Engineering geological mapping for urban development in low relief semi-arid regions (Outapi, northern Namibia)

Submitted as partial requirement for the degree

Master of Science Engineering Geology

Submitted to:

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Submitted by:

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DECLARATION

I, Giesberta N. Shaanika, submit this dissertation in partial fulfillment for the requirements of the degree Master of Science in Engineering Geology at the University of Pretoria. It has not been previously submitted by me or any other person for a degree at this or any other institution. I hereby declare that the work presented in this dissertation is mine, except where authors are cited.

Signature	Date
Shaanika	September 2019

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DEDICATION

Dedicated to the amazing Mrs Maria Mwatile-Shaanika

To my praying mother, my cheerleader, my fountain of courage and my pillar of strength. Mama you have always been there for me in so many ways I cannot begin to count. Your world shattered after dad's passing but you picked up the pieces and patched up for us. I admire your strength. Your wise words of counsel always echoed in my head when the journey got rough. Thank you for your encouragement, kindness, generosity and selfless love. Those are things I can surely not repay you for, but I pray that God gives you back a million times what you have invested in me.

I love and appreciate you, Mama.

ABSTRACT

Title: Engineering geological mapping for urban development in low relief semi-arid regions (Outapi, northern Namibia)

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Considering the current lack of engineering geological mapping in urban developments in Namibia, it was necessary to pioneer the input of engineering geology in the planning of infrastructure. The benefits of engineering geological mapping in sustainable development were highlighted and present methodologies were explored, looking at their applicability to Namibia. The early activities of engineering geological mapping include terrain classification, which groups areas of terrain that have similar conditions. It applies the principle of homogeneity such that areas falling under one terrain class are treated the same during planning, as they are deemed to have the same impact on engineering structures. The traditional way of doing terrain classification places much reliance on topography features, such as valleys, streams, etc. However, this becomes fairly difficult to apply in flat lying areas where topographical features may not be readily visible from aerial photographs. Therefore, soil variability mapping using colour and texture, vegetation mapping, and damage distribution mapping or structural damage techniques were recommended to aid terrain classification in flat lying semi-arid environments. Employing these techniques, Outapi Town in northern Namibia was mapped, identifying four terrain classes. With subsequent testing methods, these were upgraded to just three engineering geological zones. The main geotechnical constraints identified include the possibility of collapse settlement given the aeolian nature of the Outapi soils, susceptibility to flooding attributed to the flat nature of the area with no properly defined pathways, potential for dispersion as the soils are rather fine and saline, and, to a lesser extent, the presence of potentially expansive soils.

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LIST OF ABBREVIATIONS AND ACRONYMS

GSN	Geological Survey of Namibia
NDP 4	National Development Plan 4
BON	Bank of Namibia
CEB	Cuvelai Etosha Basin
CSIR	Council for Scientific and Industrial Research
DWAF	Department of Water Affairs and Forestry
NDP3	Third National Development Plan
NMH	National Mass Housing
EIA	Environmental Impact Assessments
EGZ	Engineering Geological Zone
FAO	Food and Agriculture Organization
UNESCO	United Nations Educational, Scientific and Cultural Organisation
SAIEG	South African Institute of Engineering and Environmental Geologists
SAICE	South African Institution of Civil Engineers
CBR	California Bearing Ratio
DCP	Dynamic Cone Penetration
UNOSAT	UNITAR’s Operational Satellite Applications Programme
USCS	Unified Soil Classification System
PP	(Sidewall geological) Pick Penetration
TLB	Tractor-loader-backhoe
SANS 633 (2012)	South African National Standard 633 of 2012
XRF	X-Ray Fluorescence Spectroscopy
XRD	X-Ray Diffraction

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1 CHAPTER 1: INTRODUCTION

Engineering geological mapping and geotechnical site investigation (herein referred to collectively as engineering geology) are some of the most critical inputs of urban development. They require that geotechnical conditions of the site proposed for development are well-understood and taken cognize of prior to development. The exclusion or dilution of engineering geology into the design and construction of civil structures could lead to structural failure. From a Namibian perspective, engineering geology is a concept in its infancy. It is currently only implemented to a limited extend and in specific civil engineering projects, such as soil testing for roads by the Roads Authority of Namibia. However, there is an increasing need to implement of engineering geology in urban developments, so as to ensure safe and sustainable civil structures. It is therefore a goal of this thesis to create awareness in Namibia on how beneficial engineering geology can be towards sustainable development and how it can be implemented sustainably.

1.1 Rationale

This study was motivated by the current lack of engineering geology practice in Namibia. It is rationalised by past experiences in Namibia and most importantly the justification of engineering geology involvement in future projects.

There have been incidents of structural failure in Namibia often manifested as cracking walls, jamming doors and windows, sinking or uneven settlement of foundations, leaning structures, etc. With lack of engineering geology knowledge, these can be attributed to improper design and construction, as opposed to unsuitable ground conditions. Therefore, a number of such cases go undocumented and are often disregarded as soon as the damage is repaired. For this reason, many structures in northern Namibia are constantly under repair and renovation. A typical example is the Etango Shopping Complex in Oshakati where the building walls and windows were cracking, ceilings were caving in and pavements bulging. This made headlines in the Namibian Sun newspaper because according to the article author Iileka (2013), the incidence had tenants working in fear for their lives. It is therefore becoming increasingly important that the concept of engineering geology is incorporated into all development projects.

The northern part of Namibia is predominantly flat and has been targeted to benefit from the methodology of this paper. It is also known to host the majority of the country's population as it contains good soils for agriculture. In terms of geohazards, comfort is taken in the fact that the northern part of Namibia falls within the interior of the Congo craton, which makes it tectonically stable ground. This means there is very little chance of seismic triggered geohazards such as earthquakes. However, the area has disasters of its own. Northern Namibia is a notorious flood-prone region and it has in recent years seen a series of flooding events. Mendelsohn *et al*. (2000) have stated that in a mean period of 20 years, about eight (8) extensive floods occur, of which three (3) are major floods. The biggest event was recorded in 2011 (Long *et al*., 2014). Most towns in northern Namibia suffered victim of these floods, and huge economic losses were experienced. According to Long *et al.* (2014) houses were destroyed, transport services were disrupted such that certain areas of the townships became inaccessible, and inhabitants suffered from the outbreak of water borne diseases. Rural areas were cut off from urban centers from which they get most of their basic needs, such as medical services. Hooli (2016) noted that inappropriate spatial planning and population growth have disturbed the river system in the northern part of Namibia and as a result, aggravated the social impacts of the flood events. Flooding, although not the primary focus of this thesis, is a major concern that can be addressed through engineering geological mapping (proper planning) and geohazard analysis.

The studies done in northern Namibia in the past were mostly tied to the search for water resources and good agricultural land, as opposed to other land uses. This includes Walzer (2010) and Lindenmaier *et al.* (2012), focusing on ground water exploration in northern Namibia, and Mendelsohn *et al. (*2000), who did a general profile of northern Namibia and its population trends. Consequently, the engineering properties of soils in northern Namibia are not known. Other studies done in Namibia are for instance the geochemical surveys conducted by the Geological Survey of Namibia (GSN) that avails geochemical data for the whole country. This data is used as a guide for mineral exploration. However, there is no such database with geotechnical information to guide engineering works.

A further impediment to applying engineering geological mapping is lack of government involvement. At present, Namibia has no laws or regulations in place to enforce the practice of engineering geology as a part of structural development. In addition, there is no governing body or organisation to oversee the practice of engineering geology, or the absence thereof.

These are some lessons for Namibia, however, of equal importance is the long term outlook for future developments. Namibia has seen an increase in population in recent years as well as increased urbanisation as people migrate to cities in search for jobs and a better life. According to the Namibian Statistics Agency (2014), the national population is projected to increase from an estimated 2.11 million in 2011 to 3.44 million by 2041. A growing population comes with a need for development. This will require expansion of existing urban areas and establishment of new ones. This means that in the near future, infrastructure development will take place even in areas that were previously regarded as geologically unfavourable.

Additionally, the National Development Plan 3 (NDP 3) document was launched in 2008 as a guiding tool to an industrialised Namibia by the year 2030. In this document, housing was named as one of the bridging activities to the realisation of vision 2030. A study done by the Bank of Namibia (BON) in 2011 proved that 70% of Namibians cannot afford to buy urban land or decent houses. The national demand for houses was found to be rapidly rising, and according to Bank of Namibia studies a housing deficit of up to 100 000 units nationwide was observed in 2011, leading to mushrooming of informal settlements. After seeing the need for proper and affordable housing for Namibians, the head of state took the initiative of a National Mass Housing (NMH) project that aims to facilitate production of housing units. This mass housing project will cover a wide range of land, requiring an understanding of ground conditions, and a thorough appraisal of soil and rock properties making up the ground, as well as their behaviour under various loading conditions, that is, structure-ground interaction. This can only be achieved through a well-structured and comprehensive engineering geological investigation.

All the scenarios discussed above, call for an encouraged practice of engineering geology as input in civil and structural engineering projects to prevent the past imbalances and address geotechnical constraints prior to any future development.

1.2 Problem statement

The northern part of Namibia has been chosen as an application of this practice, as it is known to host the majority of the country's population. However, after revision of the current engineering geological methods, it was discovered that the land systems approach as a means of terrain classification could not be applied directly to this area, given its flat nature.

1.3 Aim of study

The primary aim of this study is to pioneer the practice of engineering geology, encourage the practice of engineering geological mapping as a tool in the planning of urban developments and set a trend for the upcoming developments in Namibia. Given the inapplicability of the current terrain classification methodology to flat lying areas, the study will also adapt an orderly approach of engineering geological mapping that is efficient and cost effective for flat laying, arid to semi-arid regions including northern Namibia.

1.4 Study objectives

Therefore, to reach the goal of this study, the following objectives will be met:

- Study the existing methodologies of engineering geological mapping, how they were successfully applied in other parts of the world;
- understand the different standards and guidelines considered when siting structures in an urban set up;
- adapt a methodology for best practice of terrain classification as part of engineering geological mapping in flat terrain, arid to semi-arid environments;
- present a case study on Outapi, northern Namibia as an application of the revised methodology, and;
- produce an engineering geological map of Outapi, which will be used to inform decision making and guide urban planning.

1.5 Chapter summary and outlook

The current status of engineering geology practice in Namibia was discussed, looking at both the past mishaps which could prove to be good lessons for this practice as well as the future plans that call for application of engineering geology. Some of the discussed factors are structural damage and flooding, and equally highlighted was Namibia's growing population, that comes with a need for housing and urban expansion to meet the needs of the population, which calls for engineering geological input for the proposed national developments. Considering the current lack of engineering geology practice in urban developments, this thesis will discuss how beneficial this practice can be and how to apply it efficiently and cost-effectively. The second chapter (Chapter 2) of this thesis will provide an understanding of engineering geology as well as the existing guidelines for siting different civil structures in an urban set up. The third chapter (Chapter 3) will discuss the current methods of doing engineering geological mapping. Chapter 4 will pay particular attention to Stage 1 activities of engineering geological investigations, discussing the inapplicability of current terrain classification methods to flat lying areas, thereafter presenting the possible mapping aids for these areas. The fifth chapter (Chapter 5) will then present a case study based on flat lying northern Namibia town of Outapi, in which the methodology from Chapter 3 is used, with alterations presented in Chapter 4 for terrain classification. Chapter 6 will present and discuss the findings of the case study and lastly, Chapter 7 with conclusions and recommendations.

2 CHAPTER 2: ENGINEERING GEOLOGY AN APPLICATION TO URBAN DEVELOPMENTS

2.1 What is engineering geological mapping?

Engineering geology is an application of geological sciences to engineering studies, for the purpose of ensuring that the geological factors regarding the location, design, construction, operation and/or maintenance of engineering works are accounted for (Dearman, 2013). Tepel (2010) alternatively defines engineering geology from a societal point of view, as the management of geologically sourced risks that affect people and their institutions as they interact with the built and natural environment. Therefore, it can be said that engineering geological mapping is the process of identifying and managing geological parameters that could influence the built environment. Richards *et al.* (2006), in his study for Pietermaritzburg city area stated that engineering geological mapping aims to identify and assess all potential constraints or geohazards that are likely to affect future land use planning decisions or initiatives. In other words, it analyses the natural environment to identify components that could pose a threat to the envisaged engineering developments and take necessary measures to prevent or minimise them.

This exercise requires a thorough understanding of the natural environment. For this reason, it is usually done by engineering geologists, trained from a geological background as they are believed to have a good understanding of the earth and its materials. These are geologists with interest in the relevance of geology to civil engineering and building constructions (Clayton *et al*, 1995). The focus of engineering geologists is essentially in the area of earth-structure interactions, that is, how the natural environment can impact man-made structures, and vice versa. Engineering geological mapping is often confused with geotechnical site investigations. Both exercises aim at understanding the natural environment prior to development of structures, therefore they both require a fundamental understanding of the geological environment (Dearman and Fookes, 1974). For this reason, there is a considerable degree of overlap between the two, however there are also substantive differences.

2.2 Engineering geological mapping versus site investigations

One major difference between engineering geological mapping and geotechnical site investigations is that the former is generic, whereas latter is a more specific assessment for a known development. Information obtained from engineering geological mapping gives a basis on how to plan land use and site different structures. However, site investigations assess how suitable a certain area may be for a specific development. For this reason, engineering geological mapping requires as an end product an engineering geological map outlining general pros and cons of an area, and usually entails distribution of different terrain features, different material occurrences, and their engineering geological properties, based on which decisions can be made in planning of different development schemes. Conversely, maps produced during geotechnical site investigations present geotechnical constraints that may impact on a proposed development and the accompanying report discusses suitability of the area for that development, further recommending how it can be improved to suit that particular development. Bell *et al.* (1986) have also noted that maps produced during engineering geological mapping are more applicable to planning than design.

Dearman and Fookes (1974) also made this distinction in their review for engineering geological practice in Britain, in which the terminologies engineering geological maps and plans were used to refer to the outcomes of engineering geological mapping and geotechnical site investigations, respectively. The other important distinction is the scale of practice. They further noted that engineering geological mapping is done at 1:10 000 scale or smaller, therefore covering a large area as opposed to site investigations that are usually done at a large and more detailed scale. Additionally, engineering geological mapping is mostly descriptive, with sparse quantitative data, whereas site investigations are comprehensive, with sufficient quantitative data to influence design. Kleinhans (2002) also noted that information obtained at regional scale can be used to assist in the selection of the most appropriate terrain for development. Therefore, it can be said that engineering geological maps give direction to geotechnical site investigations.

2.3 Applications of engineering geological mapping

In practice, engineering geology can be applied to a wide range of developments. For instance, in mining, it can be applied in the siting of tailings dams and indirectly to monitoring slope stability of pit walls. In civil engineering it can be projects such as siting of bridges and tunnels, siting dam structures, and monitoring stability of dam walls. Engineering geological mapping also allows for the assessment of land for the identification of resources such as water, good land for agriculture, potential borrow pitting sites for sourcing construction materials etc. In the development of urban centres, engineering geology is involved in siting of different components including residential areas, industrial areas and service centres, waste disposal sites, and planning orientation of linear structures, such as roads, which Dearman (1991) termed motorway alignments; rail networks and pipelines. For the purpose of present research, work will focus on applications of engineering geology in urban developments.

2.4 Role of engineering geological mapping in sustainable urban development

The term urban area is often used to refer to cities, towns and suburbs. An urban setting usually includes the following constituents: residential areas, industrial areas and commercial centres, roads and other transport networks, water and power connections, sanitation infrastructure, waste disposal sites, cemeteries etc. All these components are essential to the livelihood of the urban inhabitants, therefore in a sustainable urban set-up, they ought to coexist with the natural environment. Sustainable development, as defined by World Commission of Environment and Development (1987), refers to development that meets present needs without compromising the ability of future generations to meet their own needs.

Engineering geological mapping has an important part to play in sustainable development because it allows the use of land in such a way that there is coexistence of civil structures and the natural environment. In other words, it meets human development needs (by providing the structures) while maintaining a good balance with the environment (by having well sited structures to allow best use of land). In addition, it allows structures to be sited in areas where they will best contribute to the built environment with minimal impact on the natural environment. The above concept was also highlighted by Price (1981), who states that geotechnical information allows planners and designers to develop the country in the best possible harmony with the geologic environment.

For this reason it can be said that the ultimate goal of engineering geological mapping is to help achieve sustainable development. In this process, attention is given to the impact that the structures can potentially have on the natural environment, as well as the reverse relationship of potential impact of the natural environment on the built structures. Therefore, considerations for a sustainable urban set-up ought to include but are not limited to environmental, financial, and social components of planning. Constituents of an urban set up are discussed below, taking note of the crucial standards and considerations during their development.

2.4.1 Infrastructure considerations

This section takes into account the stability, usability and durability of groundworks of civil structures, which are largely dependent on the type of ground on which the structures are erected. This is why, the type of ground and the environment proposed for construction must be well understood prior to construction, so as to avoid structural failure. This means that, different potential ground responses must be predicted and potential effect of geohazards must be assessed during engineering geological investigations. In so doing, consequences such as founding on poor soil conditions, building in areas susceptible to flooding, landslides or areas of high seismicity can be avoided.

Another determining factor of structural durability is the type of material used in the construction of the structure. Therefore, it is important that the quality of construction materials is not compromised. Different civil engineering developments in an urban set up are outlined below, including guidelines on how to site them. The overall goal is to ensure that these structures are founded on good ground, where they will serve their purpose with minimal impact on the environment.

2.4.1.1 Housing developments

The main consideration when it comes to housing developments is safety. Houses should be founded on stable ground that supports the building foundation. Kleinhans (2002) states that residential developments favour areas with flat slopes, and gradients of less than 12°. Additionally, these areas should be well drained so as to reduce damage and geotechnical constraints induced by water.

2.4.1.2 Roads, highways and infrastructure services

In terms of roads and other linear structure as well as subsurface infrastructure, an important consideration is excavatibility of the area. This is because the ease to excavate determines the type of equipment required, which in turn determines the cost of excavation. Soft grounds may only require a tractor loader back-hoe (TLB) to excavate, whereas hard rock areas may require blasting. Other requirements include good construction material that usually have specific requirements and mixing ratios for each layer of the road.

2.4.1.3 Industrial areas

For industrial developments, it is important to understand the process of that specific industry. Inputs and outputs of the industry ought to be well understood so as to have clarity on the impacts that the system can potentially have on the environment. Most activities put out effluent or gas emissions. These should be controlled to meet environmental requirements of the area. Therefore, the role of engineering geology in this case is to take care of the location of industrial areas relative to other civil developments. Proper siting will allow industrial areas to coexist with other structures and attain a sustainable urban set up. For instance, it should be located well away from the residential areas.

2.4.2 Preservation of natural resources

Here, focus is given to all natural resources that can be beneficial not only to a particular project but to the long term needs of the community. This is to ensure that natural resources such as wetlands, potential borrow pitting sites for construction materials and others are preserved and protected. During engineering geological mapping, these areas are identified and demarcated on engineering geological maps, so that they can be avoided during construction, which ensures that they are not covered up by other developments. It can also be a financial benefit when potential quarries are discovered in the proximity of the urban area, as it helps to minimise on transport costs (Zawada, 2000).

2.4.3 Environmental protection

The impact of civil structures on the natural environment is inevitable, however, with proper planning, this impact can be minimised. Engineering geological mapping allows structures to be sited in such a way that they do not adversely affect the surrounding environment. For developments in critical areas of the natural environment, extra care should be taken. This takes into account water bodies in the area, sensitive sites and areas hosting endangered plant and animal species.

Looking at the long-term importance of engineering geology, Knill (2003) has noted that this field has a much broader scope as a result of increasing environmental issues. Skutsch and Flowerdew (1976) named three approaches on how to address the impact of structures on the environment. These are: (1) impact identification which is designed to identify possible impacts of different projects; (2) impact evaluation designed to assess or quantify impact; and (3) impact comparison, which entails comparing impacts of different developments and selecting the least damaging one. This should form a big part of siting structures. In practice, this part is usually taken care of during environmental impact assessments (EIAs).

There are certain constituents of an urban setup that are a serious concern when it comes to environment. These are for example cemetery sites, waste disposal sites, service/gas stations and ground-based sanitation systems such as pit latrines and septic tanks. When they are not properly sited, they can largely impact the environment. For this reason, these land uses are subject to mandatory EIAs. Some of these developments are discussed below, and care must be taken when siting them.

2.4.3.1 Solid waste disposal sites

Increasing urban population implies increased production of waste, which calls for proper waste management plans. Waste disposal, when not properly managed, can have short term impact on the environment including odour, windblown litter and flies; and long-term effects including water regime pollution and gas emission Department of Water Affairs and Forestry (DWAF) (1998). Most township developments have mere waste dumpsites as a means of disposing waste. These are often not well-engineered to protect the environment. However, modern day waste management introduce landfills, which require that location, design, operation and monitoring are done to ensure compliance to environmental regulations (Meegoda *et al.*, 2016). Landfills require that general waste is disposed of, covered, and compacted on a daily basis, to help reduce the short-term impacts. Considering the long-term effect, Meegoda *et al.* (2016) stated that monitoring systems should be in place, to allow early detection of groundwater contamination. Infiltrating rain water and liquids resulting from the biodegradation of waste, collectively known as leachate, can also be managed by lining the landfill with an impermeable layer or membrane, which prevents leachete from infiltrating into the ground and potentially contaminating groundwater. An example of a modern landfill is shown in **Figure 1.** An added advantage of this landfill is that it allows leachate to be pumped out and treated. Additionally, modern landfill design allows collection of potentially harmful gas emissions which can be converted into energy.

A common practice of siting landfills in South Africa, as outlined in DWAF (1998), recommends a minimum of 2m as the permissible separation between waste and ground water. Therefore, it can be said that areas with thick unsaturated zones should be considered when siting landfills, so as to allow a good separation between waste and ground water, and also as distal from surface water bodies as possible.

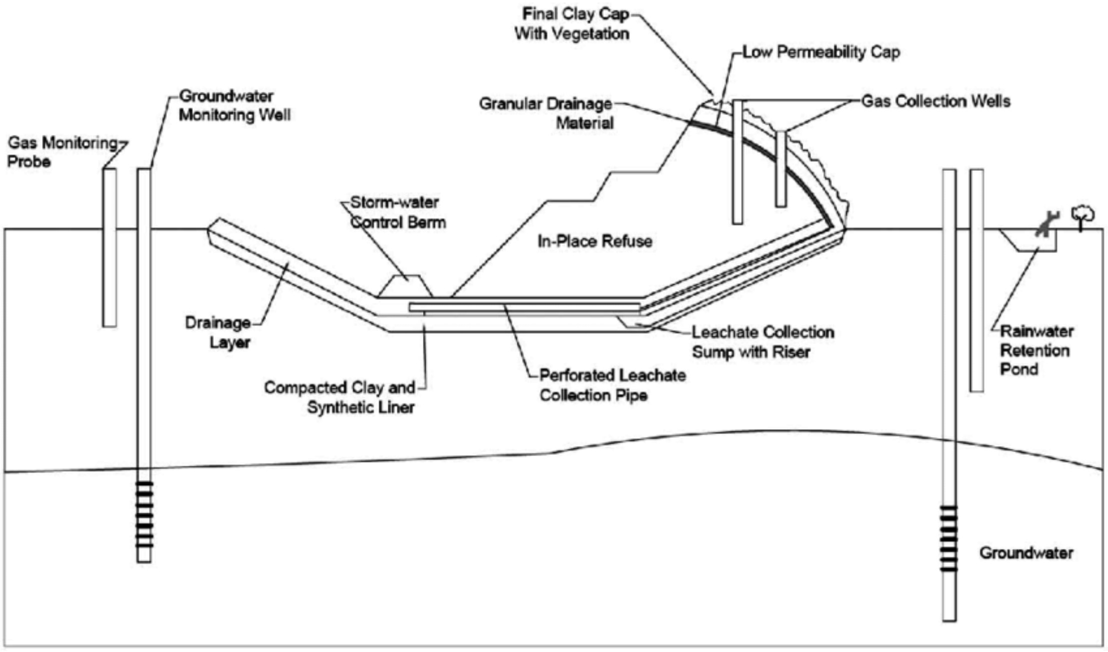

Figure 1: A cross-section of a modern municipal landfill from Meegoda *et al.* (2016).

2.4.3.2 Pit latrines and septic tanks

Other developments include day-to-day provision of basic town services, such as pit latrines, septic tanks, and gas stations. They all can potentially release harmful substances into the ground, some more harmful than others, however all are a concern. For instance, Graham and Polizzotto (2013) highlighted that pit latrines can release chemicals and microbial contaminants into groundwater which may negatively impact human health. Therefore, most criteria for siting such developments consider the long-term effect that they could pose on the environment, often recommending that a good separation between such developments and water bodies is allowed.

2.4.3.3 Cemeteries

In comparison to other developments listed above, the impact of cemeteries on water resources is relatively insignificant. This is because the decay of human bodies is a slow process, and bacteria do not survive for long periods outside a living human body (Department of Water Affairs (DWA), 2010). However, Dippenaar (2015) noted that when cemeteries are poorly sited, they can pose a pollution threat to ground water, and the risk of pollution increases with increased proximity to water bodies. The main sources of contamination in cemeteries as noted by Dippenaar (2015) include the release of pathogens from decaying bodies, release of metals from ornamental materials as well as nutrients from landscaping. Therefore, the basic criteria for siting of cemeteries were proposed, so as to reduce possible environmental and water contamination. These are summarised in **Figure 2**.

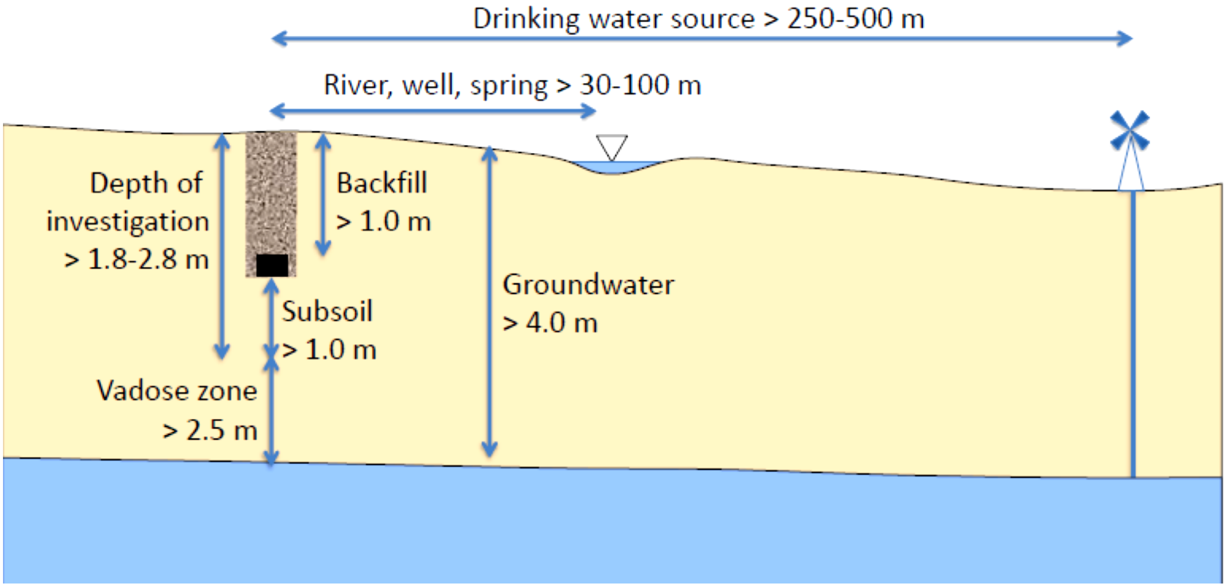

Figure 2: Minimum requirements of siting cemeteries after Dippenaar (2015).

2.4.4 Financial consideration

This section focuses on the financial resources required for development. Generally, developmental projects come with big financial requirements and large sums of money are committed to designing, construction, construction materials and maintenance, as well as the labour involved. Therefore, with proper planning and sufficient engineering geological input, such investments can be protected. Cunningham (2013) summarises the factors affecting the cost of building works, which includes the type of development, the location of the project, materials and equipment used, availability of services (developing in a virgin area will cost more than extension from an already developed site). Richards *et al.* (2006) also noted that the cost of remedial measures taken to make a site suitable for development is often lower than the cost of repairs if development affects the environment, or if the development was affected by certain geotechnical condition. Therefore, it can be said that civil structures sited and designed based on good engineering geological input will have minimal impact on the environment, which means that, no extra budget will be required during rehabilitation, clean up, or restoration of the environment. Using construction materials of good quality will in turn help to reduce maintenance and repair costs. Therefore, it is important that all the other considerations are taken care of, in order to protect financial resources committed to these developments.

2.5 Relevance of engineering geology

Problems resulting from unfavourable engineering geological conditions have confirmed that engineering geological input is a fundamental prerequisite for urban planning (Schalkwijk and Price, 1990). It must therefore be incorporated in every development and must be implemented at every stage of infrastructural development. Careful consideration of environmental aspects must be done to understand ground-infrastructure interactions, so that decisions can be made on whether to improve the conditions of the site or relocate the structure to a more suitable location. The ultimate goal is to have safe and durable structures that are financially viable, with low maintenance costs and minimal impact on the environment. This will allow the practice of sustainable development in urban areas.

2.6 Chapter summary

This chapter gave a background of engineering geology and its relevance in the development of civil structures in urban areas. It promotes coexistence of the built environment with the geological and natural environments, thereby contributing to sustainable development. Different components of an urban set-up were discussed, with some considerations and guidelines of siting. Some of the main considerations highlighted in this chapter are infrastructure consideration, focusing on safety and durability of civil structures and preservation of construction materials, so as to avoid covering up of potential borrow pitting sites. Environmental protection paid particular attention to certain urban components that can adversely affect the environment when not properly located. This includes pit latrines and septic tanks, waste disposal sites and cemeteries. And finally, the financial viability of projects, which was said to be influenced by the type of development, area of development, type of material and equipment needed and the availability of services in the area proposed for development. All these considerations highlighted the importance of engineering geological input in urban infrastructure. The subsequent sections will therefore discuss the methodology of engineering geological mapping including parameters of soils and rocks that should be analysed to quantify and understand material behaviour.

3 CHAPTER 3: CURRENT METHODOLOGY OF ENGINEERING GEOLOGICAL MAPPING

3.1 Background

In the past, decisions on land use were straight forward and easy to make. This is because there were enough resources and little competition. The evolution of settlement was also easy back then, because it was a gradual process that extended over generations, and according to Golany (1982), this allowed inhabitants to learn their lessons over time and apply their experiences in solving problems associated with selecting new sites. This however, is no longer feasible, because there is a need for rapid expansion of cities and urban centres to meet the needs of a fast growing population. Therefore, it is becoming increasingly important that decisions on land use are made on the basis of appropriate information, with input from engineering geology.

Applications of engineering knowledge dates back to the 18th century to what began as soil engineering (application of soil mechanics) (Skempton, 1985). Engineering geological mapping as discussed in Chapter 2, allows extraction of information from the environment to help in decision-making for urban developments. Engineering geological mapping has been done in other parts of the world and there are standard methodologies on how to do it. These were discussed and pioneered by authors such as Gonzales de Vallejo and Ferrer (2011) and Dearman (2013); and for Southern Africa by Price (1981), Brink (1985), and Van Rooy and Stiff (2001). Although different methodologies were presented, they all had one aim in common, that is, to understand the environment and its interaction with the proposed structures.

The general approach of engineering geological mapping can be presented in different stages or phases, which usually include desktop study and terrain evaluation, reconnaissance, subsurface investigation, laboratory testing, and reporting. Desktop study aims to understand the area under consideration using the existing information as well as different factors of the environment. Terrain evaluation allows assessment of different landscapes and identification of land facets that are later confirmed during site walk over and reconnaissance survey. Detailed investigation, sometimes referred to as subsurface assessment, allows the study and sampling of material occurring in the area, after which samples are tested in the laboratory for different geotechnical parameters and results are interpreted during the reporting stage and presented to relevant parties. This methodology is further explained below.

3.2 Desk study

The first stage of engineering geological investigation is desk study, whereby existing information about the area is collated. For engineering studies, study material to be collected include topographical maps, geological maps and remotely sensed images (satellite images, aerial photographs etc.). Additional information can include land use history, ground water conditions, ground investigation reports from previous works, and climate data (rainfall, temperature etc.), which are further interpreted as per project requirements. This information is normally available at national geological surveys, local authorities, and township municipalities. The maps and images can be used either as a source of information or as a baseline for plotting field information.

Understanding the natural environment can be done by interpretation of landforms present in the area, prevailing geological processes, and history of the area, which in turn can help with predicting expected changes of environment. Kleinhans (2002) noted components of the geologic environment which from the point of view of engineering geology are of decisive significance. These include distribution and properties of rocks and soils, ground water and characteristics of the relief, and present geodynamic processes. Some key considerations when it comes to the natural environment are discussed below, with associated geotechnical implications.

3.2.1 Geology: Rocks and soils

Certain rock types, in their natural state are known to be problematic to engineering developments. These are for instance dolomites, schists, and other fractured and/or weathered rock units. Other rock types are stable in their natural form, but can produce through weathering, soils with characteristic engineering problems, such as expansive and collapsible soils. Common geotechnical problems for rocks and soils are presented in the subsections below.

3.2.1.1 Soluble rock

Studies by Farrant and Cooper (2008) have discussed the importance of evaluating soluble rocks that exhibit karst features or potential for solubility, stating that they may result in engineering problems such as subsidence, settlement of karst, and irregular rockhead. This is common in rocks such as limestones, dolomites, slacking mudstones and other soluble rocks that form dissolution cavities (Waltham *et al.* 2005 and Price, 1981). Ideally, existing geo-hazard maps ought to delineate and display areas consisting of soluble rocks. These rock units may not be readily visible from surface or may be concealed by surficial cover. For this reason, authors such as Dobecki and Upchurch (2006), Gutierrez *et al.* (2008) and Chalikakis *et al.* (2011) have recommended and employed geophysical methods to detect soluble rock units, sinkholes and other kart features. This is good practice for when soluble rocks have not already been mapped out.

3.2.1.2 Soils prone to consolidation settlement

Consolidation refers to the gradual reduction in volume of a fully saturated soil due to change in effective stress or compression by a static load (Knappett and Craig, 2012). Knappett and Craig (2012) further explain that this change in volume occurs as a result of expulsion of water from the voids of the soil. Consequently, the type of soil determines the rate at which water dissipates from the soil, hence the rate at which consolidation occurs. The South African Institute of Engineering and Environmental Geologists [SAIEG] (1996) also presented this concept, noting that consolidation happens relatively fast in soils with high permeability (i.e. coarse-grained soils), and is much slower in soils with low permeability (i.e. fine soils). This is because, for fine or clayey soils, the load is initially carried by the water present in the pore spaces and with continual loading it dissipates, after which the load is then carried by the solid particles of the soil. For engineering geological applications, the main concern lies mostly with knowing how much consolidation can occur in a certain soil, as well as the rate at which it will occur. This is because the change in soil volume that occurs during consolidation induces an amount of vertical displacement called consolidation settlement, which might impact the structures (Knappett and Craig, 2012). Consolidation settlement becomes a concern when it happens unevenly, causing differential settlement, such that some parts under the foundation settle more than others triggering distortion and cracking (Bell *et al.*, 1995).

3.2.1.3 Collapsible soils

A technical note for civil engineers by the Department of Public Works (DPW) (2007) defined collapsible soils as partially saturated materials that exhibit additional settlement upon wetting. At a low in situ moisture content, these soils can withstand relatively large amounts of stress with small settlement. However, when inundated, they tend to exhibit volume change with additional settlement, with no increase in applied stress (DPW, 2007). This is due to their grain structure, which was explained by Schwartz (1985), highlighting that these soils have colloidal coating around the grains, often referred to as clay bridges, which breakdown upon wetting, collapsing the grain structure. This phenomenon is often confused with consolidation settlement. However, unlike consolidation settlement, it requires that a collapsible fabric is present and that the soil must be partially saturated as highlighted in (DPW, 2007). Thereafter there must be addition of water or an increase in moisture content, which will trigger the mechanism of collapse. In consolidation settlement, the soils are already saturated and water dissipates upon loading. Collapsible soils are generally very light due to their high void ratios. This was noted by Brink *et al*., (1982) who says their densities normally range from 900-1600 kg/m^3.

3.2.1.4 Expansive soils

The property of expansion is common in soils with significant amounts of expansive clays. Expansive clays have a skeleton that allows them to shrink or swell as a response to soil moisture content (DPW, 2007; Gonzales de Vallejo and Ferrer, 2011). This is due to their mineralogical structure and micro-fabric which allows absorption of water (Gonzales de Vallejo and Ferrer, 2011). The basic structure of most clay minerals consists of composite layers of silica tetrahedron and alumina octahedron sheets, which are combined by different bonds demonstrated by Karol (1960); DPW (2007) and Das (2013), and it is these differences in clay structure that causes difference in behaviour. The weak bonds joining them allow water to penetrate between the silica sheets and take up space within the crystal structure without any chemical reaction taking place (Gonzales de Vallejo and Ferrer, 2011). This causes them to expand. If the opposite happens, whereby water molecules leave the crystal structure (i.e. dehydration), these clays shrink. This volumetric change is called heaving, and can cause movement beneath the foundation of civil engineering structures. Therefore it is important to understand the clay mineralogy of soils. For instance, montmorillonite clays have an open site that allows cation exchange and water addition, which makes it expansive as opposed to kaolinite clays.

3.2.1.5 Dispersive and erodible soils

According to Kleinhans (2002), dispersivity of a soil measures its susceptibility to erosion, that is, the disaggregation and deflocculation in contact with water. In the presence of water, clays flocculate, which means that particles are detached from the clay surfaces and released into suspension. Therefore, it can be said that dispersion is dependent on clay mineralogy and chemistry of water present in the soil as well as the eroding water. Also, dispersive soils usually have a high percent of exchangeable sodium percentage (ESP), which according to DPW (2007) increases susceptibility to dispersion. This means ESP is governed by the percentage of absorbed sodium cations on surface relative to the quantity of other cations (such as calcium, magnesium or aluminium), as well as by the amount of dissolved salts in the water, such that when the content of dissolved salts is low, sodium saturated clays are more likely to disperse. If the flow velocity of water is sufficient, this process can lead to erosion. Presence of aslats is often indicated by the electric conductivity of a soil, therefore it can also be an indicator of dispersion of soils. Dispersion is a common problem in embankment dams, roads and other developments that require compacted soils.

3.2.1.6 Soft clays

These clays are characterised by a soft nature and high saturation usually containing organic matter, and as a result, they are highly deformable with very low resistance to undrained shear stress. They have an undrained shear strength between 15 and 50 kPa (Gonzales de Vallejo and Ferrer, 2011) or 10 to 40 kPa (DPW, 2007). This means they have a very low bearing capacity and often not suitable for use as founding material. It is therefore important to identify these clays to allow proper planning. Some of the field identifications of soft clays discussed in DPW (2007) include easily moulded and when squeezed they exude through the fingers.

3.2.2 Geomorphology

Fookes *et al.* (2005) define geomorphology as the study of landforms (earth's surface form) and landform changes (processes). Landscape or landform governs the distribution and occurrence of environmental features such as soils, water and land use (Partridge, 1994). Past processes responsible for the formation of present landscape together with processes active at present time offer a predictive tool of the impending development of features. Understanding the origin along with the genetic relationships of the landscape can allow educated guesses on what material types to expect in certain areas. For instance the example given by Partridge (1994) that if an alluvial fan exists in an escarpment that has quartzites, it can be inferred without field visit that the fan will contain gravelly colluviums. In terms of topography produced by geomorphological processes, a slope can be classified as steep or flat, which in turn determines the stability of the structures.

3.2.2.1 Slope instability

According to Kleinhans (2002), areas with slope instability are those with unstable geological materials that could move either gradually (creep) or suddenly (as a slump or slide). This is usually determined by the nature of the slope, especially when it is too steep. Although slope instabilities can be caused by natural factors such as seismicity, percolation of water through rock joints, fault zones and fractures, and gradient of the slope, it can also be induced by human activities such as mining and road cuts.

3.2.3 Hydrology and hydrogeology

This discipline gives consideration to the water component of the environment. It deals with distribution and movement of surface and subsurface water. The components evaluated include: water bearing soils and rocks, infiltration conditions, seepage from water-bearing horizons, direction and velocity of flow, depth to water table and range of fluctuation, field permeability, as well as prediction of any future changes in the fluvial regime due to development (UNESCO (1978), Price (1981), and Kleinhans (2002)). In addition, water quality is also assessed, meaning hydrochemical properties such as pH, salinity, corrosiveness, usually to establish baseline conditions of water so that changes brought about by development can be monitored. This is also because water plays a major role in geodynamic processes such as weathering, development of karsts, slope movement and others (UNESCO, 1978 and Kleinhans, 2002). Therefore they can provide input in engineering geological mapping for safe urban developments.

3.2.3.1 Surface water and flooding

Surface water includes drainage channels, floodplains, pans, and other water-logged areas. Surface drainage is an important consideration, because when water volumes exceed the holding capacity of the flow channels, or moves out of the floodplains it can lead to flooding. Generally, it is recommended that residential developments should not be established in areas below the 1:100 years flood line (DFA, 1995) or 1:50 years flood line (Richards *et al.,* 2006). In addition to occasional flooding, presence of surface water could present additional geotechnical constraints. These are, for example, seasonal shrinking and swelling, due to variations in moisture especially in areas that have active and expansive soils. Additionally, Richards *et al.* (2006) have noted that presence of water may have an effect on the bearing capacity of soils. This emphasises the importance of allowing a considerable stretch of space between the drainage channels and areas proposed for development.

3.2.3.2 Shallow ground water

Areas with shallow ground water are those whose permanently saturated zone occurs near surface. The same can be said about perched water tables, except for the fact that perched water tables are localised, meaning the water table of a local zone is higher than the regional water table. When the ground water table is shallow, it can be unsafe for both the development as well as for the ground water quality. Fluctuations in the shallow ground water levels can cause a cyclic shrink-swell effect of expansive soils. It also lowers the bearing capacity of soils and may cause slope instability. Equally, when the ground water table is shallow, it makes the water vulnerable to contamination which affects the water quality. Kleinhans (2002) noted that fluctuating water tables could be recognised during test pitting, from the presence of pedogenic concretions such as ferricrete that tend to develop at the base of a current or previous perched water table.

The above discussed geological and environmental factors, among others, highlight how important it is to understand the environment in which development will be taking place. Engineering geological mapping allows for the identification of areas that could potentially hinder development, so that they can be avoided or improved prior to development. An additional process called terrain evaluation is also carried out during the early stages of engineering geological mapping to allow land classification. This process is discussed in the subsequent section.

3.3 Terrain evaluation

Terrain evaluation is another procedure used at the early stages of engineering geological mapping to understand the environment in which developments will take place, and identify ground conditions that may be significant to the development. It is an old technique of classifying land and was pioneered by authors such as Price (1981), Brink *et al.* (1982), Edwards *et al.* (1982), Mitchell (1991), Lawrence *et al.* (1993) and Partridge (1994). It is usually employed in the view that particular information about the terrain helps us to understand fundamental processes of the environment, which allows educated guesses about material occurrences, therein allowing geological inference and prediction of expected structural response to these conditions or material.

Terrain evaluation is sometimes called terrain analysis Zende *et al.* (2012), land classification McKenzie *et al.*, (2008) or land surface evaluation Edwards *et al.* (1982), and these terminologies are herein used interchangeably. McKenzie *et al.* (2008) defined land classification as the segmentation of land into units that can be described or measured in the field and subsequently represented on maps. Zende *et al.* (2012) note that terrain analysis fundamentally provides predictive information about the terrain and the environment. Edwards *et al.* (1982) in their working party report defined land surface evaluation as the evaluation and interpretation of land surface features using a combination of ground mapping and visual remote sensing techniques. Rengers and Soeters (1980) also noted that land classification allows for the subdivision of an area into land units of sufficiently homogeneous zones of rocks and soils. Lawrence *et al.* (1993) state that during terrain evaluation, different terrain units are mapped from remotely sensed images and are delineated to produce a land classification maps. Therefore, it can be said from all the definitions given above that terrain evaluation is the process of grouping similar or homogenous parts of land into terrain classes that can be analysed collectively to obtain predictive information about those areas, done from remotely sensed images.

Terrain evaluation employs the assumption that similar landforms present similar conditions (Howland, 1979 and Lawrence *et al.*, 1993). This was also highlighted by Dearman and Fookes (1974), who noted that terrain evaluation delineates morphological units that will possibly have similar influence on the plan and design of civil engineering structures, i.e. have similar engineering behaviours. Therefore, areas with similar land forms are grouped under one terrain class. Partridge (1994) concurs that land classification must succeed in bringing similar sites into one terrain class, such that information collected at one site can be used to plan operations at another site in the same terrain class. Grouping of areas or terrain classification employs the principle of homogeneity or uniformity, which is discussed below.

3.3.1 Uniformity of terrain

As previously noted, terrain classification applies the assumption that similar or homogenous environments will present similar conditions and are likely to impact civil structures similarly. However, natural environments are never really homogenous. This was noted by Lawrence *et al.* (1993), who stated that variability of environment arises from variations in factors that contribute to landform development such as microclimate, permeability of profile, and mineralogy of parent rock. Acknowledging the heterogeneous nature of natural environments, Lawrence *et al.* (1993) further clarifies that in engineering terms, an environment is said to be uniform or homogenous when the amount of variations in it is not sufficient to necessitate a modification of design, in order to take these variations into account. Therefore, the vast heterogeneous environment must be divided into small portions that are deemed essentially homogenous for the intended land use.

The principle of homogeneity is what allows extrapolation of information. That means, for a given area, if land classes are identified and tested, information obtained can be applied to similar land classes that were not tested. In practice, the design is kept constant within the same land class, sampling will be limited to certain selected sites that are deemed to be representative of that particular land class, and properties described at representative sites are extrapolated to other sites within the same class that were not tested. The main goal for terrain evaluation is to avoid repetitive investigation in areas where landforms are recurrent and it also helps to lower sampling, while obtaining sufficient information. It allows use of available data which eliminates the need for costly and time consuming repetitive investigations within the same terrain class (Partridge, 1994). There are different ways of doing terrain evaluation depending on the purpose of investigation.

3.3.2 Terrain classification approaches

According to Zuidam and Zuidam (1979), terrain classification has three main approaches, namely: the genetic approach, the parametric and the land systems approach, with the latter being the most commonly applied for engineering purposes.

3.3.2.1 Genetic approach

The genetic approach focuses on the geological processes than landforms. The area is divided into subunits based on the different forms that resulted from specific geologic processes. For example, an area may be divided into forms of fluvial, volcanic, structural, denudational processes etc. (Zuidam and Zuidam, 1979).

3.3.2.2 Parametric approach

A parametric approach, as discussed by Mitchell (1991), considers terrain from the point of view of the envisaged land uses. This approach devises a list of attributes that are of relevance to that particular land use, after which a class limit is drawn up per attribute before mapping. Parameters relevant to the study are then measured at different sites to obtain an array of numerical values. Thereafter, contours are drawn in to represent certain critical values for each parameter and in parallel, set boundaries between the different classes identified.

This method was applied successfully by Jewitt (1955) in an attempt to characterise Sudan soils using sodium values, soil texture, and alkalinity. An example of parametric approach that was presented in Partridge (1994) classifies land for rice plantations. Boundaries were demarcated to indicate areas with clay content of more than 20% and areas with (a class of) slope between 5-10%. Parametric approach however can be time consuming and much reliance is placed on quantification, which requires detailed field sampling.

3.3.2.3 Landscape/land systems approach

Amongst the three approaches, the land systems approach is the most commonly used, such that in some instances, when terrain evaluation is discussed, it is almost equated to land systems classification. The land systems approach (also known as physiographic approach) recognises external features of the land and their relationships (McKenzie *et al.,* 2008). It is a useful technique for ground investigations for engineering purposes and it is well documented by researchers such as Cooke and Doornkamp (1974), Mitchell (1991), Lawrence *et al.* (1993), Partridge (1994), Griffiths (2001), Fookes *et al.* (2005) and Walker (2012), amongst others. The land systems approach employs a hierarchal division of land at different scales and many nomenclatures of land systems approach aroused. This includes that proposed in Christian and Stewart (1952) comprising of 10 units covering a global to local scale. However, land was not conveniently mappable at some scales. Therefore, a hierarchy of landscape with seven orders of terrain was suggested by Brink *et al.* (1966). These are land zone, land division, land province, land region, land system, land facet, and land element, in decreasing order of size. Of the seven orders of this hierarchy, only the three lowest orders are used in practice as illustrated in

Figure 3: Hierarchical representation of land system, **land facet** and land element (after Edwards *et al.*, 1982; Lawrence *et al.*, 1993 and Walker, 2012).

The three orders have been defined individually as follows:

3.3.2.3.1 Land system

Lawrence *et al.* (1993) defines land system as a large area with recurring pattern of landforms, soils and hydrological regime. In agreement, Numan and Al-Barany (1995) define it as a large area of characteristic land forms, drainage patterns and association of materials developed in an essentially similar geologic situation. Lawrence *et al.* (1993) further states that land systems are recognized and mapped from their pattern of streams, landforms and vegetation, such that a substantial change in any of these features indicate change in land system. Usually extend over areas of at least 100km2, and are mappable at about 1: 250 000 – 1: 1000 000 scales (Lawrence *et al.,* 1993).

3.3.2.3.2 Land facet

A land facet according to Lawrence *et al.* (1993) and Numan and Al-Barany (1995) is a land unit with uniform slope, single soil type, and uniform hydrogeological conditions and developed on a uniform parent material. Stiff (1994) referred to it as a ground area with a simple surface form, specific soil profile horizons (with uniform properties with varying thickness) and a characteristic ground water regime. Land facets are building blocks of land systems (Brink *et al*., 1966). Land facets are sufficiently homogenous to be considered uniform for practical purposes, and are usually mapped at scales between 1: 10 000 and 1: 100 000 (Lawrence *et al.,* 1993).

3.3.2.3.3 Land element

Land elements are the smallest land units of this classification. These are particular parts of a land facet, with significantly different effect on land use (Lawrence *et al.* 1993). They are usually too small to be mapped individually, generally mapped at scales between of 1: 25 000 or more (Lawrence *et al.,* 1993).

The land systems approach has been used by Howland (1979) in the evaluation of land for roads construction in South Africa. Howland (1979) stated that mapping of landforms is a viable way of mapping material types, further noting that since the same factors that influence soil profile, that is mineralogy and grading, also affect geotechnical properties, it is only logical that materials with similar engineering geological characteristics will be found on similar landforms in areas with the same geology, climate and similar relief.

This is because at those scales, engineering attributes can be evaluated in detail and design decisions can be taken on the basis of the information they provide (Edwards *et al.*, 1982 and Lawrence *et al.*, 1993).

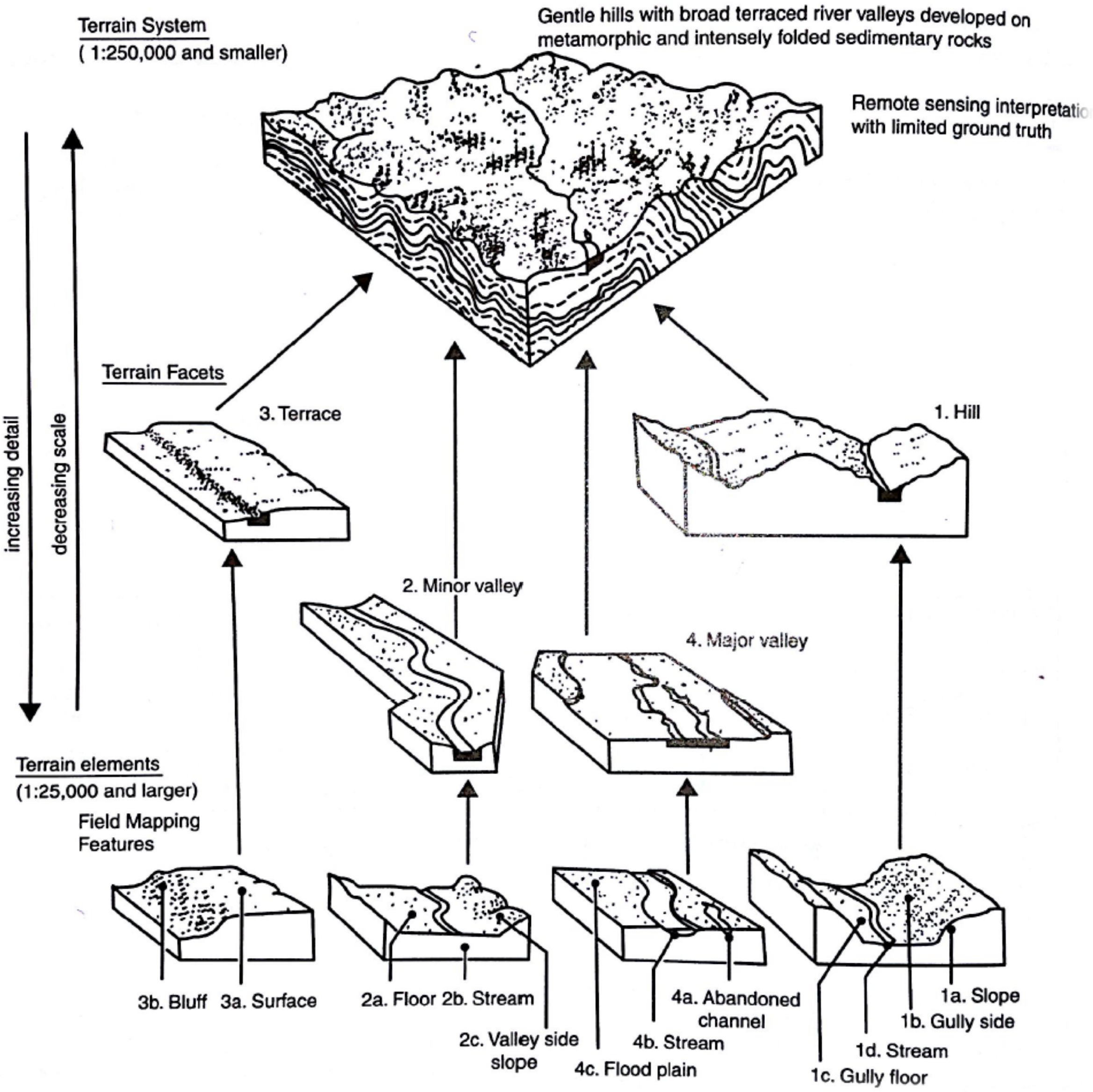

Figure 3: Hierarchical representation of land system, land facet and land element (after Edwards *et al.*, 1982; Lawrence *et al.*, 1993 and Walker, 2012).

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Terrain evaluation is usually done through interpretation of features from air photographs and other remotely sensed images. The common technique is visual assessment of aerial photographs.

3.3.3 Remote sensing and image interpretation in engineering geological mapping

Remote sensing in its general meaning is when information about an object is obtained without making physical contact with it (Mitchell, 1991; Gonzales de Vallejo and

Ferrer, 2011). For engineering geological mapping, information about earth materials is captured either by ground based photographs taken during field visits or aerial photographs taken at different angles from a plane and to a lesser extend images capture by satellites from space as demonstrated in **Figure 4**.

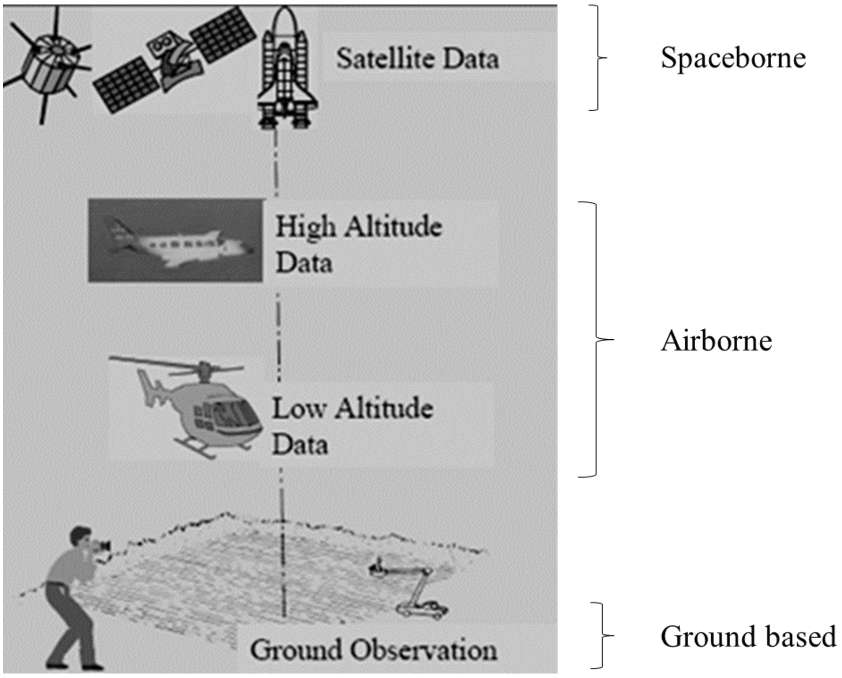


Figure 4: An illustration of remote sensing methods at different scales (after Woldai, 2005).

3.3.3.1 Air photo interpretation

Aerial photographs are captured by cameras mounted to a moving aircraft, and they capture the view of an area, either from directly above it (producing orthophotographs) or at an angle (producing oblique air photos). Aerial photographs proved to be a useful tool for engineering geological mapping during desk study and reconnaissance surveys (Gonzales de Vallejo and Ferrer, 2011). The aerial view captured gives a good representation of landscape, making it easy to carry out land/ terrain classification, as part of engineering geological mapping. Terrain classes summarize topographical, geological, and hydrological features of a landscape (Lawrence *et al.,* 1993) as seen on aerial photographs. Air photo interpretation has been a subject of research and has been discussed exhaustively by the American Society of Photogrammetry (1960), Sully (1969), Fezer (1971), Verstappen (1977), Lillesand and Kiefer (1987), Avery and Berlin (1992), Clayton *et al*., (1995) and Rampal (1999) who all agree that it is a cost effective method of mapping, since air photos can be cheaply produced. Air photo interpretation requires the interpreter to be able to recognise different components of the environment as seen on the photographs. It can therefore be a challenge for many as there are no standard ways of doing it. Clayton *et al.* (1995) and Rampal, (1999) noted that airphotograph interpretation entirely depends on the interpreter, which therefore allows room for subjectivity, suggesting that it helps to have knowledge of the area or have experience in air photo interpretations. Considering the difficulty of the subject, some properties of air photos were suggested to aid land classification and identification of terrain features of interest. These were discussed by Lawrence *et al.* (1993), Clayton *et al.* (1995) and Rampal (1999), and are summarized below.

3.3.3.1.1 Tone

Tone refers to the shades or colours resulting from the amount of light reflected from land surface. Reflectivity of surfaces is associated with different compositions, colours or moisture content of materials (Clayton *et al*., 1995). Clayton *et al.* (1995) further states that dark tones are indicative of wet conditions or dark coloured materials such as basalts and peat, whereas light tones indicate dry conditions and light coloured materials such as chalk. Tone is expressed qualitatively as light, medium or dark (Rampal, 1999).

3.3.3.1.2 Texture

Texture defines the smoothness or roughness of a surface. It is produced by an aggregate of unit features that are too small to be discerned individually. This is, for instance, plant leaves that are too small to be seen individually from aerial photos but collectively, they produce textures that allow the interpreter to differentiate between shrubs and trees. For this reason, it can be said that texture is the frequency of tonal change and it is often recognised from the alternations of dark and light tones, which make objects appear rough. This can be expressed qualitatively as coarse, medium, or fine (Rampal, 1999).

3.3.3.1.3 Pattern

This is the spatial arrangement of features on the ground (Rampal, 1999). Pattern is often recognised from the repetition of objects or groups of objects on a scale coarse enough for each element of the pattern to be individually seen (Lawrence *et al.,* 1993). These are, for example, drainage patterns, land use patterns, lineaments etc.

3.3.3.1.4 Shape

Shape refers to the general outline or geometrical appearance of a feature (Lawrence *et al.,* 1993). For example, line shaped features displayed on air photos can be linear structures such as roads, railways, pipelines, water canals etc. Some features of the environment have unique and distinctive shapes which can be readily identified. For instance, geomorphological features such as sand dunes, volcanic cones, alluvial fans and ox-bow lakes have very diagnostic shapes.

3.3.3.1.5 Association

Principles of association are based on the fact that certain objects are often found in association with others. For instance, different terrain features may host different types of rocks and soils. Therefore, one is able to infer the type of soils and/or rocks expected in a known terrain.

3.3.3.1.6 Site

Site refers to geographical or topographical location. This aids the identification of certain landforms and vegetation. Knowing the geographical location of the area helps with interpretations of climatic conditions and can therefore infer typical responses of soils and rocks. For instance, arid regions, due to their climate, can expect a mechanical type of weathering, as opposed to humid regions where chemical weathering is predominantly expected.

The elements discussed above may be used individually or in combination. An example given by Lawrence *et al.* (1993) identifies an alluvial fan using its lobate plan form and its occurrence at the foot of an escarpment. The aids involved in the identification of this alluvial fan are shape and principles of association.

3.3.3.2 Satellite imageries

Satellite imageries, unlike aerial photographs are space borne and they use multi-spectral scanners (MSS) that allow for the simultaneous detection of both reflected and emitted radiation in several spectral bands (Clayton *et al.,* 1995). Technological advances in this field led to a combination of air photo interpretation with other remotely sensed images such as LandSat, SPOT, ASTER, and other digital images.

When it comes to engineering geological mapping, air photographs are still by far the most commonly used and satellite imageries are used to a limited extent. This has to do with the fact that acquisition of space borne imageries is more expensive when compared to air photographs, and it requires subsequent image processing. Consequently, they are often not readily available, especially in developing countries. For this reason, they are usually an option for areas with harsh conditions that do not permit human inhabitants (useful in studies for climate change), or for areas that may be inaccessible, what Cooke and Harris (1970) have termed terrestrial environments. However, a bigger concern is the resolution of these images. Considering the practice of engineering geological mapping at regional scale, air-photos have a much better resolution of 10m as opposed to satellite images, whose resolution is 30m for LandSat. This may not bring out the features of interest, especially in flat lying areas. Satellite images with resolutions of up to 2-5m are commercial images, which are usually very costly and only covering a small area. Digital images may, however, be advantageous over air photos, as they can be interpreted digitally, which reduces subjectivity from the interpreter.

The variability of terrain determines how much sampling is required, and sampling can therefore be planned per land class identified. The past years have seen extensive use of aerial photographs and other remotely sensed images for this exercise. Land classification from remotely sensed photographs and images is a very effective way of terrain evaluation, however, the land classes identified should still be confirmed during reconnaissance survey.

3.4 Reconnaissance survey / Site walk over

This stage aims at familiarisation of the area, and confirmation of the information gathered during desktop study and terrain analysis. The different terrain classes and sampling points identified are confirmed during this stage and boundaries are adjusted accordingly. Sometimes the nature of terrain dictates the type of equipment to be used during investigation. Therefore, at this stage, accessibility is also assessed to determine whether or not the localities proposed for subsurface investigation are accessible by heavy equipment. Thereafter, a detailed field investigation is undertaken to further understand the environment.

3.5 Detailed field investigation

At this stage, field observation is done to understand subsurface conditions. This can be done from existing quarries and road cuts in the area, however, for fresh exposure, new borings are required. This includes opening up new test pits, auger boring etc. It allows soil profiling and description of material in place as well as sampling. In rocky terrains, investigation techniques may include core logging to obtain information about subsurface conditions. In addition to soil and rock description, in-situ tests may also be done at this stage.

3.5.1 Soil description

Ideally, soil descriptions should include information that helps with understanding the soil transport history (genesis) and its present features that allow prediction of response to loading. The MCCSSO method of describing soil profiles by Jennings *et al*. (1973) and South African National Standard (SANS) 633 (2012) includes the soil parameter discussed below:

- Moisture content described as dry, moist to wet.
- Colour - described by predominant (primary) colour and secondary which can be patches of another colour or bands depending on orientation.
- Consistency – measured by the ease of penetration by the sharp end of a geological pick, described as very loose to very dense in non-cohesive soils and very soft to very stiff for cohesive soils.
- Soil structure - this is described based on observed structures such as voids, joints, pinholes, fissures etc.
- Soil type – gives an estimation of clay, silt, sand and gravel fractions, with the soil name given in increasing order of abundance. For instance, if a soil has 30% silt and 70% sand, it would take the name silty sand.
- Origin – describes the genesis of the soil. Options here include residual or transported, which can further be divided into alluvial, aeolian etc. depending on the mode of transport.

In addition to these descriptors, side notes are made on seepage, sidewall instabilities, root channels, and animal burrows, and reason for final depth of the profile (Dippenaar *et al*., 2015).

3.5.2 Rock description

Descriptive attributes of rocks include lithological sequence, state of weathering, orientation and distribution of structural discontinuities such as beddings, and joints as they influence rock strength. Rock descriptions have been covered exhaustively by authors such as Anon (1977), Rengers and Soeters (1980), Clayton *et al.* (1995), SAIEG (1996) and Dearman (2013), and are usually divided into rock mass properties and rock material properties.

Rock mass properties take account of structures and discontinuities occurring in a rock mass. This includes fractures and joints, which can be mapped during discontinuity surveys. Assessment of discontinuities includes their nature (i.e. aperture (width), roughness, fillings, material fill etc.), as this governs the extent to which water moves through them (Dippenaar *et al.*, 2015), consequently impacting the rock strength. Rock material properties include colour (usually a result of mineral composition of rock or secondary weathering colours), texture and rock fabric, grain size etc. It also includes state of weathering, which describes the degree of weathering, from unweathered (intact and show no visible signs of alteration) to completely weathered rocks (resembling soil, which can have minor preservations of rock fabric).

3.5.3 Field testing techniques

In-situ testing allows the determination of material properties, while the material is still in place or in their natural undisturbed state. These tests include among others the cone and standard penetrometer tests (CPT and SPT respectively), dynamic cone penetration (DCP) tests etc. Generally, they all give an elementary understanding of the consistency of the type of material being penetrated, usually deduced from the ease of penetration as equipment advances through the profiles. SPT records the number of blows required to penetrate a continuous 300mm depth, which is expressed as penetration resistance (N). CPT measures resistance as a function of depth of soil penetrated. In both cases, the resistance values obtained can be correlated to geotechnical parameters of soils such as friction angle, relative soil density, California Bearing Ratio (CBR) etc. Therefore, this makes it easy to describe lithological units encountered at different depths of the profiles. Detailed descriptions of these tests is beyond the scope of this study, however, they are discussed extensively in basic geotechnical engineering books including Byrne *et al.*(1995); Liu and Evett (2009) and Gonzales de Vallejo and Ferrer (2011).

3.5.4 Sampling

Sampling technique is dependent on the type of sample that is desired as well as the reason for sampling. Samples can either be disturbed or undisturbed. Disturbed samples do not require preservation of in-situ properties, that even during sampling, no effort is given to retaining the in-situ configuration. They have undergone modification in their structure and water content, but preserved mineralogical composition (Gonzales de Vallejo and Ferrer, 2011). Disturbed samples are often suitable for grain size analysis, determining Atterberg limits, soil geochemistry, x-ray diffraction for clay mineral identification, compaction tests and other tests that do not rely on the in-situ configuration of the soil. Undisturbed samples on the other hand are required for performance tests because they are conducted to determine the intrinsic or in-situ properties of soils and rocks. Care must be taken during sampling, packaging and transporting of undisturbed samples to ensure minimal disturbance and preserve the structure and in situ conditions of these soils. Tests done on undisturbed samples analyse performance of soils including shear strength, deformability and permeability (Gonzales de Vallejo and Ferrer, 2011). At this point, a list of samples is generated to include information on tests required and it accompanies the samples to the laboratory for analysis and further testing.

3.6 Laboratory testing

Laboratory tests are important for quantifying the influence of the geological environment, as the previous sections were largely descriptive and qualitative. Tests to be done are selected depending on the purpose of investigation. It is worth noting that when engineering geological mapping is done at a regional scale, the main aim of sampling is to get a general feel of the foundation indicators, as opposed to getting values for designing. For this reason, a considerable number of disturbed samples are tested versus undisturbed samples. Kleinhans (2002) noted that although undisturbed samples can be tested, it is not standard procedure for regional geotechnical mapping. Undisturbed sampling for performance tests only becomes beneficial at design stage, where design parameters are tested for a known or specific proposed development. Common testing methods are not discussed in detail here, as they are well covered in other publications, and they are herein summarised according to Liu and Evett (2009) and Knappett and Craig (2012).

3.6.1 Index tests

3.6.1.1 Grain size analysis of soil

Grain size analysis is done to establish the relative proportions of different grain sizes Knappett and Craig (2012). Liu and Evett (2009) and Knappett and Craig (2012) explain that this analysis is done in two parts, especially when soils comprise of a mixture of different grain sizes. The first part is a sieve analysis, which takes care of soils coarser than 0.075 mm. The amount retained by each sieve is weighed to determine the weight percent of each grain size. The second part of the analysis caters for soils finer than 0.075 mm, which are further analysed using a sedimentation method referred to as hydrometer analysis. This analysis applies Stoke’s law to determine the settling velocity of particles. Results of grain size analysis are presented as grain size distribution curves on a semi-logarithmic scale, from which the dominant grain size can be recognised. Dominant grain size means the portion of the soil that will have the most influence on the behaviour of that particular soil.

3.6.1.2 Atterberg limits

Atterberg limits quantify the water content of soils discussed by Craig (2004), Knappett and Craig (2012) and Das (2013), which in turn influences soil consistency and behaviour. A continuous increase in moisture content sees soils move from solid state through semi-solid state to plastic state. This change in state is also associated with change in soil behaviour, whereby soils are expected to transition from brittle behaviour, where they crack and crumble through plastic to fluid behaviour as shown in **Figure 5**. The moisture content at which the transition from solid to semi-solid takes place is called the shrinkage limit, while moisture content during transition from semi-solid to plastic state is called plastic limit, and finally moisture at transition from plastic to liquid state is called liquid limit. These are collectively known as Atterberg Limits. Plasticity index (PI) can therefore be calculated as: PI = liquid limit (LL) – plastic limit (PL).

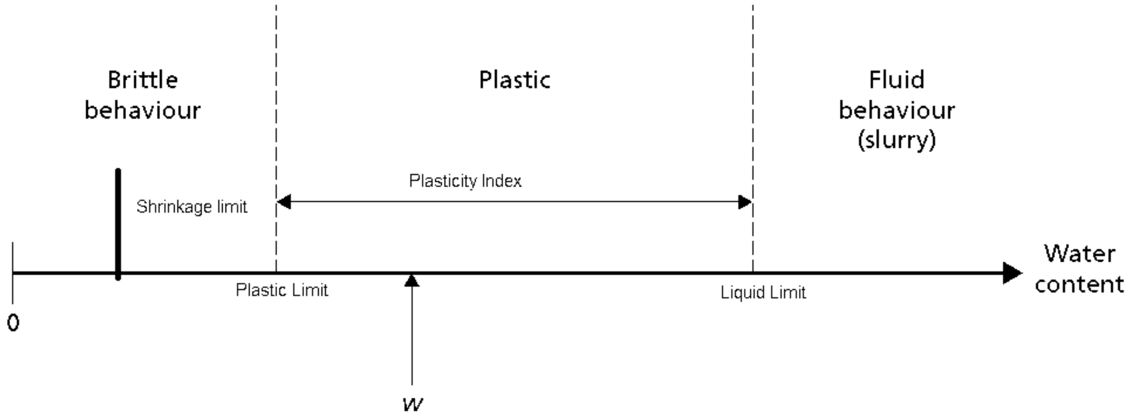


Figure 5: A representation of Atterberg limits to show change in soil behaviour with increased water content (after Craig, 2004)

Plasticity index can be plotted against liquid limit on a plasticity chart proposed by Casagrande (1932), that has an empirical A-line representing the relationship established from testing different soils. This A-line separates inorganic clays from inorganic silts, which plot above and below the A-line, respectively (Das, 2013). The different ranges of liquid limit define these soils in terms of compressibility (for silts) and plasticity (for clays).

Atterberg limits also helps with identification of expansive soils. Skempton (1953) observed a linear correlation between plasticity index and the percent of clay-sized fraction present in it, termed activity. Activity can therefore be used as an index for determining the swelling potential of clay soils, with activity values of various clay minerals listed by Mitchell (1976). Additionally, plasticity index, when plotted against clay fraction of the whole sample on the Van der Merwe's potential swell prediction chart (**Figure 6**), can give an estimation of expected heave.

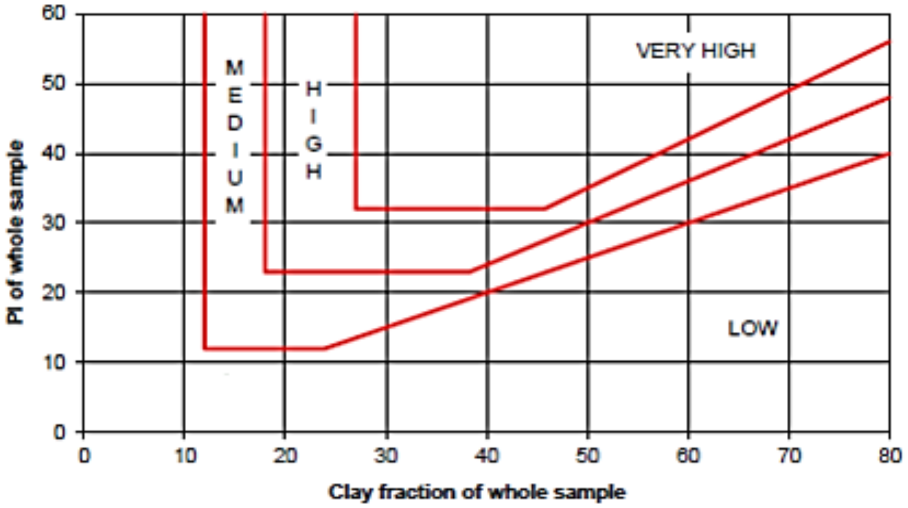


Figure 6: Van der Merwe's potential swell chart (Van der Merwe, 1964).

3.6.1.3 Permeability test

Permeability of a soil is described using a permeability constant, also known as coefficient of hydraulic conductivity (*K*), expressed in m/s. It measures the ability of material to conduct fluids through a permeable medium (Clayton *et al.,* 1995). Hydraulic conductivity of soils is dependent on water viscosity, pore-size distribution, void ratio roughness of mineral particles and degree of saturation. In rocks it is influenced by rock fabric and most importantly by the distribution and orientation of discontinuities such as joints, fractures and beddings. Ideally, permeability tests should be performed in-situ, especially in cases where undisturbed samples cannot be obtained. However, it can also be determined from laboratory tests using constant-head method (suitable for granular soils) or falling-head permeability test (preferred for fine soils) (Das, 2013). Empirical formulas can also be used to estimate the permeability coefficient of soils, using input data from grain size analysis. These formulae include among others, Hazen (1892), Slichter (1899), Terzaghi (1925), Beyer (1964) and Barr (2001) methods.

3.6.2 Performance tests

Structures exert pressure on the ground on which they are erected, and the ground usually responds to this pressure. Performance tests are therefore used to predict the ground response to changed loading conditions. For this reason, it is more beneficial to perform these tests at site investigation stage, once a specific development has been proposed for a given area as opposed to regional geological mapping which is a generic investigation.

3.6.2.1 Consolidation settlement and collapse

Consolidation refers to a process whereby a reduction in soil volume is experienced due to compression by a static load as explained in **section 3.2.1.2**. The consolidation settlement brought about by this static load becomes a concern when it is uneven as it is said to cause distortion and cracking (Bell *et al.,* 1995). Therefore, it is important to know how much consolidation settlement will take place and at what rate. The amount of consolidation can be quantified as the coefficient of volume change (m_v), expressed in m^2/MN as shown in **Table 1**. This coefficient gives an indication of whether the soils have been subjected to pressures higher or lower than the current overburden pressure (DPW, 2007). The former will mean soils are overly consolidated whereas the latter implies normally consolidated. In practice this means that if a soil is over consolidated, there will not be much room to further compress it.

Table 1: Typical values of coefficient of volume change m_v -values of soils according to Tomlinson (1980).

Type of material	**Qualitative description**	**m_v (m^2/MN)**
Heavily over consolidated clays	very low compressibility	below 0.05
Over consolidated clays	low compressibility	0.05 – 0.10
Normally consolidated clays at depth	medium compressibility	0.10 – 0.30
Normally consolidated alluvial clays	highly compressibility	0.30 - 1.50
Highly organic alluvial clays and peat	very high compressibility	above 1.50

The amount of settlement occurring in a soil can either be consolidation settlement or collapse settlement. The former is tested by double oedometer testing and the latter by collapse potential test. Double oedometer requires two undisturbed samples, which are both placed under a seating load for 24hours, after which one sample is inundated and the test is continued, producing two curves (one at NMC and the other at saturation), on a graph relating void ratio to the logarithm of applied pressure (DPW, 2007). Collapse potential test is performed on one undisturbed sample that is subjected to incremental pressures of up to 200kPa, until there is no further compression. Thereafter, the same sample is inundated for 24 hours before the test is continued to the final load. Results are recorded as one continuous plot on a graph that relates void ratio to a log of pressure or load applied. A noticeable sudden drop in void ratio would indicate reduction that occurs upon inundation without a change in applied load, which is an indication of collapse.

3.6.2.2 Shear testing

Shear strength of a soil is measured by its ability to deform along a predetermined plane or along internal surfaces in a mass. It can be tested in laboratories using either direct shear or triaxial testing (Knappett and Craig, 2012).. These tests are performed either on consolidated or unconsolidated samples, which can be drained or undrained to represent different conditions. For instance, a combination of consolidated undrained sample can be representative of a soil that has been compacted but moisture content was not reduced. In practice it can be equated to shearing an over consolidated sample at natural moisture content. According to e Sousa *et al.* (2007) hear strength is a function of two important engineering properties namely, cohesion (c) and angle of internal friction (φ). The preceding results are analysed using the Mohr circle, from which failure is deduced. These parameter can be related to bearing capacity, to determine how much pressure a soil can withstand before it undergoes shear failure.

3.6.2.3 California bearing ratio (CBR)

The CBR test is used to give an indication of the strength of a subgrade soil, sub-base, and base course material for use in roads, highways and airfield pavements. It is performed on remoulded specimens to determine empirically, the required thickness of flexible pavements of highways and airfields (Knappett and Craig, 2012). Samples for CBR are compacted to their maximum unit weight (i.e. at their optimum moisture content), and later immersed into water to simulate poor conditions.

3.6.2.4 Soil pH and electric conductivity

The pH of a soil measures its acidity and alkalinity. Acidic soils may react with metallic structures causing corrosion. The electric conductivity (EC) of a soil measures its electrical response. EC of a soil is dependent on the nature of soil composition (particle size distribution, mineralogy), structure (porosity, pore size distribution, connectivity), water content, and temperature (Bai, 2013). It is enhanced by the presence of salts, which is likely to be the case for arid and semi-arid regions. EC is important because in addition to its corrosive effect, it also determines the soils potential for erosion and piping which is common for dispersive soils (DPW, 2007). This behaviour can be problematic in embankment dams, roads and other developments that require compacted soils (Kleinhans, 2002).

3.6.2.5 X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF)

XRF and XRD analyses determine, for soils and rocks, the the elemental and mineralogical compositions, respectively. For soils, an XRD analysis can give essential mineral phases, particularly clay minerals, therefore indicating whether or not the clay can be expansive. Presence of clays such as montmorillonite (as discussed under expansive soils in section) means the soil is potentially expansive.

All the above discussed properties, when quantified for soils, can influence decision on usability of these soils either as founding ground or as construction material. These properties form an important part of engineering geological input and such information is presented in an engineering geological report and depicted on an engineering geological map.

3.7 Engineering geological classification and reporting

3.7.1 Engineering geological maps

The end product of this exercise is an engineering geological map. Engineering geological maps, unlike geological maps, depict components of the geological environment that are significant to land use planning and design, construction and maintenance of structures UNESCO (1976). In agreement with this, Price (1981) states that engineering geological maps ought to show distribution and spatial relationships of the basic components of the environment that affect engineering-based decisions. In other words, these are maps that outline a broad overview on suitability of land for engineering use. Given the wide range of applications of engineering geology, Dearman (1991) categorised engineering geological maps using three (3) criteria, namely: purpose (which can either be general or for a particular development); the map content (which can be comprehensive or specialised), and finally, the scale of the map (can be small, medium or large).

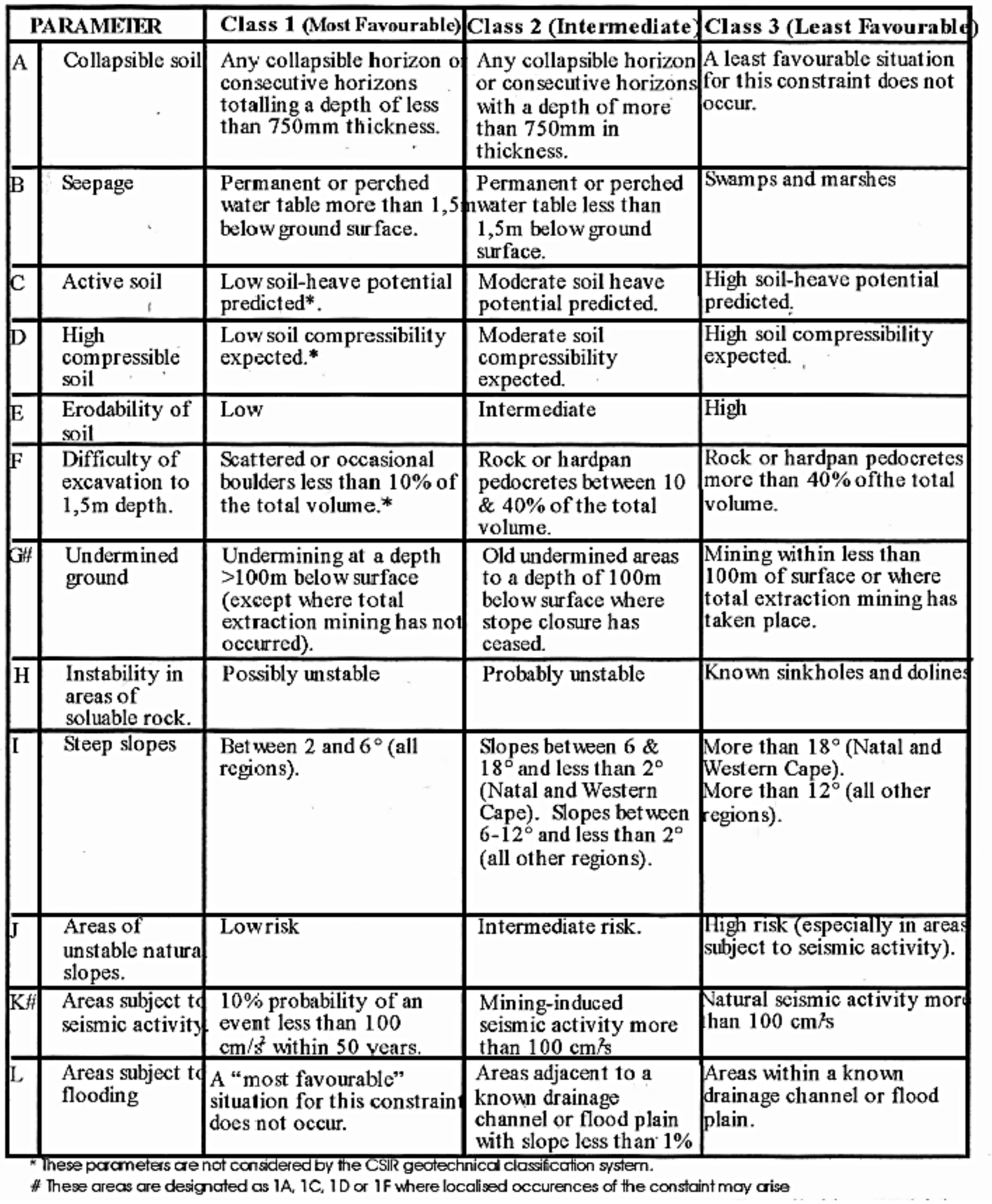
Furthermore, Price (1981) states that engineering geological maps may not replace a detailed site investigation. They are rather a guide to spatial planning and siting of structures, therefore for specific structures, a detailed geotechnical site investigation must be carried out.

3.7.2 Scale of mapping

Dearman (1991) has stated that the scale of engineering geological mapping is determined by the purpose for which the map is intended and the amount of detail that has to be shown. For instance, maps produced during engineering geological mapping are for general use or purpose, used to plan a wide range of developments, therefore they are presented on a medium scale of 1: 10 000 – 1: 100 000 (UNESCO (1976); Price (1981) and Dearman (1991)) or smaller Dearman (2013). This allows coverage of large areas. Complexity of terrain also influences scale of mapping (Price, 1981). Areas with complex geology and terrain ought to be mapped at medium scale to ensure that information presented is meaningful. The scale should not be too small to miss important details, however, it should also not be too big as it then loses its regional credibility (Kleinhans, 2002).

3.7.3 Engineering geological zoning

Different methodologies of presenting geotechnical information have been devised. The Geotechnical Classification for Urban Development criteria developed by Partridge *et al*. (1993) divides the area into engineering geological zones (EGZ) using letters to represent different geotechnical constraints used together with numbers which indicate the severity of the constraints as indicated in **Figure 7.** The bigger the number, the more severe the constraint and small numbers represent less severe cases. For example Partridge *et al.* (1993) assigned the letter B to flooding, and severity is such that B3 will mean more prone to flooding than B1 which would be less prone.



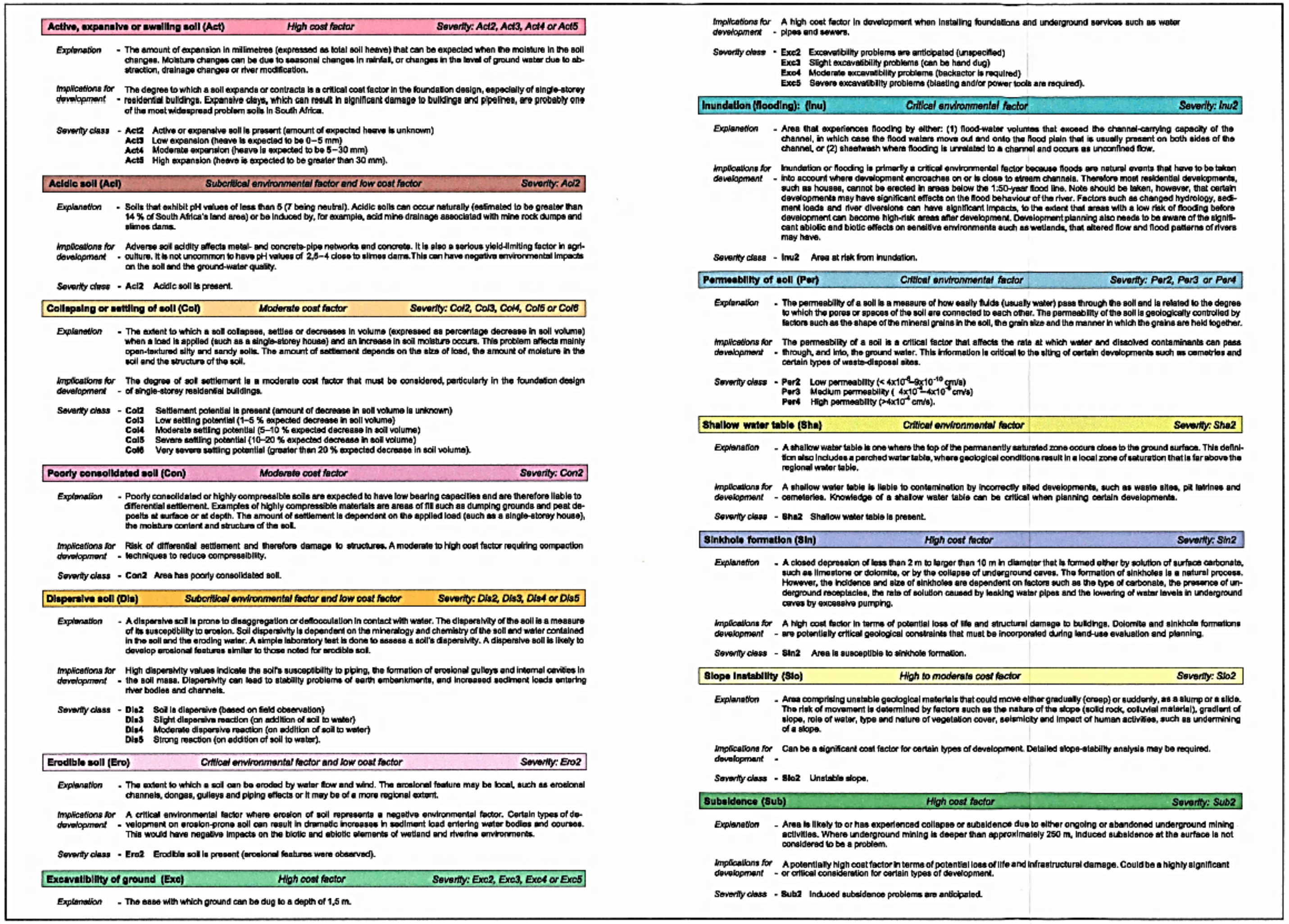
PARAMETER		Class 1 (Most Favourable)	Class 2 (Intermediate)	Class 3 (Least Favourabl)
A	Collapsible soil	Any collapsible horizon o consecutive horizons totalling a depth of less than 750mm thickness.	Any collapsible horizon or consecutive horizons with a depth of more than 750mm in thickness.	A least favourable situation for this constraint does not occur.
B	Seepage	Permanent or perched water table more than 1,5m below ground surface.	Permanent or perched water table less than 1,5m below ground surface.	Swamps and marshes
C	Active soil	Low soil-heave potential predicted*.	Moderate soil heave potential predicted.	High soil-heave potential predicted.
D	High compressible soil	Low soil compressibility expected.*	Moderate soil compressibility expected.	High soil compressibility expected.
E	Erodability of soil	Low	Intermediate	High
F	Difficulty of excavation to 1,5m depth.	Scattered or occasional boulders less than 10% of the total volume.*	Rock or hardpan pedocretes between 10 & 40% of the total volume.	Rock or hardpan pedocretes more than 40% ofthe total volume.
G#	Undermined ground	Undermining at a depth >100m below surface (except where total extraction mining has not occurred).	Old undermined areas to a depth of 100m below surface where stope closure has ceased.	Mining within less than 100m of surface or where total extraction mining has taken place.
H	Instability in areas of soluable rock.	Possibly unstable	Probably unstable	Known sinkholes and doline
I	Steep slopes	Between 2 and 6° (all regions).	Slopes between 6 & 18° and less than 2° (Natal and Western Cape). Slopes between 6-12° and less than 2° (all other regions).	More than 18° (Natal and Western Cape). More than 12° (all other regions).
J	Areas of unstable natura slopes.	Low risk	Intermediate risk.	High risk (especially in areas subject to seismic activity).
K#	Areas subject t seismic activity	10% probability of an event less than 100 cm/s^2 within 50 years.	Mining-induced seismic activity more than 100 cm/s	Natural seismic activity mor han 100 cm/s
L	Areas subject t flooding	A "most favourable" situation for this constrain does not occur.	Areas adjacent to a known drainage channel or flood plain with slope less than 1%	Areas within a known drainage channel or flood plain.

* These parameters are not considered by the CSIR geotechnical classification system.

\# These areas are designated as 1A, 1C, 1D or 1F where localised occurences of the constaint may arise

Figure 7: Geotechnical classification for urban developments (Partridge *et al.,* 1993)

A similar methodology has been presented by Kleinhans (2002) as a modification to Zawada's (2000) methodology, whereby the mapped geotechnical factors are shortened and termed together with numbers to indicate severity. Additionally, this method also colour codes each factor and the shade of colour depends on the severity of the geotechnical factor, with darkest colours assigned to the most severe classes while light colours were assigned to the least severe classes. For example, ‘Exc’ is the code for excavatibility of an area, which is assigned a green colour, where a lighter green indicates a lesser severity (i.e will not have excavatibility problems) than a darker green (which might require blasting to excavate) as shown in **Figure 8**.



Active, expansive or swelling soil (Act) *High cost factor* *Severity: Act2, Act3, Act4 or Act5*

Explanation - The amount of expansion in millimetres (expressed as total soil heave) that can be expected when the moisture in the soil changes. Moisture changes can be due to seasonal changes in rainfall, or changes in the level of ground water due to abstraction, drainage changes or river modification.

Implications for development - The degree to which a soil expands or contracts is a critical cost factor in the foundation design, especially of single-storey residential buildings. Expansive clays, which can result in significant damage to buildings and pipelines, are probably one of the most widespread problem soils in South Africa.

Severity class -
Act2 Active or expansive soil is present (amount of expected heave is unknown)
Act3 Low expansion (heave is expected to be 0–5 mm)
Act4 Moderate expansion (heave is expected to be 5–30 mm)
Act5 High expansion (heave is expected to be greater than 30 mm).

Acidic soil (Aci) *Subcritical environmental factor and low cost factor* *Severity: Aci2*

Explanation - Soils that exhibit pH values of less than 5 (7 being neutral). Acidic soils can occur naturally (estimated to be greater than 14 % of South Africa's land area) or be induced by, for example, acid mine drainage associated with mine rock dumps and slimes dams.

Implications for development - Adverse soil acidity affects metal- and concrete-pipe networks and concrete. It is also a serious yield-limiting factor in agriculture. It is not uncommon to have pH values of 2,5–4 close to slimes dams.This can have negative environmental impacts on the soil and the ground-water quality.

Severity class - **Aci2** Acidic soil is present.

Collapsing or settling of soil (Col) *Moderate cost factor* *Severity: Col2, Col3, Col4, Col5 or Col6*

Explanation - The extent to which a soil collapses, settles or decreases in volume (expressed as percentage decrease in soil volume) when a load is applied (such as a single-storey house) and an increase in soil moisture occurs. This problem affects mainly open-textured silty and sandy soils. The amount of settlement depends on the size of load, the amount of moisture in the soil and the structure of the soil.

Implications for development - The degree of soil settlement is a moderate cost factor that must be considered, particularly in the foundation design of single-storey residential buildings.

Severity class -
Col2 Settlement potential is present (amount of decrease in soil volume is unknown)
Col3 Low settling potential (1–5 % expected decrease in soil volume)
Col4 Moderate settling potential (5–10 % expected decrease in soil volume)
Col5 Severe settling potential (10–20 % expected decrease in soil volume)
Col6 Very severe settling potential (greater than 20 % expected decrease in soil volume).

Poorly consolidated soil (Con) *Moderate cost factor* *Severity: Con2*

Explanation - Poorly consolidated or highly compressible soils are expected to have low bearing capacities and are therefore liable to differential settlement. Examples of highly compressible materials are areas of fill such as dumping grounds and peat deposits at surface or at depth. The amount of settlement is dependent on the applied load (such as a single-storey house), the moisture content and structure of the soil.

Implications for development - Risk of differential settlement and therefore damage to structures. A moderate to high cost factor requiring compaction techniques to reduce compressibility.

Severity class - **Con2** Area has poorly consolidated soil.

Dispersive soil (Dis) *Subcritical environmental factor and low cost factor* *Severity: Dis2, Dis3, Dis4 or Dis5*

Explanation - A dispersive soil is prone to disaggregation or deflocculation in contact with water. The dispersivity of the soil is a measure of its susceptibility to erosion. Soil dispersivity is dependent on the mineralogy and chemistry of the soil and water contained in the soil and the eroding water. A simple laboratory test is done to assess a soil's dispersivity. A dispersive soil is likely to develop erosional features similar to those noted for erodible soil.

Implications for development - High dispersivity values indicate the soil's susceptibility to piping, the formation of erosional gulleys and internal cavities in the soil mass. Dispersivity can lead to stability problems of earth embankments, and increased sediment loads entering river bodies and channels.

Severity class -
Dis2 Soil is dispersive (based on field observation)
Dis3 Slight dispersive reaction (on addition of soil to water)
Dis4 Moderate dispersive reaction (on addition of soil to water)
Dis5 Strong reaction (on addition of soil to water).

Erodible soil (Ero) *Critical environmental factor and low cost factor* *Severity: Ero2*

Explanation - The extent to which a soil can be eroded by water flow and wind. The erosional feature may be local, such as erosional channels, dongas, gulleys and piping effects or it may be of a more regional extent.

Implications for development - A critical environmental factor where erosion of soil represents a negative environmental factor. Certain types of development on erosion-prone soil can result in dramatic increases in sediment load entering water bodies and courses. This would have negative impacts on the biotic and abiotic elements of wetland and riverine environments.

Severity class - **Ero2** Erodible soil is present (erosional features were observed).

Excavatibility of ground (Exc) *High cost factor* *Severity: Exc2, Exc3, Exc4 or Exc5*

Explanation - The ease with which ground can be dug to a depth of 1,5 m.

Implications for development - A high cost factor in development when installing foundations and underground services such as water pipes and sewers.

Severity class -
Exc2 Excavatibility problems are anticipated (unspecified)
Exc3 Slight excavatibility problems (can be hand dug)
Exc4 Moderate excavatibility problems (backactor is required)
Exc5 Severe excavatibility problems (blasting and/or power tools are required).

Inundation (flooding): (Inu) *Critical environmental factor* *Severity: Inu2*

Explanation - Area that experiences flooding by either: (1) flood-water volumes that exceed the channel-carrying capacity of the channel, in which case the flood waters move out and onto the flood plain that is usually present on both sides of the channel, or (2) sheetwash where flooding is unrelated to a channel and occurs as unconfined flow.

Implications for development - Inundation or flooding is primarily a critical environmental factor because floods are natural events that have to be taken into account where development encroaches on or is close to stream channels. Therefore most residential developments, such as houses, cannot be erected in areas below the 1:50-year flood line. Note should be taken, however, that certain developments may have significant effects on the flood behaviour of the river. Factors such as changed hydrology, sediment loads and river diversions can have significant impacts, to the extent that areas with a low risk of flooding before development can become high-risk areas after development. Development planning also needs to be aware of the significant abiotic and biotic effects on sensitive environments such as wetlands, that altered flow and flood patterns of rivers may have.

Severity class - **Inu2** Area at risk from inundation.

Permeability of soil (Per) *Critical environmental factor* *Severity: Per2, Per3 or Per4*

Explanation - The permeability of a soil is a measure of how easily fluids (usually water) pass through the soil and is related to the degree to which the pores or spaces of the soil are connected to each other. The permeability of the soil is geologically controlled by factors such as the shape of the mineral grains in the soil, the grain size and the manner in which the grains are held together.

Implications for development - The permeability of a soil is a critical factor that affects the rate at which water and dissolved contaminants can pass through, and into, the ground water. This information is critical to the siting of certain developments such as cemetries and certain types of waste-disposal sites.

Severity class -
Per2 Low permeability (< $4x10^{-6}$–$9x10^{-10}$ cm/s)
Per3 Medium permeability ($4x10^{-4}$–$4x10^{-6}$ cm/s)
Per4 High permeability (>$4x10^{-4}$ cm/s).

Shallow water table (Sha) *Critical environmental factor* *Severity: Sha2*

Explanation - A shallow water table is one where the top of the permanently saturated zone occurs close to the ground surface. This definition also includes a perched water table, where geological conditions result in a local zone of saturation that is far above the regional water table.

Implications for development - A shallow water table is liable to contamination by incorrectly sited developments, such as waste sites, pit latrines and cemeteries. Knowledge of a shallow water table can be critical when planning certain developments.

Severity class - **Sha2** Shallow water table is present.

Sinkhole formation (Sin) *High cost factor* *Severity: Sin2*

Explanation - A closed depression of less than 2 m to larger than 10 m in diameter that is formed either by solution of surface carbonate, such as limestone or dolomite, or by the collapse of underground caves. The formation of sinkholes is a natural process. However, the incidence and size of sinkholes are dependent on factors such as the type of carbonate, the presence of underground receptacles, the rate of solution caused by leaking water pipes and the lowering of water levels in underground caves by excessive pumping.

Implications for development - A high cost factor in terms of potential loss of life and structural damage to buildings. Dolomite and sinkhole formations are potentially critical geological constraints that must be incorporated during land-use evaluation and planning.

Severity class - **Sin2** Area is susceptible to sinkhole formation.

Slope instability (Slo) *High to moderate cost factor* *Severity: Slo2*

Explanation - Area comprising unstable geological materials that could move either gradually (creep) or suddenly, as a slump or a slide. The risk of movement is determined by factors such as the nature of the slope (solid rock, colluvial material), gradient of slope, role of water, type and nature of vegetation cover, seismicity and impact of human activities, such as undermining of a slope.

Implications for development - Can be a significant cost factor for certain types of development. Detailed slope-stability analysis may be required.

Severity class - **Slo2** Unstable slope.

Subsidence (Sub) *High cost factor* *Severity: Sub2*

Explanation - Area is likely to or has experienced collapse or subsidence due to either ongoing or abandoned underground mining activities. Where underground mining is deeper than approximately 250 m, induced subsidence at the surface is not considered to be a problem.

Implications for development - A potentially high cost factor in terms of potential loss of life and infrastructural damage. Could be a highly significant or critical consideration for certain types of development.

Severity class - **Sub2** Induced subsidence problems are anticipated.

Figure 8: Alphabetical listing of geotechnical factors mapped for the Rietvlei Dam map sheet with definitions, implications for development and classes of severity (after Zawada, (2000) from Kleinhans (2002)).

Different maps presenting different geotechnical factors are overlain to produce the overall engineering geological map. Furthermore, it is important to note that this information can only be useful if it is communicated effectively to the right parties and in pertinent time. Engineering geological maps are used by a wide range of professionals involved in the engineering projects. For instance, in the case of urban development, involved professionals include town planners, civil engineers, geotechnical engineers, (architects) and engineering geologists. For this reason, engineering geological maps must be simplified to their understanding. Colour coding is an amiable option, user-friendly and allows presentation of self-explanatory maps. Colour coding of engineering geological maps has also been done by Muller (1938) to publish maps of Marke Parish as discussed in Dearman (2013). Muller used the following colours:

- Green and yellow: for ground suitable for construction, permitting bearing pressure of not less than 2.5 bars.
- Orange: to indicate moderate ground.
- Orange cross-hatching: to indicate least favourable ground conditions at present state with restricted allowable bearing pressure. These were for instance areas with variable hydrogeological conditions that needed special attention.
- Red: corresponds to poor ground requiring costly foundations.

3.8 Chapter summary

This chapter covered the current methodology of doing engineering geological mapping. The approach presented included: desktop study and terrain evaluation, reconnaissance survey; detailed field investigation; laboratory testing; reporting; and engineering classification. Desktop study entails gathering existing information about the area and performing terrain analysis, also termed terrain evaluation. Insight was given to aspects of the environment that form part of important considerations in engineering geological mapping, including the geology and soils, hydrogeology and geomorphology. The terrain evaluation process involves partitioning of land into similar terrain classes, usually based on the different landscapes and landforms. It uses the assumption since the same landscapes present similar conditions, they are bound to have similar effect on the civil structures, and for this reason, they should be treated the same when it comes to infrastructural planning. The different land classes mapped during terrain evaluation are then confirmed during the site walk over survey, also herein referred to as reconnaissance survey, therefore forming a basis for investigation. Thereafter, a detailed field investigation is then carried out to further understand the land classes and acquire descriptive information about the area. At this stage, *in-situ* tests are performed, test pits are opened so as to expose fresh ground for observation of material in place, as well as for profiling and sampling. Samples collected during this stage are then submitted for laboratory testing to obtain quantitative information about the materials. Parameters tested for include foundation indicators such as grain size distribution, Atterberg Limits, pH and electric conductivity, which require disturbed samples. However, depending on the need, tests may include shear strength, oedometer testing for settlement and collapse potential, which require undisturbed or block samples, and CBR mainly for roads, which require disturbed bags of upto 40kg. It was also highlighted that information obtained from laboratory testing done as part of the regional engineering geological mapping is done rather to give a basis for general planning as opposed to it being used for designing. The final stage focuses on reporting, whereby the findings from the earlier stages are presented on a user-friendly EGM. Maps presenting different geotechnical factors are overlain to produce the overall engineering geological map that is usually simplified to the understanding of all affected professionals that may not have a geological background. The standard practice is colour coding, with each colour on the map representing the potential use of land. The purpose of this is so that based on the engineering geological map, land uses can be recommended for different land classes, after which detailed investigations are then conducted for those particular land uses (at site investigation stage).

After the revision of the present terrain evaluation methodology, it was discovered that the approach could not be applied directly to the area under investigation for present research, given the method's reliance on landscapes. It was therefore necessary to faintly modify the approach to make it suitable for flat-lying semi-arid environments. The subsequent chapter discusses this in detail.

4 CHAPTER 4: THE CONCEPT OF TERRAIN EVALUATION AND PROPOSED MAPPING AIDS FOR HOMOGENOUS GEOLOGY, FLAT-LYING ARID TO SEMI-ARID REGIONS

4.1 Introduction

In the past, the planning stage of development projects entailed the use of a grid system to partition land into equal blocks, each of which would be studied and tested to obtain information about the area. After partitioning, exploration density is then determined, that is, the number of exploratory holes per unit area. The handicap of this method however, is that the number of exploratory holes required may be too many, some of which could yield the same information. This repetitive investigation can be time-consuming, and places an extra burden on the investigation budget. Therefore, to reduce duplication of field effort in areas where landforms are recurrent, the approach of terrain evaluation was introduced. Terrain evaluation allows homogenous areas of the environment to be grouped under one terrain class and treated the same during planning. However, acknowledging that natural environments are never really homogenous. It is important to note that from an engineering perspective, an environment is said to be homogenous "…when the amount of variations in it are not sufficient to necessitate a modification of design, to take these variations into account." (Lawrence *et al.*, 1993). The principle of homogeneity is what allows extrapolation of information from areas that have been tested to those that were not tested, but are within the same terrain class, as discussed in **Section 3.3.1.**

For this reason, when terrain evaluation is used as a basis of planning, the design is kept constant for the same land units. Sampling will be limited to certain selected sites that are deemed to be representative of that particular land unit, where thereafter, properties described at representative sites are extrapolated to other sites. In so doing, the available data is put to good use and it eliminates the need for costly and time consuming repetitive investigations within the same terrain class (Partridge, 1994). Central to this phase is that it provides a preliminary geological and geotechnical setting of the project area prior to the actual field visit (Walker, 2012). This helps with the planning of subsequent phases of investigation such as siting of test pits and the extent of investigation required. The general approach of terrain evaluation, specifically using land systems classification has been applied successfully in different parts of the world using air photographs. Applications of this approach range from military (in search for military hide outs) to agriculture (in search for good land for farming) and for the exploration of mineral resources as well as in engineering (in search for suitable sites for infrastructural development). From an engineering context, Phipps (2001) highlights that terrain evaluation summarises the principal characteristics of an area and their implications on engineering projects. The land systems approach was also found to be useful over a wide range of geographical and geological environments.

4.2 Terrain evaluation a mapping technique for arid and semi-arid regions (drylands)

Considerable engineering geological research effort has been directed towards understanding its applications to specific environments such as tropical regions, arid regions, areas with permafrost, etc. One important outcome arising from past research is that attention must be given to problems specific for that particular environment. For instance, work in permafrost regions must consider the fluctuation in moisture content due to the melting of ice. As a result, methodologies designed to cope specifically with conditions unique for these regions were put in place. This includes Malomo *et al*. (1983) who studied different weathering processes in the tropical regions to aid planning of Nigeria's capital Abuja. In the present research, focus was narrowed down to semi-arid and arid environments, herein referred to as warm drylands.

4.3 Drylands geomorphology

Drylands is a collective term used to refer to environments with either arid, semi-arid or dry sub-humid conditions (Bull and Kirkby, 2002). Drylands are defined based on aridity which is a function of temperature and precipitation, with aridity index usually less than 0.50 (Food and Agriculture Organization (FAO), 1989). Drylands cover a significant portion of the Earth, which according to Meigs (1953) includes no less than a third of the world's land surface. Thus, they require serious consideration when it comes to development. Maintaining that it is important to pay attention to site specific conditions, problems common for drylands were noted. In terms of weathering, it is noted from Weinert's (1974) relationship between precipitation and evaporation, that these areas have a numerical index value of $N>5$. This implies that mechanical weathering is the dominant form of weathering as opposed to chemical weathering, due to water scarcity. Mechanical weathering, caused by wind, usually gives rise to geotechnical constraints such as wind erosion, as well as formation of dispersible and collapsible soils. One of the key characteristics of arid and semi-arid environments is that they experience extreme ends of both temperature and precipitation. These regions experience long periods of drought and at other times, periods of flooding.

It is notable that drylands have variable landscapes, tectonism and moisture contents as noted by Cooke *et al.* (1982), mentioning the limestone plateau in South Australia, in contrast to the sand seas of Sahara. Landscape as established earlier, is an important parameter when it comes to terrain evaluation. They further noted that many drylands are typical of close coincidence of soils and landform boundaries. Stiff (1994) has also noted that in arid to semi-arid regions, areas with similar host lithologies and that have undergone similar soil forming processes, can be compared to analogues in other areas. This is why most drylands could successfully apply the land systems approach of terrain classification. In cases where the land systems approach could not be used, different generic association models were devised in an attempt to classify land. For instance, Young (1971) proposed partitioning of slope profiles into separate units according to their slope gradient. Mitchell and Perrin (1966) partitioned sand dunes into three repetitive surfaces, depending on the dominant processes. Both examples allow educated guesses about the types of soils expected on different slope profiles or on the different dune surfaces. However, for areas where landforms are not properly defined in terms of altitude, i.e. flat-lying environments, the question of terrain evaluation remains unanswered.

4.4 Flat lying environments and the need for modification

Although the land systems approach proved to be useful in terrain analysis and has been used successfully in some arid and semi-arid regions, it remains a challenge when it comes to flat-lying environments. As established before, the present methodology of terrain evaluation focuses on physiographic features and geomorphological processes. Much reliance is placed on different landscapes and topographical features. This makes it challenging for arid to semi-arid environments that are flat lying or have low relief, and show limited detail of landscape. McGraw-Hill Dictionary of Scientific and Technical Terms (2003) defines flat lying bodies to have a relatively flat dip (inclination) of less than five degrees (5˚). In other words, these are areas with very little change in altitude over a considerable stretch of distance. Their flat nature makes it relatively challenging to classify land, in which case one is required to use other identifiable features or use substitutional knowledge to delineate topographical features. Mapping techniques that can aid land classification in flat-lying arid to semi-arid regions are proposed in the subsequent section.

4.5 Proposed mapping aids for land classification in flat-lying arid to semi-arid environments

The methodology proposed for terrain evaluation in flat-lying or low relief arid to semi-arid environments involves the use of aerial photographs to produce a series of maps depicting different components of the environment as observed from the photographs. Therefore, landscapes that are not readily visible from air photographs can be inferred from other visible parameters. Proposed mapping aids for land classification are presented below, including soil variability, vegetation, and drainage. In addition, damage distribution maps can be produced at reconnaissance stage, in cases where the assessment is for expansion (i.e., the area already has existing structures).

4.5.1 Soil colour variability mapping

Soil variability mapping refers to the identification of different soil occurrences by noticing textural and tonal variations from aerial photographs. Land is divided into various soil units, producing a soil map. According to UNESCO’s (1976) paper on engineering geological mapping, the soil boundaries drawn in delimit soil units that are characterised by a certain degree of homogeneity in basic engineering geological properties. As previously discussed in **Section 3.3.1.1** of present research**,** under the concept of uniformity, a structural plan will be kept constant throughout a specific land unit, and only change when soil conditions change i.e., transition into another soil unit.

Soil colour is often a result of their chemical composition or the subsequent weathering processes, which are highly influenced by the origin and genesis of a particular soil. Therefore it can be said that soils derived from the same parent material or that have undergone the same weathering process are likely to have same colour, and can, as such, be differentiated from others. In addition, the soil textures picked up from air photographs mimic the textures underneath which may represent palaeo-environments or underlying rock units. This is typical for arid and semi-arid regions, where aeolian deposits are common and often overlaying older rock formations.

Other soil parameters discussed by Jenny (1980) and Smith and Hudson (2002) that can aid soil identification include climate, organisms, relief, and time. Therefore, by looking for changes in one or more of these factors as the landscape traverses, one can identify likely boundaries between the different soil bodies (Smith and Hudson, 2002). The indefinite soil boundaries drawn in for soil variability mapping should be confirmed during the reconnaissance survey. Another option proposed as a guide to understanding soils is to do indirect interpretations using vegetation.

4.5.2 Vegetation mapping

This is a visual assessment of vegetation from air photographs to infer soil conditions. Vegetation mapping was divided into two assessments namely: (1) vegetation occurrence and (2) vegetation distribution, whereby the former addresses why plants occur in certain localities as opposed to others, while the latter pays attention to the patterns and arrangements of vegetation. Vegetation mapping applies the principle that vegetation responds to water conditions, therefore can be a good indicator of soil moisture content or water regimes in semi-arid regions where water is scares. Areas with high moisture contents tend to support considerable amounts of vegetation. This concept can aid mapping of faults, streams, and other water regimes that may not readily show on aerial photographs (Mitchell, 1991). However, it should be noted that when it comes to arid regions, care must be taken when using vegetation as a guide to soil variability mapping. This is because arid vegetation has unique adaptations of dealing with the harsh arid conditions, such that some plant species rely on fog and other forms of precipitation, and not on groundwater. This in turn means that the natural occurrence of plants in certain localities of the arid environment may not necessarily be related to the underlying soil conditions. It is therefore advisable that for investigations in arid regions, the adaptations of plant life existing in the study area should be understood when using them as a guide in land classification.

Vegetation also plays a role in understanding subsurface condition. The presence of certain plants in certain environments dictate expected soil conditions. Svensson (1972) has stated that moisture conditions and general ground water regime can be surveyed by observing hydrophilic vegetation. Meaning the presence of hydrophilic vegetation can be used to deduce depth of the ground water table, which is an important factor for site investigations and becomes a concern when it is shallow. As noted by Lie and Evett (2009) the water table, when near or at footing of a foundation can reduce the bearing capacity of a soil. It is this concern, coupled with the fact that shallow groundwater is more vulnerable to contamination that makes depth to groundwater an important deliberation and should be considered when siting developments such as cemeteries, sanitary landfills and hazardous waste.

Additionally, plants can also be useful for damage analyses during reconnaissance surveys. They can give an indication of the type of soils to expect in an area, from the impact they have on nearby structures. This is of particular interest when expansive soils are a concern. For instance, buildings that have trees next to them might experience cracking. This could be an indication that there are expansive soils present in the area, in which case, the cracks will be attributed to the extraction of minerals from the soil by these plants. This is because, plants take up their minerals in watery solutions and the continuous uptake of water induces a change in moisture content, and as a response, expansive soils undergo heaving (Day, 1999). Owing to their structure, when expansive clays lose their water, they shrink, and when they take in water, they expand as previously discussed under Expansive soils, in S**ection 3.2.1.4**. This expansion and shrinkage can lead to change in soil volume, resulting in cracking of nearby structures. Certain plant species require more water than others, and for this reason, the extend of heaving following the removal of water by plant roots vary depending on the plant species, plant size as well as plant density.

Two contrasting views on the use of vegetation in defining terrain units have emerged from literature. Authors such as Mabbutt and Sterwart (1965), as well as Robins (1976), and Mitchell (1991) agree with the use of vegetation as an index for recognition of terrain types. However, Zimmermann and Thom (1982) and Lawrence *et al.* (1993) used the temporary nature of vegetation to argue the opposite, stating that vegetation is subject to change anytime, depending on circumstances present. Zimmermann and Thom (1982) have stated that vegetation is an ephemeral rather than a permanent characteristic of landscape, adding that it is in a continuous change of state, whereby it can easily be affected by human activities, grazing, burning, and natural colonisation. Other circumstances presented by Lawrence *et al.* (1993) are such as successive years of drought, change in agricultural activity, and deforestation.

Considering how useful vegetation can be in defining land units, it is still seen relevant to incorporate it in land classifications especially in flat terrains where indications for classifying land are limited. Mitchell (1991) has noted that repetitive coverage of satellite imaging allows monitoring of seasonal and annual changes of ground features.

Furthermore, Singh and Dubey (2011) in their land use mapping of Gorma Basin also stated that there are advancements in the field of remote sensing that monitors change in the status of terrain and assess the dynamic changes over space and time. This can help to overcome the challenge presented by Zimmermann and Thom (1982) and Lawrence *et al*. (1993).

4.5.3 Structural damage distribution surveys

Structural damage distribution refers to assessment of a site based on the performance of existing structures. This is done during the reconnaissance survey, whereby slope failures, uneven settlement of foundations, cracking and collapsing structures, failure of embankments etc. are recorded. This approach is rather for developed areas as opposed to undeveloped rural environments and pristine areas. It can be useful for instance in investigations for the purpose of expansion of townships and urban centres.

There is always movement in and around the built environment, which is why structures are usually designed to cope with these movements, and once these movements are not factored into the design, the structure may fail in response, either by cracking or collapsing etc. It is important to note that when structural failure occurs, it may not always be accredited to geotechnical problems, or conditions associated with the founding ground. Failure of civil structures can also be caused by external factors, such as strong winds, seismic activities and other geohazards. At times the problem may lie with the quality or the type of material used in the construction of the structure, or the manner in which the material was put together or incorporated in the design, causing internal defects to the building structure. Of interest to the present subject, however, are the external factors related to foundation or unfavourable ground conditions. Therefore, tests should be performed on material taken from the vicinity of the damaged structures, to understand material properties and confirm or deny speculations thereof.

All these techniques can help delineate different land classes, which can be used as a basis for further investigation and at the same time give an idea of site performance. Deliverables at this stage of investigation are: a vegetation map, soil variability map, land use map, geological and topographical maps, either produced from air photo mapping or readily obtained. A preliminary map of land classes is then produced, using a combination of all the parameters that were mapped. This map can then be a substitute of the land facets map that could be produced using the land systems method. At this point, positions for detailed investigation are identified to cover all land classes demarcated and ensure that they will all be profiled and studied in the subsequent phases.

4.6 Compilation of engineering geological maps

Ideally, engineering geological maps ought to have input from all stages of the geotechnical mapping. The land systems approach should be used to produce land classification maps, or land facets maps for areas with variable terrain, while the mapping aids discussed above can be used to produce land facets maps for uniterrain areas. Thereafter, the engineering geological mapping process should continue as per standard practice, whereby the identified land facets are then confirmed during the reconnaissance visit, followed by a detailed investigation phase, during which qualitative information or material descriptions are obtained. And finally, supplemented by quantitative summary of soil parameters is added as per the laboratory tests. All this information contribute to partitioning of land into engineering geological zones, each is summarised in terms of geohazards and other geotechnical constraints, as well as vulnerability of the area, thereby producing an engineering geological map. This methodology is summarised in **Figure 9**.

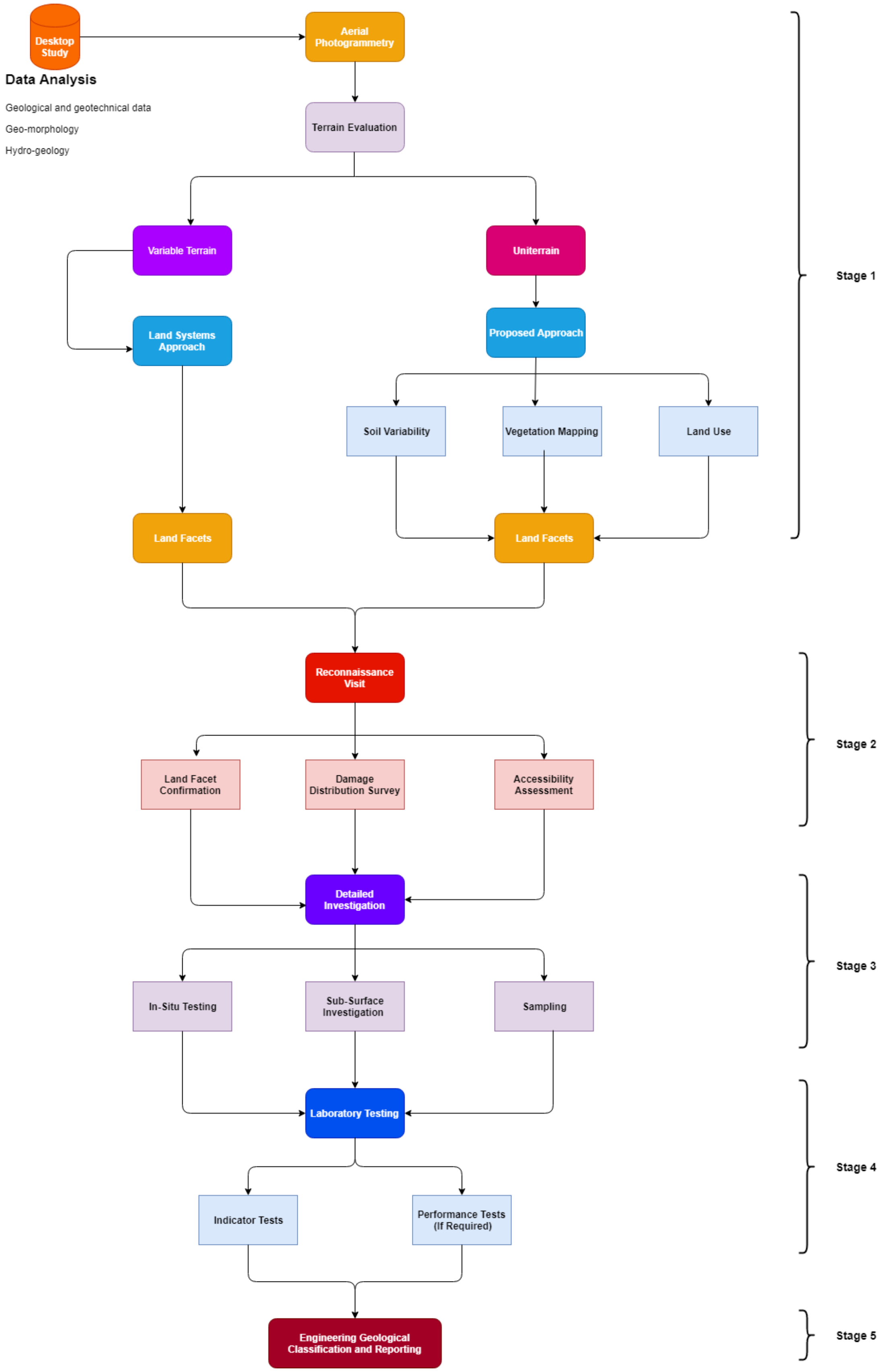


Figure 9: A depiction of different stages of engineering geological mapping, with terrain evaluation branched into two, depending on the type of terrain under consideration.

4.7 Chapter summary

This chapter discussed the concept of terrain evaluation and its role in the planning of engineering works. Terrain evaluation groups similar areas into terrain classes by applying the principle of homogeneity. Acknowledging the heterogeneous nature of the natural environment, it was further clarified that in engineering terms, an area is said to be homogenous when the changes in it are not significant enough to necessitate a change in engineering design. For this reason, the grouping of these areas into one terrain class allows a quick and cost effective way of analysing the environment for engineering use. The chapter also discussed how the land system classification was applied successfully in area with variable terrain, thereby highlighting the inapplicability of this method to flat, uniterrain areas. Other mapping aids were then recommended for flat lying semi-arid areas. Proposed techniques include soil variability mapping, vegetation, as well as damage distribution mapping. Soil variability mapping delineates different soil occurrences using textural and tonal variations. These give insight into soil genesis, which is a determinant of soil properties. In terms of vegetation, occurrence and distribution were proposed, where the former examines why vegetation occurrs in certain localities as opposed to others, and the latter assesses into different distributions and patterns of vegetation, which could be indicative of water flow regimes. While on vegetation, it was also claimed that in arid environments, it is often wise to understand the adaptations of the plants as some of them source their water from other forms of precipitation, as opposed to ground water. Plants were also identified as good indicators of heaving soils, because of their influence on moisture variations. Their extraction of water from the soil triggers a reduction in moisture content, which may cause shrinkage to expansive soils, resulting in change in soil volume, which in turn affects nearby infrastructure. A damage distribution survey was also recommended, as an assessment of soils based on existing structures. Soils in the vicinity of damaged properties were recommended for testing to confirm whether or not the damage is due to poor soil conditions. At reporting stage, colour coding was deemed an enviable option, so as to allow understanding of engineering geological maps by all involved professionals, even those without a geological background. This method, as discussed, has been tailored for flat-lying semi-arid to arid environments, and the subsequent sections will test its applicability.

5 CHAPTER 5: CASE STUDY: ENGINEERING GEOLOGICAL MAPPING OF SOILS IN OUTAPI, NORTHERN NAMIBIA

5.1 Introduction

This chapter presents a case study of a selected area of Outapi, in the flat-lying northern region of Namibia. The main aim was to apply the current methodology of engineering geological mapping, incorporating terrain evaluation techniques proposed for flat lying arid to semi-arid regions, as discussed in Chapter 4. The study further tests Outapi soils for their usability as founding material for urban use, paying particular attention to housing, as Outapi is one of the towns targeted by the National Mass Housing project to counter the current housing backlog. Soil testing was confined to the developed parts of the town, with few samples taken from the areas proposed for future developments. In the absence of Namibian standards, the South African National Standard (SANS) 634 (2007) code of practice for geotechnical investigations for township development was used. The methods used to achieve this are presented in the subsequent sections, with the outcome presented in **Chapter 6**.

5.2 Techniques employed for engineering geological mapping of Outapi

The techniques used in the study of Outapi soils include a desktop study, terrain evaluation, reconnaissance surveys, and detailed ground investigations, where profiling and sampling were done, followed by laboratory testing and reporting.

5.2.1 Stage 1: Desk study and Terrain evaluation

Background information about the study area is provided in this section. It discusses the present land use of the study area covering aspects of present infrastructure, water and waste water facilities, and the general social status of the town and surrounding area. The physical environment was assessed based on existing information concerning the geology of the area, climate, hydrology, topography etc., which allows inference into how the natural environment can potentially affect or impact the proposed developments and vice versa. An understanding was also obtained from interpretation of aerial photographs of the area.

5.2.1.1 Desktop study

5.2.1.1.1 Location of study area

Outapi Town is located in northern Namibia, 800 km north of Namibia's capital Windhoek, some 110 km north west of Ondangwa and 100 km south of the Namibia-Angolan borders. It is the capital town of the Omusati Region. The geographical position of the town is 17° 30’ 35.44”S and 14° 59’ 19.26”E. The location of Outapi within the selected research area is indicated in **Figure 10**. A base digital elevation model (DEM) was used to show the position of the town relative to the landscape as well as the location of other towns in the basin. The town is connected to its major neighbouring towns – Oshakati and Ruacana via the C46 road. The research area was designed to include Outapi Municipal land as well as its outskirts as an outlook for urban expansion. It covers a surface area of approximately 38000 Ha.

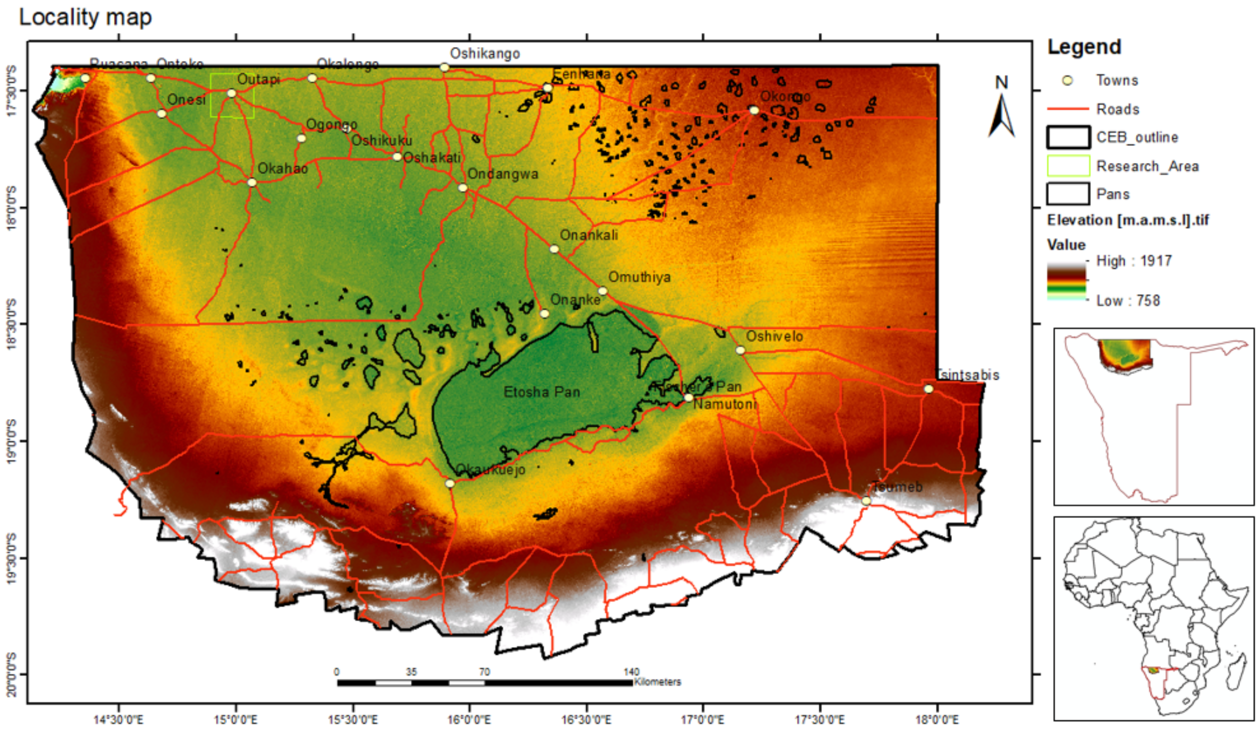


Figure 10: The location of Outapi Town area and the outlined study area relative to the CEB.

5.2.1.1.2 Geology and soils of the area

Outapi falls within an inland sedimentary basin called the Owambo Basin, which covers northern Namibia, extending into Angola Miller (2008) as seen in **Figure 11**. It is a sub-basin and forms part of the bigger intracontinental Kalahari Basin.

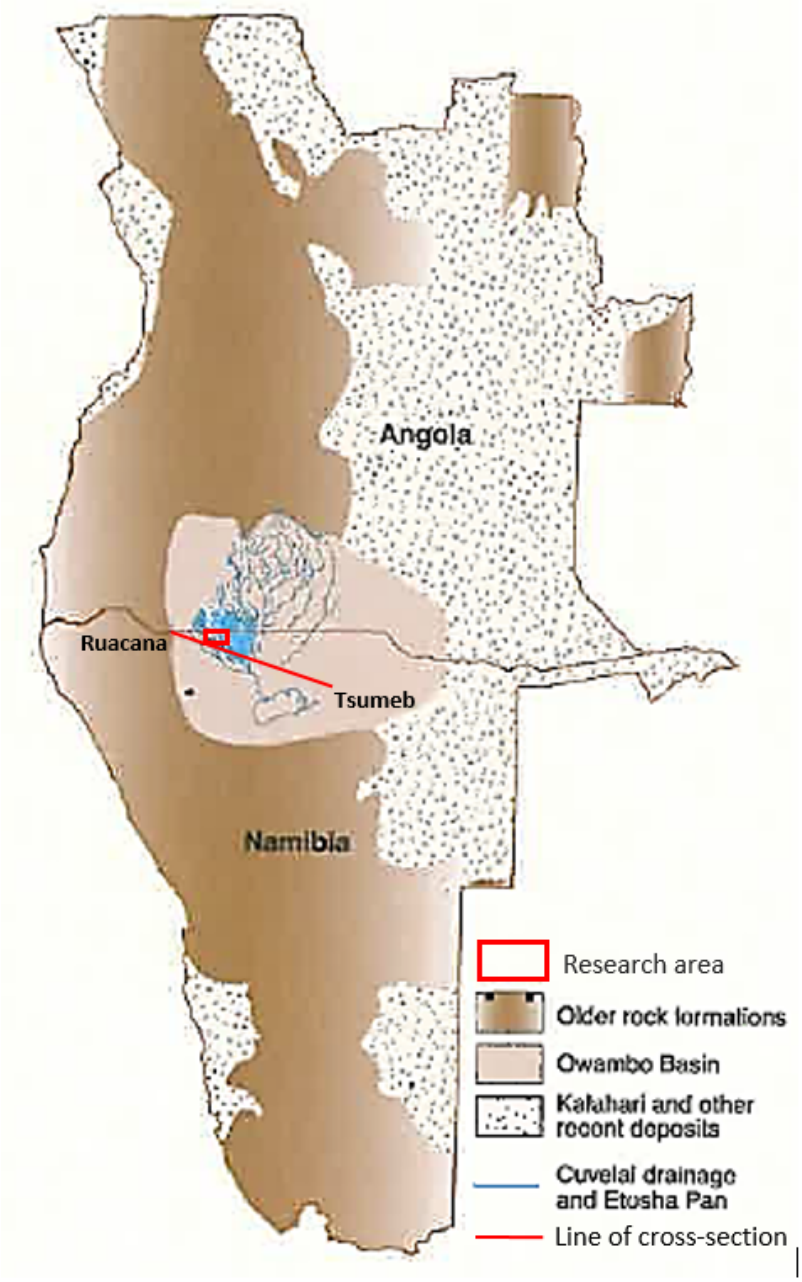


Figure 11: Map of Namibia showing highlands and basins in the country and the position of the Owambo Basin (taken from Mendelsohn *et al*. 2000, cross-section and research area added).

This basin is an ancient depression that is underlain by Pre-Damaran rocks comprising of old continental base granites, gneisses and volcanic rocks which were formed around 2600 to 1700 million years ago (Ma) (Mendelsohn *et al*., 2000). These rocks are found at depths of thousands of meters below the present landscape, only outcropping on the western and southern parts of the basin as remnant hills (Mendelsohn *et al.,* 2000 and Miller, 2008). At around 1000 Ma, intercontinental rifting formed deep valleys that were filled with sediments, which became sandstones of the Nosib Group. During the Rodinia land mass break up, oceans formed and sediments of limestone and dolomite were deposited on the extensive continental platform, forming the Otavi Group. The reversal of plate motion from spreading to collision brought about closure of oceans, which ultimately culminated in the formation of Gondwana (Miller 1983). These mountains are observed today on the southern and western rims of the basin. An erosion period occurred at about 600 Ma, when the topographically higher terrains in the surrounding areas were eroded, depositing another layer of sediments to form sedimentary rocks of the Mulden Group (Hipondoka, 2005). This completed the Damara Sequence (i.e., rock units that were formed after the intercontinental rifting). These are overlain by the Karoo Sequence, followed by thick Kalahari Group sediments, thinning out towards the basin margins where they lie directly on the basement units, as shown in the cross section in **Figure 12**. These various rock and soil formations filled the basin, separated by major erosional unconformities (Miller, 1997; Mendelsohn *et al.*, 2000) with younger Kalahari sediments capping it to produce the current flat landscape, as seen in **Figure 12**. The uplift during Pliocene resulted in eroded sands being washed into the basin and later reworked into sand dunes during late Pliocene (Miller *et al.*, 2010)

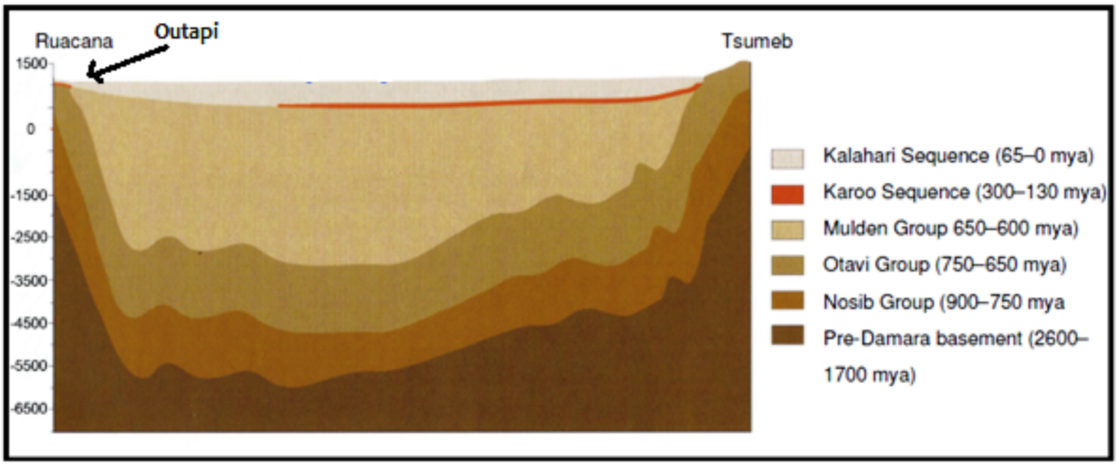


Figure 12: A cross section through the basin from Ruacana to Tsumeb, with the black arrow indicating the approximate position of the research area. (black arrow by author, image source: Mendelsohn *et al.* 2000).

Of interest to the present study are the topmost formations of the Kalahari Group (Holocene alluvium - about 65 Ma), as they are the ones covering the ground or sufficient depths that have an impact on housing and other township developments. The Kalahari Group consists of young sediments formed in arid to semi-arid conditions alternating with wet and dry phases, which can thus be distinguished from each other (Hipondoka, 2005). The Kalahari Group comprises of four (4) formations namely, the Ombalantu, Beisep, Olukonda and Andoni Formations, which are summarised in **Table 2**.

Table 2: The stratigraphy of the Kalahari Group (summarised from Miller, 1997).

Era	Sequence	Formation	Lithology	**Max.** thickness [m]
Recent to Tertiary	Kalahari Sequence	Andoni	white sand, light green clayey sand, green clay	550
		Olukonda	reddish brown, poorly sorted sand	152
		Beisep	red sand and clay	50
Cretaceous		Ombalantu	red semi consolidated clay	80

According to Mendelsohn *et al.* (2000), the formation of these soils is a result of mixed action between windblown sands and water-borne clayey sediments, which Miller (2008) referred to as repetitive climate change. For this reason, soil units clearly reflect the hydrological conditions and elevation gradient as seen in **Figure 13**. The soils in the Outapi area are generally sodic in low lying areas, whereas the other areas are covered by arenosols (typically quarzitic Kalahari sands) (Mendelsohn *et al.,* 2002). Sodic soils form due to high percentages of sodium ions and other soluble salts caused by the recurring cycle of flooding and evaporation (Blume *et al.,* 2010).

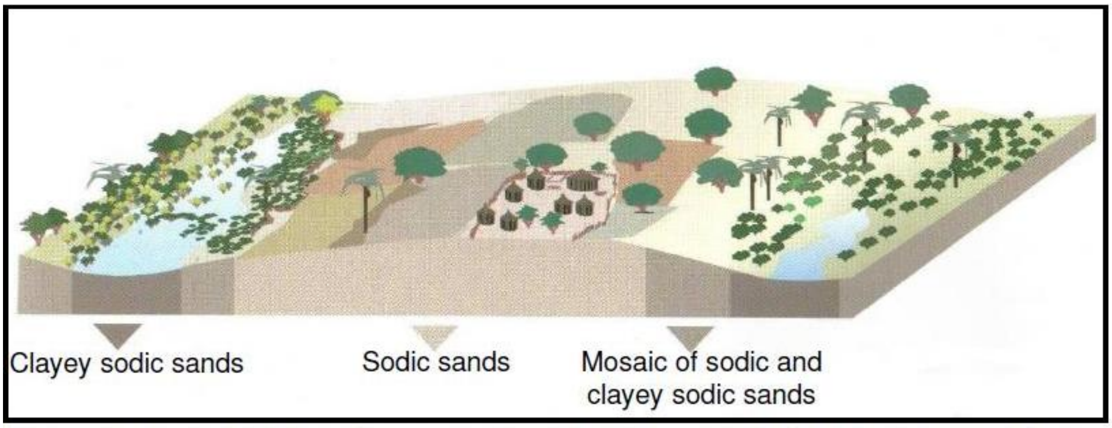


Figure 13: Characteristic soil patterns and land use taken from Mendelsohn *et al.* (2000).

5.2.1.1.3 Hydrology and geomorphology

North-central Namibia's hydrology forms part of the Cuvelai-Etosha drainage system, within the Cuvelai-Etosha Basin (CEB), which forms part of the bigger Owambo Basin. The Cuvelai-Etosha drainage system represented by red lines in **Figure 14** has catchments falling between those of Kunene River in the west and the Cubango/Kavango

River in the east (Mendelsohn *et al.* 2000). The Cuvelai originates from highlands of central and southern Angola, flowing southwards into Namibia and forming a massive inland delta that flows to Etosha Pan as seen in **Figure 14**, the lowest point of the basin (Mendelsohn *et al.*, 2000; Niipele and Klintenberget 2006).

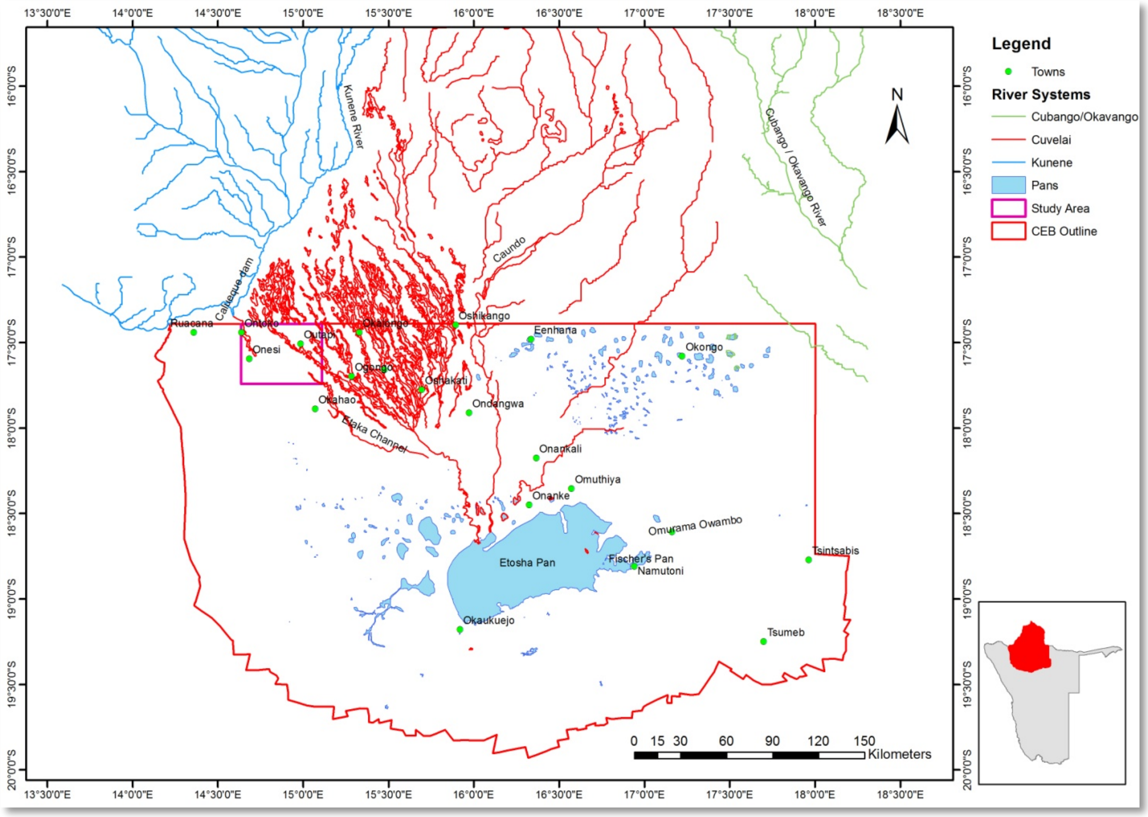


Figure 14: The Cuvelai- Etosha drainage system, and neighbouring Kunene and Cubango/Okavango drainage systems. From Mendelsohn *et al.* (2000).

Noteworthy from **Figure 14** is how the shape of the Cuvelai-Etosha drainage system is changing from proper streams in central Angola to interconnected water pans in southern Angola entering Namibia. This is primarily due to change in landscape from mountainous highlands in central Angola to a relatively flat terrain in northern Namibia, with no proper gradient to aid water flow. Consequently, instead of well-pronounced streams and rivers, northern Namibia has interconnected water channels or pans, which are static water bodies found at lower elevations, locally termed *iishana* (Niipele and Klintenberget, 2006). Persendt and Gomez (2016) have referred to them as unique series of anastomosing temporary shallow channels. The flow of water through these channels is largely dependent on water volume. This requires the individual water channels fill up to capacity and then overflow into the neighbouring channels (hence the interconnection), after which they flow towards Etosha Pan (the lowest point of the basin), as depicted in **Figure 15**.

The recurring flooding events recorded in the area are often a result of heavy rains occurring in Angola or good local rains experienced in the catchment. **Figure 15** is an image produced during the 2008 flooding event in the Oshakati area (one of the neighbouring towns of Outapi), showing interconnected water channels. According to Hayes *et al.* (1998), it is these seasonal flooding of the channels that recharges groundwater aquifers in the basin, further stating that the degree of recharge depends on intensity, volume, as well as duration of the floods. The average regional depth to ground water is estimated to be at close to 40 m (Mendelsohn *et al.* 2013).

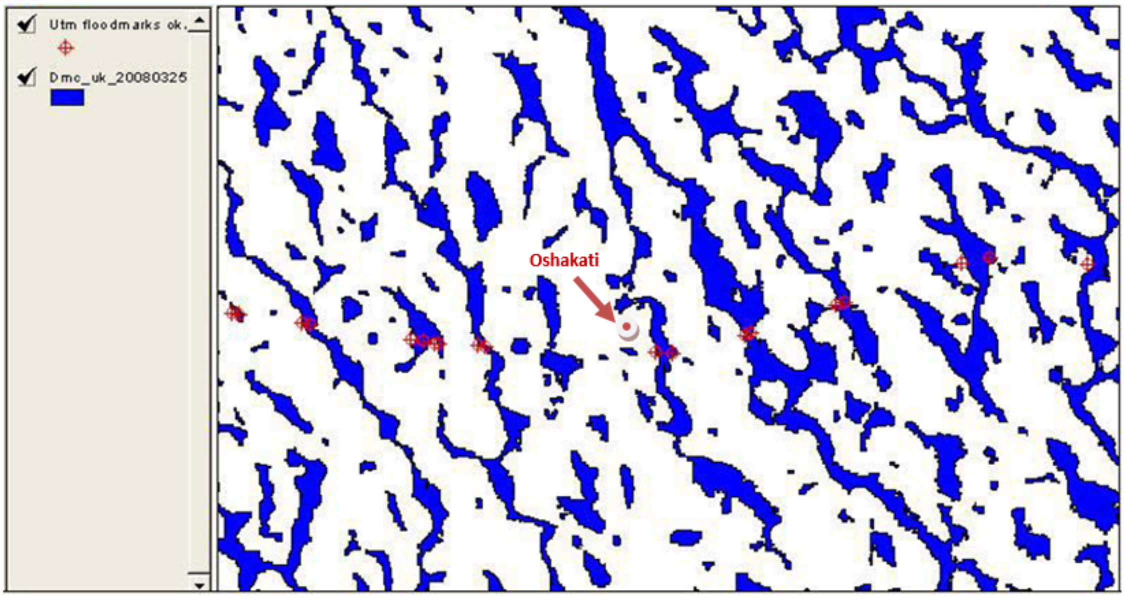


Figure 15: Interconnected water channels as identified from UNOSAT images (Flood Control Surveys, 2008).

5.2.1.1.4 Climate and vegetation

Outapi town falls within the western part of the Owambo Basin, which is characterised by semi-arid conditions as per rainfall figures, by Mendelsohn *et al*. (2000). The area has a hot and dry climate, with average annual rainfall ranging between 350 and 400 mm and average annual temperatures normally ranging between 26 and 30 degree Celsius (Mendelsohn *et al*., 2000; Niipele and Klintenberget, 2006). The area experiences rainfall in the austral summer months (December to April) when temperatures are highest (Persendt and Gomez, 2016). Due to the prevalence of summer rains, coupled with the sandy nature of the soils, much of the water is lost to evaporation or seeps into the soils (Hipondoka, 2005). The mean potential evapotranspiration exceeds the amount of rainfall by a factor of six, during the months of September to January reaching values up to 2500 mm/a (Mendelsohn *et al.,* 2000). The high evaporation rates lead to the accumulation of salts. The climate of the area is summarised **Table 3.**

Table 3: The climate conditions of the area are summarised below (Mendelsohn *et al*., 2000).

Conditions	**Classification**
Classification of climate	Semi-arid area
Average rainfall	300-550 mm per year.
Potential evapotranspiration	1960-2100 mm per year.
Average water deficit	1300-1500mm per year.
Average temperatures	More than 22° C per year.
Wind direction	Predominantly easterly winds

In terms of vegetation, the area is dominated by Savannah vegetation, covered mainly by hardwood vegetation, shrubs, and different grass species. As established earlier, the soils present in the area dictate the type and amount of vegetation. Blume *et al.,* 2010 noted that high salinity reduces the amount of plant available water due to high osmotic potential, making saline soils only suitable for specialised salt tolerant plants. The lowlands and wetter areas are covered by thick, long stretches of grass species and short shrubs, while the higher grounds between them are dominated by Mopane shrubs and trees (Mendlesohn *et al.,* 2013). Other plant occurrences include Acacia trees, baobab trees, jackal berry and marula trees, as well as Makalani palm trees, which Mendelsohn *et al.* (2013) has noted are more prominent in areas that are somewhat saline.

5.2.1.1.5 Present land use and socio-economic baseline of Outapi

Outapi is both a residential area and a place of business. It is the capital town and home to the regional office council, of the Omusati Region. The main infrastructures include a state hospital, a police station, post office, retail shops and several schools, which all together provide basic services not only to the Outapi residents, but also to the surrounding villages. Additionally, it has three (3) open markets, where the local community can sell their produce. It has both formal and informal settlements, both under the jurisdiction of the Outapi Municipality. Outapi also features some of Namibia’s tourist attraction sites including the famous baobab tree with a big trunk, which was previously used as a post office before independence and it is today proclaimed a national heritage site.

The most common activity in the surrounding villages is subsistence farming which involves mostly a mixture of large and small stock farming as well as growing crops. Crops produced include pearl millet (locally termed *Mahangu*), maize, beans, peanuts, melons, and sorghum. Animal farming includes poultry, goats, pigs, cattle and donkeys, which are used for meat production, however, large livestock can also serve transportation or ploughing purposes (Zandler, 2011). The set-up is such that the area used for growing crops is the one immediately around the homestead, usually fenced off to separate it from the woodland which is used for grazing livestock. Crop farming takes place without irrigation in these areas, which is why agricultural activities are planned to coincide with the rainy season (Mendelsohn *et al.,* 2000). It is also important to note that when it comes to township expansions, a change in land use is involved, whereby previous land owners in the surrounding villages are compensated to give land to Outapi Municipality.

5.2.1.1.6 Water infrastructure in the town

The town gets its water from the Calueque Dam in the Kunene River. This water is conveyed by the Calueque-Namibia canal to Ombalantu Purification Plant, where it is purified before it is distributed as tap water to the town and nearby villages. This concrete lined water canal was constructed during the early 1970s in line with the Water Master Plan of 1974 to provide water to all the townships between Calueque and Oshakati. This water canal runs just to the west of Outapi town, where it occurs as an open water source. For this reason, water obtained directly from the canal is used for irrigation and building as opposed to domestic use (human consumption). The surrounding villages also rely on ground water from shallow discontinuous perched aquifers which are exploited from hand dug wells as seen in **Figure 16**.

Figure 16: A hand-dug well tapping water from a shallow aquifer, used for watering livestock (Zandler, 2011).

5.2.1.1.7 Solid waste and waste water management

The solid waste produced by the town is collected on a weekly basis by truck and hauled to a waste disposal site located about 2 km south west of the township. Here, waste sorting is undertaken to separate recyclable waste from the rest, which is then burned. Sewage water from the town is pumped to the treatment ponds south of the township. Waste from septic tanks in the informal settlements is used in a green scheme community development project, where it is reused for agricultural purposes. The sewage water is put through a purification process that aims at recovering clean water for irrigation, solids or sludge which is dried and used as fertilizer for the municipal gardens, and finally, methane gas that is harvested from the purification tanks and used to generate power for the machines onsite. This project does not only avail jobs and vegetable produce to the local community, but it also allows sustainable use of water and energy in the town.

Outapi Town currently has an indicated population of 6600 according to the Namibia Housing and Population census (National Planning Commission, 2011). This number is subject to increase, and this will require further development and expansion of the town. Given the dependency of the village community on the town for basic needs such as medical services and others, a considerable rural to urban migration is expected. Furthermore, Outapi is one of the towns targeted by the national mass housing project discussed in Chapter 1. Outapi Town Council and Municipality also strive to transform the town into a preferred destination for investors and tourists. It is this endeavour, coupled with the town's growing population that call for proper planning of basic town services and utilities, which requires careful assessment of geotechnical and engineering geological conditions prior to development. This will also allow cost effective and maximum use of available land. After this desktop information was obtained, the mapping exercise continued as per the subsequent sections.

5.2.1.2 Terrain evaluation and Aerial photo interpretation

Terrain evaluation was done from coloured digital orthophotographs covering northern Namibia as flown in 2007 (the most recent available). These were obtained from the Ministry of Land Reform Namibia, Surveyor General's Office. Mapping on these photographs was done at a medium scale of 1:50 000 and more as recommended by Kleinhans (2002), which also falls within the 1: 10 000 and 1: 100 000 range recommended by UNESCO (1976). As established from the site description (geology, hydrology and geomorphology), the area is flat and has no obvious topographical features noticeable from the aerial photographs. Therefore, delineation of land facets was undertaken by visual assessment and interpretation of the mapping aids proposed for flat lying areas as discussed in **Chapter 4**.

5.2.1.2.1 Soil colour and texture variability mapping

As established in the earlier chapters, arid and semi-arid environments experience both extreme ends of temperature and precipitation. Consequently, the different soil colours, tones and textures can be related to soil origin, and could thus be set apart by visual analysis. Soils displaying different textures and colours were demarcated based on visual assessment. **Figure 17** shows how different soils were mapped. Boundaries between the different soil occurrences were labelled with solid lines or dashed lines to indicate degree of certainty, with the former being possible and the latter being probable. Considering that soil occurrences are a representation of past geomorphological and hydrogeological processes, it makes them good ground for understanding soil behaviour. Other features, such as water canals, were identified from their distinct shape, occurring as linear and smooth features.

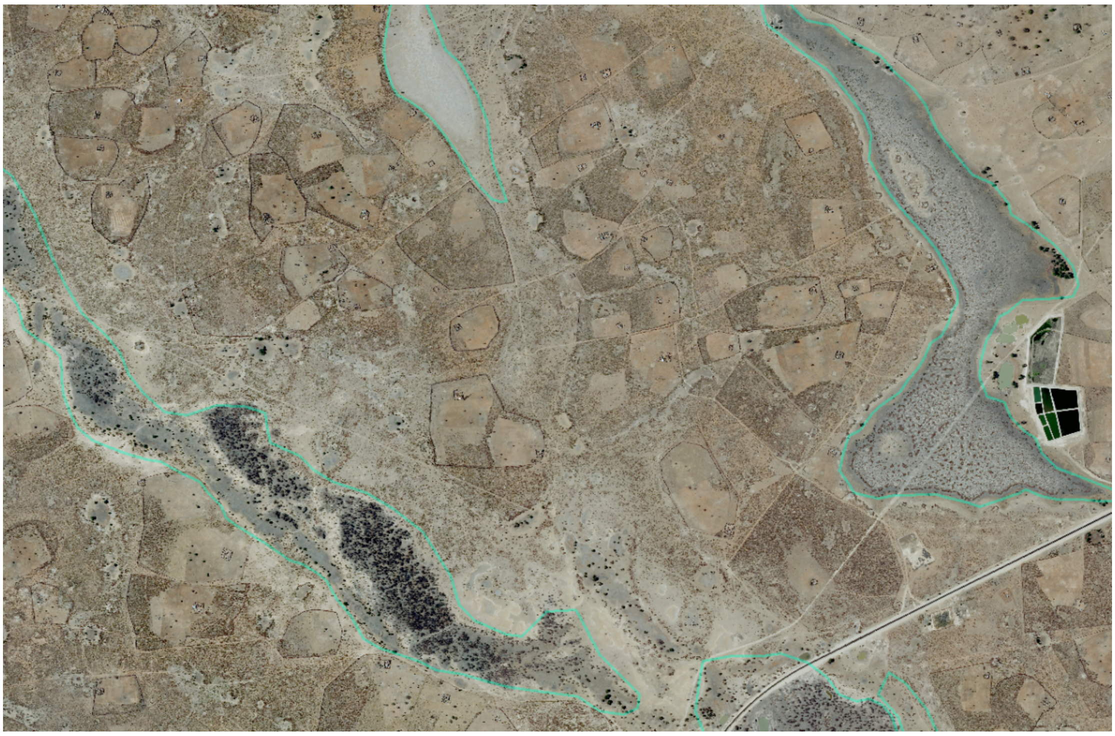


Figure 17: Mapping of different soil occurrences from air photographs.

5.2.1.2.2 Vegetation mapping

The technique of vegetation mapping was primarily applied to pristine areas of the town as opposed to those that have already been serviced for development. It has been established that vegetation in semi-arid areas respond well to moisture, and can therefore be used to map out water regimes that may not be readily visible on air photographs.

Vegetation mapping focused on vegetation occurrence, that is, the presence of vegetation in certain localities as opposed to others (see **Figure 18**) as well as vegetation distribution, focusing on patterns and arrangements (**Figure 19**). Vegetation occurrence and distribution are highly influenced by the availability of water, which therefore makes them good indicators of soil moisture content. Moreover, the indirect interpretation of vegetation as highlighted in Chapter 4 aids the identification of features that may not be readily visible on air photographs such as shallow groundwater regimes.

Figure 18: Mapping vegetation occurrence from aerial photographs.

Figure 19: Mapping vegetation distribution and patterns from aerial photographs.

5.2.2 Stage 2: Reconnaissance

5.2.2.1 Surface exploration and site walk-over

The site walk over was done to ascertain the boundaries between different environments or land facets that were identified during Stage 1 using soils, vegetation etc. Boundaries that were previously labelled as probable and possible were confirmed and upgraded to a higher degree of certainty. Furthermore, the site walk-over allowed assessment of accessibility of the sites proposed for boring and sampling. All sites were found to be fairly accessible by TLB (tractor-loader-backhoe), except in the vicinity of damaged properties due to confinement, in which case hand auger boring was implemented.

5.2.2.2 Structural damage distribution mapping

A structural damage distribution survey was also conducted during the site walk-over, whereby cracking buildings were recorded as well as other damaged properties in the township, thereafter producing a spatial damage distribution map. This was done to assess site performance based on existing structures, as well as to establish whether or not the damage is due to engineering properties of the underlying soils or structural defects.

At this stage, representative sites for boring and test pitting were selected and mapping traverses were planned so as to try and cover all the accessible land facets identified in the area. Test pitting and boring were planned in accordance to SAIEG (1997), with a minimum of three (3) test pits recommended per area of same geology and terrain (land facet). Selected sites for further investigation are presented in **Table 4**.

Table 4: The planned test pitting and auger boring sites.

Test pit/ Auger hole number	**Location**	**Land facet**
CM	Borrow pit	Borrow pit
Open excavation	Landfill	Land Facet 3
TP 01	Next to the landfill	Land Facet 3
TP 02	Water Treatment Ponds	Land Facet 3
TP 03	Oukwa Extension 13	Land Facet 3
TP 04	Green area	Land Facet 2
TP 05	Behind hospital	Land Facet 2
TP 06	Kamsele house	Land Facet 3
TP 07	Okalonda	Land Facet 1

TP 08	Onhimbu	Land Facet 1
TP 09	Municipal Gardens	Land Facet 3
TP 10	New School	Land Facet 3
TP 11	Next to NHE houses	Land Facet 1
TP 12	NAMWATER	Land Facet 1
TP 13	Next to water canal	Land Facet 2
TP 14	Regional Council office	Land Facet 3
TP 15	Anamulenge open space	Land Facet 2
AH 1	ERF 458	Land Facet 3
AH 2	ERF 549 (green house)	Land Facet 3
AH 3	ERF 656	Land Facet 3
AH 4	ERF 1675 (pink house)	Land Facet 3
AH 5	ERF 1061 (new house)	Land Facet 3
AH 6	ERF 593 (next to Baobab)	Land Facet 3
AH 7	Building next to the soccer field	Land Facet 3

5.2.3 *Stage 3: Detailed investigation*

The information obtained from Stages 1 and 2 of mapping was then supplemented by subsurface investigation. Activities at this stage were done as per recommendations from the previous stages, so as to obtain further information about the identified land units or facets. Two techniques were employed for material observation and description as well as profiling. These are augering with a hand held 1 m auger and test pitting by TLB as shown in **Figure 20**, and sampling was done in parallel.

Figure 20: The methodologies applied in studying material and profiling.

5.2.3.1 *Soil profiling*

Soil profiling entailed inspection and description of material. This was done in freshly excavated test pits that were opened using a TLB machine provided by the Outapi Municipality. The test pits were excavated in such a way that three sides were vertical and one side was cut at 45 degrees angle to allow access into the pits. Test pits were backfilled and reinstated immediately after investigation as a safety measure. Additional profile descriptions were done from auger boring, while others were described from open excavations close to the waste dumping site and in borrow pits where the town sources some of its construction material. Auger boring was implemented to depths of about 1.0 m while test pits reached a maximum depth of 2.3 m due to TLB competency. At each site, physical properties of soils were described in accordance to the MCCSSO method of describing soil profiles by Jennings *et al.* (1973) and SANS 633 (2012) as discussed in Chapter 3. A total of fifteen (15) test pits were excavated by means of TLB and seven (7) holes by means of hand augering.

5.2.3.2 *Sampling*

A total of 36 soil samples were taken from prominent soil horizons observed across the different land facets, of which 6 were undisturbed or block samples and a total of 30 disturbed samples (17 from test pits and 13 hand auger samples). Duplicate samples were also taken for geochemical analysis including x-ray fluorescence (XRF) and x-ray diffraction (XRD) analyses. Undisturbed samples were wrapped in layers of foil and secured with plastic covering to preserve the moisture content, while disturbed samples were put in sampling bags and secured with cable ties. Sample labels included the test pit number and the depth at which they were taken. The test pitting and sampling localities are shown on **Figure 21**.

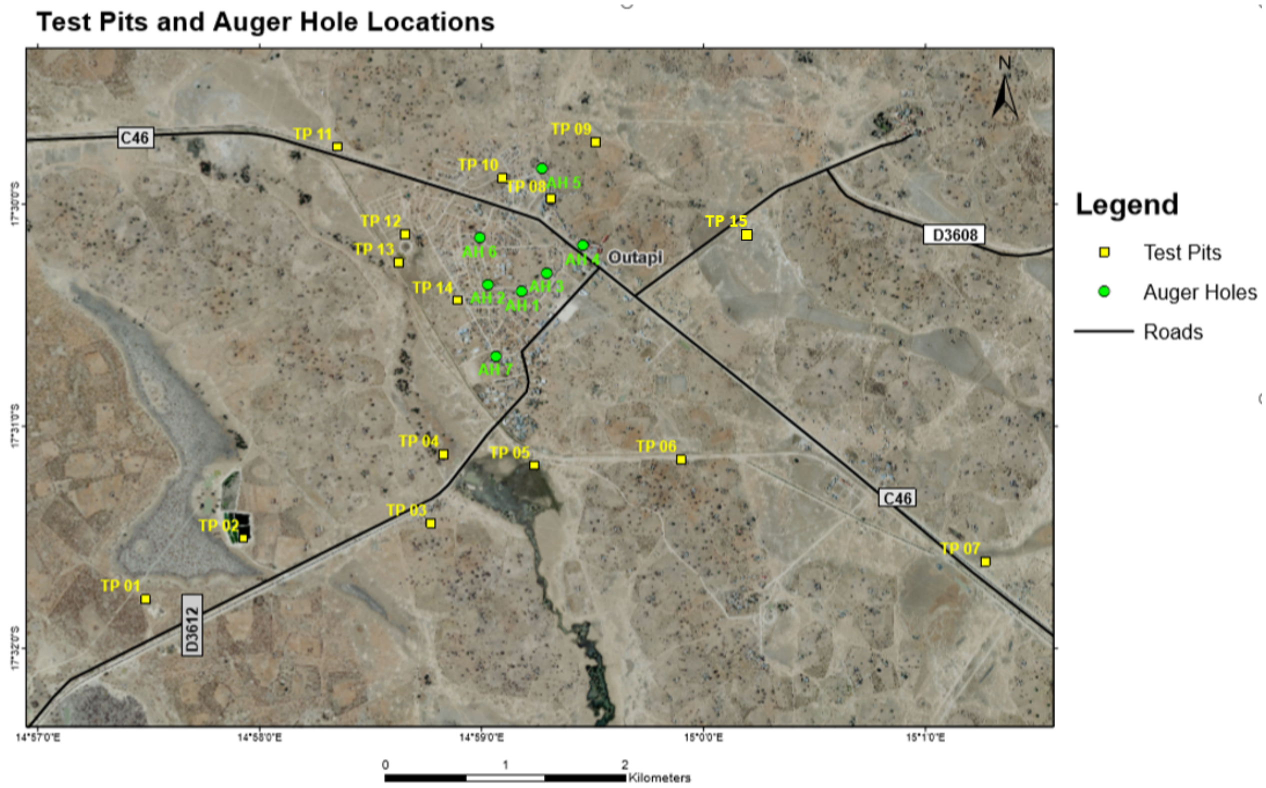


Figure 21: Sampling and test pitting localities around the town

5.2.4 *Stage 4: Laboratory testing*

The collected soil samples were submitted to Soillab commercial laboratory in Pretoria where they were analysed for different geotechnical properties. Tests performed include moisture content, grain size distribution, Atterberg limits, double oedometer for compressibility and collapse potential, triaxial tests for soil strength, as well as pH and electric conductivity (EC). Empirical formulas were used to calculate the hydraulic conductivity of the soils. Finally, for geochemical analysis, seven (7) selected soil samples were sent to the Geological Survey of Namibia for XRF and XRD analyses to determine their element and mineral compositions, respectively. A summary of samples tested is presented in **Table 5** below.

Table 5: A summary of samples tested and tests performed.

Sample ID	**Depth [m]**	**Sample type**	**Laboratory tests conducted**								
			PSD	**AL**	**DO**	**PE**	**pH**	**EC**	**SS**	**XRF**	**XRD**
CM1	6.30	Disturbed	✓	✓	-	✓	✓	✓	-		
CM3	10.00	Disturbed	✓	✓	-	✓	✓	✓	-		
TP02	0.93-1.80	Disturbed	✓	✓	-	✓	✓	✓	-		
TP03-1	0.35-0.65	Disturbed	-	-	-	-	-	-	-	✓	✓
TP03-2	0.65-1.80	Disturbed	✓	✓	-	✓	✓	✓	-	✓	✓
TP04	0.25-0.70	Disturbed	✓	✓	-	✓	✓	✓	-		
TP06	1.50	Block	-	-	-	-	-	-	✓		
TP08	1.00	Block			✓				-		
TP10-1	0.30-0.65	Disturbed	✓	✓	-	✓	✓	✓	-		
TP10-2	0.65-1.85	Disturbed	✓	✓	-	✓	✓	✓	-		
TP11	0.60	Block			✓				-		
TP12-1	0.30-0.50	Disturbed	✓	✓	-	✓	✓	✓			
TP12-2	0.50-1.50	Disturbed	✓	✓	-	✓	✓	✓			
TP13	0.50-1.28	Disturbed	✓	✓	-	✓	✓	✓			
TP14	0.60	Block			✓						
AH1-1	0.30-0.50	Disturbed	✓	✓	-	✓	✓	✓			
AH1-2	0.50-0.90	Disturbed	✓	✓	-	✓	✓	✓			
AH3-1	0.15-0.30	Disturbed	✓	✓	-	✓	✓	✓			
AH3-2	0.30-0.65	Disturbed	✓	✓	-	✓	✓	✓			
AH3-3	0.65-1.00	Disturbed	✓	✓	-	✓	✓	✓			
AH5-1	0.20-0.65	Disturbed	✓	✓	-	✓	✓	✓			
AH5-2	0.65-1.00	Disturbed	✓	✓	-	✓	✓	✓			
AH6-1	0.25-0.60	Disturbed	✓	✓	-	✓	✓	✓			
AH6-2	0.60-0.98	Disturbed	✓	✓	-	✓	✓	✓			

Key	
AL – Atterberg Limits	PE – Potential expansiveness
DO – double oedometer	PSD – Particle Size Distribution
EC – Electric Conductivity	SS - Shear Strength
XRD - X-ray Diffraction	XRF - X-ray Flourecence

5.2.5 Stage 5: Engineering geological classification and reporting

Results from all the previous stages were considered as input to determine the geotechnical merit of different engineering geological zones which were colour coded and presented on an engineering geological map. The following colours were adopted for present study:

- Green: for ground which is the most favourable or suitable for development, meaning they do not have geotechnical constraints
- Yellow: areas only suitable for development after precaution is taken. These have geotechnical constraints but can be overcome on a low cost
- Orange: indicative of moderate ground - areas suitable for development but have serious cost implications to make them favourable. This includes for instance areas that require expensive raft or pile foundations or that may require blasting during excavation.
- Red: corresponds to poor ground that is the least favourable or suitable for development. This includes land that is within the 1:100 year flood line.

5.3 Chapter summary

This chapter discussed the baseline conditions of the study area including its geology, hydrology, topography, climate, as well as the present land use. Owing to the flat nature of the area as noted from its geology (the flat deposited sediments of the Kalahari Formation), hydrology and topography, vegetation distribution and occurrence were used in conjunction with soil colour and texture variability to aid terrain mapping. A land facet map was then produced from this combination after which, auger boring and test pitting sites were predetermined to cover all land facets identified. A reconnaissance survey was then undertaken to confirm the land facets that were mapped from aerial photographs, and to assess accessibility of the identified auger boring and test pitting sites. A damage distribution survey was also undertaken to locate damaged infrastructure around the town and incorporate those sites in the investigation. During Stage 3, a detailed ground investigation was carried out whereby test pits were opened using a TLB provided by the Outapi Municipality. Fresh exposures allowed visual examination of material, profiling and sampling. A hand-operated auger was used for ground investigation in areas that were not accessible by TLB such as in the vicinity of cracked buildings. Disturbed and undisturbed samples collected during the detailed assessment phase were sent to Soillab (Pty) Ltd commercial laboratory for testing, so as to quantify different geotechnical parameters. The findings and discussion of results from this exercise are presented in the subsequent chapter.

6 CHAPTER 6: RESULTS AND DISCUSSION

6.1 Introduction

This chapter presents the findings of the engineering geological mapping undertaken as per field techniques outlined in **Chapter 5**. Results are herein presented in stages as acquired.

6.2 Stage 1: Terrain evaluation and Aerial photo interpretation

Terrain evaluation was successfully done using the techniques proposed for areas of homogenous geology, flat lying arid to semi-arid regions. Visual assessment and interpretation of aerial photographs enabled identification of different soils and vegetation occurrences, subsequently outlining different land facets as discussed below.

6.2.1 Soil colour and texture variability

Using variable soil colours and textures as a mapping aid, four different environments were identified. These were distinctively set apart by different colours and textures, as summarised in **Table 6**. Consequently, a soil colour and texture variability map was produced, and it is shown in **Figure 22**. The dark colours seen on the aerial photos could be areas with high moisture contents (Soil Category 2), while the lighter colours could be representative of well-drained soils with low moisture contents (Soil Category 1). Soil Categories 3 and 4 soils were observed to be relatively similar in terms of texture, however the Soil Category 4 were often enclosed in polygons and were more brown, which could be attributed to disturbance caused by cultivation.

Table 6: Different soil categories identified from aerial photographs.

Soil category	**Identification of soil category from aerial photograph**
Soil Category 1	Light grey to white, and smooth.
Soil Category 2	Dark grey with rough textures and occasionally smooth
Soil Category 3	Brown to greyish brown with rough textures, occasionally pale yellow to light grey
Soil Category 4	Brown, often enclosed in polygons

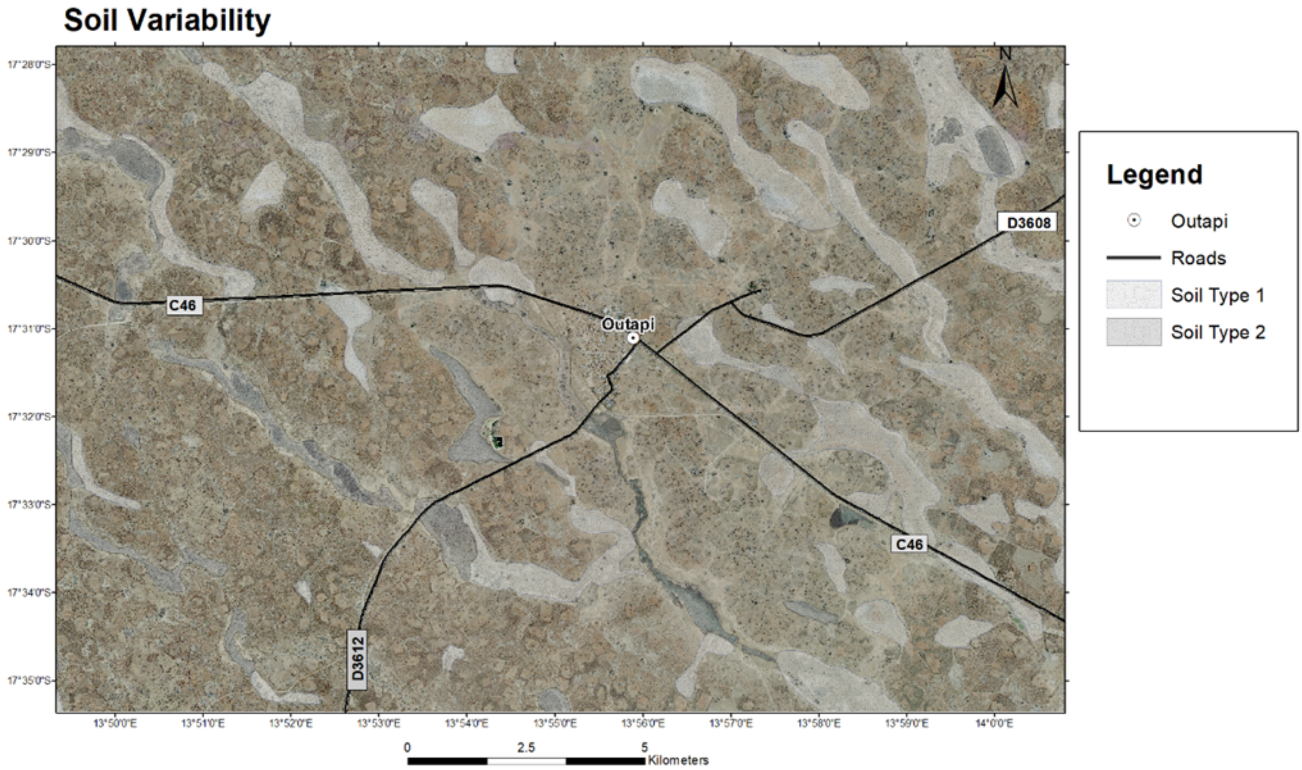


Figure 22: The soil map produced from aerial photographs.

6.2.2 Vegetation mapping

Different vegetation occurrence and patterns were mapped as a complimentary approach to support soil variability mapping. It was found that certain vegetation was associated with certain soil categories, as summarised in **Table 7**. This association is an indication that there is good correlation between soils and vegetation in the area, which makes vegetation a dependable mapping aid.

Table 7: A summary of vegetation in relation to soils identified.

Class types	**Soil identification from aerial photograph**	**Vegetation identification from aerial photograph**
Type 1	Light grey to white, smooth.	Poorly vegetated to no vegetation
Type 2	Dark grey with rough textures and occasionally smooth	Supports a lot of vegetation
Type 3	Brown to greyish brown with rough textures, occasionally pale yellow to light grey	Vegetated with shrubs and trees
Type 4	Brown often enclosed in polygons	Crops in cultivated areas (seasonal)

Both the presence of vegetation and absence thereof were useful guides to soil mapping. Light coloured soils (Soil Category 1) had little to no vegetation. The dark soils (Soil Category 2) were densely vegetated with very distinct vegetation patterns. Soil Category 3 had variable vegetation that had no particular orientation. Soil Category 4 (cultivated fields) did not have any vegetation at the time of the study; however, from local knowledge of the area, it is known that these areas are used for growing crops during the rainy season. Vegetation used as an aid to identifying land classes is shown in **Figure 23**.

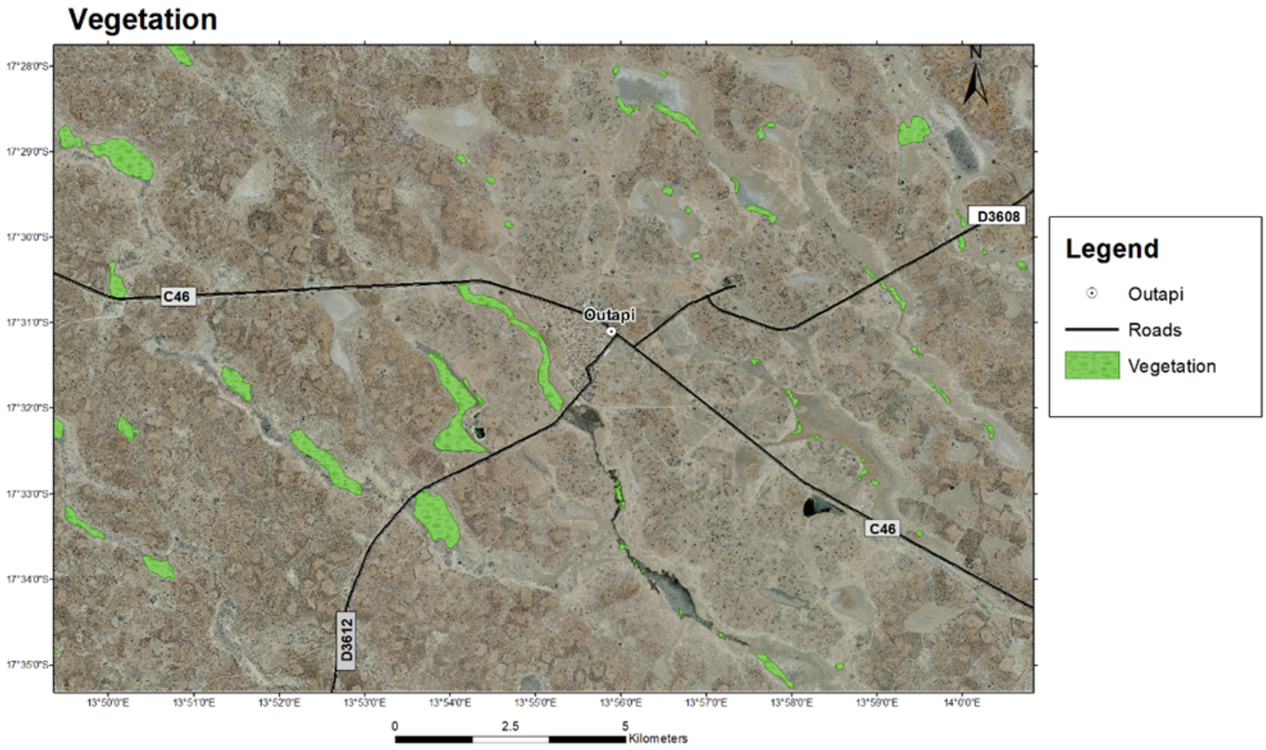


Figure 23: Vegetation map produced from aerial photographs.

A combination of soils and vegetation was then used to outline different land facets of the environment. These are discussed in detail, in the succeeding section.

6.2.3 Land facets identified from air photographs

Four (4) mapped zones were identified from air photographs, based on colour and texture of soils used in combination with vegetation distribution and occurrence. Although this was the case, these were narrowed down to only three (3) distinctive land classes or facets. Soil Category 3 and 4 were combined under one land facet, as they were deemed to be fairly similar in terms of soils, which means they are likely to have similar impact on engineering works. The brown colours on Soil Category 4 were said to be due to soil disturbance brought about by cultivation. The polygons seen on the aerial photograph enclosing these soils are actually fences and traditional homesteads meant to keep animals out of the cultivated fields. The identified land classes are therefore, Land Facet 1 with Category 1 soils, Land Facet 2 with Category 2 soils and Land Facet 3 hosting a combination of Soil Categories 3 and 4.

6.2.3.1 Land Facet 1

This land facet consists of Type 1 soils, which were identified from their light grey to white-colours with smooth textures. The lighter areas categorised under this land facet were observed to have little to no vegetation and the sparse vegetation occurring in this land facet is only found on the edges as opposed to the facet interior as shown in **Figure 24.** This could mean the soils present in the interior of this facet do not support vegetation.

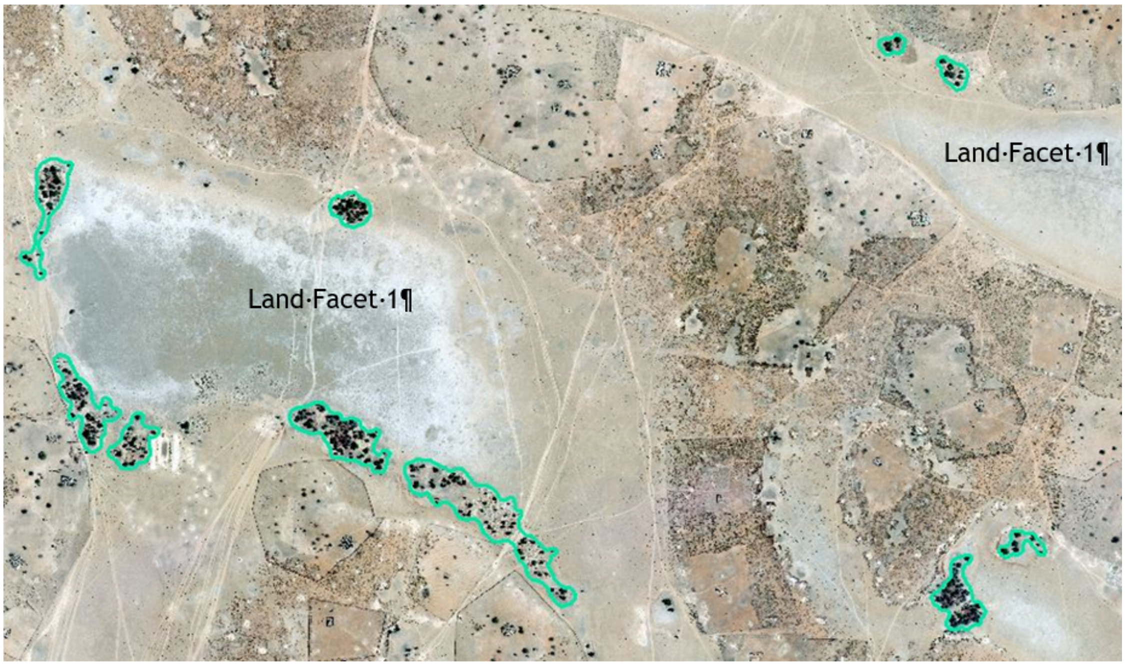


Figure 24: Land Facet 1 characterised by pale grey to white colours which could be accredited to presence of salts, therefore supporting sparse vegetation occurring on the edge of these facets as outlined in green.

6.2.3.2 Land Facet 2

Land Facet 2 consists of Type 2 soils which are characterised by dark grey colours. These areas host a lot of vegetation therefore appearing rough in texture. Occurrence of this land facet is shown in **Figure 25** as seen from air photographs at 1:50 000 scale. The dark colours could be due to poor drainage, which keeps the soils moist to wet. They also host a lot of vegetation.

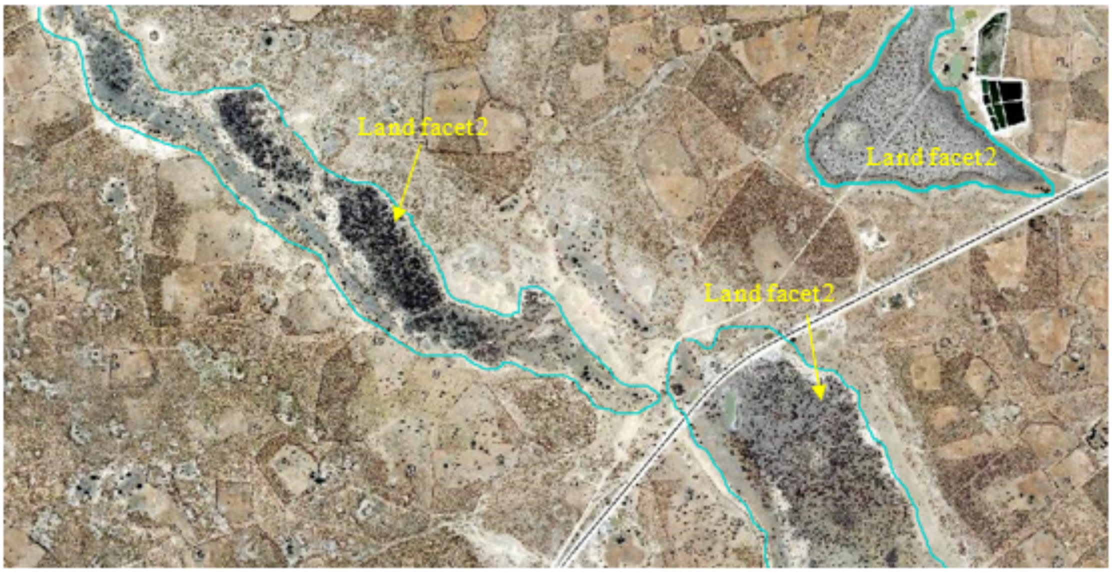


Figure 25: Land Facet 2, evident from its dark grey colours and rough texture outlined in green.

6.2.3.3 Land Facet 3

Land Facet 3 was found to be the most dominant environment, occurring in-between Land Facets 1 and 2, and hosting vegetation, which makes it appear rough. It has a combination of Soil Categories 3 and 4. The lighter colours on this facet can be attributed to the presence of well-drained soils and possibly the presence of dry vegetation. The brown coloured soils in Land Facet 3 identified in farmlands could be due to soil disturbance brought about by crop farming activities. An example of Land Facet 3 occurrence is shown in **Figure 26.**

Figure 26: Land Facet 3 with distinctive brown colours and polygons representative of traditional homesteads.

The different land facets were combined on a single map to produce a land facets map presented in **Figure 27** which would normally be achieved by using the land systems approach.

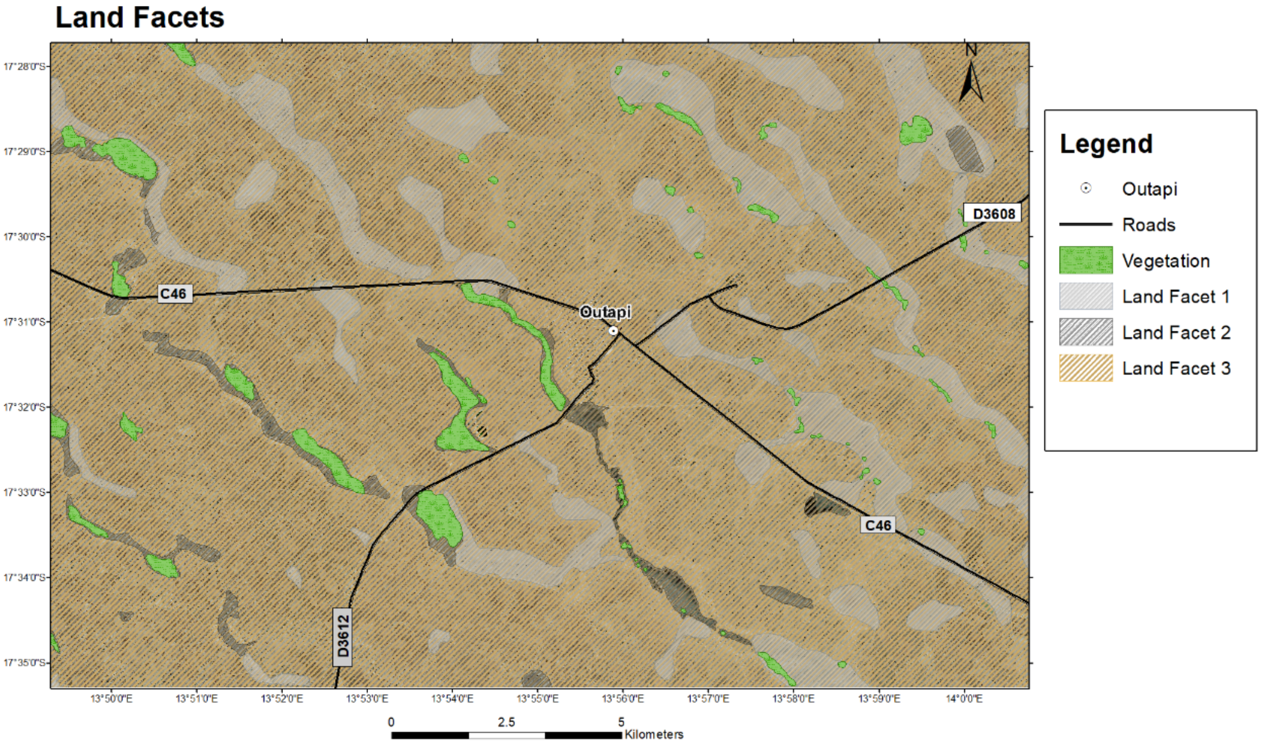


Figure 27: Land facets map as produced from aerial photographs.

As seen in **Figure 27** the orientation of the mapped land facets has NW-SE trend, similar to that of the paleaodunes occurring in the Kalahari sediments. This trend agrees with that of water flow, which could mean that some land facets are representations of drainage channels, identified from the different soil occurrences and vegetation. Land

Facet 1 forms part of the indefinite flow paths of water, and in some cases extension of Land Facet 2.

6.3 Stage 2: Reconnaissance

6.3.1 Site walk-over

The site visit revealed that in addition to difference in vegetation and soils, the land facets are also distinguished by small differences in elevation, which could not be picked up or was not noticeable from air photographs. It was found that Land Facet 3 was slightly elevated, in comparison to the surrounding facets. For this reason, areas falling under Land Facet 3 were herein referred to as highlands or high grounds. It was also noticed that most of the present development is taking place on highlands/Land Facet 3. Observations done during the site walk over are presented below, for the different land facets.

6.3.1.1 Land Facet 1

The smooth grey areas identified under Land Facet 1 correlated to dry pans. These were low-lying areas that had very little to no vegetation. At the time of observation, these pans were found to be dry with desiccation cracks observed in certain localities as shown in **Figure 28**. Desiccation cracks are a common response of clays to reduced moisture content with Day (1999) noting that the size of the cracks is determined by the degree of potential swell. Therefore, the general presence of desiccation cracks is an indication that there are clay-bearing soils on this facet. The presence of clays and other fine materials can be attributed to the flat nature of terrain, which dictates slow movement of water or low energy transport,.

Figure 28: The desiccation cracks found in Land Facet 1.

The presence of cracks in a soil mass can be concerning, especially given the potential effects associated with them, as noted by different researchers. Groenevelt and Grant (2004) noted that upon drying, the evaporation of soil water results in volume shrinkage and differential movement, which can cause damage to foundations, road embankments and other infrastructure. In agreement, Costa *et al.,* (2008) stated that desiccation cracking could have severely detrimental effects on the performance of clayey soils or generally of geomaterials in various engineering applications including road pavements, buried pipelines, dam cores, shallow foundations etc. Additionally, the presence of cracks in the soil can modify the transport process, as the cracks are now the preferred flow paths in the profile (Tang *et al.,* 2011), and this in turn also affects the hydraulic conductivity of that soil, increasing it by several orders of magnitude. Tang *et al.* (2011) further noted that these cracks also create weak zones in a soil mass, causing an overall reduction in mechanical strength.

6.3.1.2 Land Facet 2

The areas with darker shades that were identified from the air photographs as Land Facet 2 were found to be poorly drained pans as confirmed from the site visit (see **Figure 29**). These areas were found to be relatively moist and damp, and supported a lot of vegetation, most of which was green vegetation.

Figure 29: Some areas in Land Facet 2 that were water-logged and had green vegetation.

Wet clays form an impermeable layer which hampers infiltration, causing the water to stand for a while especially after the rainy seasons, which could be the reason why these areas are waterlogged. The presence of water makes these areas sensitive in terms of potential contamination of water by development.

6.3.1.3 Land Facet 3

It was noted from the field visit that the areas identified as Land Facet 3 from the aerial photographs were found to occur at altitudes higher than their surroundings. Differences in altitude were about 1-5 m. Although this could not be picked up from the aerial photographs, these differences in elevation play a big role in water movement and consequently, in the deposition of soils. Land Facet 3 was observed to be well vegetated with sparse grass, thorn bushes and trees with only green vegetation in some areas. This could mean that there are variations in soil moisture content within Land Facet 3. The dry grass observed in Land Facet 3 could be the reason for the pale yellow to light grey colours observed on the aerial photograph, as grass normally tends to have a high reflectance. Some of the brown agricultural fields identified from aerial photos occur in the immediate vicinity of the township. In such cases, landowners are usually compensated to give land to Outapi Municipality for township expansion. Therefore, it can be said that a change in land use is involved, whereby land that was previously used for agricultural purposes would henceforth be used for construction. This change ought to be taken into consideration during geotechnical investigations on the reclaimed land.

The observations done during site walk over are summarised in **Table 9**, adding to the descriptions done from aerial photographs. **Figure 30** shows a locality at which the three mapped land facets are coming together.

Table 8: A summary of land facets mapped, with added observations done during the site walk over.

Land Facet	**Identification using soils**	**Vegetation**	**Landscape observed**	**Drainage**
LF 1	Light to dark grey, smooth	Poorly vegetated to no vegetation	Low laying	Dry pans
LF 2	Dark grey with rough textures and occasionally smooth	Densely vegetated with green grass	Low laying	Poorly drained Wetlands
LF 3	- Pale yellow to light grey with rough textures - Greyish brown often enclosed in polygons	-Vegetated with dry grass, shrubs and trees -Crops in cultivated areas (seasonal)	Highlands Highlands	Well-drained Well-drained Soils disturbed by cultivation

Figure 30: One of the localities where all three land facets were observed. The land facets are demarcated by the green line. The variations in soil moisture content can also be noticed among the three land facets.

6.3.2 Structural damage distribution survey

A structural damage distribution map was produced at reconnaissance stage to indicate the spatial distribution of damaged infrastructures in the town. This was overlain with the land facets map, to establish if there is a relationship between structural damage and land facets. This map is shown in **Figure 31**. It can be seen from the map that all the damaged structures, that were mapped, indicated by the location of the auger holes are falling within Land Facet 3. A closer look into the cracks revealed two cracking scenarios as described below.

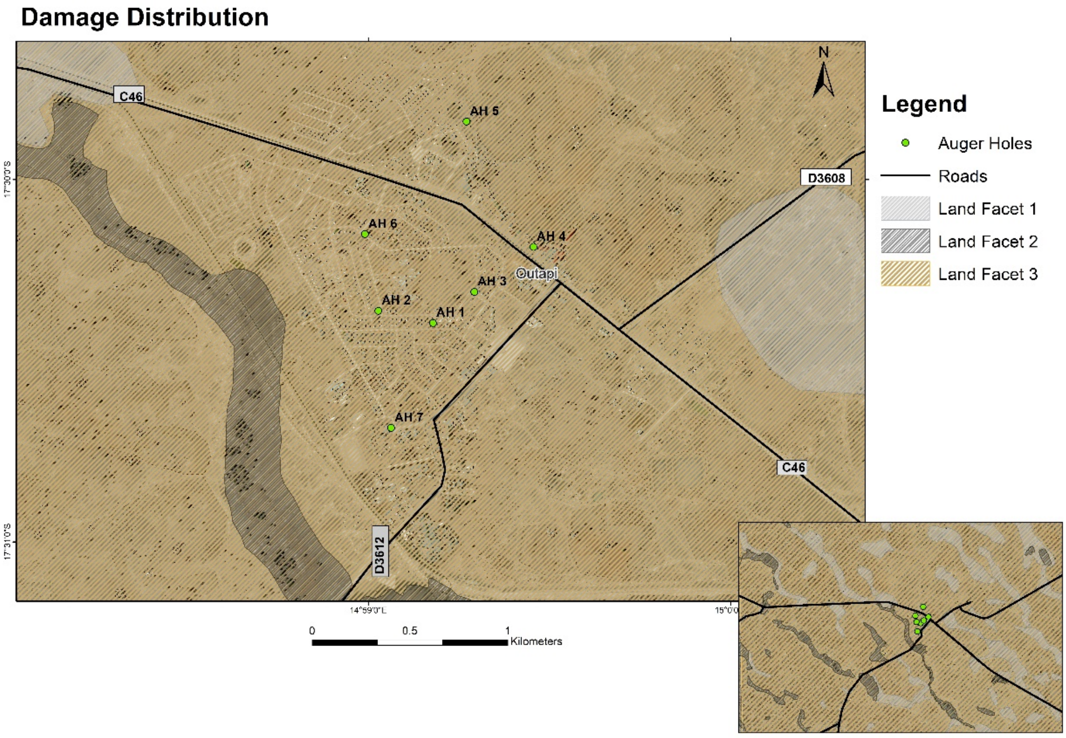


Figure 31: Spatial damage distribution around the town.

6.3.2.1 Scenario 1

In the first scenario, the cracks were occurring just anywhere in the buildings, with no particular preferred orientation as seen in **Figure 32**. Furthermore, some of these cracks were observed to widen towards the top of the building and were much thinner at the bottom as seen in **Figure 32A**. Widening to the top is a typical response to foundation movement, whereby the middle part of the foundation slab undergoes progressive and upward swelling, causing the walls to lean outward, as noted by Home Owners of Texas [HOT] (2009), who termed it doming. Alternatively, it could be that the edges of the foundation are undergoing collapse settlement due to localised inundation, which causes differential settlement, with only the ends of the building that are settling.

Figure 32: Cracking houses surveyed showing cracks with no particular orientation and in A, the cracks widen towards the top.

6.3.2.2 Scenario 2

The second scenario was observed to a lesser extent, whereby the cracks were associated with doorframes, window frames, or along joints in the building where walls meet (**Figure 33**). This scenario could also be a response to ground conditions, however, it is different in that the response is channelled along existing zones of weakness within the building structure, hence the orientation along the building joints.

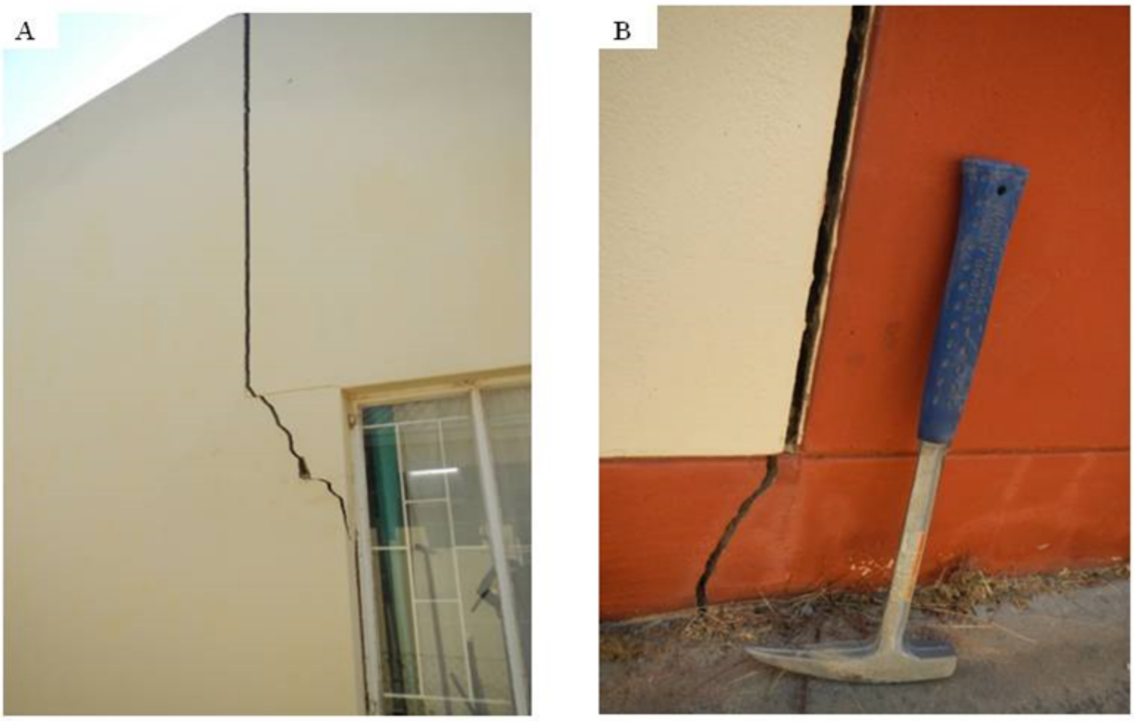


Figure 33: Cracking houses showing cracks occurring along the building joints.

6.4 Stage 3: Detailed ground investigation

For subsurface investigation, two techniques were implemented, namely hand auger boring, and test pitting, to expose fresh ground for soil profiling, observation and sampling. The findings are presented below.

6.4.1 Auger boring

Auger boring was employed for investigation of damaged structures as these areas were not accessible by TLB. Although previous phases revealed that all damaged properties were found on Land Facet 3, the auger profiles proved otherwise. It was discovered that although most of the town's construction was done on highlands, not all of it was natural ground. This was evident from the presence of imported orange red sand (**Figure 34**) that was interpreted to be backfilling material used to elevate ground prior to construction, so as to minimise water flow in these areas. This means, it could be the case that previously low-lying areas (i.e., Land Facets 1 and 2), which currently identify as Land Facet 3, were upgraded to usable land by backfilling. For this reason, it can be said that damage is not confined to Land Facets 3, suggesting that the cause of damage is not found in one particular land facet.

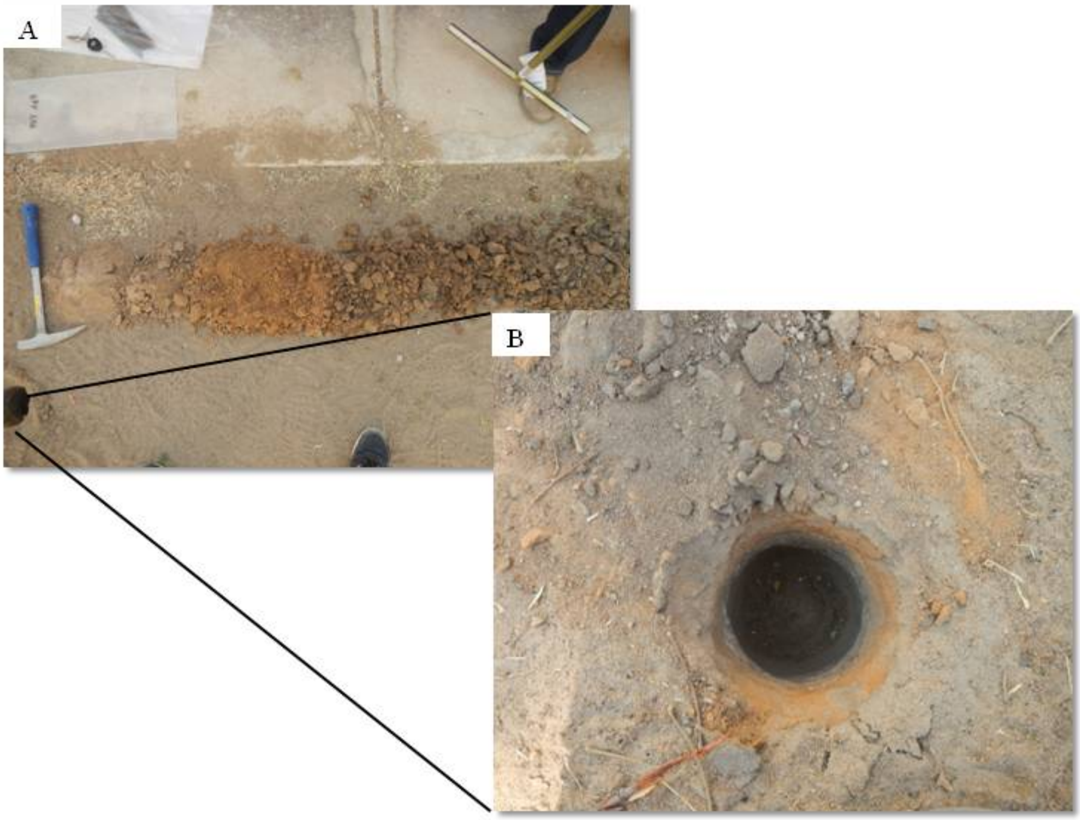


Figure 34: An auger hole in B was developed in the vicinity of a damaged house, showing the red imported sand. This auger hole was profiled, yielding the different soil layers shown in A, with a very distinct red layer of this sand.

The profiles from different auger holes are presented in **Table 9** below. The descriptions were however missing consistency, and structure components of soil description, as augering does not permit preservation of these two parameters. This is because the soils are already disturbed by the time they are brought to surface. The auger profiles are presented in **Appendix A**.

Table 9: A summary of auger holes profiled and the land facets they represent.

Auger hole ID	Depth [m]	Description	Land facet
AH 1 (ERF 458)	0.0-0.30	Dry, light brown to cream, sandy silt, Aeolian	Land Facet 3
	0.30-0.70	Dry, light brown to cream, sandy silt, Aeolian	
	0.70-1.0	Dry to slightly moist, brown speckled white, silty fine sand with friable calcrete gravels, Aeolian	
AH 2 (ERF 549)	0.0-0.20	Dry, cream, silty sand, Alluvial	Land Facet 3
	0.20-0.60	Dry, light brown to cream, sandy silt, Aeolian	
	0.60-1.0	Slightly moist, grey brown, silty fine sand with friable calcrete gravels, Aeolian	
AH 3 (ERF 656)	0.0-0.15	Dry, cream, sandy silt, Aeolian	Land Facet 3
	0.15-0.20	Dry, light brown to cream, sandy silt, Aeolian	
	0.20-0.40	Dry to slightly moist, orange brown, silty sand, Aeolian	
	0.40-0.80	Dry to slightly moist, brown, silty sand, Aeolian	
	0.80-1.0	Slightly moist, brown speckled white, silty fine sand with friable calcrete gravels, Aeolian	
AH 4 (ERF 1675)	0.0-0.20	Dry, grey to cream, clayey silty sand, Alluvial	Land Facet 3
	0.20-0.50	Dry, light brown to cream, sandy silt, Aeolian	
	0.50-0.65	Dry, orange brown, silty sand, Aeolian	
	0.65-1.0	Slightly moist, grey brown, clayey, silty fine sand with friable calcrete gravels, Aeolian	
AH 5 (ERF 1061)	0.0-0.15	Dry, light brown, silty sand, Aeolian	Land Facet 1
	0.15-0.30	Dry, orange brown, silty sand, Aeolian	
	0.30-0.70	Dry to slightly moist, brown, silty sand, Aeolian	
	0.70-1.0	Slightly moist, grey brown to cream, silty fine sand with friable calcrete gravels, Aeolian	

AH 6 (ERF 593)	0.0-0.40	Dry, light brown to cream, sandy silt, Aeolian	Land Facet 3
	0.40-0.70	Dry, brown to cream, sandy silt, Aeolian	
	0.70-0.90	Dry, brown speckled white, silty fine sand with friable calcrete gravels, Aeolian	
AH 7	0.0-0.25	Dry, orange brown, silty sand, Aeolian	Land Facet 1
	0.25-0.40	Dry, light brown to cream, sandy silt, Aeolian	
	0.40-0.60	Dry to slightly moist, orange brown, silty sand, Aeolian	
	0.60-1.0	Slightly moist, grey brown to cream, silty fine sand with calcrete gravels, Aeolian	

6.4.2 Test pitting

Test pitting was done in the different land facets to attain a minimum of three test pits per land facet. From the test pits, two main soil origins were discovered. These are silty sands of aeolian origin, which were the dominant soil type, and the clayey units (sandy clays and clayey silty sands) of alluvial origin, which were confined mainly to low-lying areas and drainage networks. A general occurrence of calcrete was observed throughout the area. Calcrete is a common indicator of semi-arid conditions, which represents existence of wet seasons and prolonged dry seasons, with high evaporation rates that result in calcium precipitation. Generally, moisture content was observed to increase with increase in depth, and seepage was encountered in some test pits. Profiles representative of the different land facets studied were described and observations are discussed below. Representations of the studied soil profiles were produced using Strater 4.0 software. These are shown in **Appendix B**.

6.4.2.1 Land Facet 1

Test pits in this land facet had two distinctive layers. The first 0.6 m of most profiles comprised of a grey medium dense unit, which was underlain by a brown to creamish yellow layer that had friable calcrete nodules. The first 0.2 m of the uppermost layer had white vertical streaks of about 10-30 mm thickness, as shown in **Figure 35**. These were interpreted to have been desiccation cracks that developed long after the rainy season in clayey sand dominated environments and subsequent dry periods allowed these cracks to be filled by windblown sands, producing white streaks as observed in these profiles.

Figure 35: A profile of Land Facet 1 showing white to cream streaks produced by infilling sand and friable nodules in the bottom part of the hole.

Additionally, some profiles also exhibited an accumulation of salts, including calcrete, gypsum (**Figure 36**) and halite, in decreasing order of abundance. The occurrence of calcrete was attributed to fluctuations in moisture content in the soils, whereas the occurrence of other salts such as halite were said to be due to high evaporation rates. This was aggravated by the presence of clays and other fine material, which leads to a high water retention capacity in these soils, causing surface water to be lost to evaporation other than to infiltration. The presence of salts in this facet could be the reason why vegetation is only found on the edge of the pans as opposed to the interior as noted from terrain evaluation. These salt contents lessen the soils' ability to support vegetation.

Figure 36: A soil lump with white gypsum precipitate (approximately 5 cm across).

6.4.2.2 Land Facet 2

Test pits in this land facet had three (3) distinctive layers. The first 0.2 m of most profiles comprised of a light grey layer that supported a lot of grass roots. Below it was a moist, intact, dark grey layer of very clayey fine sand, which was about 0.6 m thick, underlain by a creamish yellow, silty sand layer with calcrete nodules. This facet had the most calcrete nodules, which were observed to increase in abundance, size and hardness with progress in depth. Netterberg (1969, 1971), discusses two methods of calcrete formation, namely (1) deposition of carbonate in the host material above a shallow perched or permanent water table (groundwater calcrete); and (2) by downward leaching and deposition of carbonate from upper soil horizons by infiltrating rainwater (pedogenic calcrete). Considering the two calcrete forming processes, the calcrete in this land facet relates more to groundwater, however in this case, it is rather from perched than permanent water tables. Scholz (1971) described this calcrete type to form from deep soil formation (for soils that can keep their moisture for prolonged periods) or formed due to rising of groundwater by means of capillary action, in which case the former is true for soils in this land facet. The soil moisture content was also observed to increase with progress in depth, such that groundwater seepage was experienced in some test pits as shown in **Figure 37**. Seepage into test pits is an indication of shallow, perched ground water tables. Collapse of the sidewalls was also observed in such test pits, proving the weakness of these soils under high moisture contents.

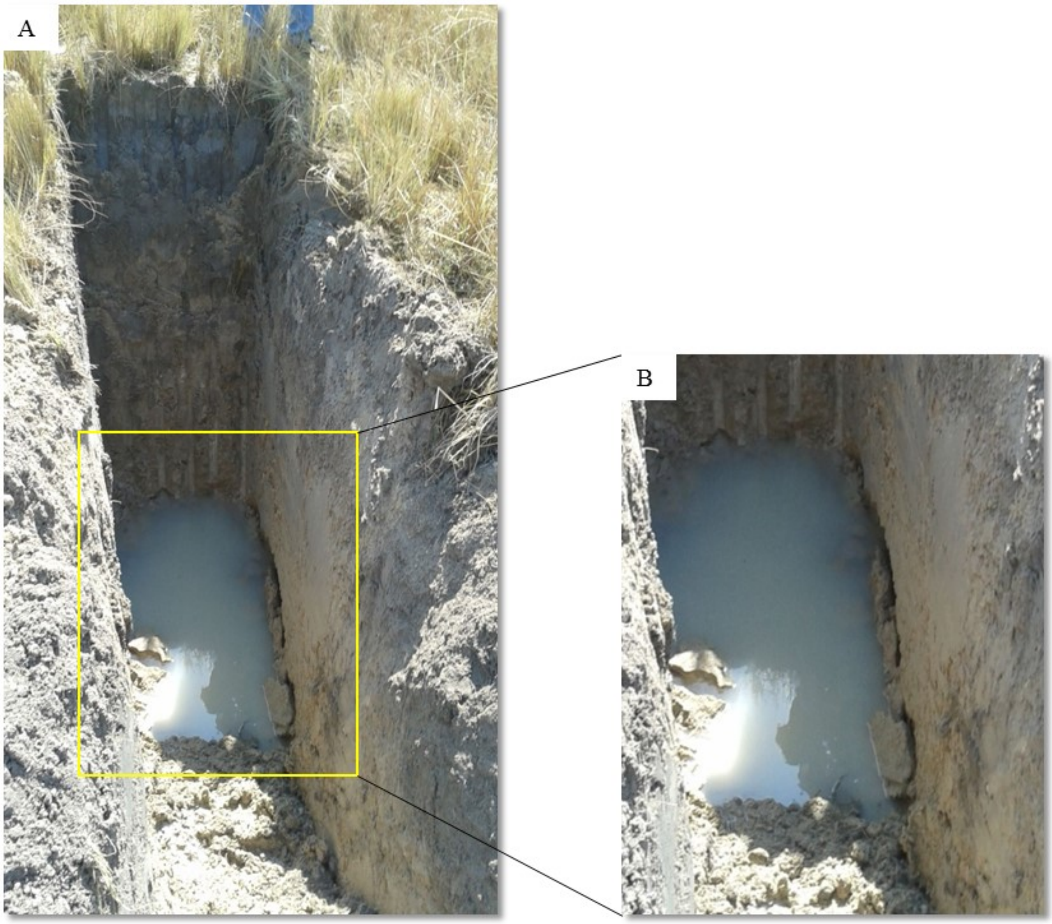


Figure 37: Test Pit 4 showing water that seeped into the pit in A and the collapsing sidewall in B.

6.4.2.3 Land Facet 3

Land Facet 3 had two representative profiles, depending on whether or not the area was developed. In both cases, a topsoil comprising brownish grey silty sands, which had grass roots, covered the Facet. However, the profiles described in the pristine parts of the municipal area had two (2) distinct soil layers; the dry, brown, medium dense, intact layer of silty sands, with maximum thickness of about 0.6 m, underlain by a slightly moist calcified silty sand, which was encountered from depths of 0.8 to 1.5 m and in some areas, until the end of the hole. An example of these test pits is shown in **Figure 38**. It was noted from these profiles that the calcrete was relatively minimal in comparison to the other land facets, which could be attributed to the low moisture contents of this land facet.

Figure 38: A test pit in the pristine area of the municipal land.

Profiles described in already developed parts of the town had an additional layer of red sand, as seen in the profile in **Figure 39**, which could be a remnant of the red windblown sand dunes that dominated the area during what Miller (2008) termed repetitive climate during Pliocene. However, because it was only observed in developed areas of the township, it was rather interpreted as imported material used in backfilling the area prior to development. The soils on this facet proved to be intact and occasionally pinholed, to slightly voided, which could potentially induce settlement.

Figure 39: Typical profile of developed areas of Land Facet 3 with red sand imported as fill material.

6.5 Stage 4: Laboratory test results

As previously stated, laboratory tests were done to give a general feel of the foundation indicators across the different land facets as opposed to getting values for designing. In terms of design parameter, this was also qualified by Kleinhans (2002), who stated that although undisturbed samples can be tested, it is not standard procedure for regional geotechnical mapping. For this reason, performance tests were only done on a limited number of samples and analysis for performance was only done based on development requirements for low-cost housing. The laboratory test results are found in Appendices C to I: Appendix C presents effective grain sizes attained from the sieve analysis, D hydraulic conductivity of the soils, E potential expansiveness, F XRF and XRD results, G calculations for bearing capacity, H Consolidation and collapse settlement and lastly Appendix I which gives electric conductivity and pH.

From the laboratory tests, the samples gave fairly comparable results, with only a few outliers. The one that was distinctively different was CM 3, which was taken from a borrow pit from which the town obtains its construction material. This borrow pit occurs some 15 km outside the township. However, at the time of sampling, the borrow pit was about 10 m deep and the sample was taken from the bottom of the pit. With this in mind, the properties of this sample that were distinctively different can be explained. Although this borrow pit is outside the research area, it was important to test the soils from there, to rule out the possibility of damage due to the quality of construction material.

Soils were classified according to the unified soil classification system (USCS) and most soils were categorised as SM or SC for silty sands and clayey sands, respectively. The laboratory results are discussed in detail below.

6.5.1 Index tests

6.5.1.1 Grain size distribution

Particle size distribution results obtained from sieve analyses and hydrometer tests are presented in **Figure 40**. It is evident from this depiction that all samples tested exhibit a fairly similar grading and the main constituent is sand. A few samples indicated considerable amounts of fines for example samples TP 04 and TP 12-2 with more than 20% clay. These samples were taken from Land Faces 1 and 2, which were identified as low-lying areas based on the site walk over. The sample CM 3 had a notably high percent of fines comprising about 45% clay. This could be explained by the sampling location, which is the interior of a local borrow pit. The borrow pit is an open hole (i.e. a low point), which makes it a target for sediment accumulation, whereby the coarse sediments are expected to settle first followed later by the finer material. For this reason, it is expected that fine grained soils are present at the lowest point of the borrow pit, where sample CM 3 was taken. Additionally, the amounts of gravel recorded for these soils were interpreted as calcrete nodules retained from the samples. This was also realised from the fact that most samples that recorded percent gravel were taken from the depths of the test pits where the calcified layer occurs, as per the soil profiles.

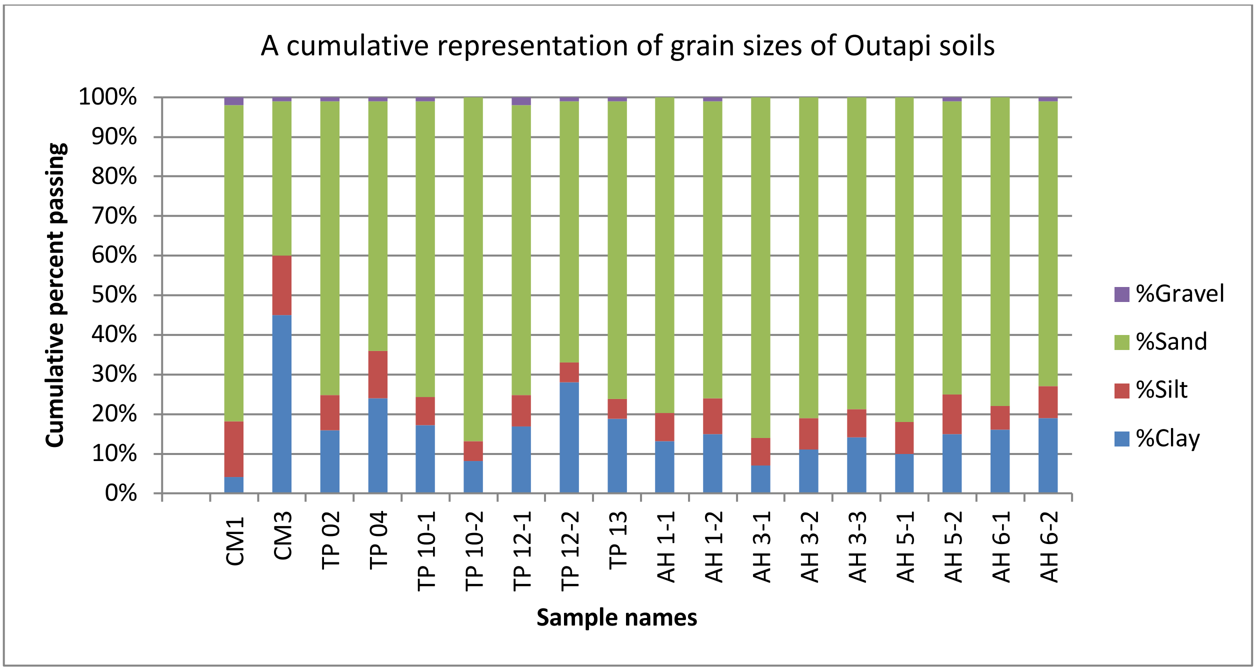


Figure 40: A cumulative representation of grain size distribution of Outapi soils.

Particle size distribution results were also plotted as cumulative curves in **Figure 41**.

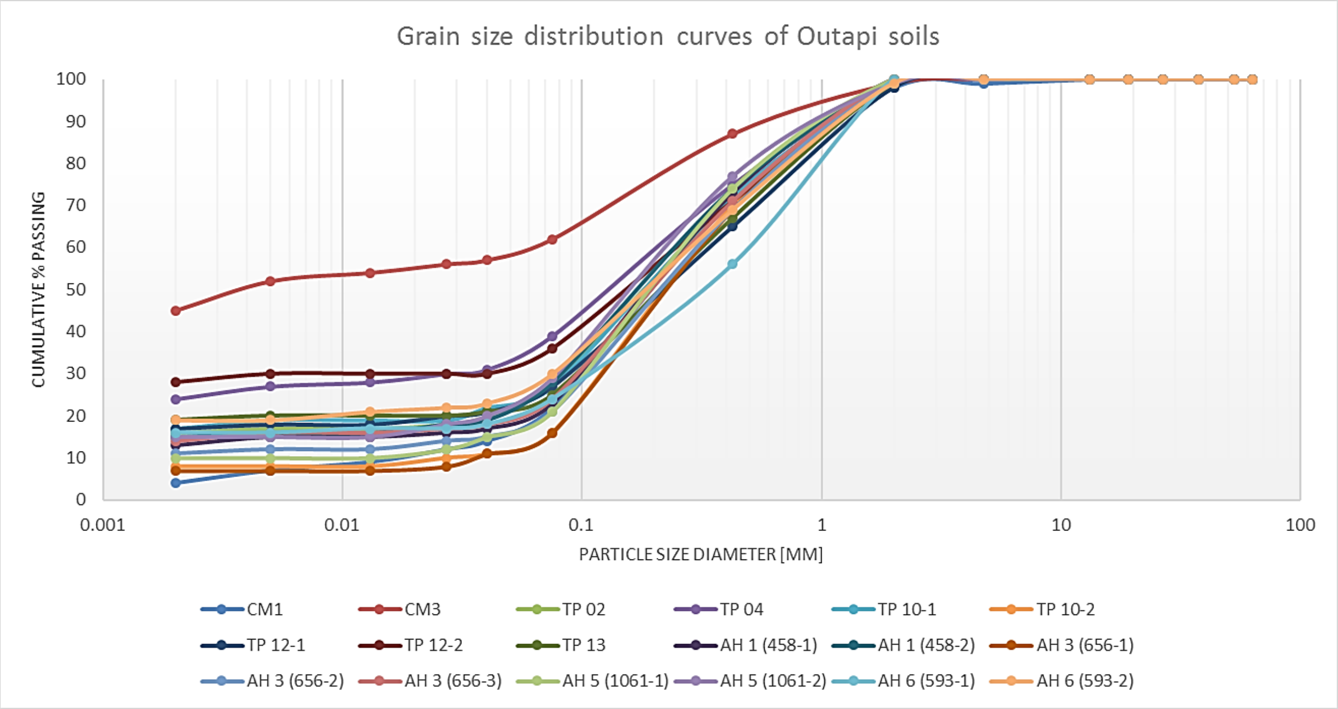


Figure 41: Particle size distribution curves of Outapi soils.

From the cumulative curves, the S-shapes are rather steep than flat, which according to Knappett and Craig (2012) would qualify these soils as poorly graded. The greatest percentage of these soils is falling in the sand fraction, causing a significant drop, which makes the curves steep.

Grading was also confirmed using the coefficient of uniformity (C_u) defined by Knappett and Craig (2012) as follows: $\mathbf{Cu = D_{60}/D_{10}}$, and coefficient of curvature (C_z) defined as $\mathbf{Cz = D^2_{30}/D_{60}D_{10}}$, where D_{10}, D_{30} and D_{60} represent the particle sizes corresponding to 10%, 30% and 60% passing on the distribution curve. These are summarised in **Table 10.**

Table 10: A summary of the coefficient of uniformity and coefficient of curvature of Outapi soils.

Sample ID	Coefficient of Uniformity (Cu)	Coefficient of curvature (Cz)	Grading modulus	USCS
CM1	15	1.9	1.08	SM
CM3	-	-	0.52	CH
TP 02	-	-	1.02	SC
TP 04	-	-	0.87	SC
TP 10-1	-	-	1.02	SM & SC
TP 10-2	11	1.6	1.15	SM
TP 12-1	-	-	1.09	SC
TP 12-2	-	-	0.94	SC
TP 13	-	-	1.09	SC
AH 1-1	-	-	1.05	SC
AH 1-2	-	-	0.99	SC
AH 3-1	9	1.3	1.15	SM
AH 3-2	-	-	1.10	SM & SC
AH 3-3	-	-	1.06	SC
AH 5-1	-	-	1.06	SM
AH 5-2	-	-	0.95	SC
AH 6-1	-	-	1.20	SM
AH 6-2	-	-	1.02	SC

Knappett and Craig (2012) refers to a soil as well-graded if $1 \leq \mathbf{C_z} \leq 3$ and $\mathbf{C_u} > 4$ (for gravels) or $\mathbf{C_u} > 6$ (for sands), else the soil is either poorly graded or gap-graded. Accordingly, only samples CM 1, TP 10-2 and AH 3-1 qualify as well graded, while the rest are poorly graded, with the exception of CM 3, which is well graded to almost gap graded, given its relatively low proportion of intermediate grain sizes. The generally poor gradation is because these soils are predominantly comprised of sand than other grain sizes.

In engineering terms, well-graded soils are preferred over poorly graded soils, due to their ability to be compacted into a dense mass. This is because, a mixture of different grain sizes allows interlocking of particles, resulting in minimum voids and a higher density, which can support heavy loads. The sample CM 1 (the red sand) displayed this quality because despite it being a sandy soil, it had a good composition of fines. This could be the reason why it was imported (from the borrow pit) as fill material to elevate Land Facet 1 and make it suitable for development. Poorly graded soils on the other hand do not possess this quality of interlocking, therefore would not attain maximum densities.

6.5.1.2 Atterberg Limits

Atterberg limits give an indication of soil behaviour at different moisture contents. Atterberg limits of the different soils are summarised in **Table 11**. With reference to the USCS values, soils were classified as either clayey sands (SC) or silty sands (SM) with an exception of CM 3, which was classified as CH representative of highly plastic clays. As expected, it was found that samples with high clay contents had a high liquid limit. Additionally, soils previously identified to be well-graded were found to be slightly plastic (SP) to non-plastic (NP), with insignificant values for plasticity index. This can be attributed to their low clay contents and variable grain sizes, which outweigh the ability of clay to behave in a plastic manner.

Table 11: A summary of Atterberg Limits of Outapi soils.

Sample ID	Liquid limit	Plasticity Index	Clay fraction of whole sample [%]	USCS	Linear shrinkage	Potential expansiveness (Van der Merwe, 1964)
CM 1	-	SP	4	SM	1.00	Low
CM 3	68	37	45	CH	16.5	Very High
TP 02	29	13	16	SC	6.0	Low-Medium
TP 04	42	23	24	SC	11.0	Medium-High
TP 10-1	28	7	17	SM & SC	1.5	Low
TP 10-2	-	NP	8	SM	0.0	None
TP 12-1	36	12	17	SC	5.0	Low
TP 12-2	51	24	28	SC	7.5	High
TP 13	31	16	19	SC	3.0	Medium
AH 1-1	24	12	13	SC	2.0	Low
AH 1-2	29	12	15	SC	5.0	Low
AH 3-1	-	NP	7	SM	0.0	None
AH 3-2	22	6	11	SM & SC	1.5	Low

AH 3-3	28	10	14	SC	3.0	Low
AH 5-1	-	SP	10	SM	1.0	Low
AH 5-2	28	11	15	SC	3.0	Low
AH 6-1	34	10	16	SM	4.5	Low
AH 6-2	36	17	19	SC	4.5	Medium
Key						
SP – Slightly plastic						
NP – Non plastic						

These values were plotted on the Casagrande (1932)'s plasticity chart (**Figure 42**), which relates plasticity index to liquid limit, to see how the samples plot relative to the A-line. It can be seen that samples most samples plotted below the A-line, which implies that they have more clay than silt. Although this is the case, only three (3) samples (CM 3, TP 04 and TP 12-2) had a PI above 20, of which only two (2) had a LL>50. A high plasticity index of a soil (usually indicated by LL>50) implies that the soil has a high chance of behaving in a plastic manner (for clays) or they are highly compressible (for silts).

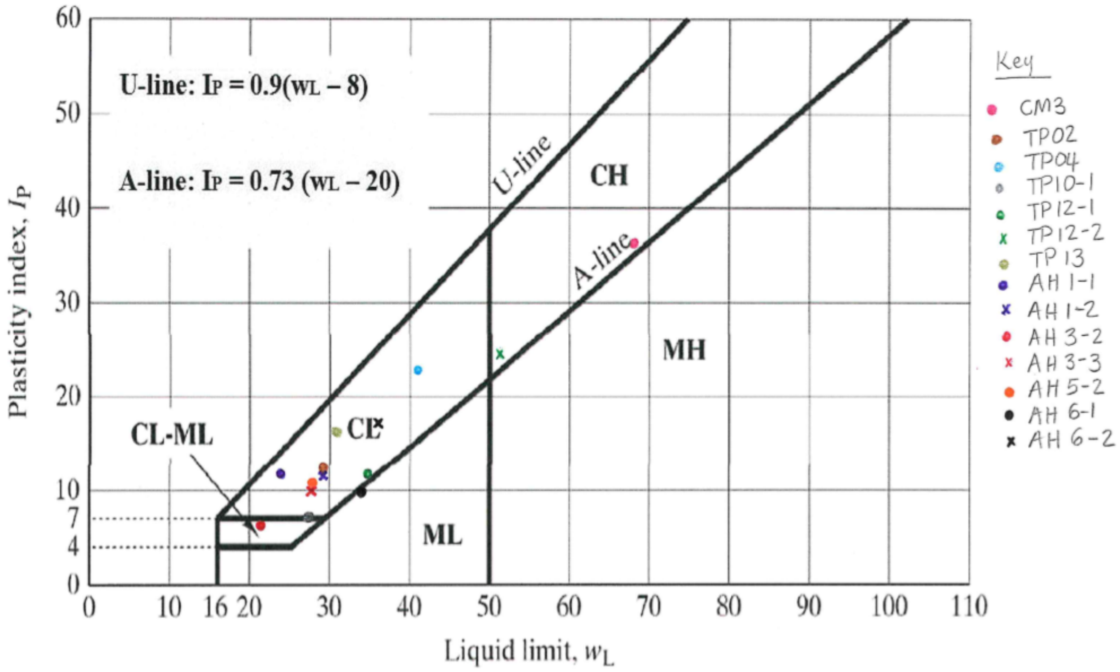


Figure 42: A plot of Outapi soils on the Cassagrande chart.

6.5.1.3 Potential expansiveness

The potential expansiveness of soils was deduced from their plasticity index plotted against clay fraction on the Van der Merwe (1964) activity chart, as illustrated in **Figure**

43. According to this chart, a plasticity index of less than 12% indicates an expected low expansiveness, medium expansiveness between 12% and 23% and PI>23% for high expansiveness. Although, most samples had low to medium expansiveness as seen on the plot, there were also samples that indicated high potential expansiveness. These are for example sample CM3 with very high expansiveness, and samples TP04 and TP12-2 also standing out with medium to high expansiveness. This expansiveness induce a volume change that can cause movement beneath the foundation of civil engineering structures, which could lead to cracking and distortion. Relative to the land facets, samples showing high to very high expansiveness were sourced from Land Facets 1 and 2, which had considerable amounts of clay

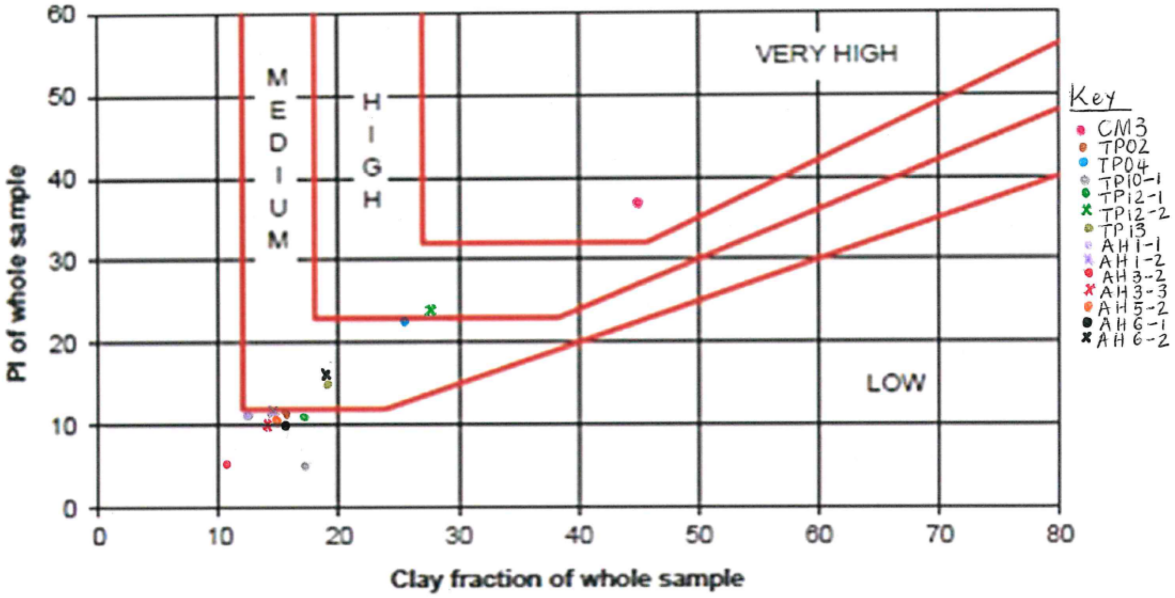
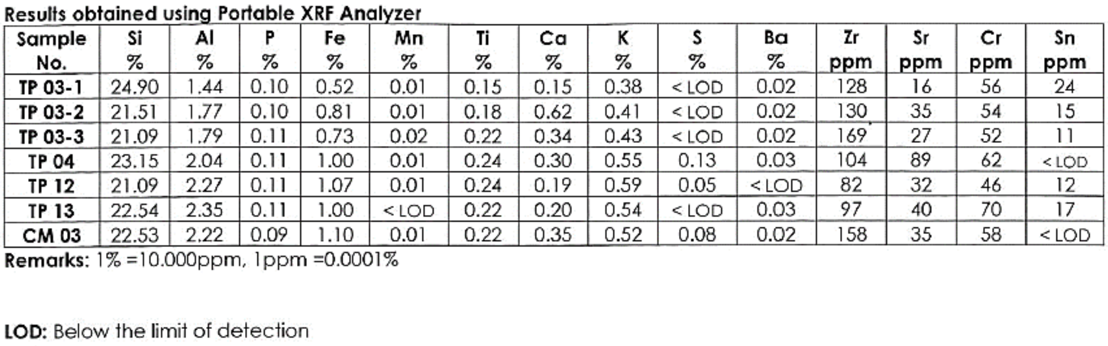


Figure 43: Shows potential expansiveness of different samples plotted on the Van der Merwe activity plot.

In addition to physical properties previously discussed, a soil's expansiveness can also be deduced from its chemical composition (Ardani, 1992). The XRD analyses conducted did not indicate distinct curves for expansive minerals, however it revealed that most samples consisted partial amounts of non-swelling minerals, such as quartz. Other mineral phases detected include Sanidine ($KAlSi_3O_8$) and Microcline ($KAlSi_3O_6$), which was present in some samples, albeit in low concentrations of usually less than 3%. Halite ($NaCl$) and Rhodium Amine Hydrogen Chlorate ($RhH(NH_3)5(ClO_4)_2$) were also found to be present with relatively low concentrations of 1.80% and 2.08%, respectively. From XRF analysis, all samples were predominately silica in content with considerable amounts of aluminum and iron. The lowest elemental concentration was sulphur, which was observed to be below detection limit in four of the seven samples analysed. The elements detected, in decreasing order of abundance are as follows Si>Al>Fe>K>Ca>Ti>Mn>P>Ba>Zr>Sr>Cr>Sn>S. The results of this analysis are shown in **Table 12**, while the XRD results of are shown in **Appendix F**.

Table 12: XRF results of Outapi soils.



Results obtained using Portable XRF Analyzer

Sample No.	Si %	Al %	P %	Fe %	Mn %	Ti %	Ca %	K %	S %	Ba %	Zr ppm	Sr ppm	Cr ppm	Sn ppm
TP 03-1	24.90	1.44	0.10	0.52	0.01	0.15	0.15	0.38	< LOD	0.02	128	16	56	24
TP 03-2	21.51	1.77	0.10	0.81	0.01	0.18	0.62	0.41	< LOD	0.02	130	35	54	15
TP 03-3	21.09	1.79	0.11	0.73	0.02	0.22	0.34	0.43	< LOD	0.02	169	27	52	11
TP 04	23.15	2.04	0.11	1.00	0.01	0.24	0.30	0.55	0.13	0.03	104	89	62	< LOD
TP 12	21.09	2.27	0.11	1.07	0.01	0.24	0.19	0.59	0.05	< LOD	82	32	46	12
TP 13	22.54	2.35	0.11	1.00	< LOD	0.22	0.20	0.54	< LOD	0.03	97	40	70	17
CM 03	22.53	2.22	0.09	1.10	0.01	0.22	0.35	0.52	0.08	0.02	158	35	58	< LOD

Remarks: 1% =10.000ppm, 1ppm =0.0001%

LOD: Below the limit of detection

6.5.1.4 Hydraulic conductivity

Different empirical formulas were used to estimate the coefficient of permeability or the hydraulic conductivity (*K*) of Outapi soils. These were computed in HydrogeoSieveXL, by inputting data obtained from grain size analysis. Where d_{10} values could not be obtained from the grading curves, effective grain size (d_e) was used. Fifteen (15) empirical formulae were used and the results of each formula per sample are shown in **Figure 44**.

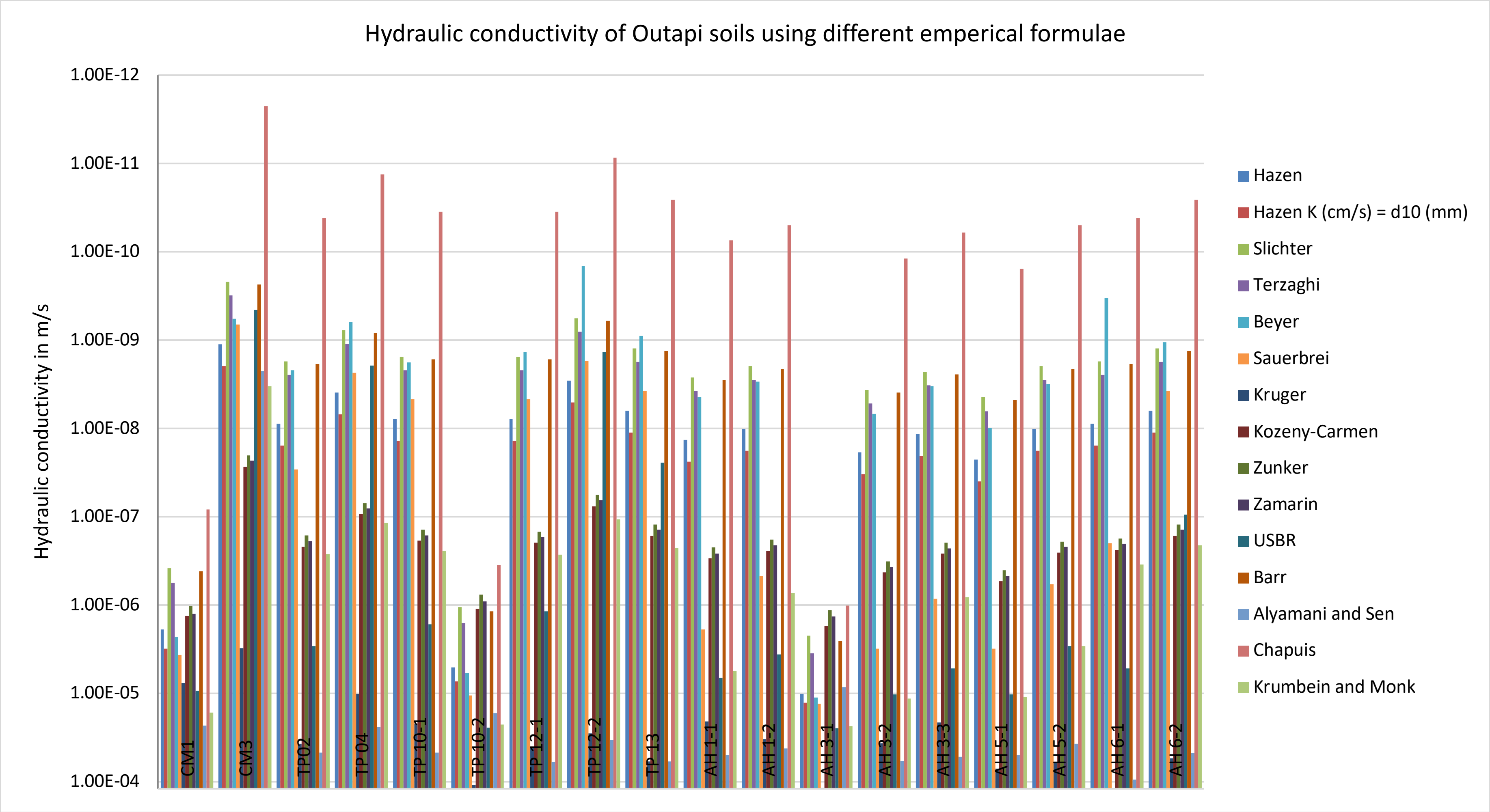


Figure 44: Hydraulic conductivity of Outapi soils, determined using different empirical formulas.

Out of the Fifteen (15) formulas that were used, three were within same order of magnitude. These are Zunker, Kozeny-Carmen and Zamari Methods. An average value of *K* was therefore calculated from the selected formulas, to come up with representative values for these soils. The results are summarised in **Table 13**.

Table 13: A summary of the hydraulic conductivity of Outapi soils.

Sample ID	**Estimation of Hydraulic Conductivity [m/s]**			
	Kozeny-Carmen	Zunker	Zamari	Arithmetic mean
CM1	1.319E-06	1.02E-06	1.257E-06	1.1987E-06
CM 3	2.704E-08	2.01E-08	2.312E-08	2.34202E-08
TP02	2.192E-07	1.637E-07	1.889E-07	1.90604E-07
TP 04	9.38E-08	6.997E-08	8.071E-08	8.14927E-08
TP 10-1	1.869E-07	1.398E-07	1.618E-07	1.62835E-07
TP 10-2	1.094E-06	7.662E-07	9.043E-07	9.21393E-07
TP 12-1	1.979E-07	1.475E-07	1.699E-07	1.71767E-07
TP 12-2	7.661E-08	5.679E-08	6.512E-08	6.6173E-08
TP 13	1.646E-07	1.225E-07	1.409E-07	1.42634E-07
AH 1-1	2.952E-07	2.227E-07	2.596E-07	2.59153E-07
AH 1-2	2.432E-07	1.82E-07	2.105E-07	2.11893E-07
AH 3-1	1.719E-06	1.139E-06	1.348E-06	1.40217E-06
AH 3-2	4.23E-07	3.19E-07	3.717E-07	3.71245E-07
AH 3-3	2.611E-07	1.964E-07	2.283E-07	2.28599E-07
AH 5-1	5.366E-07	4.043E-07	4.706E-07	4.70532E-07
AH 5-2	2.557E-07	1.908E-07	2.201E-07	2.2221E-07
AH 6-1	2.368E-07	1.759E-07	2.021E-07	2.04927E-07
AH 6-2	1.642E-07	1.221E-07	1.403E-07	1.42195E-07

As it can be seen from the mean *K*-values calculated, most of these soils have *K*-values of 10^{-7} m/s, which according to Yolcubal *et al.* (2004) and Domenico and Swartz (1960) is a typical K-value for clayey sands, indicative of moderate to low permeability. In comparison to the grainsize distribution data, it can be seen that low permeability values were associated with samples that had considerable amounts of clay. Although these soils were primarily sands, it could be that the clays and other finer particles filled the voids, which in turn lowers their ability to conduct fluids. However, Knappet and Craig (2012) discussed water viscosity as a contributing factor to low permeability, with primary influence of temperature, which is common in arid to semi-arid regions. The dominance of dissolved salts lower the viscosity of the water, consequently, causing low mobility. Individual samples that showed slightly higher K-values were mainly the voided wind-blown sands.

Soils with a low hydraulic conductivity have a low ability to conduct fluids, which makes them usable as filler material, and therefore commonly used in lining water retaining structures. Soils with high hydraulic conductivity on the other hand allow fluids to go through them. For this reason, they are normally avoided when siting structures such as cemeteries and waste disposal sites given the high potential of transmitting contaminants to groundwater.

6.5.1.5 The pH and electric conductivity of soils

Results of pH and electric conductivity (EC) were plotted as shown in **Figure 45** and as it can be seen from the figure, CM 3 displayed the highest EC, with a value greater than 1 S/m. Considering that it was taken from the bottom of a borrow pit, the high EC could be attributed to high salinity. Salts washed through the borrow pit were carried in solution to this lowest point, and once water is lost to evaporation, the salts are left behind to precipitate. Thus, it is expected that the highest concentration of salts is found here. According to criteria in Table C7 of the Council for Scientific and Industrial Research (CSIR) Report No BOU/R9705, a conductivity of >0.050 S/m is indicative of very corrosive material. Therefore, it can be said from the plot that most of the samples are corrosive, which makes them problematic to steel structures. Additionally, a high electric conductivity can be an indication of potential dispersion in soils, as it implies that the amount of salts can cause internal erosion.

It terms of pH, all the samples were of alkaline nature with pH values above 7, with only two exceptions (TP 10-2 and AH1-1) falling below 7, which is indicative of acidic conditions. A low pH is known to intensify corrosion, which again can be a concern when it comes to metals infrastructures.

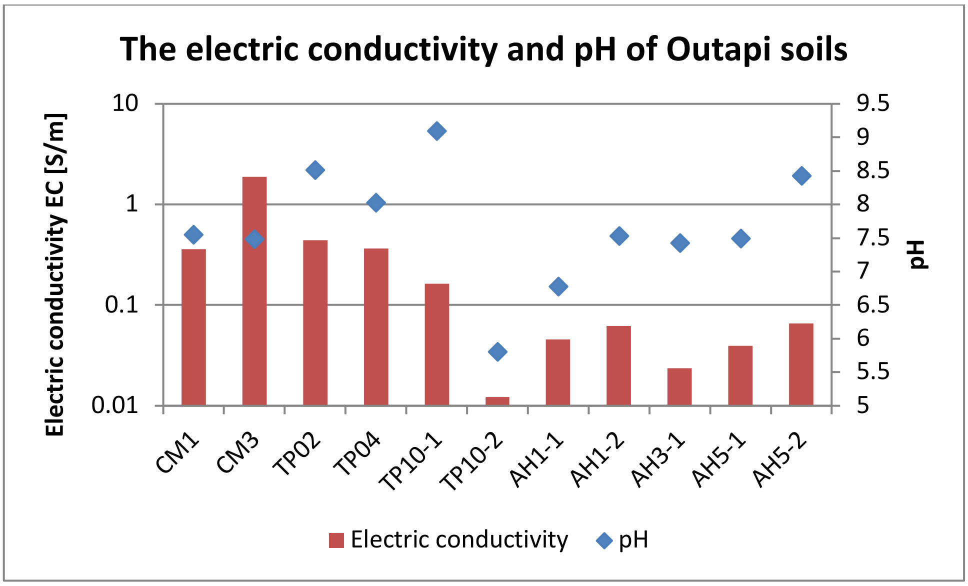


Figure 45: The pH and electric conductivity of Outapi soils.

6.5.2 Performance tests

Analysis and interpretation of performance tests was limited to single storey buildings, herein termed low-cost housing, as it is one of the biggest needs for the town. In addition, the test pits used in this study were excavated to maximum depths of about 2.3 m due to TLB capability. This depth is sufficient for low-cost housing as opposed to bigger developments, which may require soil investigations to go to greater depths. For this reason, subsequent calculations were tied to low-cost housing developments, where, for practical purposes, bearing pressures of up to 50 kPa were assumed for these houses.

6.5.2.1.1 Soil bearing capacity

Soil bearing capacity was calculated based on soil strength parameters (angle of internal friction (φ') and cohesion (c) values) obtained from shear strength testing. A shear box test was performed on sample TP 06 taken at 0.6 m, which is representative of the founding layer in Land Facet 3. The general equation for ultimate bearing capacity of strip foundations developed by Terzaghi (1943) was used and calculations are demonstrated in **Appendix G**. From laboratory results cohesion (*c*) of this soil was found to be 6.3 kPa (where the failure envelope cuts the Y-axis) with an angle of friction (φ') of 25.8˚ (the angle between the envelope and X-axis) as shown in **Figure 46**.

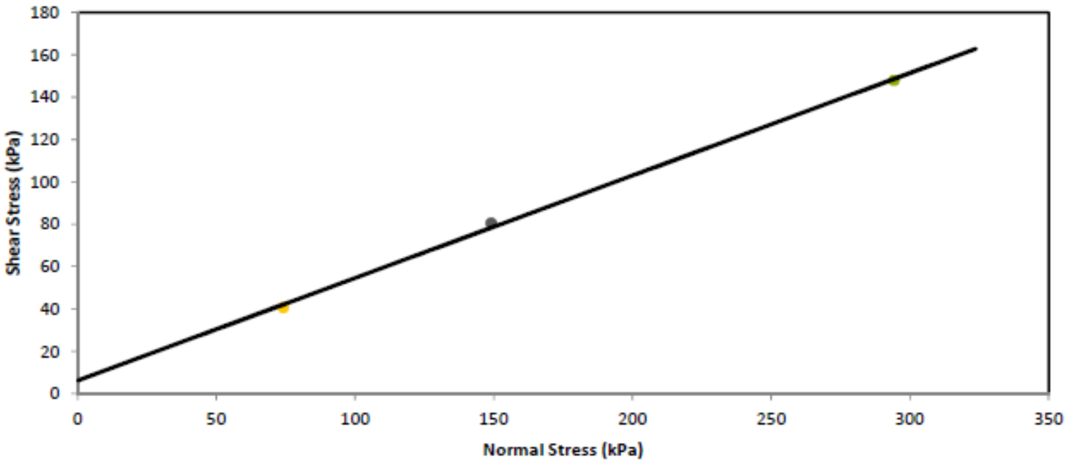


Figure 46: The failure envelope produced after three specimens of the sample were subjected to stress.

From the three specimen of this sample that were tested, the ultimate bearing capacity (q_u) of the founding layer was found to be 325 kN/m^2. Applying a factor of safety (FoS) of 3 to this value implies that the allowable bearing capacity (q_a) is 108 kN/m^2. This means a bearing capacity of up to 108 kPa is allowed, beyond which it becomes unsafe and shear failure may be experienced.

6.5.2.1.2 Consolidation settlement and collapse

The double oedometer results were used to determine both consolidation and collapse settlement. The amount of consolidation settlement expected was calculated at 50 kPa, to give an estimation of how much volume change can be expected as a result of compression of the soil by a single-storey building. The amount of volume decrease (consolidation beneath footing) was calculated, thereafter related to the width of foundation to get the magnitude of settlement. Similarly, collapse settlement was calculated based on the initial void ratio, to establish the amount of settlement induced by increased moisture content. In both cases, the Terzaghi and Peck (1948) method was used and the results are summarised in **Table 14** below.

Table 14: A summary of consolidation and collapse settlement.

Sample ID	**P_c [kPa]**	**P_o [kPa]**	**Status of consolidation**	**Δe_s**	**Δe_c**	**Settlement at unchanged moisture content [mm/m]**	**Collapse settlement [mm/m]**
TP 06 (1.5m)	21	27	Normally consolidated	0.01	0.025	6	15-

TP 08 (1.0m)	30	19	Over consolidated	0.015	0.02	9	12
TP 14 (0.6m)	12	11.64	Normally consolidated	0.006	0.048	4	32

The graphical reconstruction indicated that of the three (3) samples that were tested, two samples were normally consolidated. These graphs are shown in **Appendix H.** As seen in **Table 14,** sample TP 08 was over consolidated, as their P_c value was 1.53 times larger than P_o values. Moreover, the m_v values calculated for this sample falls in the over consolidation category of the Tomlinson (1980) table for values of coefficient of volume change. Seeing as this sample was taken from the township, it could be that the area was previously developed, such that the amount of load it was previously exposed to is heavier than the current overburden pressure. This means if a soil is over consolidated, there will not be much room to further compress it (i.e it will have a very low to low compressibility). The results revealed significant differences between consolidation settlement at natural moisture content and that brought about when material becomes saturated. This implies that material has a collapsible nature. For instance in the case of TP 14, consolidation settlement of 4mm/m of profile is expected and a further collapse settlement of 32mm/m, which could be experienced if material becomes saturated. This is about 3.2% settlement, which according to Zawada (2000) falls within the low settling potential class (i.e Col3). Although this is the case, care should be taken when it comes to induced moisture, especially when it is localised (for instance from broken sewer pipes), as it could result in differential settlement.

6.6 Stage 5: Engineering geological classification

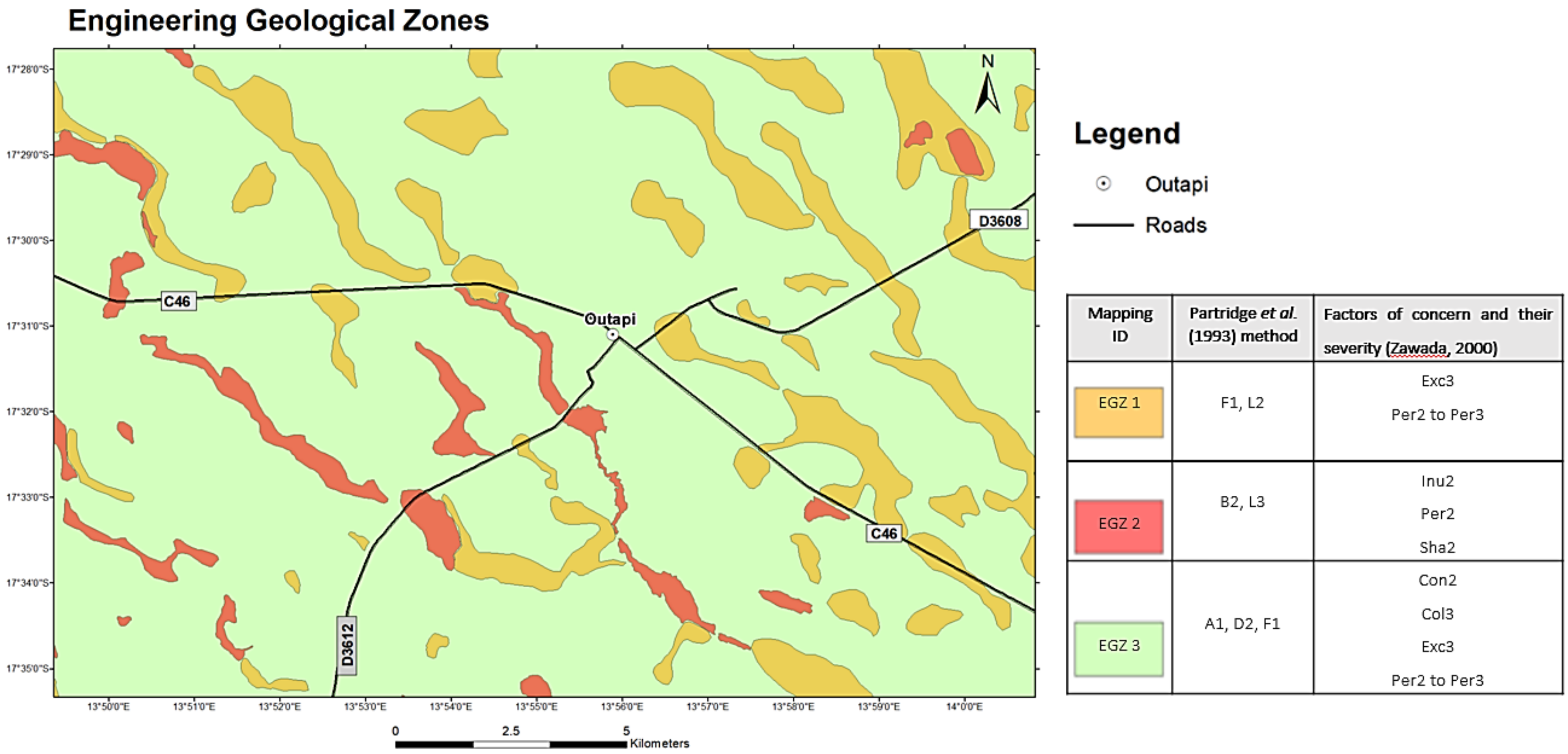
A combination of series of maps produced, along with subsurface investigation and laboratory test results, complimented by knowledge of the area, were used to produce an engineering geological map. The three (3) land facets that were identified, translated into three (3) engineering geological zones (EGZs), based on their potential impact on civil structures. These were colour coded to ensure that they are well understood by the wide range of professionals who would be using the map as a basis for planning. The colour choice was guided by suitability of these areas for development, with suitable areas in yellow green, moderately suitable areas in orange and non-suitable areas in orange red, as shown in **Figure 47**.. Both Partridge *et al.* (1993) and Zawada (2000) geotechnical classifications were used to summarise geotechnical constraints per EGZ. Geotechnical conditions and constraints established per EGZ are summarised in **Table 15** discussed in detail in the subsequent section.

Table 15: A summary of studied engineering geological zones and their geotechnical constraints.

Zone ID	**Colour code**	**Rating**	**General geotechnical constraints**	**Description**	**Justification**	**Suitability for development**
EGZ 1	Orange	Partridge et al. (1993) method	C2	Moderate soil heave potential predicted	Samples displayed medium to high expansiveness	Moderately favourable (can be improved)
			F1	Scattered or occasional boulders less than 10% of the total volume	Calcrete nodules here are friable	
			L2	Area adjacent to a known drainage channel or floodplain with slope less than 1%	Extensions of prominent water channels	
		Factors of concern and their severity (Zawada, 2000)	Act3	Low expansion	Samples displayed medium to high expansiveness. Presence of desiccation cracks	
			Exc3	Slight excavatibility problems	Calcrete nodules here are friable	
			Dis2	Soil is dispersive based on field observation	High salt contents and EC	
			Inu2	Area at risk of inundation	It is a low-laying area (extention of prominent water channels)	

			Per3	Medium permeability	Low permeability aided by desiccation cracks	
EGZ 2	Orange red	Partridge et al. (1993) method	B1	Permanent or perched water table more than 1.5m below ground surface	Seepage encountered at 1.92m	Least / not favourable
			C3	High soil heave potential predicted	Samples displayed high expansiveness	
			F1	Scattered or occasional boulders less than 10% of the total volume	Due to hard calcrete nodules	
			L3	Area within a known drainage channel or floodplain	Water channels	
		Factors of concern and their severity (Zawada, 2000)	Act4	.Moderate expansion	Samples displayed high expansiveness	
			Dis2	Soil is dispersive based on field observation	High salt contents and EC	
			Exc4	Moderate excavatibility problems	Due to hard calcrete nodules	
			Inu2	Area at risk of inundation	Low lying area (water channel) with clayey soils	
			Per2	Low permeability	Waterlogged area due to presence of clays	

			Sha2	Shallow water table is present	Seepage into the test pit experienced	
EGZ 3	Yellow green	Partridge et al. (1993) method	A1	Any collapsible horizon totalling to a depth of less than 750mm	Collapse calculated to about 320mm	Most favourable
			C1	Low soil heave potential predicted	Samples displayed low expansiveness	
			D2	Moderate compressibility expected	Due to voided soils	
		Factors of concern and their severity (Zawada, 2000)	Act2	Active or expansive soil present	Samples displayed low expansiveness	
			Col3	Low settling potential	Soils of Aeolian origin and displayed potential for collapse of about 3%	
			Con2	Area has poorly consolidated soils	Consistency of some soils ranged from loose to very loose	
			Per3	Medium permeability	Soils had some values in the range of 10^{-}	



Mapping ID	Partridge *et al.* (1993) method	Factors of concern and their severity (Zawada, 2000)
EGZ 1	F1, L2	Exc3 Per2 to Per3
EGZ 2	B2, L3	Inu2 Per2 Sha2
EGZ 3	A1, D2, F1	Con2 Col3 Exc3 Per2 to Per3

Figure 47: The Engineering geological map of Outapi.

6.6.1.1 EGZ 1

This zone is categorised by low-lying areas covered in clayey silty sands. These areas are known to hold water temporarily during the rainy seasons, after which the water evaporates leaving behind salts. This presents two constraints, namely: possibility of inundation (during the rainy season) as well as an increased salinity and possibly a high acidity, which can affect metal pipes, and concrete works. Additionally, the presence of salts makes these soils erodible and increase their potential for dispersion. Another geotechnical factor that was realised for this zone was the occurrence of desiccation cracks, which were interpreted to be a response of soils to loss of water. Presence of desiccation cracks could mean that there are expansive clays in the area, and as noted by Day (1999), the size of the cracks is determined by the degree of potential swell. This could also be seen from the results of potential expansiveness, as most samples falling in this EGZ displayed low to medium expansiveness. Desiccation cracks can cause a reduction in the mechanical strength of soils. However, considering that the desiccation cracks were not deep and often confined to the first 20-30 cm of the profiles, it can be said that soils will not experience large volume changes and will not for that reason adversely impact civil structure. The calcrete nodules observed in this zone were friable and would not affect excavatibility.

These areas were given an orange colour for moderate suitability, which means they cannot be used in their present state, however can be improved to make them usable. The soil layer affected by desiccation cracks can be scrapped off to expose a fresh soil layer. Other improvements can include back filling to replace the expansive layer that has been removed, and to elevate ground prior to construction. Water diversion systems can also be applied so as to create new pathways or confine the water to the old paths.

6.6.1.2 EGZ 2

This zone is characterised by low-lying, swampy, poorly drained and often water logged areas, that contain inundated soils, dominated by clayey sands and sandy clayey soils. These are the preferred pathways of water and care should be taken not to encroach or cause any obstructions to these channels as this will increase the risk of flooding when the water sidetracks to establish new pathways. Samples from this zone indicated a high to very high activity rating, which means a large change in volume (high expansiveness) can be expected when a change in moisture content occurs. Additionally, the presence of perched and shallow perched water tables in these areas makes them sensitive to contamination. For this reason, developments such as waste disposal sites, cemeteries and sanitation systems should be sited well away from these areas. Some soil samples in this EGZ displayed high salinity, evident from high EC values, which makes them susceptible to erosion and dispersion. Sidewall collapse was experienced in Test Pit 04 falling under this EGZ. This is evidence of unstable ground and collapse happen when there are high moisture contents. This EGZ also had a high occurrence of calcrete nodules, which were observed to increase in abundance, size and hardness with progress in depth. This could pose excavatibility problems and wearing out of excavating machinery.

For the above-mentioned reasons, these areas were given an orange-red colour on the engineering geological map, suggesting that they are the least favourable for development and it will be costly to make them usable for urban development.

6.6.1.3 EGZ 3

This zone covers majority of the mapped area. Soils in this zone were mostly silty sands that were dry to slightly moist. However, from the field investigation the layers of aeolian origin were found to be pinholed and occasionally voided and in terms of consistency, some profiles had loose to very loose soils. These open textured soils are generally susceptible to consolidation settlement, which brings about volume decrease. Therefore, these soils should be compacted prior to construction, so as to overcome this grain structure, close up the voids, which in turn increases their density, thereby allowing them to carry large loads. This reduces the possibility of consolidation settlement. Additionally, the potential for collapse settlement of 32 mm/m as calculated from sample TP 14 (which is about 3.2% of the founding layer), falls within the low settling potential class. Watering during compaction is advised to overcome this collapsible structure. In terms of excavatibility, the zone is easily excavatable, as it has loose sands and would not require power tools for the installation of underground services and foundations.

The yellow green colour given to this zone indicates that it is the most suitable for construction, given the minimal constraints it presents at regional scale. This means further investigation will still be required in terms of quantifying design parameters for each development.

6.7 Chapter summary

The early stages of engineering geological mapping employed the proposed methodology whereby soil colour and texture variability mapping was used in conjunction with vegetation mapping, to classify land as opposed to the standard land systems classification approach. The findings were discussed in stages. From the air photograph mapping, three land facets were identified. These include: Land Facet 1 which was represented by pale grey to white colours and a smooth texture; Land Facet 2 represented by dark grey to deep green areas with a rough texture and finally Land Facet 3 which made up majority of the area, characterised by pale yellow with rough textures and brown soils enclosed in polygons of different sizes. Confirmation from the site walk over matched Land Facet 1 to dry pans, which had diagnostic features including desiccation cracks and salts with very little to no vegetation. Land Facet 2 was matched to waterlogged areas that hosted a lot of green vegetation, and Land Facet 3 was matched to areas that were slightly elevated in comparison to the surrounding facets, and were for this reason herein referred to as highlands. The brown soils enclosed in polygons were found to be agricultural fields used for crop farming.

A detailed ground investigation revealed occurrence of salts including halite and gypsum in Land Facet 1 while for Land Facet 2 soils were predominantly clayey, and were found to be moist with sidewall collapse experienced in some test pits, indicative of shallow water tables. For Land Facet 3, in-situ observation suggested that soils were pinholed and occasionally voided, and some areas of this facet had imported sand, which was used to elevate ground prior to construction.

From laboratory tests, soils from Land Facet 1 and 2 were found to contain considerable amounts of clay, with dry clays in Land Facet 1 and wet ones in Land Facet 2. This explains the desiccation cracks as a response of clays to moisture loss in Land Facet 1, and conversely, the ability to hold water due to their impervious nature in Land Facet 2. Permeability was found to be generally low especially in Land Facets 1 and 2, with values of ranging between 10^{-8} to 10^{-6} m/s indicative of clayey silty sands. Outapi soils were also found to have electric conductivity values that were high enough to qualify them as corrosive material, and additionally making the soils susceptible to erosion and dispersion. Some samples from Land Facets 1 and 2 displayed medium to high expansiveness, which means these soils can exhibit volume change when subjected to moisture variations.

In terms of structural damage distribution, cracking was observed in both Land Facet 1 and 3. For Land Facet 1, it could be due to the presence of expansive soils as revealed by some samples (such as AH 6) from this facet. This is especially from the orientation of the cracks, with noticeable widening to the top cracks, which is a typical response to foundation movement. For Land Facet 3, most samples displayed low expansiveness; however another constraint was collapse settlement, which might have impacted some of these structures. In some instances, damaged buildings could not be linked to any geotechnical constraints, in which case damage was rather attributed to natural deterioration or poor workmanship.

Three (3) Engineering Geological Zones (EGZs) were identified based on geotechnical merit. For EGZ, the main geotechnical constraints include high salt contents resulting in high EC, which can affect metal structures and make the soils prone to erosion and dispersion. EGZ 1 also had expansive soils, evident from presence of desiccation cracks, as well as possibility of seasonal flooding. The possibility of seasonal flooding was highlighted for EGZ 2, coupled with sidewall collapse, which proves that material in this land facet is weak under high moisture contents. It also presents expansiveness problems as well as dispersion due to high salt contents. Additionally, presence of hard calcrete nodules can pose excavatibility problems. EGZ 3 was found to be dominated by moderately to poorly consolidate silty sands of aeolian origin, some of which displayed potential for collapse.

7 CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

Namibia's increasing population and rapid urbanisation has necessitated the input of engineering geology in land use planning, to achieve optimum development potential and make optimal use of available land. The geotechnical constraints of available land are an important consideration, as they can be a serious limiting factor and ought to be addressed prior to any development. Considering the current lack of compulsory geotechnical investigations in Namibia, this study was undertaken as a leading example, advocating for the practice of engineering geological mapping for safe urban development. The case study was based on an upcoming town of Outapi, located in northern Namibia. Existing methodologies were explored, some of which were altered to suit the area under consideration.

The early chapters sought to provide insight into engineering geology, the existing guidelines for siting different structures in an urban environment, as well as the current practice of engineering geology. After a careful study of the present land systems methodology of terrain evaluation as part of engineering geological mapping, it was established that the methodology was potentially not feasible for Outapi, given the flat nature of the area. The traditional land systems classification approach places much reliance on land forms, which made it difficult to apply in the topographically featureless and flat-lying Outapi. The topographical nature of the study area does not allow successful identification of landscapes and landforms. Additional techniques of delineating land facets were therefore presented in Chapter 4, suggesting the use of soil colour and texture mapping, vegetation mapping, as well as soil assessment based on existing structures, herein referred to as structural damage distribution surveys. The applicability of these techniques were tested in the Outapi case study, and they both proved to be useful tools in land classification of uniterrain areas with semi-arid conditions. The mapping exercise also revealed a good correlation between soil moisture content and vegetation, with darker soils found to host a lot of vegetation, whereas areas with pale colours were drier, with well-drained soils and lesser vegetation. The inconclusive soil boundaries demarcated during photographic interpretation were confirmed during the walk over survey. Structural damage distribution survey as a third technique used in soils assessment allowed understanding of soils based on the performance of existing structures.

In addition to the mapping methodology, this study was undertaken in an effort to understand the engineering properties of soils in Outapi and deduce thereof, their influence on structural developments. The combined techniques of mapping allowed partitioning of land into different land facets that were described in engineering geological terms, thereby updated to produce engineering geological zones. The three land facets identified were described in terms of visual assessment from air photo interpretation, then supplemented by descriptive information from the site walk-over, as well as from the detailed ground or subsurface investigation, thereafter described from laboratory results.

The geotechnical constraints revealed in this study include collapse settlement given the aeolian nature of Outapi soils; susceptibility to flooding attributed to the flat nature of the area with no properly defined pathways; and, to a lesser extent, the presence of potentially expansive soils. With regards to flooding and inundation, it is recommended that design of structures take into account the NW-SE trend in drainage, as established from the hydrology of the area and the land facets. This pattern should as such, influence the design and positioning of future developments. A good separation must also be kept between these areas and the built environment. In cases where structural development has already taken place, intersecting non-perennial water bodies, it is recommended that precautions be taken in order to canalise storm water past the structures via drainage dikes. This will improve drainage around the structures. In terms of potential collapse settlement for Land Facet 3, it is recommended that these soils be compacted prior to construction, so as to overcome the grain structure, close up the voids and increase the density of the soils, which allows them to carry large loads. Watering during compaction is also advised to overcome the collapsible structure. Areas with active or expansive soils should be avoided, however if they do not occur to significant depths, the expansive horizons can be stripped off prior to development and replaced by engineered designed earth mattresses.

Other than the above discussed constraints, there were no other significant geotechnical issues noted that could hinder the use of land for low-cost housing. However, it must be noted that this assessment was based on limited work and should as such be considered a preliminary investigation that should be subjected to detailed assessment depending on the proposed development. Generally, the area was found to have poorly consolidated soils, easily rippable to depths of about 2.3m (maximum depth reached during investigation due to TLB capability). For this reason, it can be said that the soils have no excavatibility problems, which makes it easy for installation of underground services such as water pipes and power cables.

It has also been established that the use of terrain evaluation as a basis of engineering geological mapping eliminates the need for repetitive investigation as available information is confidently extrapolated to areas that were not tested. This allows large areas to be studied over a short period of time, which in turn helps to save the two most important resources of any project, namely time and money. It is therefore recommended that studies being carried out in areas with a similar setting can use the methodology employed in this study to perform terrain evaluation, as per the flow chart devised in Chapter 4. Additionally, similar studies can be done for other developing towns in Namibia, so that a database of engineering geological information can be created for the whole country and be made available to interested parties. This will not only provide a working framework for engineering geologists, town planners and engineers, but will in turn allow effective and sustainable infrastructure development, as planning will be done on the basis of merit geotechnical information.

It is also the present author's intention that the engineering geological map produced in this study for Outapi be used to guide planning of future developments. The present author also disclaims that this engineering geological map may not in any way substitute detailed site investigations for civil structures, as it is rather a guide for further investigation and development.

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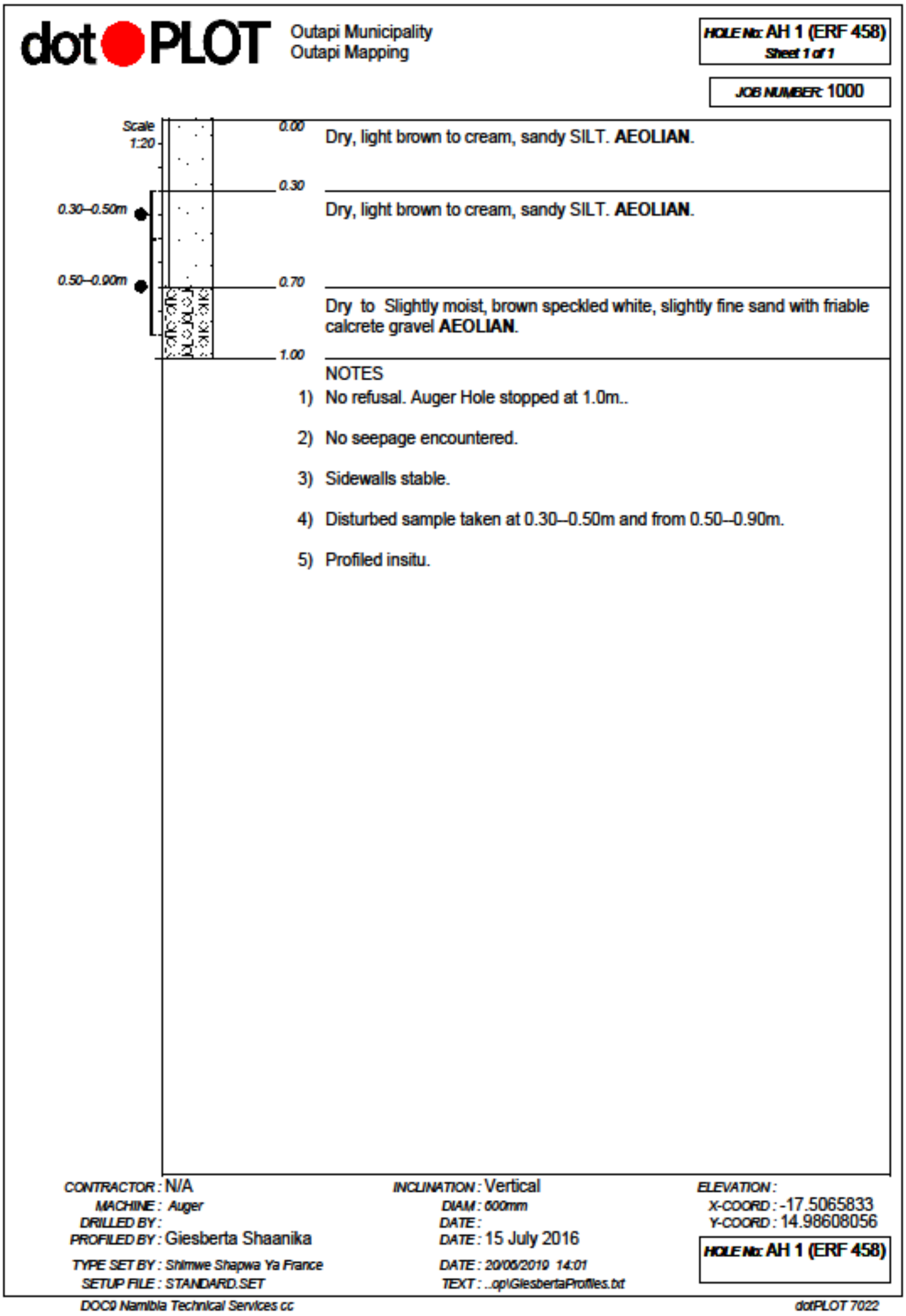
APPENDICES

APPENDIX A: AUGER PROFILES



dotPLOT Outapi Municipality
Outapi Mapping

HOLE No: AH 1 (ERF 458)
Sheet 1 of 1

JOB NUMBER: 1000

Scale 1:20

Sample	Depth (m)	Description
	0.00–0.30	Dry, light brown to cream, sandy SILT. **AEOLIAN**.
0.30–0.50m ●	0.30–0.70	Dry, light brown to cream, sandy SILT. **AEOLIAN**.
0.50–0.90m ●	0.70–1.00	Dry to Slightly moist, brown speckled white, slightly fine sand with friable calcrete gravel **AEOLIAN**.

NOTES

1) No refusal. Auger Hole stopped at 1.0m..
2) No seepage encountered.
3) Sidewalls stable.
4) Disturbed sample taken at 0.30–0.50m and from 0.50–0.90m.
5) Profiled insitu.

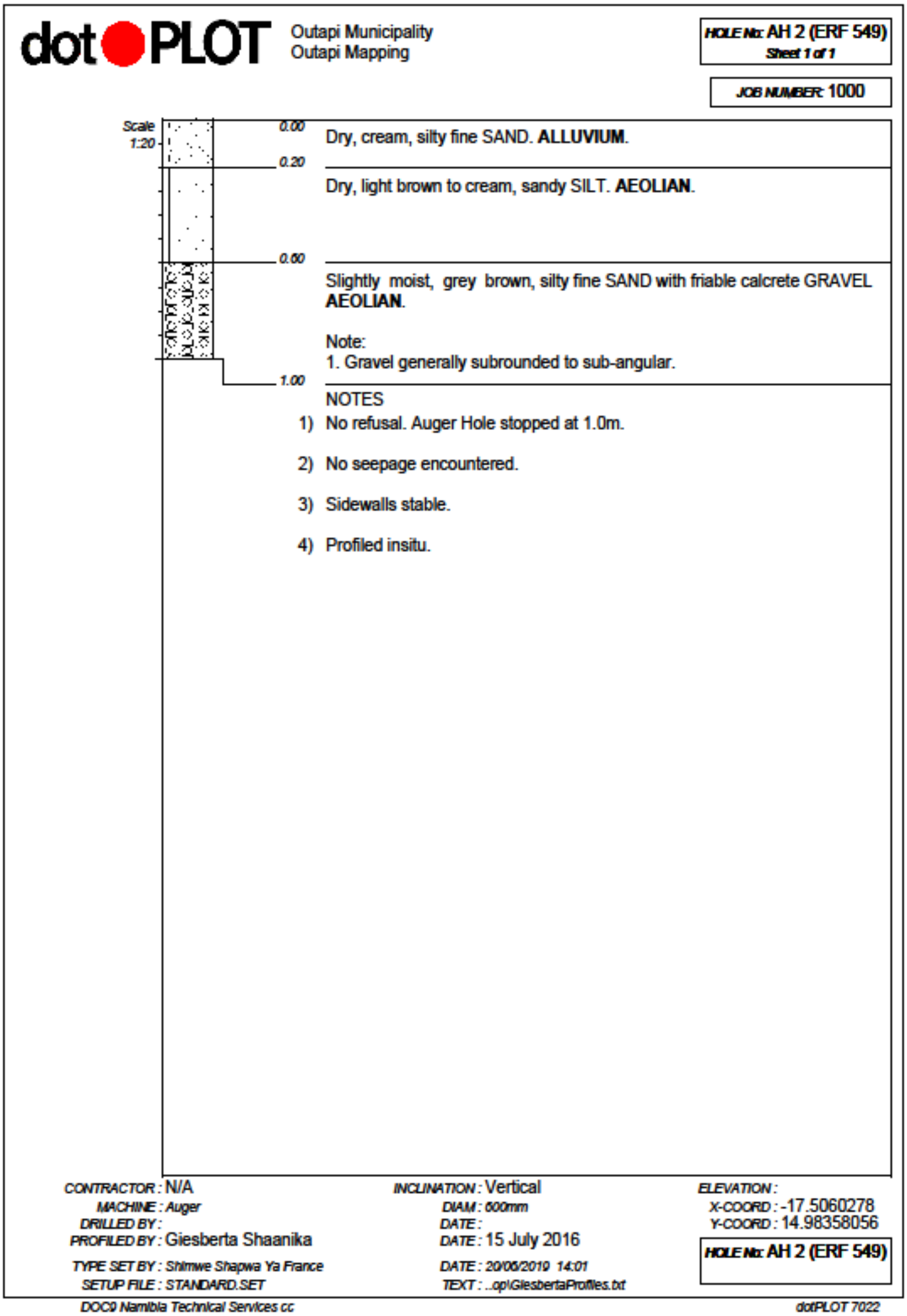
CONTRACTOR: N/A
MACHINE: Auger
DRILLED BY:
PROFILED BY: Giesberta Shaanika
TYPE SET BY: Shimwe Shapwa Ya France
SETUP FILE: STANDARD.SET

INCLINATION: Vertical
DIAM: 600mm
DATE:
DATE: 15 July 2016
DATE: 20/06/2019 14:01
TEXT: ..op\GiesbertaProfiles.txt

ELEVATION:
X-COORD: -17.5065833
Y-COORD: 14.98608056

HOLE No: AH 1 (ERF 458)

DOC9 Namibia Technical Services cc
dotPLOT 7022



dot PLOT Outapi Municipality
Outapi Mapping

HOLE No: AH 2 (ERF 549)
Sheet 1 of 1

JOB NUMBER: 1000

Scale 1:20

0.00 – 0.20	Dry, cream, silty fine SAND. **ALLUVIUM**.
0.20 – 0.60	Dry, light brown to cream, sandy SILT. **AEOLIAN**.
0.60 – 1.00	Slightly moist, grey brown, silty fine SAND with friable calcrete GRAVEL **AEOLIAN**. Note: 1. Gravel generally subrounded to sub-angular.

NOTES

1) No refusal. Auger Hole stopped at 1.0m.
2) No seepage encountered.
3) Sidewalls stable.
4) Profiled insitu.

CONTRACTOR : N/A
MACHINE : Auger
DRILLED BY :
PROFILED BY : Giesberta Shaanika
TYPE SET BY : Shimwe Shapwa Ya France
SETUP FILE : STANDARD.SET

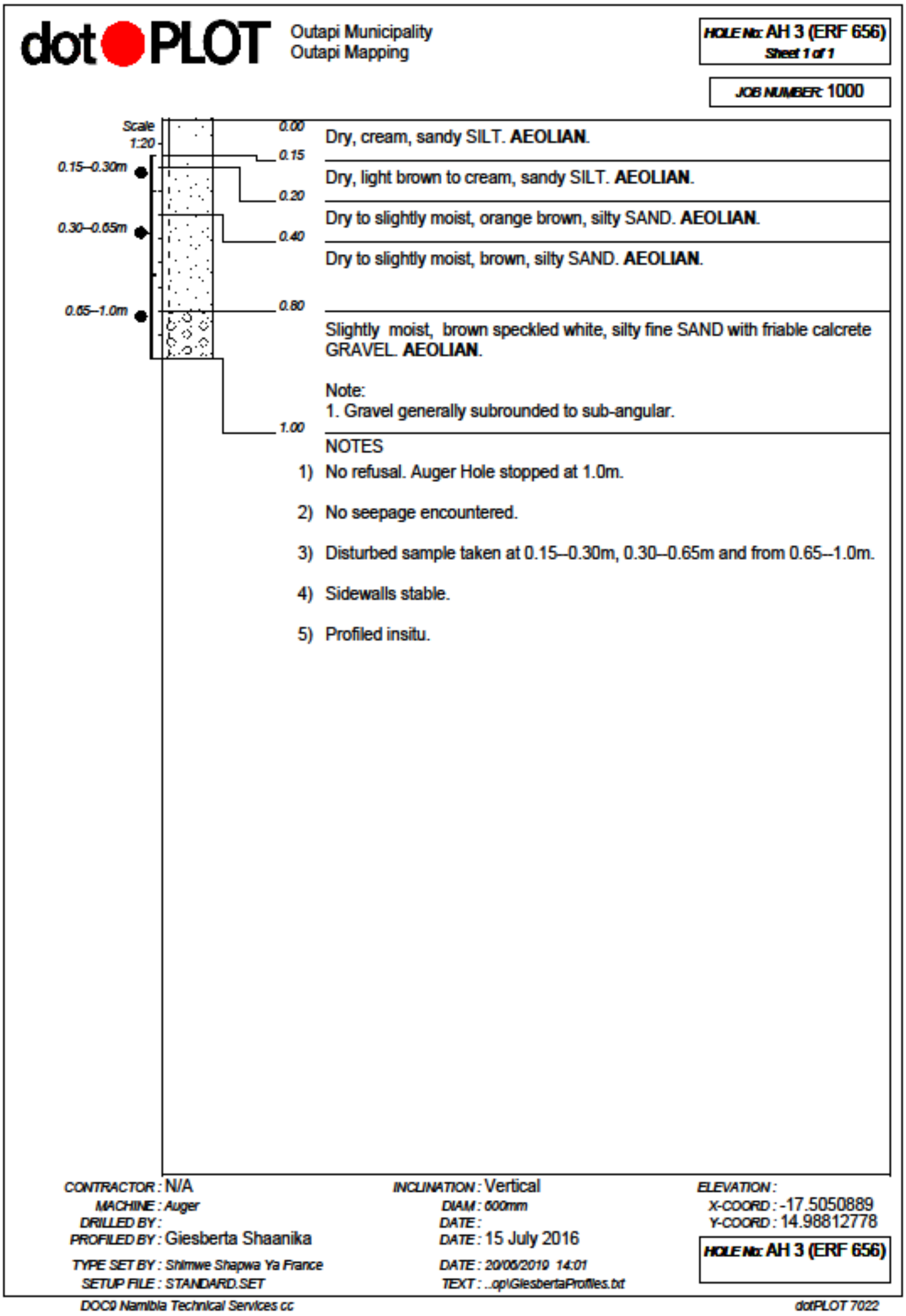
INCLINATION : Vertical
DIAM : 600mm
DATE :
DATE : 15 July 2016
DATE : 20/06/2019 14:01
TEXT : ..op\GiesbertaProfiles.txt

ELEVATION :
X-COORD : -17.5060278
Y-COORD : 14.98358056

HOLE No: AH 2 (ERF 549)

DOC9 Namibia Technical Services cc

dotPLOT 7022



dot PLOT Outapi Municipality
Outapi Mapping

HOLE No: AH 3 (ERF 656)
Sheet 1 of 1

JOB NUMBER: 1000

Scale 1:20

0.00		Dry, cream, sandy SILT. **AEOLIAN**.
0.15	0.15–0.30m	Dry, light brown to cream, sandy SILT. **AEOLIAN**.
0.20		Dry to slightly moist, orange brown, silty SAND. **AEOLIAN**.
0.40	0.30–0.65m	Dry to slightly moist, brown, silty SAND. **AEOLIAN**.
0.80	0.65–1.0m	Slightly moist, brown speckled white, silty fine SAND with friable calcrete GRAVEL. **AEOLIAN**. Note: 1. Gravel generally subrounded to sub-angular.
1.00		

NOTES

1) No refusal. Auger Hole stopped at 1.0m.

2) No seepage encountered.

3) Disturbed sample taken at 0.15–0.30m, 0.30–0.65m and from 0.65–1.0m.

4) Sidewalls stable.

5) Profiled insitu.

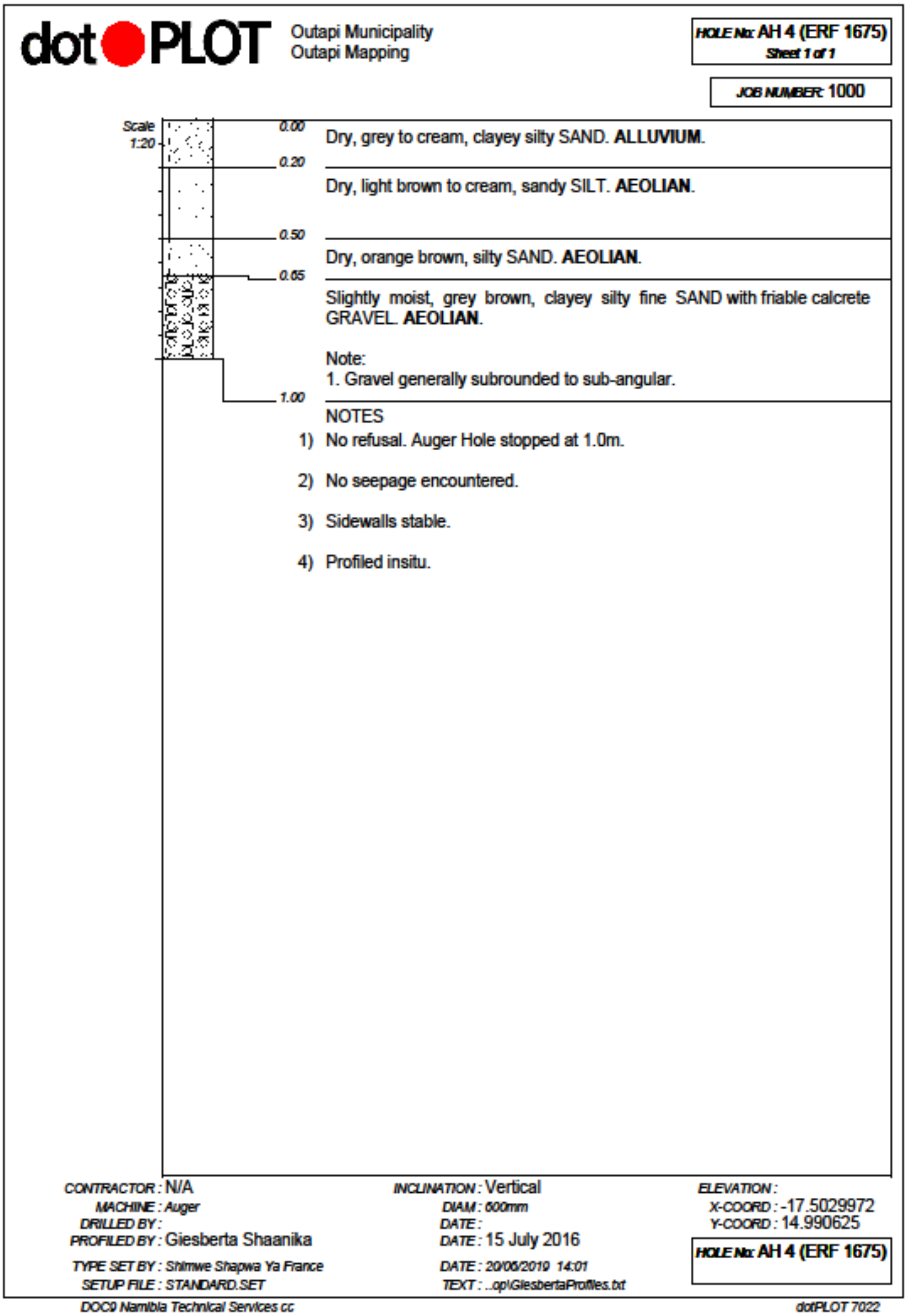
CONTRACTOR : N/A
MACHINE : Auger
DRILLED BY :
PROFILED BY : Giesberta Shaanika
TYPE SET BY : Shimwe Shapwa Ya France
SETUP FILE : STANDARD.SET

INCLINATION : Vertical
DIAM : 600mm
DATE :
DATE : 15 July 2016
DATE : 20/06/2019 14:01
TEXT : ..op\GiesbertaProfiles.txt

ELEVATION :
X-COORD : -17.5050889
Y-COORD : 14.98812778

HOLE No: AH 3 (ERF 656)

DOC9 Namibia Technical Services cc
dotPLOT 7022



dotPLOT Outapi Municipality
Outapi Mapping

HOLE No: AH 4 (ERF 1675)
Sheet 1 of 1

JOB NUMBER: 1000

Scale 1:20

0.00 – 0.20	Dry, grey to cream, clayey silty SAND. **ALLUVIUM**.
0.20 – 0.50	Dry, light brown to cream, sandy SILT. **AEOLIAN**.
0.50 – 0.65	Dry, orange brown, silty SAND. **AEOLIAN**.
0.65 – 1.00	Slightly moist, grey brown, clayey silty fine SAND with friable calcrete GRAVEL. **AEOLIAN**. Note: 1. Gravel generally subrounded to sub-angular.

NOTES

1) No refusal. Auger Hole stopped at 1.0m.

2) No seepage encountered.

3) Sidewalls stable.

4) Profiled insitu.

CONTRACTOR : N/A
MACHINE : *Auger*
DRILLED BY :
PROFILED BY : Giesberta Shaanika

TYPE SET BY : *Shimwe Shapwa Ya France*
SETUP FILE : *STANDARD.SET*

INCLINATION : Vertical
DIAM : *600mm*
DATE :
DATE : 15 July 2016

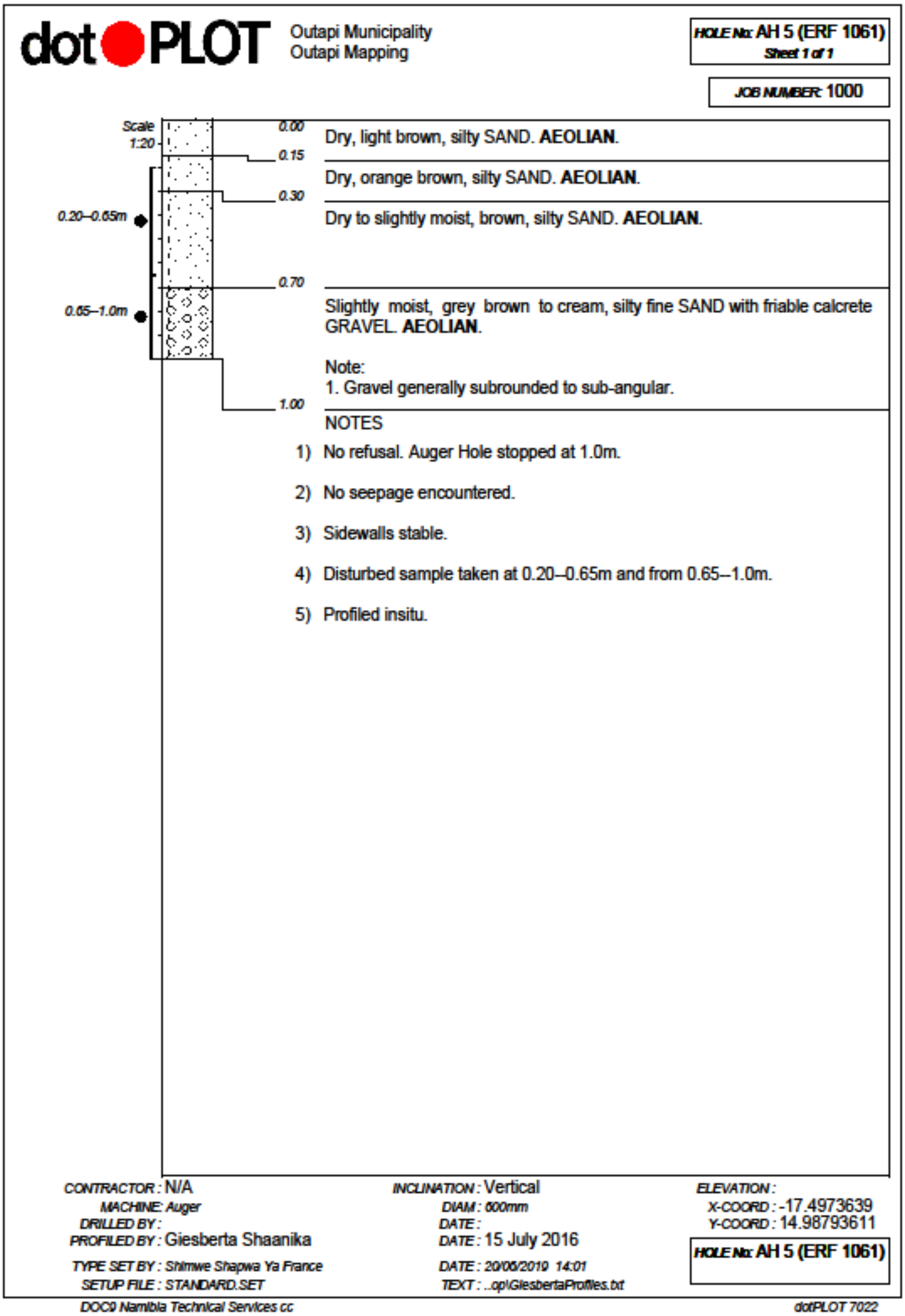
DATE : *20/06/2019 14:01*
TEXT : *..op\GiesbertaProfiles.txt*

ELEVATION :
X-COORD : -17.5029972
Y-COORD : 14.990625

HOLE No: AH 4 (ERF 1675)

DOC9 Namibia Technical Services cc

dotPLOT 7022



dot PLOT Outapi Municipality
Outapi Mapping

HOLE No: AH 5 (ERF 1061)
Sheet 1 of 1

JOB NUMBER: 1000

0.00	Dry, light brown, silty SAND. **AEOLIAN**.
0.15	Dry, orange brown, silty SAND. **AEOLIAN**.
0.30	Dry to slightly moist, brown, silty SAND. **AEOLIAN**.
0.70	Slightly moist, grey brown to cream, silty fine SAND with friable calcrete GRAVEL. **AEOLIAN**. Note: 1. Gravel generally subrounded to sub-angular.
1.00	

NOTES

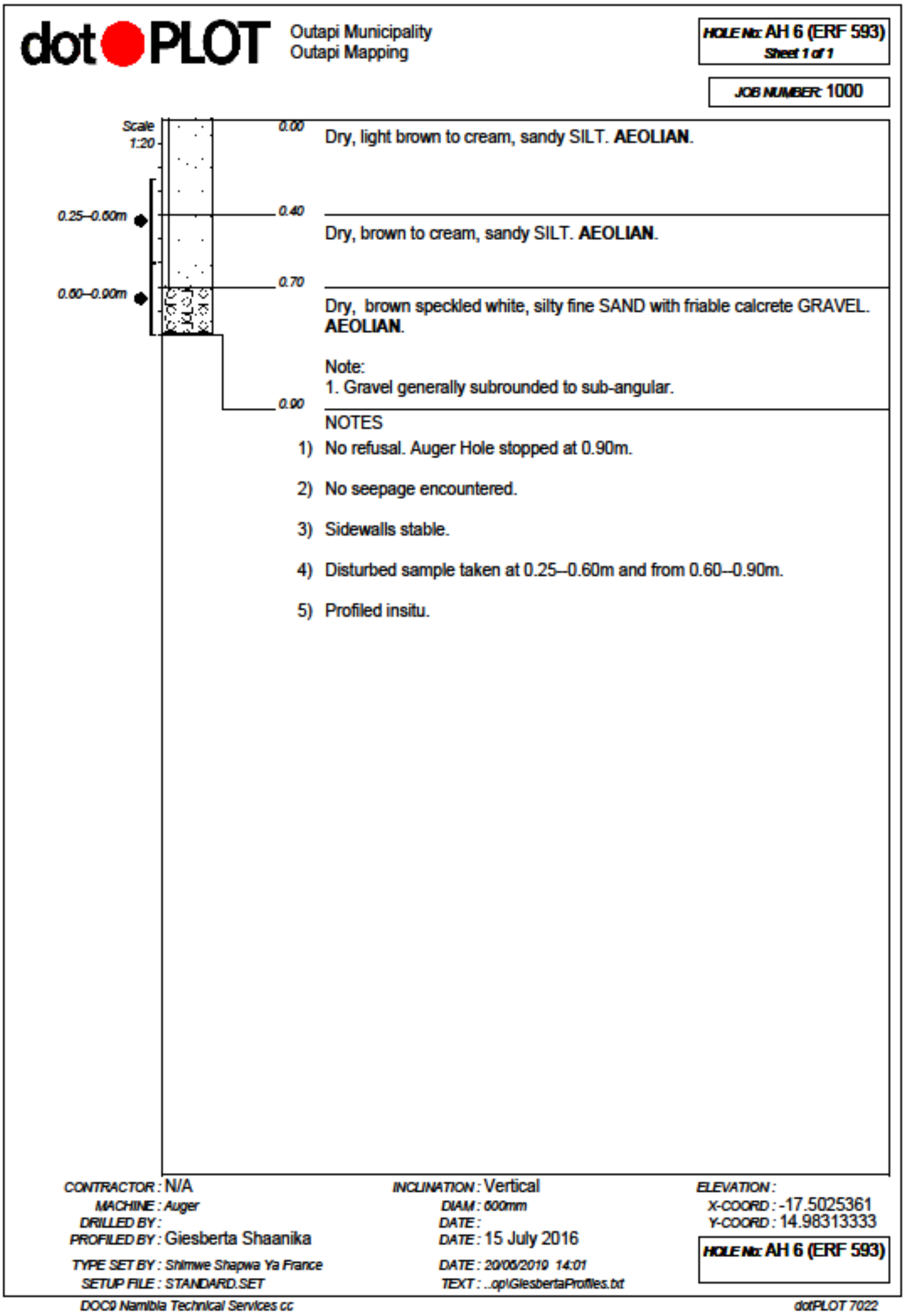
1) No refusal. Auger Hole stopped at 1.0m.
2) No seepage encountered.
3) Sidewalls stable.
4) Disturbed sample taken at 0.20–0.65m and from 0.65–1.0m.
5) Profiled insitu.

CONTRACTOR : N/A
MACHINE: *Auger*
DRILLED BY :
PROFILED BY : Giesberta Shaanika
TYPE SET BY : Shimwe Shapwa Ya France
SETUP FILE : STANDARD.SET

INCLINATION : Vertical
DIAM : 600mm
DATE :
DATE : 15 July 2016
DATE : 20/06/2019 14:01
TEXT : ..op\GiesbertaProfiles.txt

ELEVATION :
X-COORD : -17.4973639
Y-COORD : 14.98793611
HOLE No: AH 5 (ERF 1061)

DOC9 Namibia Technical Services cc
dotPLOT 7022



dot PLOT Outapi Municipality
Outapi Mapping

HOLE No: AH 6 (ERF 593)
Sheet 1 of 1

JOB NUMBER: 1000

0.00	Dry, light brown to cream, sandy SILT. **AEOLIAN**.
0.40	Dry, brown to cream, sandy SILT. **AEOLIAN**.
0.70	Dry, brown speckled white, silty fine SAND with friable calcrete GRAVEL. **AEOLIAN**. Note: 1. Gravel generally subrounded to sub-angular.
0.90	

NOTES

1) No refusal. Auger Hole stopped at 0.90m.
2) No seepage encountered.
3) Sidewalls stable.
4) Disturbed sample taken at 0.25–0.60m and from 0.60–0.90m.
5) Profiled insitu.

CONTRACTOR : N/A
MACHINE : Auger
DRILLED BY :
PROFILED BY : Giesberta Shaanika
TYPE SET BY : Shimwe Shapwa Ya France
SETUP FILE : STANDARD.SET

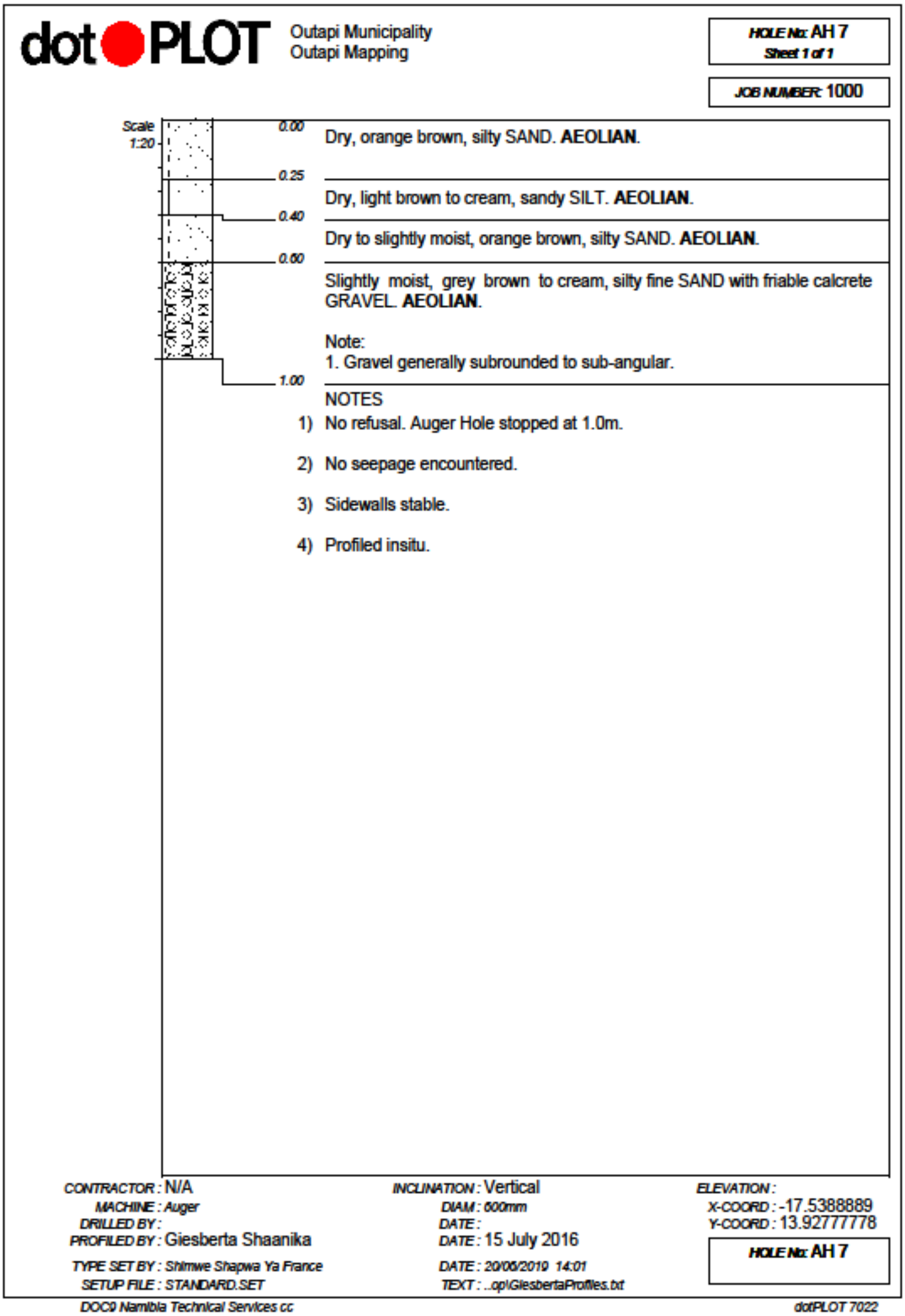
INCLINATION : Vertical
DIAM : 600mm
DATE :
DATE : 15 July 2016
DATE : 20/06/2019 14:01
TEXT : ..op\GiesbertaProfiles.txt

ELEVATION :
X-COORD : -17.5025361
Y-COORD : 14.98313333

HOLE No: AH 6 (ERF 593)

DOC9 Namibia Technical Services cc

dotPLOT 7022



dotPLOT

Outapi Municipality
Outapi Mapping

HOLE No: AH 7
Sheet 1 of 1

JOB NUMBER: 1000

Scale 1:20

0.00

Dry, orange brown, silty SAND. **AEOLIAN**.

0.25

Dry, light brown to cream, sandy SILT. **AEOLIAN**.

0.40

Dry to slightly moist, orange brown, silty SAND. **AEOLIAN**.

0.60

Slightly moist, grey brown to cream, silty fine SAND with friable calcrete GRAVEL. **AEOLIAN**.

Note:
1. Gravel generally subrounded to sub-angular.

1.00

NOTES

1) No refusal. Auger Hole stopped at 1.0m.

2) No seepage encountered.

3) Sidewalls stable.

4) Profiled insitu.

CONTRACTOR : N/A
MACHINE : Auger
DRILLED BY :
PROFILED BY : Giesberta Shaanika

TYPE SET BY : Shimwe Shapwa Ya France
SETUP FILE : STANDARD.SET

INCLINATION : Vertical
DIAM : 600mm
DATE :
DATE : 15 July 2016

DATE : 20/06/2019 14:01
TEXT : ..op\GiesbertaProfiles.txt

ELEVATION :
X-COORD : -17.5388889
Y-COORD : 13.92777778

HOLE No: AH 7

DOC9 Namibia Technical Services cc

dotPLOT 7022

APPENDIX B: TEST PIT PROFILES

Project:	Outapi Mapping	Hole No.:	TP 01
Client:	Outapi Municipality	Start date:	15 July 2016
Location:	Namibia	End date:	15 July 2016
Project No.:		Coordinates:	-17.5296638888888°
Engineering Geologist:	G. Shaanika		14.9580916666666°
			(Hand held GPS)

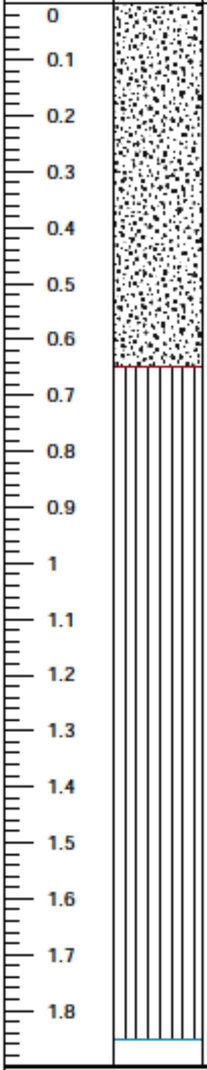
Depth (m)	Lithology	Depth (m)	Material Description
0 0.1 0.2 0.3 0.4		0.45	Dry, light brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, silty fine SAND with roots. Aeolian.
0.5 0.6 0.7 0.8		0.8	Dry, light brown speckled white, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, silty fine SAND with friable nodules. Aeolian.
0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7		1.7	Dry to slightly moist, dark brown speckled white, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, silty fine SAND with friable gravels. Aeolian.

Notes:

PP - Sidewall Geological Pick Penetration

Final depth at 1.70 m.
No groundwater seepage.
No sidewall collapse.
No samples taken.

Project:	Outapi Mapping	Hole No.:	TP 02
Client:	Outapi Municipality	Start date:	15 July 2016
Location:	Namibia	End date:	15 July 2016
Project No.:		Coordinates:	-17.5250833333333° 14.9654388888888°
Engineering Geologist:	G. Shaanika		(Hand held GPS)



Depth (m)	Material Description
0.3	Dry, light brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, silty fine SAND with roots. Aeolian.
0.65	Dry to slightly moist, light brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, silty fine SAND. Aeolian.
1.85	Slightly moist, grey brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), pinholed, fine sandy SILT with friable gravels. Aeolian.

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.85 m.
No groundwater seepage.
No sidewall collapse.
Disturbed samples taken at 0 - 0.3 m; 0.3 - 0.65 m; 0.65 - 1.85 m.

Project:	Outapi Mapping	Hole No.:	TP 03
Client:	Outapi Municipality	Start date:	15 July 2016
Location:	Namibia	End date:	15 July 2016
Project No.:		Coordinates:	-17.5239361111111° 14.9795305555555°
Engineering Geologist:	G. Shaanika		(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.1		0.15	Dry to slightly moist, grey brown, VERY LOOSE to LOOSE (pp = 70 - 80 mm), intact, silty fine SAND with roots. Aeolian.
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9		0.93	Dry to slightly moist, grey brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, silty fine SAND. Aeolian.
1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8		1.8	Slightly moist, light brown to cream, LOOSE to MEDIUM DENSE (pp = 40-70mm), pinholed, silty fine SAND with friable gravels. Aeolian

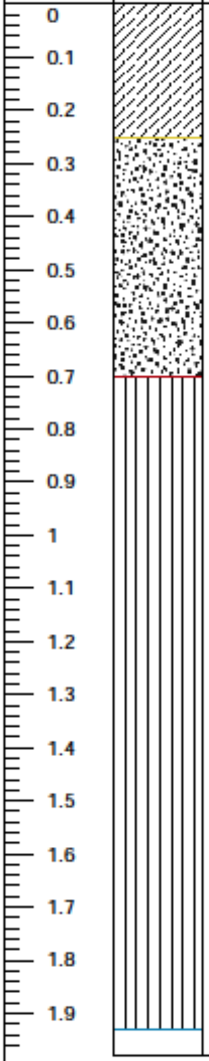
PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.80 m.
No groundwater seepage.
No sidewall collapse.
Disturbed samples taken at 0.15 - 0.93 m; 0.93 - 1.80 m.

Project: Outapi Mapping
Client: Outapi Municipality
Location: Namibia
Project No.:
Engineering Geologist: G. Shaanika

Hole No.: TP 04
Start date: 15 July 2016
End date: 15 July 2016
Coordinates: -17.5187666666666°
14.9804583333333°
(Hand hold GPS)



Depth (m)	Lithology	Depth (m)	Material Description
		0.25	Slightly moist, dark grey, FIRM (pp = 15 mm), intact, sandy CLAY with roots. Alluvial.
			Slightly moist to moist, dark grey, MEDIUM DENSE (pp = 20 - 30 mm), intact, clayey SAND. Alluvial
		0.7	Wet, cream white to yellow, LOOSE to MEDIUM DENSE, (pp = 50 - 70 mm), pinholed, sandy SILT with hard calcrete nodules. Aeolian.
		1.93	

PP - Sidewall Geological Pick Penetration

Notes:

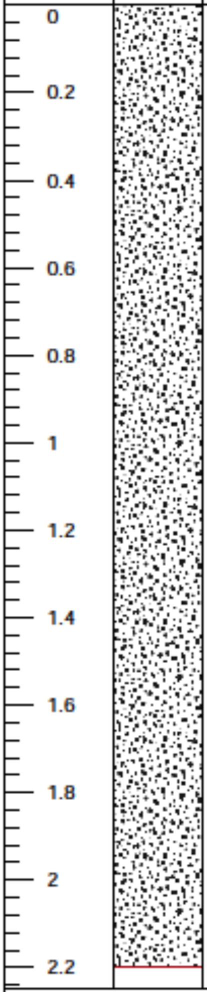
Final depth at 1.93 m.
Groundwater seepage at 1.93 m.
Sidewall collapse from 1.7 - 1.93 m.
Disturbed sample taken at 0.25 - 0.70 m.

Project:	Outapi Mapping
Client:	Outapi Municipality
Location:	Namibia
Project No.:	
Engineering Geologist:	G. Shaanika

Hole No.:	TP 05
Start date:	15 July 2016
End date:	15 July 2016
Coordinates:	-17.5173083333333° 14.9872194444444°

(Hand held GPS)

Depth (m) Lithology



Depth (m)	Material Description
0.25	Dry to slightly moist, dark grey, LOOSE to MEDIUM DENSE, (pp = 50 - 70 mm), intact, silty fine SAND with roots. Alluvial
0.62	Slightly moist, brown grey mottled orange,MEDIUM DENSE (pp = 20 - 30 mm), intact, silty fine SAND. Aeolian.
2.2	Slightly moist, cream white to yellow, MEDIUM DENSE (pp = 20-30 mm), intact silty fine SAND with with hard calcrete nodules. Aeolian.

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 2.20 m.
No groundwater seepage.
No sidewall collapse.
No samples taken.

Project: Outapi Mapping
Client: Outapi Municipality
Location: Namibia
Project No.:
Engineering Geologist: G. Shaanika

Hole No.: TP 06
Start date: 15 July 2016
End date: 15 July 2016
Coordinates: -17.519175°
14.9982916666666°
(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.1		0.15	Dry, grey , VERY LOOSE to LOOSE (pp = 70 - 80 mm), intact clayey silty SAND. Alluvial
0.2 0.3 0.4		0.4	Dry to slightly moist, greyish brown streaked white, MEDIUM DENSE (pp = 30 - 40 mm), intact, silty SAND. Aeolian.
0.5 0.6		0.65	Dry to slightly moist, grey brown, MEDIUM DENSE (pp = 30 - 40 mm), intact, silty SAND. Aeolian.
0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8		1.8	Slightly moist, light brown to cream, LOOSE to MEDIUM DENSE (pp = 40-70mm), pinholed, silty fine SAND with friable gravels. Aeolian

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.80 m.
No groundwater seepage.
No sidewall collapse.
Block sample taken at 0.60 m.

Project: Outapi Mapping
Client: Outapi Municipality
Location: Namibia
Project No.:
Engineering Geologist: G. Shaanika

Hole No.: TP 07
Start date: 15 July 2016
End date: 15 July 2016
Coordinates: -17.5183277777777°
15.010125°
(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.1 0.2		0.25	Dry, grey brown, VERY LOOSE to LOOSE (pp = 70 - 80 mm), intact, silty fine SAND. Aeolian.
0.3 0.4 0.5		0.54	Dry, grey, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact to somewhat pinholed, silty fine SAND. Aeolian.
0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8		1.8	Slightly moist, grey brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact to somewhat pinholed, silty fine SAND with friable gravels. Aeolian.

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.80 m.
No groundwater seepage.
No sidewall collapse.
No samples taken.

Project:	Outapi Mapping	Hole No.:	TP 08
Client:	Outapi Municipality	Start date:	15 July 2016
Location:	Namibia	End date:	15 July 2016
Project No.:		Coordinates:	-17.4996305555555° 14.98825°
Engineering Geologist:	G. Shaanika		(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.1		0.2	Dry, grey, LOOSE, intact, clayey silty fine SAND. Alluvial
0.2 0.3 0.4 0.5		0.55	Dry, grey brown streaked white, MEDIUM DENSE (pp = 30 - 40 mm) but VERY LOOSE to LOOSE (pp = 70 - 80 mm) in vertical joints filled with sand, pinholed and jointed, clayey silty fine SAND. Aeolian.
0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9		1.9	Slightly moist, light grey to cream, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact to somewhat pinholed, silty fine SAND with friable gravels. Aeolian.

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.90 m.
No groundwater seepage.
No sidewall collapse.
Block sample taken at 1.0 m.

Project:	Outapi Mapping	Hole No.:	TP 08
Client:	Outapi Municipality	Start date:	15 July 2016
Location:	Namibia	End date:	15 July 2016
Project No.:		Coordinates:	-17.4996305555555° 14.98825°
Engineering Geologist:	G. Shaanika		(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.1		0.2	Dry, grey, LOOSE, intact, clayey silty fine SAND. Alluvial
0.2 0.3 0.4 0.5		0.55	Dry, grey brown streaked white, MEDIUM DENSE (pp = 30 - 40 mm) but VERY LOOSE to LOOSE (pp = 70 - 80 mm) in vertical joints filled with sand, pinholed and jointed, clayey silty fine SAND. Aeolian.
0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9		1.9	Slightly moist, light grey to cream, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact to somewhat pinholed, silty fine SAND with friable gravels. Aeolian.

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.90 m.
No groundwater seepage.
No sidewall collapse.
Block sample taken at 1.0 m.

Project:	Outapi Mapping
Client:	Outapi Municipality
Location:	Namibia
Project No.:	
Engineering Geologist:	G. Shaanika

Hole No.:	TP 09
Start date:	15 July 2016
End date:	15 July 2016
Coordinates:	-17.4953527777777° 14.9919083333333° (Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7	▨	0.7	Dry, brown, MEDIUM DENSE (pp = 30 - 40 mm), intact, silty SAND. Aeolian
0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8	▨	1.8	Dry to slightly moist, light brown, MEDIUM DENSE, pinholed, silty SAND with friable gravels. Aeolian.

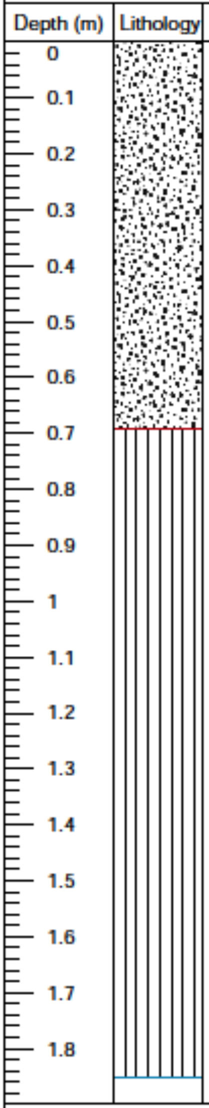
PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.80 m.
No groundwater seepage.
No sidewall collapse.
No samples taken.

University of Pretoria

Project:	Outapi Mapping	Hole No.:	TP 10
Client:	Outapi Municipality	Start date:	15 July 2016
Location:	Namibia	End date:	15 July 2016
Project No.:		Coordinates:	-17.4980416666666° 14.9849138888888°
Engineering Geologist:	G. Shaanika		(Hand held GPS)



Depth (m)	Material Description
0.3	Dry, grey brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, silty fine SAND. Aeolian
0.65	Dry, redish brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact silty fine SAND. Aeolian.
0.69	Dry, white, VERY LOOSE (pp = 90 mm), intact, fine SAND. Aeolian.
1.85	Slightly moist, grey brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), pinholed, fine sandy SILT with friable gravels. Aeolian.

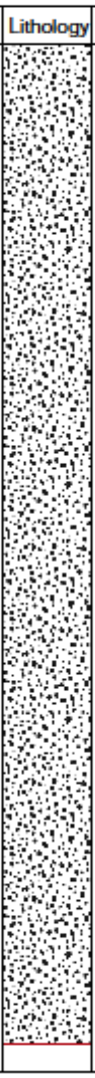
PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.85 m.
No groundwater seepage.
No sidewall collapse.
Disturbed samples taken at 0.30 - 0.65 m; 0.69 - 1.85 m.

Project: Outapi Mapping
Client: Outapi Municipality
Location: Namibia
Project No.:
Engineering Geologist: G. Shaanika

Hole No.: TP 11
Start date: 15 July 2016
End date: 15 July 2016
Coordinates: -17.4970222222222°
14.9764277777777°
(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.1		0.1	Dry, grey , VERY LOOSE (pp = 90 mm), intact clayey silty SAND. Alluvial
0.2 0.3 0.4		0.45	Dry to slightly moist, grey brown streaked white, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, silty SAND. Aeolian.
0.5 0.6 0.7		0.72	Dry to slightly moist, grey brown, MEDIUM DENSE (pp = 30 - 40 mm), intact, silty SAND. Aeolian.
0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8		1.8	Slightly moist, light brown to cream, LOOSE to MEDIUM DENSE (pp = 40-70mm), pinholed, silty fine SAND with friable gravels. Aeolian

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.80 m.
No groundwater seepage.
No sidewall collapse.
Disturbed sample taken at 0.45 - 0.72 m.

Project:	Outapi Mapping	Hole No.:	TP 12
Client:	Outapi Municipality	Start date:	15 July 2016
Location:	Namibia	End date:	15 July 2016
Project No.:		Coordinates:	-17.5022305555555° 14.9775916666666°
Engineering Geologist:	G. Shaanika		(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.1			Dry to slightly moist, light grey streaked white, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact, clayey silty SAND. Aeolian.
0.2 0.3 0.4 0.5		0.2	Dry to slightly moist, grey, MEDIUM DENSE (pp = 30 - 40 mm), intact, silty SAND. Aeolian.
0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4		0.6	Slightly moist, light brown to cream, LOOSE to MEDIUM DENSE (pp = 40-70mm), pinholed, silty fine SAND with friable gravels. Aeolian
1.5		1.5	

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.50 m.
No groundwater seepage.
No sidewall collapse.
Disturbed sample taken at 0.6 - 1.50 m.

Project: Outapi Mapping
Client: Outapi Municipality
Location: Namibia
Project No.:
Engineering Geologist: G. Shaanika

Hole No.: TP 13
Start date: 15 July 2016
End date: 15 July 2016
Coordinates: -17.5030611111111°
14.9760777777777°
(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 – 0.5	▨	0.5	Slightly moist, dark grey, SOFT to FIRM (pp = 15 - 30 mm), intact, sandy CLAY with roots. Alluvial.
0.5 – 1.28	░	1.28	Slightly moist to moist, dark grey, MEDIUM DENSE (pp = 20 - 30 mm), intact, clayey SAND. Alluvial
1.28 – 2.1	░	2.1	Moist, pale yellow to cream mottled white, LOOSE to MEDIUM DENSE, (pp = 50 - 70 mm), pinholed, clayey silty SAND with hard calcrete nodules about 20 mm in diameter. Aeolian.

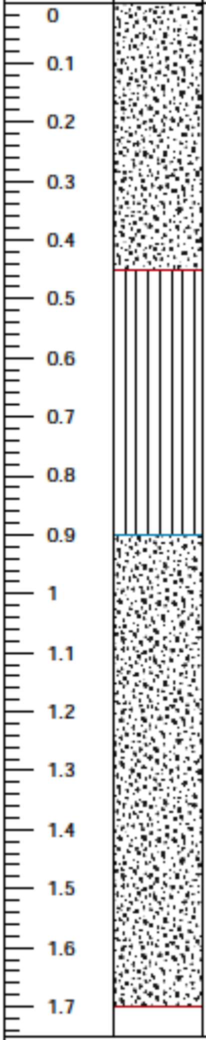
PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 2.10 m.
No groundwater seepage.
No sidewall collapse.
Disturbed sample taken at 0.5 - 1.28 m.

Project: Outapi Mapping
Client: Outapi Municipality
Location: Namibia
Project No.:
Engineering Geologist: G. Shaanika

Hole No.: TP 14
Start date: 15 July 2016
End date: 15 July 2016
Coordinates: -17.5072083333333°
14.9814972222222°
(Hand held GPS)



Depth (m)	Material Description
0.45	Dry, orange brown, LOOSE to MEDIUM DENSE (pp = 40-70mm), intact silty fine SAND. Aeolian.
0.9	Slightly moist, grey brown, MEDIUM DENSE (pp = 15 - 20 mm), pinholed, fine sandy SILT with friable gravels. Aeolian.
1.7	Slightly moist, light to dark grey brown, MEDIUM DENSE (pp = 15 - 20 mm), intact, slightly clayey silty medium SAND. Alluvium.

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 1.70 m.
No groundwater seepage.
No sidewall collapse.
Block sample taken at 0.6 m.

Project:	Outapi Mapping	Hole No.:	TP 15
Client:	Outapi Municipality	Start date:	15 July 2016
Location:	Namibia	End date:	15 July 2016
Project No.:		Coordinates:	-17.50329167°
Engineering Geologist:	G. Shaanika		14.99972222°
			(Hand held GPS)

Depth (m)	Lithology	Depth (m)	Material Description
0 0.2	▨	0.35	Slightly moist, dark grey, LOOSE to MEDIUM DENSE, intact, clayey silty SAND. Aeolian.
0.4 0.6	▨	0.8	Slightly moist, light grey brown, VERY LOOSE to LOOSE (pp = 70 - 80 mm), pinholed, silty fine to medium SAND. Aeolian.
0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4	▨	2.5	Slightly moist to moist, pale yellow to cream, LOOSE to MEDIUM DENSE (pp = 30 - 50 mm), intact, clayey silty fine SAND. Aeolian.

PP - Sidewall Geological Pick Penetration

Notes:

Final depth at 2.50 m.
No groundwater seepage.
No sidewall collapse.
No samples taken.

APPENDIX C: EFFECTIVE GRAIN SIZES PER SAMPLE

Sample ID	**Effective Grain Diameters (mm)**				
	d_{10}	**d_{17}**	**d_{20}**	**d_{50}**	**d_{60}**
CM1	0.0177	0.0531	0.0663	0.2710	0.3410
CM 3	0.0004	0.0008	0.0009	0.0041	0.0610
TP 02	0.0013	0.0050	0.0400	0.2541	0.3355
TP 04	0.0008	0.0014	0.0017	0.1819	0.2792
TP 10-1	0.2545	0.3442	0.0804	0.0804	0.0082
TP 10-2	0.0270	0.0815	0.1009	0.2954	0.3602
TP 12-1	0.0012	0.0020	0.0270	0.2868	0.3789
TP 12-2	0.0007	0.0012	0.0014	0.2150	0.3150
TP 13	0.0011	0.0018	0.0050	0.2833	0.3667
AH 1-1	0.0015	0.0400	0.0575	0.2640	0.3340
AH 1-2	0.0013	0.0200	0.0439	0.2424	0.3185
AH 3-1	0.0357	0.0816	0.1014	0.2995	0.3656
AH 3-2	0.0018	0.0517	0.0692	0.2865	0.3594
AH 3-3	0.0014	0.0270	0.0517	0.2686	0.3431
AH 5-1	0.0020	0.0517	0.0692	0.2665	0.3325
AH 5-2	0.0013	0.0223	0.0400	0.2281	0.3010
AH 6-1	0.0013	0.0130	0.0517	0.3594	0.5682
AH 6-2	0.0011	0.0018	0.0090	0.2545	0.3442

APPENDIX D: HYDRAULIC CONDUCTIVITY (K) OF OUTAPI SOILS USING DIFFERENT EMPIRICAL FORMULAS

Sample ID	**Estimation of Hydraulic Conductivity (m/s)**																
	Hazen	**Hazen K (cm/s) = d_{10} (mm)**	**Slichter**	**Terzaghi**	**Beyer**	**Sauerbrei**	**Kruger**	**Kozeny-Carmen**	**Zunker**	**Zamarin**	**USBR**	Barr	Alyamani and Sen	Chapuis	Krumbein and Monk	geometric mean	arithmetic mean
CM1	1.8971E-06	1.1183E-09	8.8463E-09	3.9317E-09	7.8362E-09	5.0499E-06	7.8362E-09	2.8886E-09	6.2733E-09	1.3400E-08	1.0065E-08	1.0066E-05	1.8716E-08	1.1554E-08	2.2647E-08	1.0065E-08	8.8463E-09
CM 3	1.1183E-09	1.9753E-09	2.1979E-10	3.1335E-10	5.7283E-10	6.6892E-10	3.0547E-06	2.7038E-08	2.0102E-08	2.3121E-08	4.5778E-10	2.3563E-10	2.2616E-09	2.2565E-12	3.3377E-09	7.0905E-10	1.0554E-09
TP02	8.8463E-09	1.5625E-08	1.7385E-09	2.4787E-09	2.1809E-09	2.9294E-08	3.7258E-05	2.1920E-07	1.6367E-07	1.8894E-07	2.9043E-06	1.8639E-09	4.6571E-05	4.1570E-11	2.6583E-07	4.7888E-07	1.6825E-05
TP 04	3.9317E-09	6.9444E-09	7.7269E-10	1.1016E-09	6.2384E-10	2.3517E-09	1.0109E-05	9.3805E-08	6.9965E-08	8.0708E-08	1.9434E-09	8.2840E-10	2.3974E-05	1.3263E-11	1.1714E-07	4.8363E-08	6.0235E-06
TP 10-1	7.8362E-09	1.3841E-08	1.5400E-09	2.1956E-09	1.7790E-09	4.6871E-09	2.1972E-05	1.8686E-07	1.3984E-07	1.6180E-07	1.6562E-06	1.6511E-09	4.6654E-05	3.5043E-11	2.4274E-07	2.8636E-07	1.3775E-05
TP 10-2	5.0499E-06	7.2900E-06	1.0550E-06	1.6135E-06	5.9258E-06	1.0478E-05	1.0883E-04	1.0938E-06	7.6615E-07	9.0425E-07	2.4407E-05	1.1713E-06	1.6768E-05	3.5129E-07	2.2407E-05	1.3807E-05	3.1932E-05
TP 12-1	7.8362E-09	1.3841E-08	1.5400E-09	2.1956E-09	1.3652E-09	4.6871E-09	4.0545E-05	1.9790E-07	1.4747E-07	1.6992E-07	1.1761E-06	1.6511E-09	5.9905E-05	3.5043E-11	2.6822E-07	3.4715E-07	2.0145E-05
TP 12-2	2.8886E-09	5.1020E-09	5.6769E-10	8.0936E-10	1.4370E-10	1.7278E-09	2.8190E-05	7.6613E-08	5.6791E-08	6.5115E-08	1.3633E-09	6.0862E-10	3.3948E-05	8.5903E-12	1.0712E-07	4.4221E-08	8.5144E-06
TP 13	6.2733E-09	1.1080E-08	1.2329E-09	1.7577E-09	8.9837E-10	3.7523E-09	5.9047E-05	1.6458E-07	1.2245E-07	1.4087E-07	2.4319E-08	1.3218E-09	5.8700E-05	2.5615E-11	2.2655E-07	3.2968E-07	2.3596E-05
AH 1-1	1.3400E-08	2.3669E-08	2.6335E-09	3.7547E-09	4.4292E-09	1.8748E-06	2.0759E-05	2.9523E-07	2.2267E-07	2.5956E-07	6.6918E-06	2.8234E-09	4.9773E-05	7.4621E-11	5.5861E-06	1.9816E-06	1.5599E-05
AH 1-2	1.0065E-08	1.7778E-08	1.9781E-09	2.8202E-09	2.9459E-09	4.6871E-07	3.2881E-05	2.4316E-07	1.8198E-07	2.1054E-07	3.5952E-06	2.1207E-09	4.2113E-05	4.9860E-11	7.3539E-07	1.0024E-06	1.5240E-05

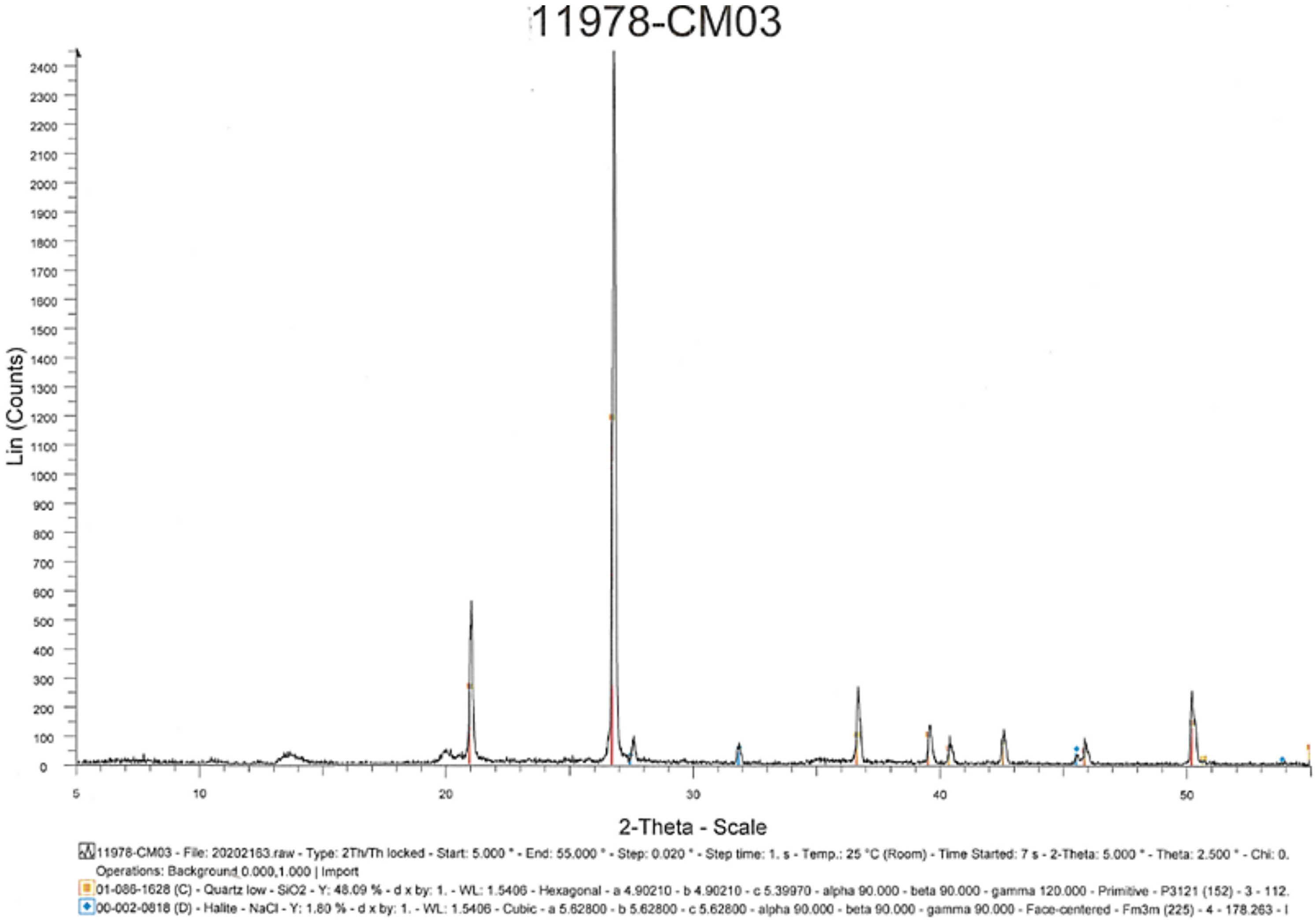
AH 3-1	1.0066E-05	1.2721E-05	2.2287E-06	3.5425E-06	1.1093E-05	1.3104E-05	1.1743E-04	1.7186E-06	1.1395E-06	1.3484E-06	2.4680E-05	2.5484E-06	8.4529E-06	1.0113E-06	2.3571E-05	1.5086E-05	3.3021E-05
AH 3-2	1.8716E-08	3.3058E-08	3.6782E-09	5.2441E-09	6.8820E-09	3.1280E-06	3.6499E-05	4.2299E-07	3.1900E-07	3.7174E-07	1.0235E-05	3.9435E-09	5.8260E-05	1.1947E-10	1.1471E-05	3.1310E-06	2.1873E-05
AH 3-3	1.1554E-08	2.0408E-08	2.2707E-09	3.2374E-09	3.3569E-09	8.5422E-07	2.1205E-05	2.6106E-07	1.9639E-07	2.2835E-07	5.2323E-06	2.4345E-09	5.1825E-05	6.0559E-11	8.1674E-07	1.1329E-06	1.4941E-05
AH 5-1	2.2647E-08	4.0000E-08	4.4507E-09	6.3454E-09	9.8785E-09	3.1280E-06	7.1383E-05	5.3661E-07	4.0434E-07	4.7064E-07	1.0235E-05	4.7716E-09	4.9772E-05	1.5628E-10	1.1021E-05	3.5756E-06	2.7062E-05
AH 5-2	1.0065E-08	1.7778E-08	1.9781E-09	2.8202E-09	3.1705E-09	5.8445E-07	5.9695E-05	2.5573E-07	1.9081E-07	2.2008E-07	2.9043E-06	2.1207E-09	3.7158E-05	4.9860E-11	2.9169E-06	1.5164E-06	2.0071E-05
AH 6-1	8.8463E-09	1.5625E-08	1.7385E-09	2.4787E-09	3.3405E-10	1.9803E-07	1.1832E-04	2.3681E-07	1.7591E-07	2.0206E-07	5.2323E-06	1.8639E-09	9.4686E-05	4.1570E-11	3.4634E-07	1.0745E-06	4.2711E-05
AH 6-2	6.2733E-09	1.1080E-08	1.2329E-09	1.7577E-09	1.0553E-09	3.7523E-09	5.4261E-05	1.6418E-07	1.2207E-07	1.4034E-07	9.3987E-08	1.3218E-09	4.7135E-05	2.5615E-11	2.0973E-07	3.0548E-07	2.0322E-05

APPENDIX E: POTENTIAL EXPANSIVENESS OF ALL SAMPLES

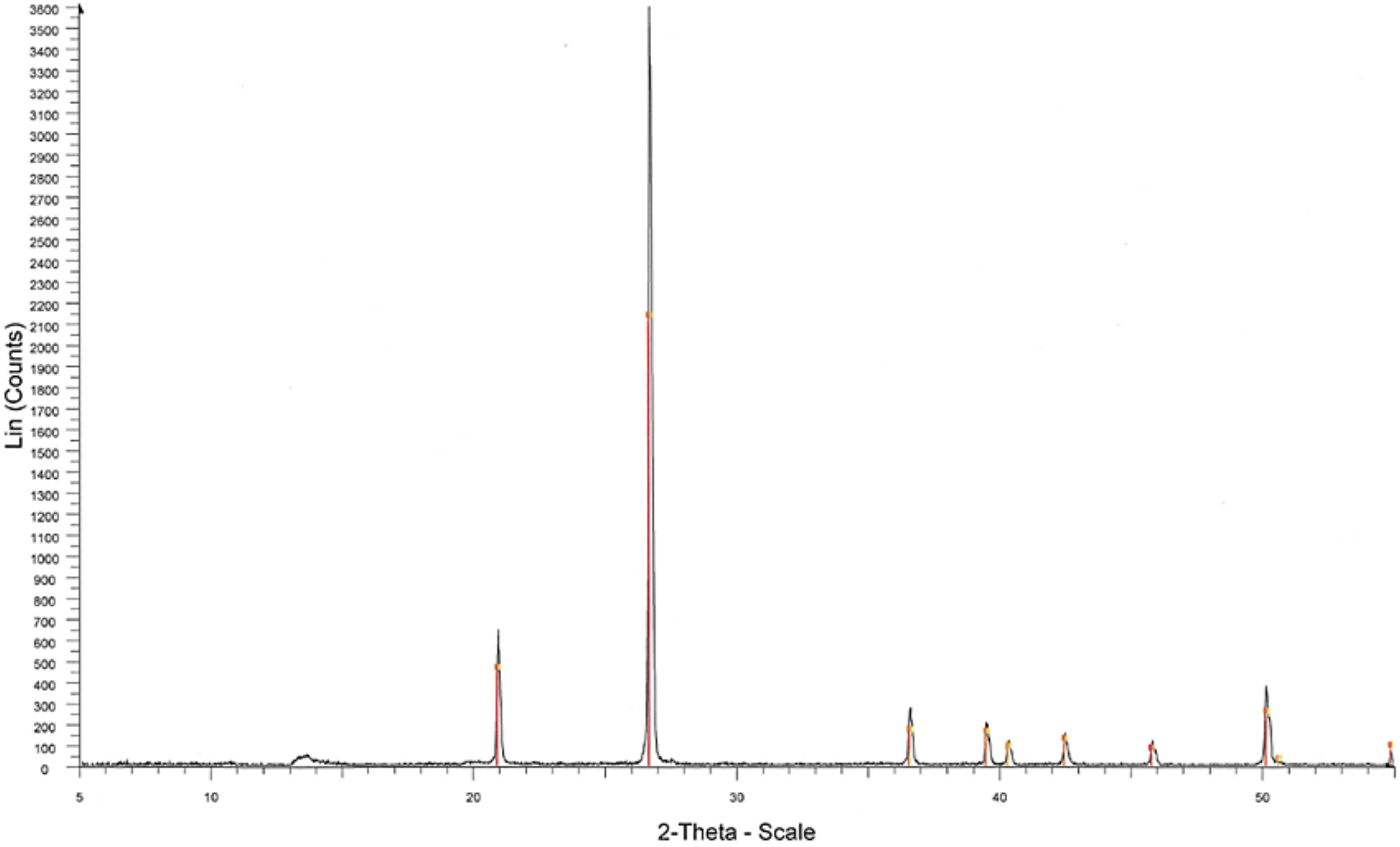
Sample ID	Plasticity Index	Liquid limit	Clay fraction of whole sample [%]	Linear shrinkage	Potential expansiveness (Van der Merwe, 1964)
CM 1	SP	-	4	1.0	Low
CM3	37	68	45	16.5	Very High
TP 02	13	29	16	6.0	Low-Medium
TP 04	23	42	24	11.0	Medium-High
TP 10-1	7	28	17	1.5	Low
TP 10-2	NP	-	8	0.0	None
TP 12-1	12	36	17	5.0	Low
TP 12-2	24	51	28	7.5	Medium-High
TP 13	16	31	19	3.0	Medium
AH 1-1	12	24	13	2.0	Low
AH 1-2	12	29	15	5.0	Low
AH 3-1	NP	-	7	0.0	None
AH 3-2	6	22	11	1.5	Low
AH 3-3	10	28	14	3.0	Low
AH 5-1	SP	-	10	1.0	Low
AH 5-2	11	28	15	3.0	Low
AH 6-1	10	34	16	4.5	Low
AH 6-2	17	36	19	4.5	Medium

Key
SP – Slightly plastic
NP – Non plastic

APPENDIX F: XRF AND XRD RESULTS

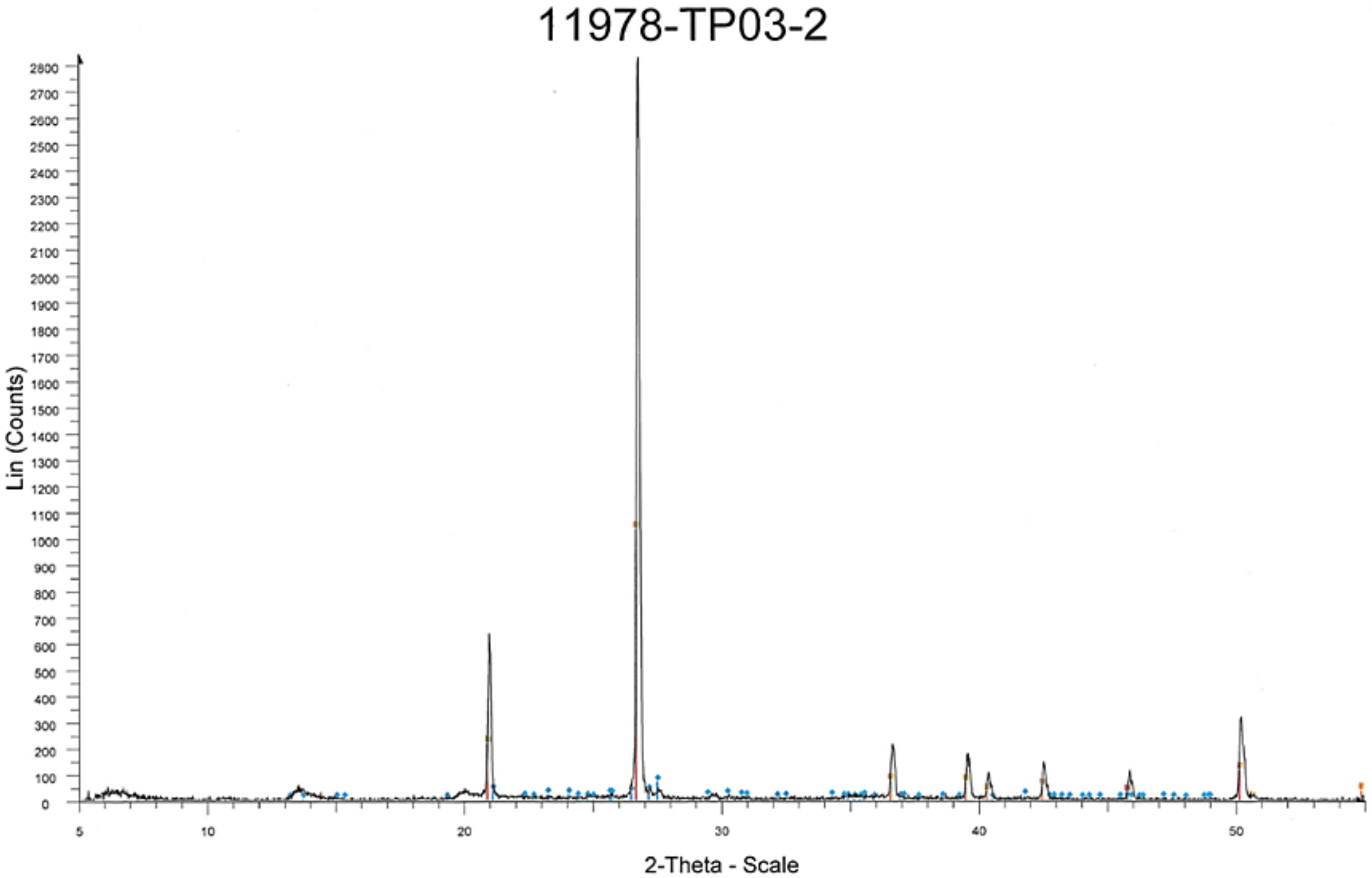


11978-TP03-1

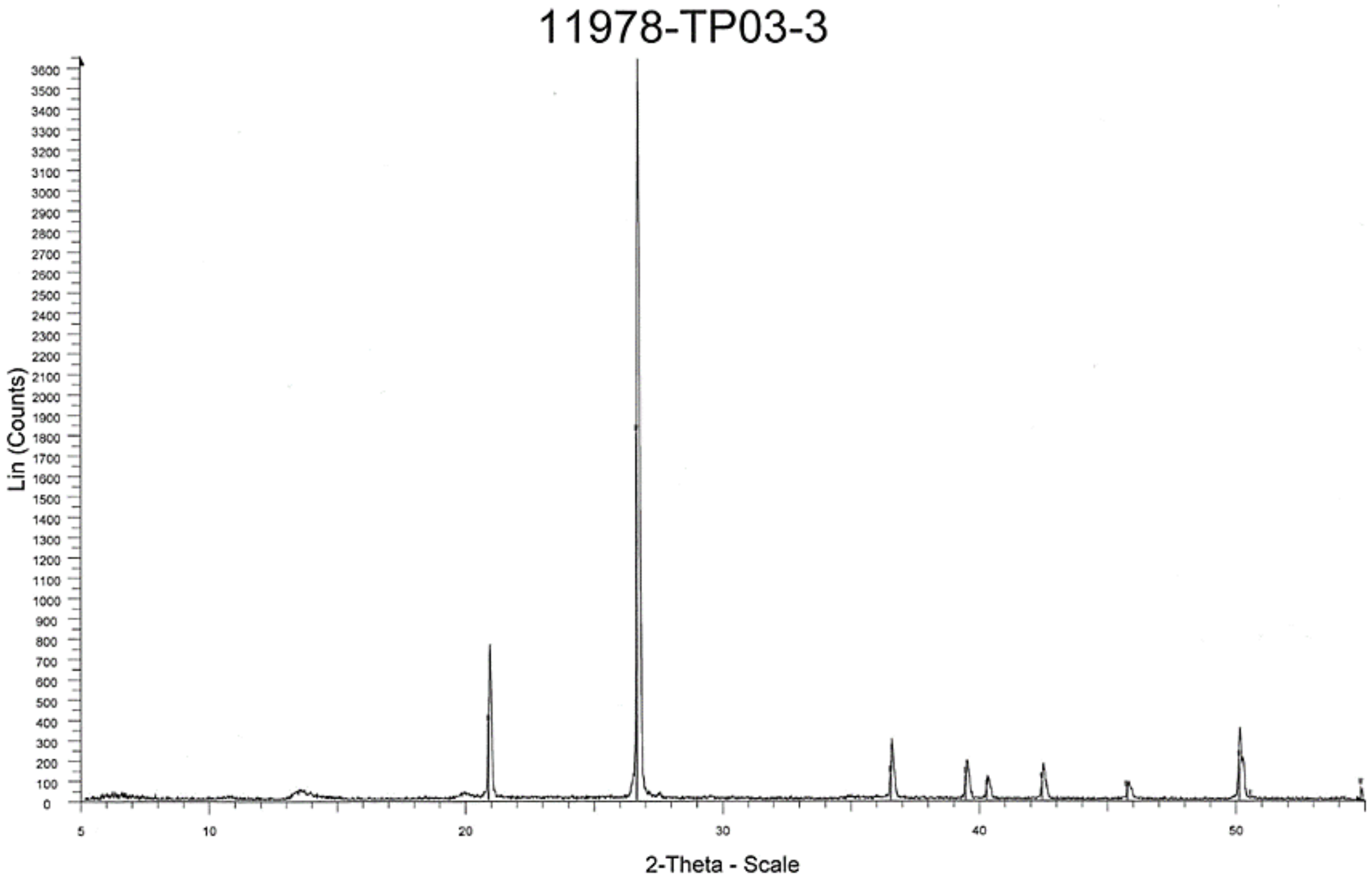


▨ 11978-TP03-1 - File: 20202169.raw - Type: 2Th/Th locked - Start: 5.000 ° - End: 55.000 ° - Step: 0.020 ° - Step time: 1. s - Temp.: 25 °C (Room) - Time Started: 8 s - 2-Theta: 5.000 ° - Theta: 2.500 ° - Chi:
Operations: Background 0.000,1.000 | Import

🟨 01-078-2315 (C) - Quartz - SiO2 - Y: 58.84 % - d x by: 1. - WL: 1.5406 - Hexagonal - a 4.91239 - b 4.91239 - c 5.40385 - alpha 90.000 - beta 90.000 - gamma 120.000 - Primitive - P3221 (154) - 3 - 112.933



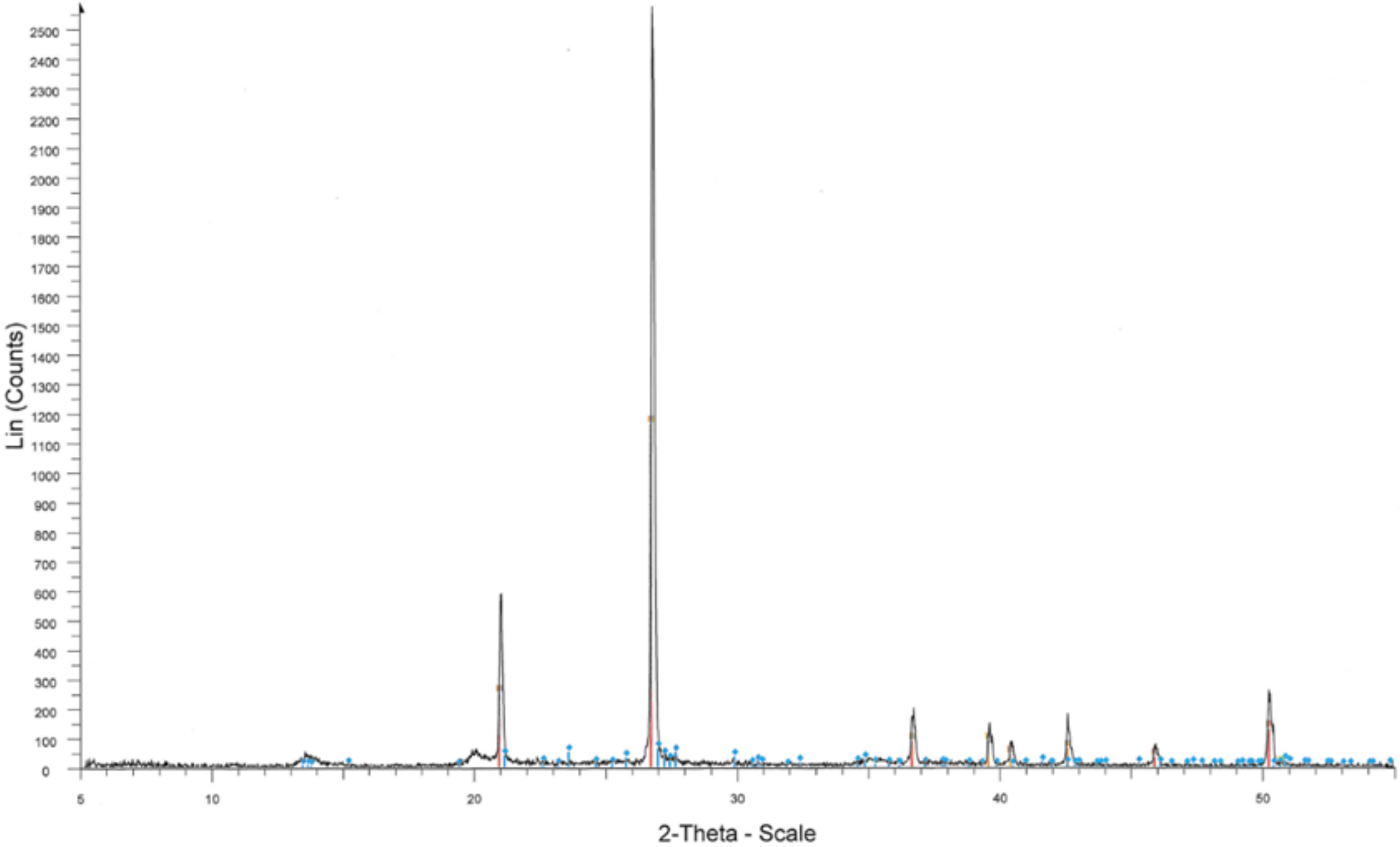
11978-TP03-2 - File: 20202170.raw - Type: 2Th/Th locked - Start: 5.000 ° - End: 55.000 ° - Step: 0.020 ° - Step time: 1. s - Temp.: 25 °C (Room) - Time Started: 14 s - 2-Theta: 5.000 ° - Theta: 2.500 ° - Chi:
Operations: Background 0.000,1.000 | Import
01-078-2315 (C) - Quartz - SiO2 - Y: 36.59 % - d x by: 1. - WL: 1.5406 - Hexagonal - a 4.91239 - b 4.91239 - c 5.40385 - alpha 90.000 - beta 90.000 - gamma 120.000 - Primitive - P3221 (154) - 3 - 112.933
00-022-0687 (D) - Microcline, ordered - KAlSi3O8 - Y: 2.43 % - d x by: 1. - WL: 1.5406 - Triclinic - a 8.56000 - b 12.96400 - c 7.21500 - alpha 90.650 - beta 115.830 - gamma 87.700 - Base-centered - C-1 (



11978-TP03-3

11978-TP03-3 - File: 20202171.raw - Type: 2Th/Th locked - Start: 5.000 ° - End: 55.000 ° - Step: 0.020 ° - Step time: 1. s - Temp.: 25 °C (Room) - Time Started: 7 s - 2-Theta: 5.000 ° - Theta: 2.500 ° - Chi:
Operations: Background 0.000,1.000 | Import
01-078-2315 (C) - Quartz - SiO2 - Y: 49.61 % - d x by: 1. - WL: 1.5406 - Hexagonal - a 4.91239 - b 4.91239 - c 5.40385 - alpha 90.000 - beta 90.000 - gamma 120.000 - Primitive - P3221 (154) - 3 - 112.933

11978-TP04

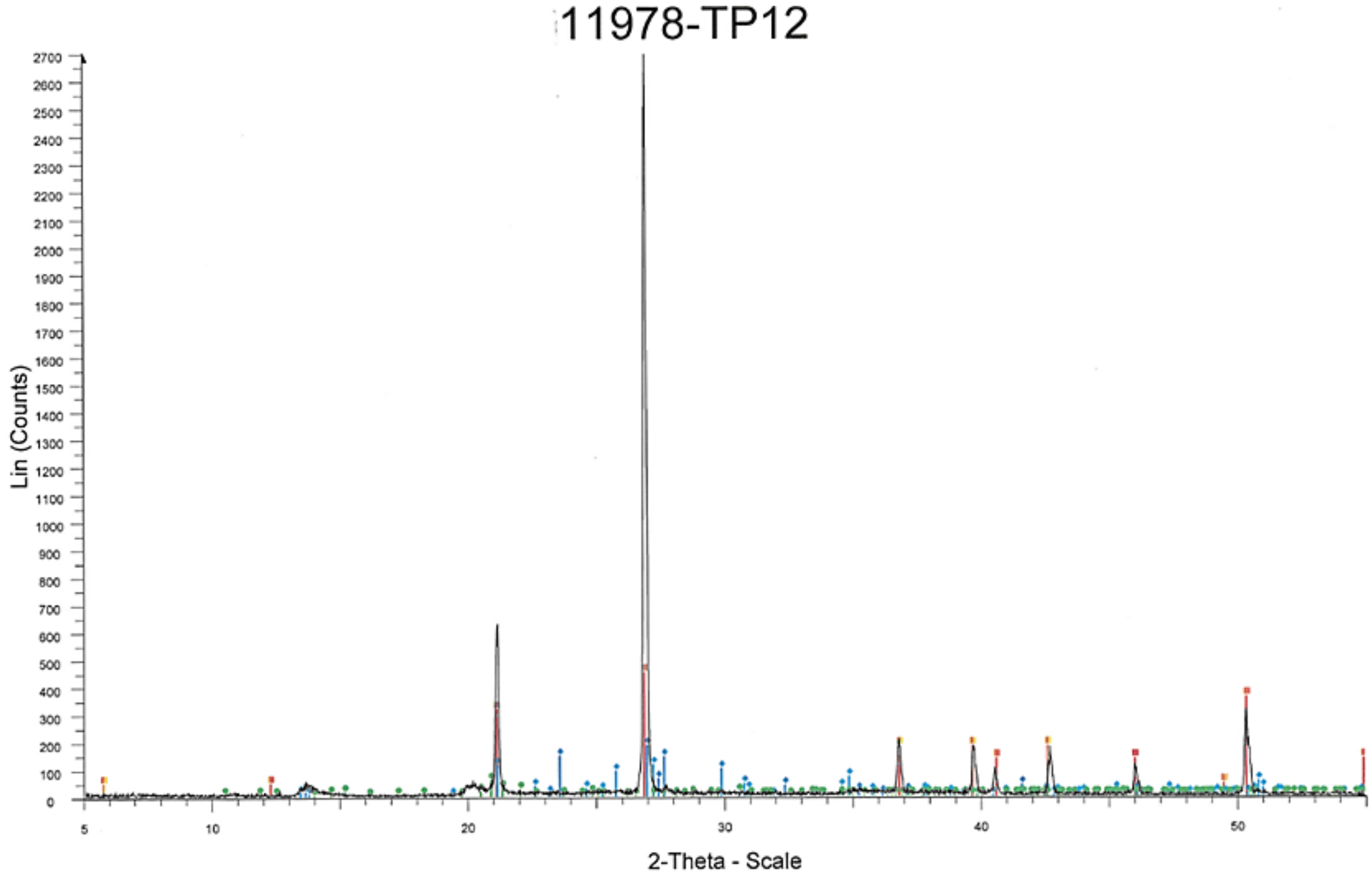


11978-TP04 - File: 20202164.raw - Type: 2Th/Th locked - Start: 5.000 ° - End: 55.000 ° - Step: 0.020 ° - Step time: 1. s - Temp.: 25 °C (Room) - Time Started: 7 s - 2-Theta: 5.000 ° - Theta: 2.500 ° - Chi: 0.
Operations: Background 0.000,1.000 | Import

◆ 01-071-1544 (C) - Sanidine low - KAlSi3O8 - Y: 2.41 % - d x by: 1. - WL: 1.5406 - Monoclinic - a 8.53900 - b 13.01500 - c 7.17900 - alpha 90.000 - beta 115.990 - gamma 90.000 - Base-centered - C2/m (12

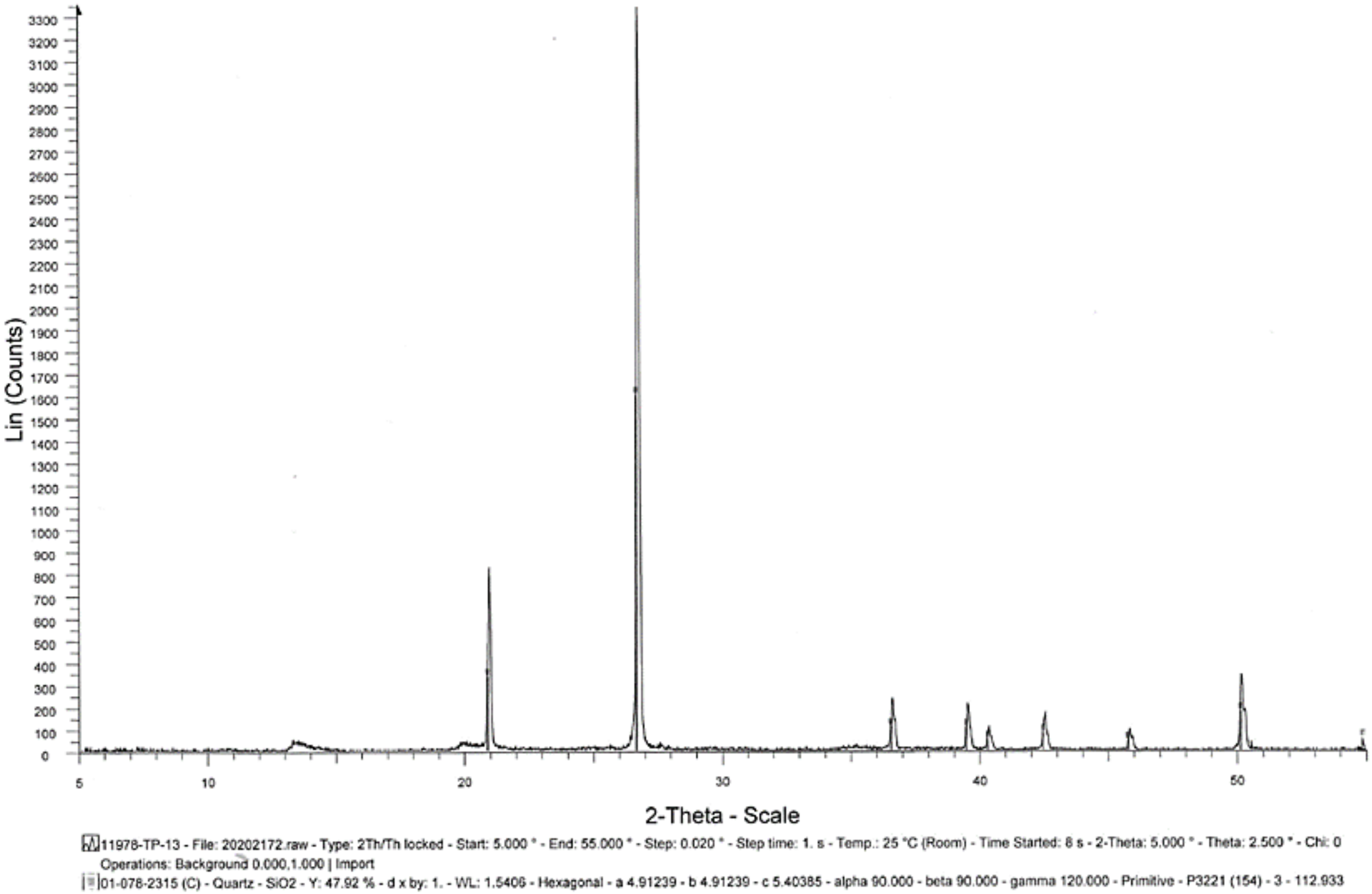
■ 01-086-1628 (C) - Quartz low - SiO2 - Y: 45.20 % - d x by: 1. - WL: 1.5406 - Hexagonal - a 4.90210 - b 4.90210 - c 5.39970 - alpha 90.000 - beta 90.000 - gamma 120.000 - Primitive - P3121 (152) - 3 - 112.

University of Pretoria



11978-TP12 - File: 20202162.raw - Type: 2Th/Th locked - Start: 5.000 ° - End: 55.000 ° - Step: 0.020 ° - Step time: 1. s - Temp.: 25 °C (Room) - Time Started: 10 s - 2-Theta: 5.000 ° - Theta: 2.500 ° - Chi: 0
Operations: Background 0.000,1.000 | Import
🟥 00-003-0444 (D) - Quartz - SiO2 - Y: 16.69 % - d x by: 1. - WL: 1.5406 - Hexagonal - a 4.90300 - b 4.90300 - c 5.39300 - alpha 90.000 - beta 90.000 - gamma 120.000 - Primitive - P3121 (152) - 3 - 112.275
◆ 01-071-1544 (C) - Sanidine low - KAlSi3O8 - Y: 6.85 % - d x by: 1. - WL: 1.5406 - Monoclinic - a 8.53900 - b 13.01500 - c 7.17900 - alpha 90.000 - beta 115.990 - gamma 90.000 - Base-centered - C2/m (12
● 01-071-1628 (C) - Rhodium Ammine Hydrogen Chlorate - RhH(NH3)5(ClO4)2 - Y: 2.08 % - d x by: 1. - WL: 1.5406 - Orthorhombic - a 10.28660 - b 8.06890 - c 15.01460 - alpha 90.000 - beta 90.000 - gam

11978-TP-13



11978-TP-13 - File: 20202172.raw - Type: 2Th/Th locked - Start: 5.000 ° - End: 55.000 ° - Step: 0.020 ° - Step time: 1. s - Temp.: 25 °C (Room) - Time Started: 8 s - 2-Theta: 5.000 ° - Theta: 2.500 ° - Chi: 0
Operations: Background 0.000,1.000 | Import
01-078-2315 (C) - Quartz - SiO2 - Y: 47.92 % - d x by: 1. - WL: 1.5406 - Hexagonal - a 4.91239 - b 4.91239 - c 5.40385 - alpha 90.000 - beta 90.000 - gamma 120.000 - Primitive - P3221 (154) - 3 - 112.933

APPENDIX G: SOIL BEARING CAPACITY CALCULATIONS

Terzaghi's bearing capacity formula for strip foundations.

$$qu = c'Nc + qNq + 0.5\gamma BN\gamma \quad (1)$$

From laboratory results cohesion (c) of this soil was found to be 6.3 kPa with an angle of friction (φ') of 25.8˚. The bearing capacity factors corresponding to 25.8˚, (which was approximated to 26˚) are as follows: $N_c = 22.25$, $N_q = 11.85$ and $N_\gamma = 12.54$. The density at natural moisture content was used to calculate unit weight of the soil (γ):

$$\gamma = \rho g \quad (2)$$

γ = density x gravitational acceleration = ρg

$= 1913.4 \text{ kg/ m}^3 \times 10 \text{ m/s}^2$

$= 19134 \text{ N/m}^3$

The unit weight of the soil was then used to calculate the effect of the soil that lies above the bottom of the foundation (overburden pressure), denoted as q. This is expressed as a product of the unit weight of the soil (γ) and the depth of foundation (D_f). The depth assumed for shallow foundations of low cost housing was 0.5 m. Therefore q was calculated as follows:

$$q = \gamma Df \quad (3)$$

$q = \gamma D_f$

$= 19134 \text{ N/m}^3 \times 0.5\text{m}$

$= 9567 \text{ N/m}^2$

The width for shallow foundations was assumed to be 0.6m.

Therefore,

$q_u = 6.3 \text{ kPa } (22.25) + 9567 \text{ N/m}^2 (11.85) + ½ (19134 \text{ N/m}^3) (0.6\text{m}) (12.54)$

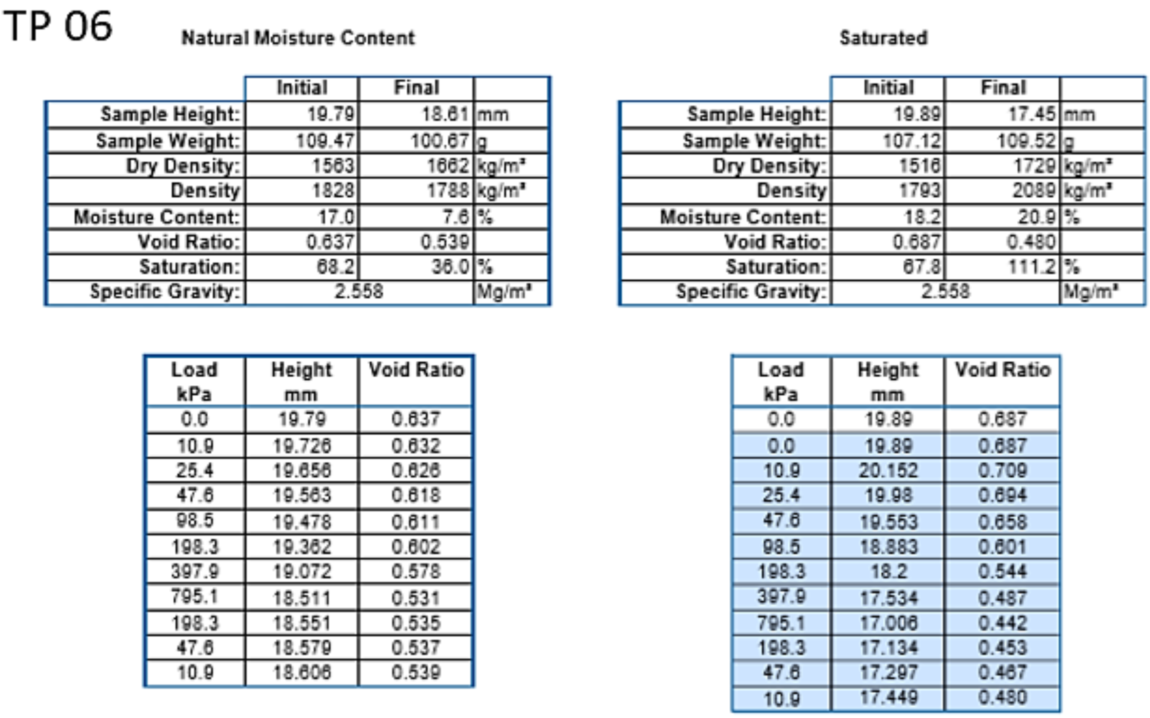
$= 140.175 \text{ kPa} + 113\ 368.95 \text{ N/m}^2 + 71\ 982.108 \text{ N/m}^2$

$= 140.175 \text{ kPa} + 185\ 351.058 \text{ N/m}^2$

$= 140175 \text{ N/m}^2 + 185\ 351.058 \text{ N/m}^2$

$= 325\ 526.058 \text{ N/m}^2$

APPENDIX H: SETTLEMENT AND COLLAPSE



TP 06

Natural Moisture Content

	Initial	Final	
Sample Height:	19.79	18.61	mm
Sample Weight:	109.47	100.67	g
Dry Density:	1563	1662	kg/m³
Density	1828	1788	kg/m³
Moisture Content:	17.0	7.6	%
Void Ratio:	0.637	0.539	
Saturation:	68.2	36.0	%
Specific Gravity:	2.558		Mg/m³

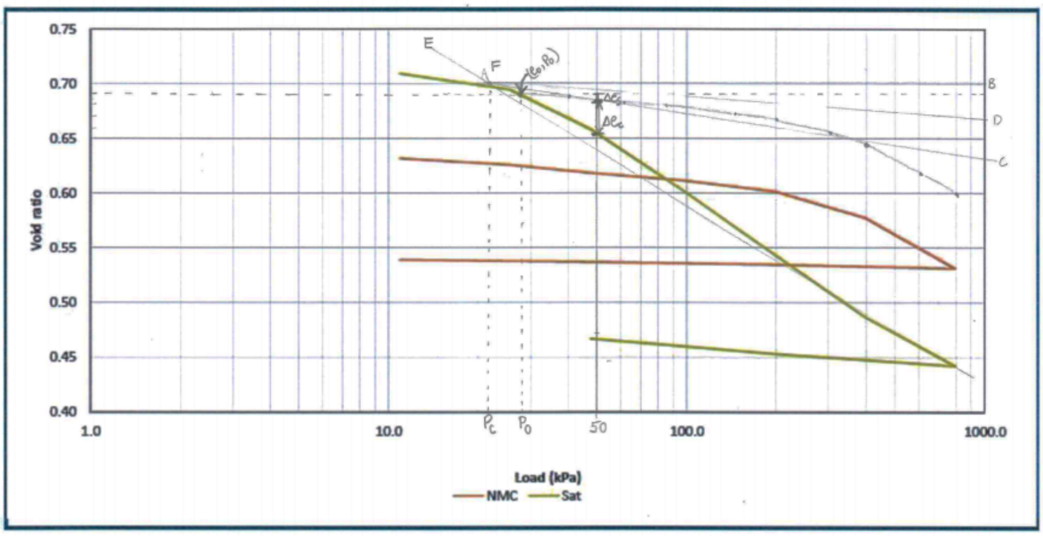
Load kPa	Height mm	Void Ratio
0.0	19.79	0.637
10.9	19.726	0.632
25.4	19.656	0.626
47.6	19.563	0.618
98.5	19.478	0.611
198.3	19.362	0.602
397.9	19.072	0.578
795.1	18.511	0.531
198.3	18.551	0.535
47.6	18.579	0.537
10.9	18.606	0.539

Saturated

	Initial	Final	
Sample Height:	19.89	17.45	mm
Sample Weight:	107.12	109.52	g
Dry Density:	1516	1729	kg/m³
Density	1793	2089	kg/m³
Moisture Content:	18.2	20.9	%
Void Ratio:	0.687	0.480	
Saturation:	67.8	111.2	%
Specific Gravity:	2.558		Mg/m³

Load kPa	Height mm	Void Ratio
0.0	19.89	0.687
0.0	19.89	0.687
10.9	20.152	0.709
25.4	19.98	0.694
47.6	19.553	0.658
98.5	18.883	0.601
198.3	18.2	0.544
397.9	17.534	0.487
795.1	17.006	0.442
198.3	17.134	0.453
47.6	17.297	0.467
10.9	17.449	0.480

TP 06



$P_c = 21$ kPa

$P_0 = 27$ kPa

$P_c/P_0 = 0.777$

$\cong 0.8$

$\Rightarrow$ Normally consolidated

$e_0 = 0.69$

1. Reconstruction of P_c done on the double oedometer plot:

$P_c = 21$ kPa

Calculating P_o

Initial dry density = 1516 kg/m^3

Initial moisture content = 18.2 %

$\therefore$ Density at initial moisture content

$= 1516\ \text{kg/m}^3 \left(1 + \frac{18.2}{100}\right)$

$= 1791.912\ \text{kg/m}^3$

$P_o = \gamma H$, where H = sample depth and γ = density at initial moisture content

$\gamma = 1792\ \text{kg/m}^3 \text{ x } 10\ \text{m/s}^2$

= 1792 Pa

= 17.9 kPa

$\therefore P_o = 17.9$ kPa x 1.5 m

= 26.85 kPa

$P_c / P_o = \frac{21\ kP_a}{26.85 kP_a} = 0.7777$, which is approximated to 0.8 $\therefore$ implies that the soils are normally consolidated.

2. Adjusting curves

$P_o = 26.85$ kPa

corresponding $e_o = 0.69$

Foundation stress is assumed to be 50 kPa for low-cost housing

From the graph, at 50 kPa,

$\Delta\ e_s = 0.69 - 0.68 = 0.01$

and,

$\Delta\ e_c = 0.68 - 0.655 = 0.025$

Unit settlement without change in moisture content

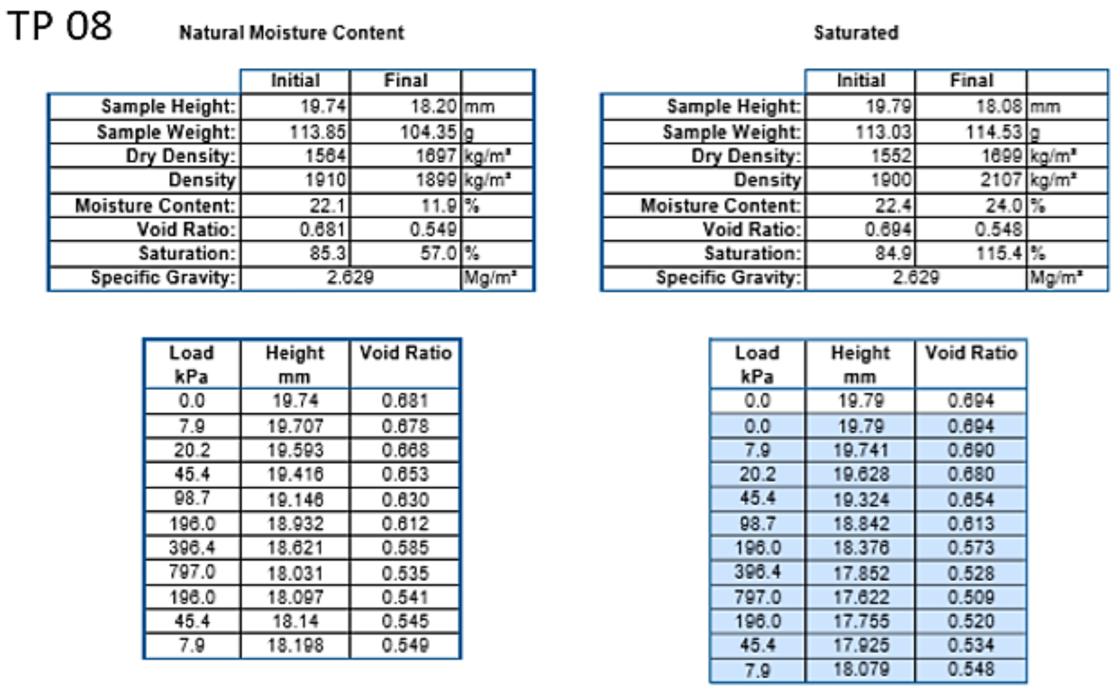
$\Delta\ e_s / 1 + e_o = \frac{0.01}{1+0.69} = 0.005917$ mm/ mm (same as 5.92 mm/ m)

i.e. 6 mm/ m.

Unit settlement with increased moisture content (collapse settlement)

$\Delta\ e_c / 1 + e_o = \frac{0.025}{1+0.69} = 0.01479$ mm/ mm (same as 14.79 mm/ m)

i.e. ~ 15 mm/ m



TP 08

Natural Moisture Content

	Initial	Final	
Sample Height:	19.74	18.20	mm
Sample Weight:	113.85	104.35	g
Dry Density:	1564	1697	kg/m³
Density	1910	1899	kg/m³
Moisture Content:	22.1	11.9	%
Void Ratio:	0.681	0.549	
Saturation:	85.3	57.0	%
Specific Gravity:	2.629		Mg/m³

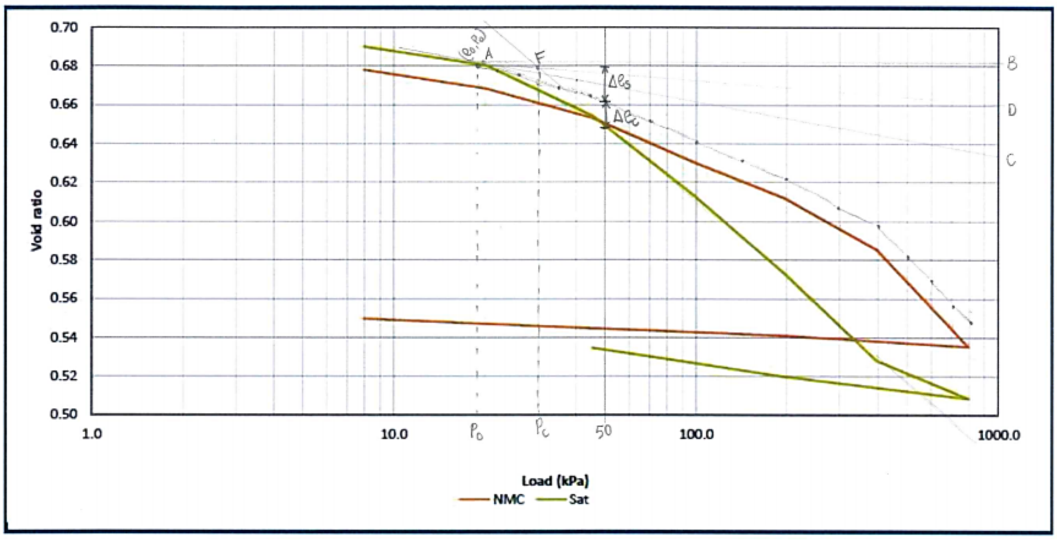
Saturated

	Initial	Final	
Sample Height:	19.79	18.08	mm
Sample Weight:	113.03	114.53	g
Dry Density:	1552	1699	kg/m³
Density	1900	2107	kg/m³
Moisture Content:	22.4	24.0	%
Void Ratio:	0.694	0.548	
Saturation:	84.9	115.4	%
Specific Gravity:	2.629		Mg/m³

Load kPa	Height mm	Void Ratio
0.0	19.74	0.681
7.9	19.707	0.678
20.2	19.593	0.668
45.4	19.416	0.653
98.7	19.146	0.630
196.0	18.932	0.612
396.4	18.621	0.585
797.0	18.031	0.535
196.0	18.097	0.541
45.4	18.14	0.545
7.9	18.198	0.549

Load kPa	Height mm	Void Ratio
0.0	19.79	0.694
0.0	19.79	0.694
7.9	19.741	0.690
20.2	19.628	0.680
45.4	19.324	0.654
98.7	18.842	0.613
196.0	18.376	0.573
396.4	17.852	0.528
797.0	17.622	0.509
196.0	17.755	0.520
45.4	17.925	0.534
7.9	18.079	0.548

TP 08



$P_c = 30$ kPa

$P_0 = 19$ kPa

$P_c / P_0 = 1.58$

⇒ over consolidated.

$e_0 = 0.68$

1. Reconstruction of P_c done on the double oedometer plot:

$P_c = 30$ kPa

Calculating P_o

Initial dry density = 1552 kg/m^3

Initial moisture content = 22.4 %

∴ Density at initial moisture content

$= 1552\ \text{kg/m}^3 \left(1 + \frac{22.4}{100}\right)$

$= 1899.648\ \text{kg/m}^3$

$P_o = \gamma H$, where H = sample depth and γ = density at initial moisture content

$\gamma = 1899.648\ \text{kg/m}^3 \text{ x } 10\ \text{m/s}^2$

$= 19000$ Pa

$= 19$ kPa

$\therefore P_o = 19$ kPa x 1.0 m

$= 19$ kPa

$P_c / P_o = \frac{30 kP_a}{19\ kP_a} = 1.58$, which is greater than 1.5, which implies that the soils are over consolidated

2. Adjusting curves

$P_o = 19$ kPa

corresponding $e_o = 0.68$

Foundation stress is assumed to be 50 kPa for low-cost housing

From the graph, at 50 kPa,

$\Delta\ e_s = 0.68 – 0.665 = 0.015$

and,

$\Delta\ e_c = 0.665 – 0.645 = 0.02$

Unit settlement without change in moisture content

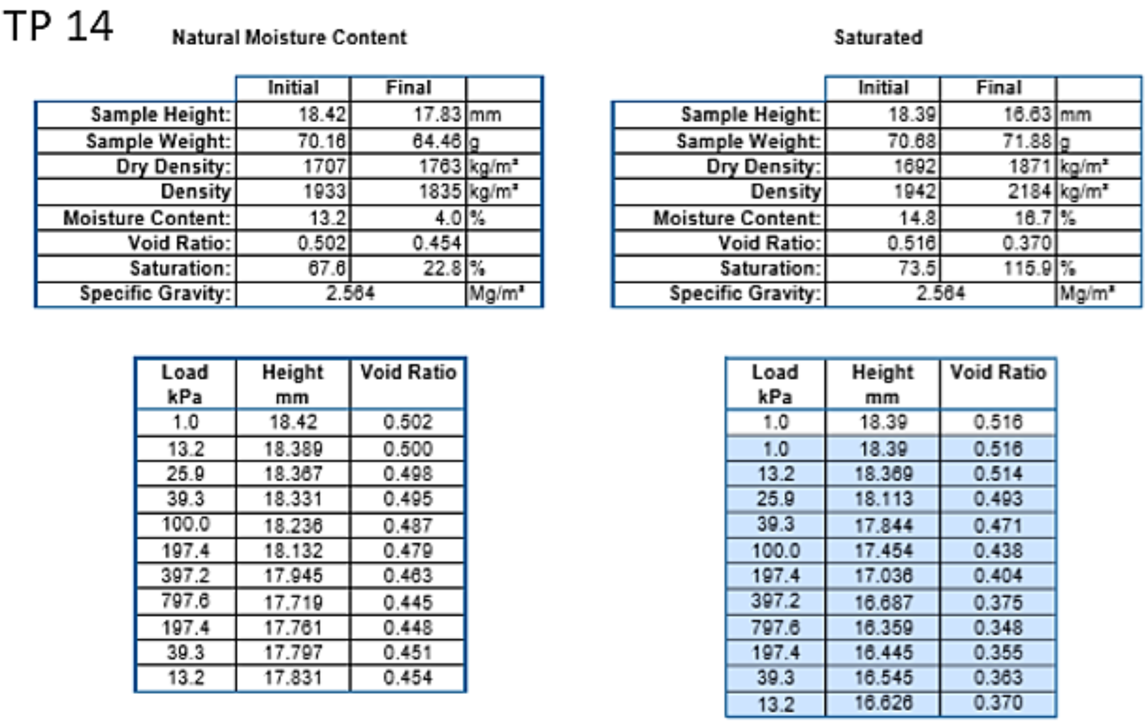
$\Delta\ e_s / 1 + e_o = \frac{0.015}{1+0.68} = 8.93$ mm/ m

i.e. 9 mm/ m.

Unit settlement with increased moisture content (collapse settlement)

$\Delta\ e_c / 1 + e_o = \frac{0.02}{1+0.68} = 11.9$ mm/ m

i.e. ~ 12 mm/ m



TP 14

Natural Moisture Content

	Initial	Final	
Sample Height:	18.42	17.83	mm
Sample Weight:	70.16	64.46	g
Dry Density:	1707	1763	kg/m³
Density	1933	1835	kg/m³
Moisture Content:	13.2	4.0	%
Void Ratio:	0.502	0.454	
Saturation:	67.6	22.8	%
Specific Gravity:	2.564		Mg/m³

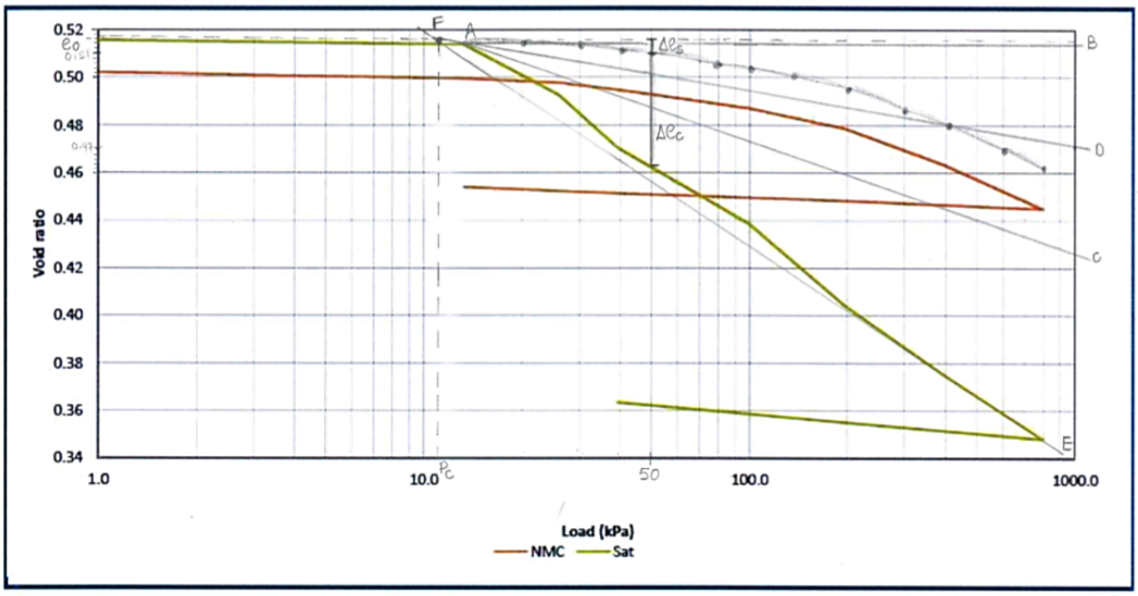
Saturated

	Initial	Final	
Sample Height:	18.39	16.63	mm
Sample Weight:	70.68	71.88	g
Dry Density:	1692	1871	kg/m³
Density	1942	2184	kg/m³
Moisture Content:	14.8	16.7	%
Void Ratio:	0.516	0.370	
Saturation:	73.5	115.9	%
Specific Gravity:	2.564		Mg/m³

Load kPa	Height mm	Void Ratio
1.0	18.42	0.502
13.2	18.389	0.500
25.9	18.367	0.498
39.3	18.331	0.495
100.0	18.236	0.487
197.4	18.132	0.479
397.2	17.945	0.463
797.6	17.719	0.445
197.4	17.761	0.448
39.3	17.797	0.451
13.2	17.831	0.454

Load kPa	Height mm	Void Ratio
1.0	18.39	0.516
1.0	18.39	0.516
13.2	18.369	0.514
25.9	18.113	0.493
39.3	17.844	0.471
100.0	17.454	0.438
197.4	17.036	0.404
397.2	16.687	0.375
797.6	16.359	0.348
197.4	16.445	0.355
39.3	16.545	0.363
13.2	16.626	0.370

TP 14



$P_c = 12kPa$

$P_o = 11.64kPa$

$P_c/P_o = 1.03$

⇒ normally consolidated.

$e_0 = 0.518$

$F = (P_c, e_0)$

TP 14

1. Reconstruction of $P_{c\ done}$ on the double oedometer plot:

$P_c = 12kPa$

Calculating P_o

Initial dry density = 1692 kg/m^3

Initial moisture content = 14.8 %

$\therefore$ Density at initial moisture content

$= 1692\ \text{kg/m}^3 \left(1 + \frac{14.8}{100}\right)$

$= 1942.416\ \text{kg/m}^3$

$P_o = \gamma H$, where H = sample depth and γ = density at initial moisture content

$\gamma = 1942\ \text{kg/m}^3 \text{ x } 10\ \text{m/s}^2$

= 19420 Pa

= 19.4 kPa

$\therefore P_o = 19.4$ kPa x 0.6 m

= 11.64 kPa

$P_c / P_o = \frac{12\ kP_a}{11.6\ kP_a}$ = 1.03, which is between 0.8 and 1.5, which implies that the soils are normally consolidated

2. Adjusting curves

$P_o = 11.64$ kPa

corresponding $e_o = 0.516$

Foundation stress is assumed to be 50 kPa for low-cost housing

From the graph, at 50 kPa,

$\Delta\ e_s = 0.516 - 0.510 = 0.006$

and,

$\Delta\ e_c = 0.510 - 0.462 = 0.048$

Unit settlement without change in moisture content

$\Delta\ e_s / 1 + e_o = \frac{0.006}{1+0.516}$ = 0.00395 mm/ mm (same as 3.957 mm/ m)

i.e. 4 mm/ m.

Unit settlement with increased moisture content (collapse settlement)

$\Delta\ e_c / 1 + e_o = \frac{0.048}{1+0.516} =$ 0.03166 mm/ mm (same as 31.66 mm/ m)

i.e. ~ 32 mm/ m

APPENDIX I: THE ELECTRIC CONDUCTIVITY AND PH OF OUTAPI SOILS

Sample ID	pH	Electric conductivity (EC) in S/m	Remark
CM1	7.55	0.36	Corrosive
CM3	7.48	1.87	Very corrosive
TP02	8.51	0.441	Very corrosive
TP04	8.03	0.364	Very corrosive
TP10-1	9.09	0.163	Very corrosive
TP10-2	5.8	0.0123	Mildly corrosive
AH1-1	6.78	0.0455	Corrosive
AH1-2	7.53	0.0618	Very corrosive
AH3-1	7.42	0.0235	Corrosive
AH5-1	7.49	0.0397	Corrosive
AH5-2	8.43	0.0662	Very corrosive