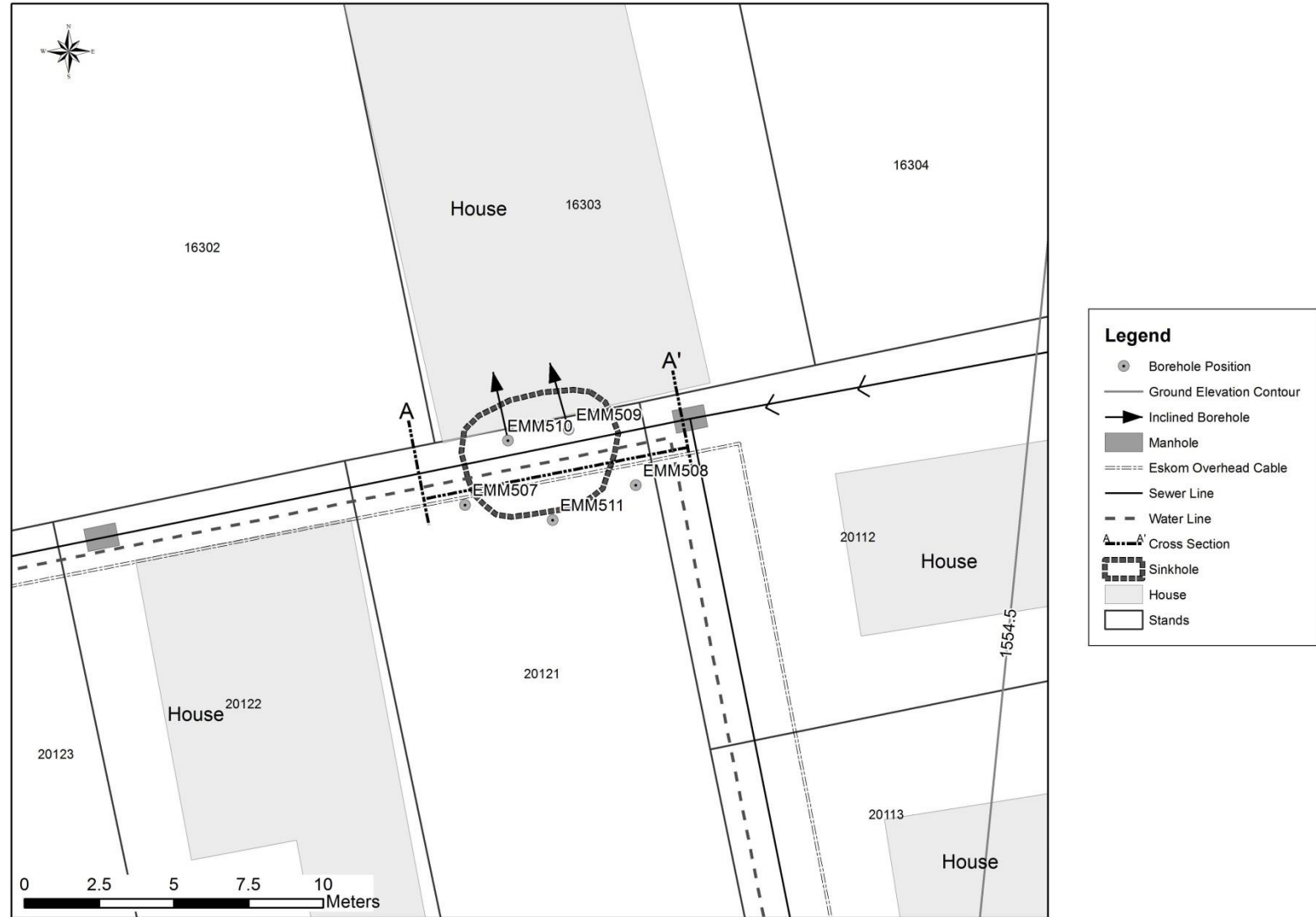


Figure I.1: Case Study 9 – Plan view of the affected area, existing infrastructure and the position of boreholes.

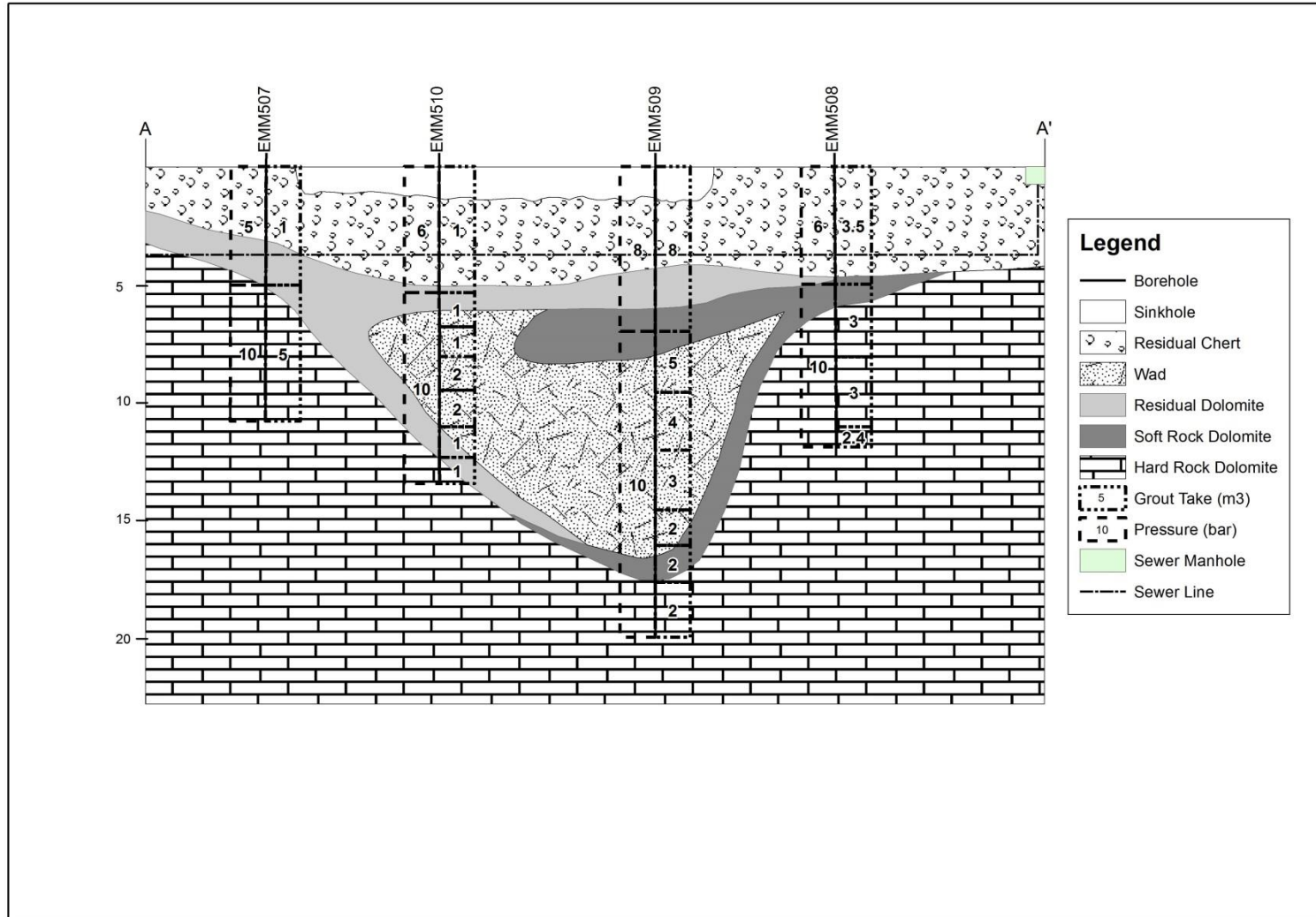


Figure I.2: Geological cross-section with grout volumes injected and pressure applied at depth.

**APPENDIX J**

***CASE STUDY 10***

## CASE STUDY 10

A sinkhole occurred on the south-western boundary of Stand 2, Flint Mazibuko Street, Tembisa Extension 1 during January 2009. The sinkhole was caused by the accumulation of surface water run-off. A site inspection of the affected area was conducted on 13 January 2009 and revealed the following (Report Number VGI3118/199/1, January 2009):

- A 7 m diameter sinkhole extending to a depth of approximately 5 m below natural ground surface (Plate J.1). Situated 0,5 m from the boundary wall between Stand 1430 and Stand 2 in an open field.



**Plate J.1: Sinkhole on Stand 2, Tembisa, photo taken towards the west.**

- The topographical gradient of Stand 2 is in a south-westerly to westerly direction towards the sinkhole.
- A stormwater outlet is situated approximately 50 m east of the sinkhole located on Stand 2.
- Surface water run-off is channelized along a north-east to south-west aligned ground canal over the first 40 m from the stormwater outlet on Stand 2 from where surface water run-off is expelled as sheetwash down the gradient up to the boundary wall of Stand 1430 where it can't go further and ponding of run-off water takes place.

- A north-east to south-west aligned sewer and water line is located to the south of the area in the northern servitude of Flint Mazibuko Street. The sewer and water lines did not contribute to the formation of the sinkhole on Stand 2.
- The 7 m diameter sinkhole extending to a depth of 5 m was caused due to uncontrolled stormwater runoff along an unpaved and unsealed channel that accumulated east of the boundary wall of Stand 1430, mobilising subsurface dolomitic materials.
- The residential structure on Stand 1430 is located approximately 3m west of the sinkhole located on Stand 2.

A dolomite stability investigation including a gravity survey and the drilling of seven percussion boreholes was conducted during July 2009 to determine subsurface conditions and the required soil improvements (Report Number VGI3118R-WO199-2, August 2009). The gravity survey on a 10 m station interval was conducted on Stand 2 and Stand 1430 to obtain information on the depth and shape of the dolomite bedrock profile. The seven percussion boreholes (Boreholes EMM247 to EMM253) were placed around the sinkhole to the north, east and south. Accessibility for a drilling rig on Stand 1430 was not possible at that stage and it was required that additional investigations be conducted on Stand 1430 after breaking down the eastern boundary wall of Stand 1430 to gain access. The additional dolomite stability investigation including the drilling of three percussion boreholes (EMM580 to EMM582) on Stand 1430 was conducted during June 2010 after access was arranged on privately owned land via the municipality.

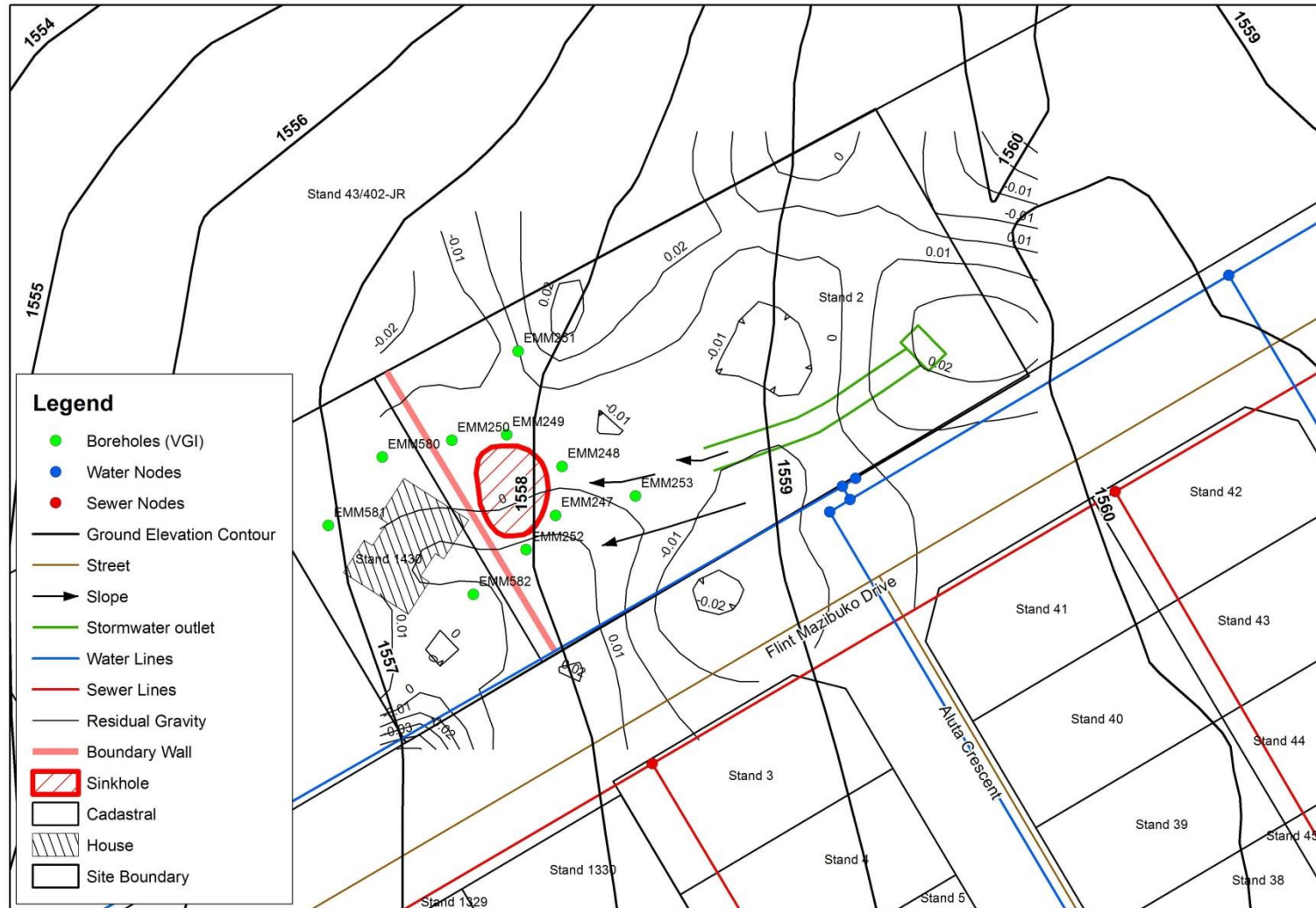
The affected area, existing infrastructure, sinkhole, gravity survey and the position of boreholes are displayed in Figure J.1. The boreholes presenting subsurface conditions as encountered during the dolomite stability investigation surrounding the sinkhole on Stands 2 and 1430 is illustrated in Figure J.2.

The gravity survey revealed the following:

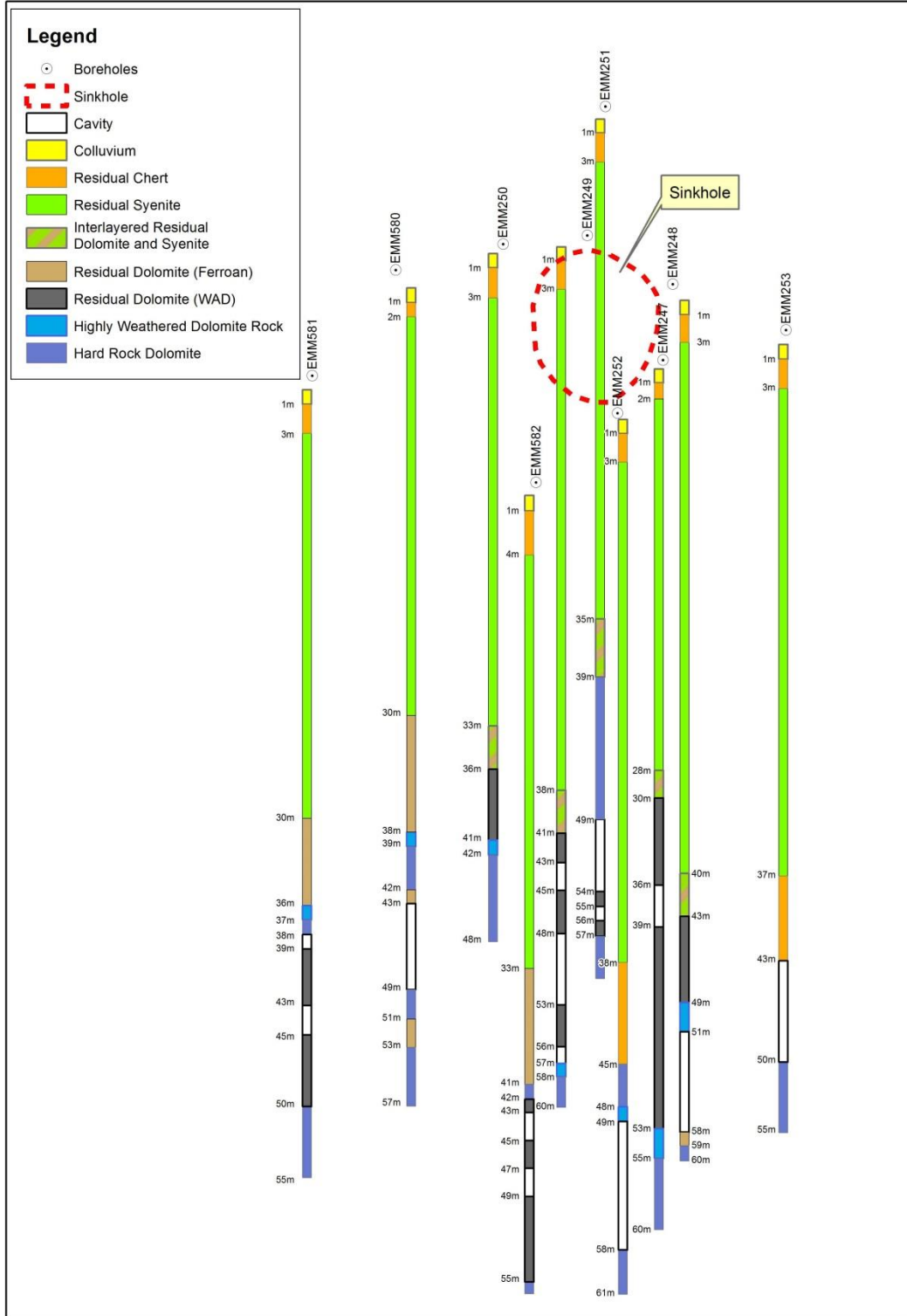
- The residual gravity contours is presented in 0,01 m Gal contour intervals. Gravity contours are usually presented at 0,1 m Gal intervals. The gravity gradients are therefore not as steep as the contours in Figure J.1 perceive it to be and therefore the gravity variation is really minimal. The total difference in gravity field is 0,04 m Gals.
- The gravity pattern did, however, reveal a north-west to south-east aligned gravity low field in the central portion of the site and a gravity low field in the south-western and north-eastern portion of the site bordering the two central gravity high areas.

The dolomite stability investigations revealed the following subsurface profile as illustrated in Figure J.2:





**Figure J.1: Case Study 10 – Plan view of affected area, existing infrastructure, sinkhole, gravity contours and the position of boreholes.**



**Figure J.2: Case Study 10 - Boreholes presenting subsurface conditions as encountered during the dolomite stability investigation surrounding the sinkhole.**

- Dolomite bedrock at a depth of 42 m to 59 m. Hard rock dolomite of 1 m to 10 m thickness was also encountered closer to ground surface between a depth of 37 m and 51 m. Highly to moderately weathered soft rock dolomite of 1 m to 2 m thickness encountered between a variable depth of 36 m and 58 m.
- The blanketing layer above dolomite bedrock comprises: A surface layer consisting of colluvium to a depth of 1 m followed by a 1 m to 3 m thick layer of residual chert to a depth of 2 m to 4 m. The surface layers are underlain by residual syenite from a minimum depth of 2 m and 4 m extending to a maximum depth of 28 m and 40 m. Interlayered residual syenite and residual dolomite (ferroan soils) of 3 m to 4 m thickness was encountered between a depth of 33 m and 43 m typically below residual syenite.
- A second layer of residual chert of 6 m to 7 m thickness was encountered in two boreholes between a depth of 37 m and 45 m. Residual dolomite (ferroan soils) of 1 m to 8 m thickness was encountered between a variable depth of 30 m and 53 m. Residual dolomite (wad or manganiferous soils) of 5 m to 23 m was encountered between a variable depth of 36 m and 59 m above and within dolomite bedrock. Rapid penetration rates, air and sample losses, cavernous conditions were recorded in all the boreholes above and within hard rock dolomite.
- Cavities of 1 m to 9 m high were intercepted in nine of the ten boreholes drilled. Cavities were recorded within the residual dolomite (wad) above and within dolomite bedrock between a variable depth of 36 m and 58 m.
- Groundwater was not intercepted in any of the boreholes drilled and all the boreholes were recorded as 'dry' 24-hours after drilling. The site is located in the Sterkfontein West Dolomite Groundwater Compartment and the regional groundwater level is at 1512 m AMSL (46 m below natural ground level) above dolomite bedrock.

Taking the existing geological conditions on site into account (e.g. depth to dolomite bedrock, presence of highly erodible and compressible residual dolomite (wad)), cavities (1 m to 9 m high) between a depth of 36 m and 58 m, a 7 m diameter size sinkhole extending to a depth of 5 m below natural ground level located 3 m away from a residential structure; improvement of the subsurface conditions required the undertaking of a grouting programme. It was advised that the grouting programme should include the creation of a grout curtain around the area of proposed improvement, followed by multi stage grouting (primary and secondary points with a possibility of tertiary points) within the area defined by the grout curtain. The cost implications related to the above mentioned grouting programme including a grout curtain and primary and secondary grouting points would have been more than R20 million in 2009. Without ground improvement, the current sinkhole area will most likely encroach on the house on Stand 1430. The following remediation measures were taken in terms of the affected area:

- The grouting programme has a major cost implication and other options such as the evacuation and demolishing of the house on Stand 1430 should be considered, with the sinkhole backfilled according to the Dynamic Compaction or Inverted Filter Method (including the use of geo-textiles as a safety precaution measure). Both these methods will only partially improve subsurface conditions, due to the fact that the cavity is seated so deep below ground surface covering a vast area. If any of these two alternative

methods or a combination of the two methods is considered, the area should be properly fenced off, allowing no access to people, effectively sterilising the area.

- As the sinkhole was caused due to poor surface water run-off, a 0,5 m high soil berm was constructed around the sinkhole and the ground surface re-contoured to divert stormwater into the open field to the north and into the stormwater system to the south along the road, away from the sinkhole.
- Stand 2 including the sinkhole area was fenced off and the land sterilised.

It is clear from the illustration in Figure J.2 that the subsurface conditions on Stand 2 and Stand 1430 and the sinkhole area presents deep seated cavities covering a vast area that can only be properly rehabilitated by means of a grouting programme. As the cost implication related to the grouting programme is so high, it was advised that the land should rather be sterilised (fenced off) and the house located 3 m away from the sinkhole be demolished. The sinkhole can then be partially rehabilitated by means of the Inverted Filter Method or the Dynamic Compaction Method or a combination of both.