CHAPTER 1

INTRODUCTION

Any rock type in opencast extraction is always susceptible to slope-stability problems. The slope profile is usually an inhomogeneous structure comprising anisotropic layers characterised by different strength parameters. These composite structures often present problems, raising questions about stresses and deformations specifically related to weaker layers or regions in the rock mass. The widely used slope-stability modelling with equilibrium methods has proved ineffective for studying the effects of horizontal stress and complex geotechnical conditions because they generally assume homogeneity, isotropy, and simple structure.

One of the most recognised books (in the field of rock slope design), namely "Rock Slope Engineering" (Hoek and Bray, 1981) was first published 26 years ago, and there have been few new developments in slope stability analysis since. The means for predicting the number and tonnage of multibench structurally controlled failures (wedge, plane shear and step-wedge) are also well developed in the CANMET(1997) "Pit Slope Manual", but this manual brings few new developments to slope stability analysis. Anderson and Richards, (1992) stated that rockmass strength models, developed stress field models, and rockmass displacement models for overall slope instability had not yet been developed, and this remains true today.

1.1 BACKGROUND TO THE PROBLEM

Most textbooks on soil mechanics or geotechnical engineering include references to several alternative limit equilibrium methods of slope-stability analysis. In a survey of these methods, undertaken by Wright et al. (1973), the characteristics of all accepted methods were summarised, including the ordinary method of slices (Fellenius, 1936), Bishop's Modified Method (Bishop, 1955), force equilibrium methods (e.g. Lowe and Karafiath, 1960), Janbu's procedure for slices (Janbu, 1957), Morgenstern and Price, (1965) and Spencer's method (Spencer, 1967). There seems to be some consensus that the Morgenstern-Price method is one of the most reliable.

All limit equilibrium methods are based on an assumption that the failing soil mass could be divided into slices. This slicing requires further assumptions regarding the magnitude and direction of the side forces influencing equilibrium. The assumption made about side forces is one of the main characteristics that distinguishes one limit equilibrium method from another, and yet is itself an entirely artificial distinction (Bromhead, 1992).

By using these analytical techniques, some broad assumptions are made for each of the failure modes, particularly where the failure mode is other than classic:

a) Constant shear strength along the failure surface;
b) Distribution of normal stress round the slip surface;

c) Distribution of interslice forces along the profile;

d) The position of the line of thrust; and

e) The *k* - ratio ($k=\sigma_H/\sigma_V$) influence on the slope-stability and failure surface.

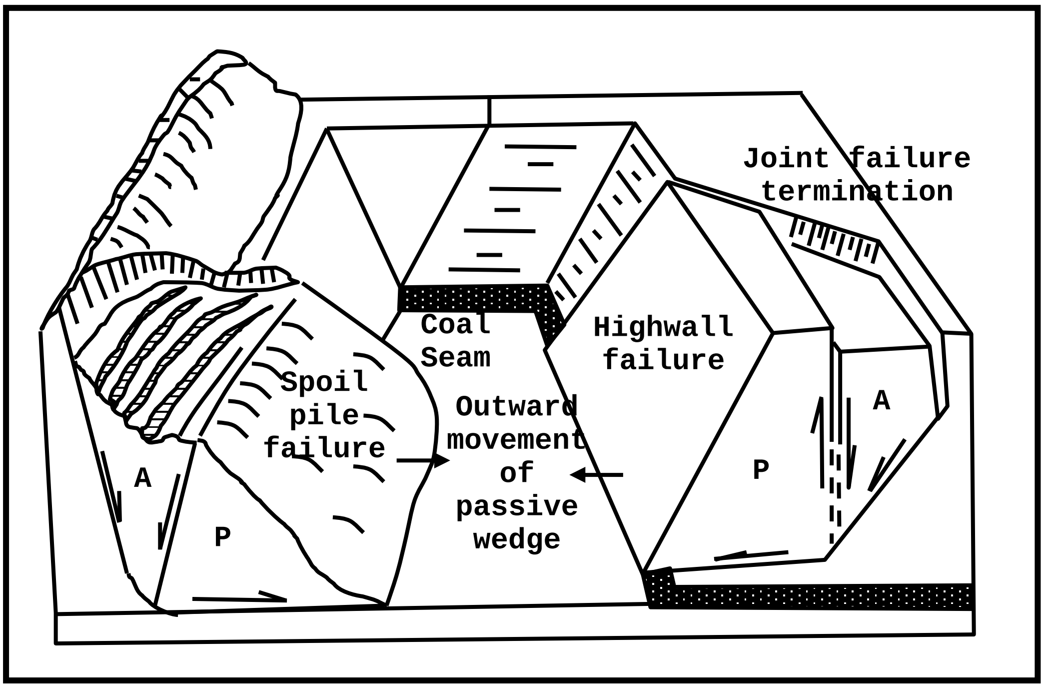


Figure 1.1

Slope and spoil failures reported by Boyd (1983)

Sturman (1984), Singh and Singh (1992), Malgot et al. (1986) and Boyd (1983 – Figure 1.1) reported different cases of slope instabilities. The failure events in their analyses dealt with divergences from the standard failure modes. In the considered cases, all of these authors recognise two block types (the so called "passive" and "active" block), which constitute the failure.

Stead and Scoble (1983) analysed 226 slope instabilities that took place in British coal mines. Their study (Figure 1.2) shows that in about 66% of the failures (the planar, biplanar and multi planar modes) the failure mode is different from the classic model as geological features trigger almost half of them. The remaining planar failures appear to be stress related. At present there is no reliable technique for application to such cases.

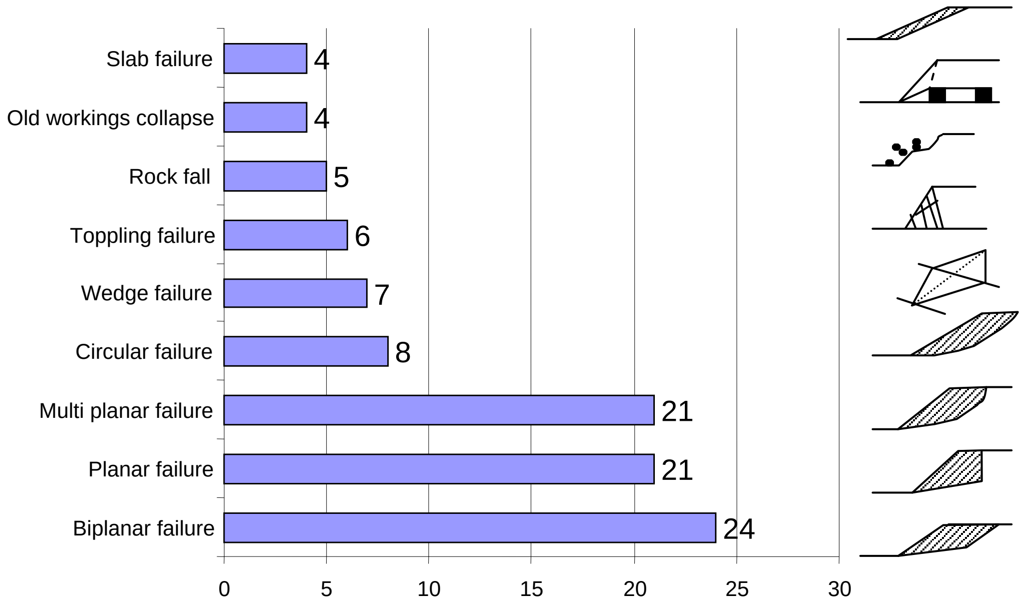
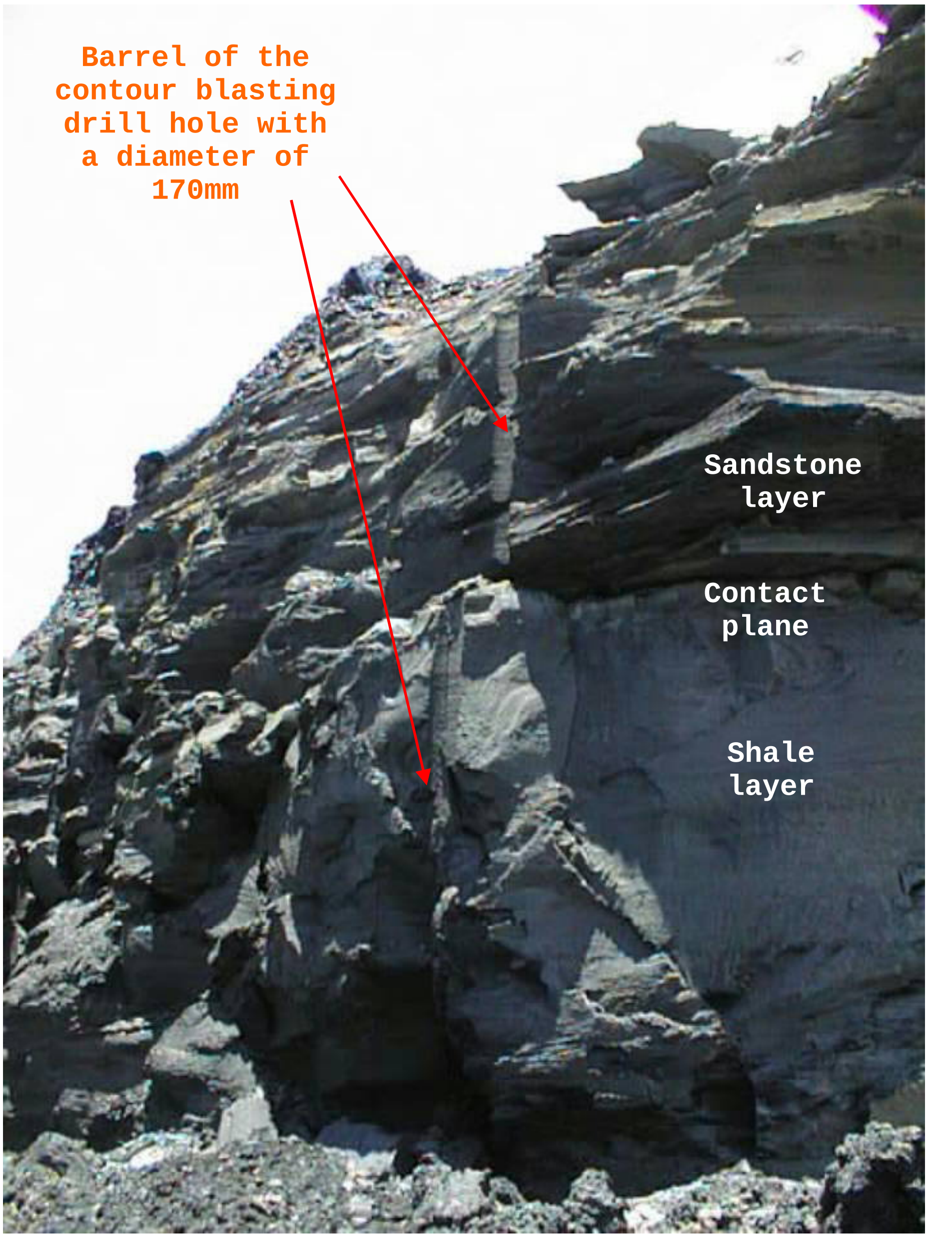


Figure 1.2

Typical failure modes (given in percentages) based on 226 study cases (after Stead and Scoble, 1983)

The author has experience with slope failures that have taken place in South African coalfields. Some coal mines exploit uneven seams in undulated strata, where slope failures exhibit the passive wedge mode as shown on Figure 1.1. The author's observations were that the most common effect of faulting in such a situation was the provision of a rear release plane, frequently with associated adversely dipping strata. In almost all of the cases, a relatively weaker layer was embedded in the profile and exposed at the toe of the slope. In almost all of the cases the weaker layer was shale. In the areas with almost flat strata it is usual to have swelling in such a shale layer, as can be seen on Picture 1.1.

The failure situation becomes more complicated if opencast mining activities are in progress in the vicinity of existing undulated strata formations. The potential for slope failure increases when these strata formations form inclined beds, dipping toward the pit.



Picture 1.1

Shale swelling exposed at the toe of slope in gently inclined strata (strata inclined at 5^0)

Further complications could be created by the remains of old mining activities in the form of pillars left underground, and now exposed at the toe of the slope.

1.1.1 Geological history and its effect on geotechnical complexity

A representative stratigraphic column can be seen in Figure 1.3. The principal palaeo-feature of the deposits is the uneven dolomite base, which has led to sediments deposited on it being uneven. The strata are not uniformly thick or level, but undulate following the dolomite base. The coal seams, as well as the other strata, are thinner above palaeo-highs and thicker above palaeo-lows. This feature has resulted in strata dipping up to 15^0 between crests and troughs in the dolomite palaeo-surface. The dolomite highs themselves are dome shaped and 200-300m in diameter. Refer to Figure 1.10 for typical features of the geological formations.

Note that the undulated strata formations described above are definitely not tectonic formations, but are the result of weathering and chemical erosion, which has sculpted a karstic topography on this dolomitic basement. This process was followed by glaciation, which smoothed the rugged karstic topography and formed tillite deposits in the sinkholes. Cairncross (1989) states that the coal sequence accumulated in the fringes of fluid-glacial currents at the end of the Paleozoic when the southern tip of Africa was located near the South Pole.

The above-described processes generated a rugged topography of ridges and sinkholes prior to the accumulation of the coal-bearing sequence above it. The undulated strata reflect the underlying dolomitic palaeo-surface by having a similar topography, in that they are approximately circular in form in plan (with a diameter of a few hundred metres) and have a hill-like form. The dolomite palaeo-surface was formed in white dolomite belonging to the Transvaal Supergroup. Further widening and joining of the karstic features in the dolomite after the deposition of the overlying sediments also contributed to the degree of undulation in formations in the overlying coal bearing strata.

Cairncross (1989) asserts that the development of coal on top of glacial deposits represents the corresponding rise in temperatures as Africa drifted away from the extreme latitudes. A more temperate climate allowed the growth of mostly deciduous vegetation in a swampy near-shore environment where rivers transported re-worked glacial tillite materials into a subsiding intracratonic basin. The coal-bearing strata probably represent the gradual formation and final drowning of retrogressive deltaic lobes, where fluid-glacial features of the Dwyka formation are overlain by retrograde deltaic sediments, which are in turn overlain by beach and marine deposits of the now-recognised Hard Overburden, and Hard Interburden (see Figure 1.3) as the sea level gradually rises (Cairncross, 1989). Grit, sand and mudstone partings within the coal seams may represent clastic inundation of peat swamps by mud from anastomosing currents, and occasional marine incursions (Cairncross, 1989).

Diagenesis and coalification of lignite deposits occurred after the onset of regional extension related to the break-up of Gondwana during the late Paleozoic to early Triassic, and corresponding intrusion of doleritic dykes (Snyman and Barclay, 1989).

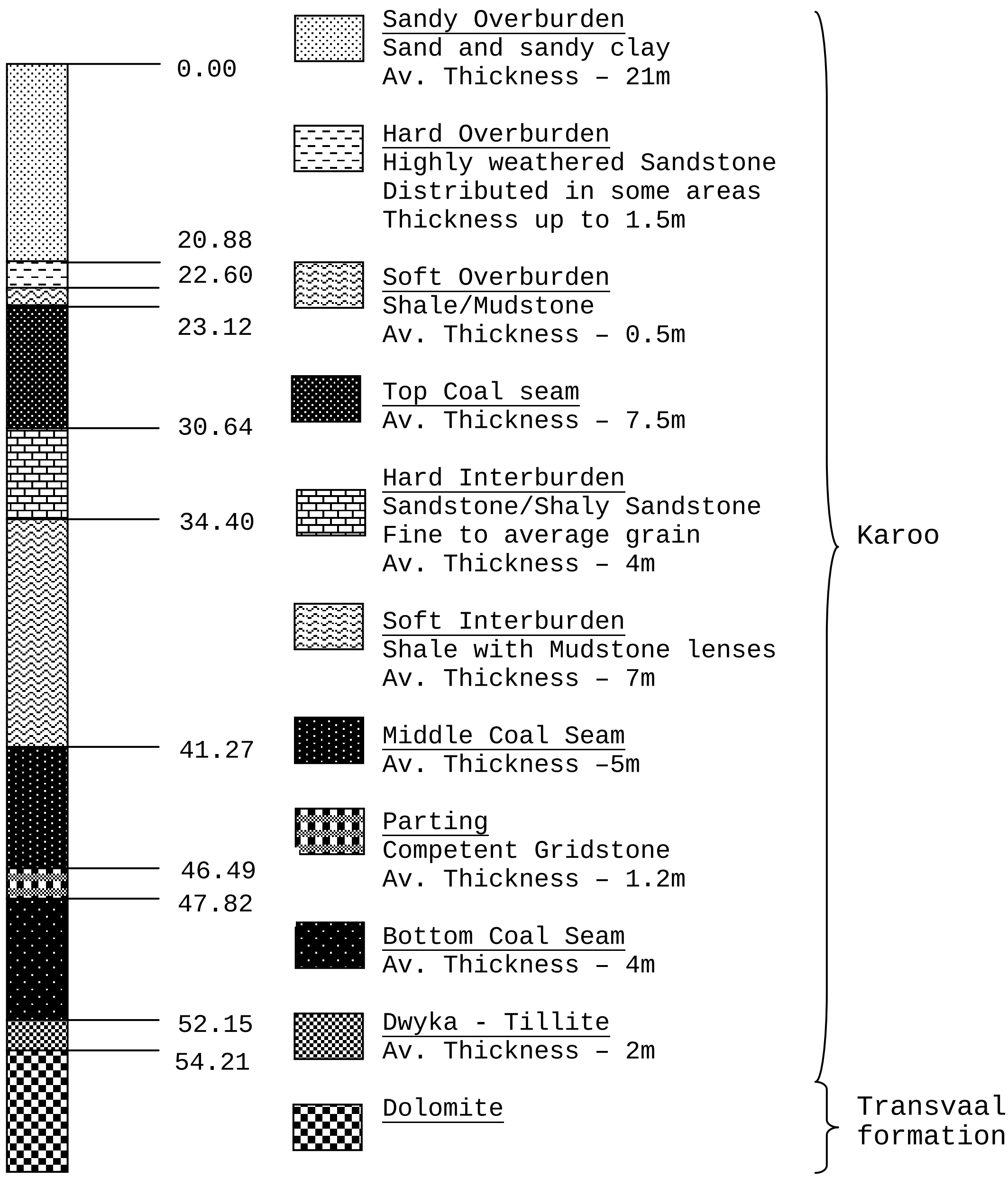


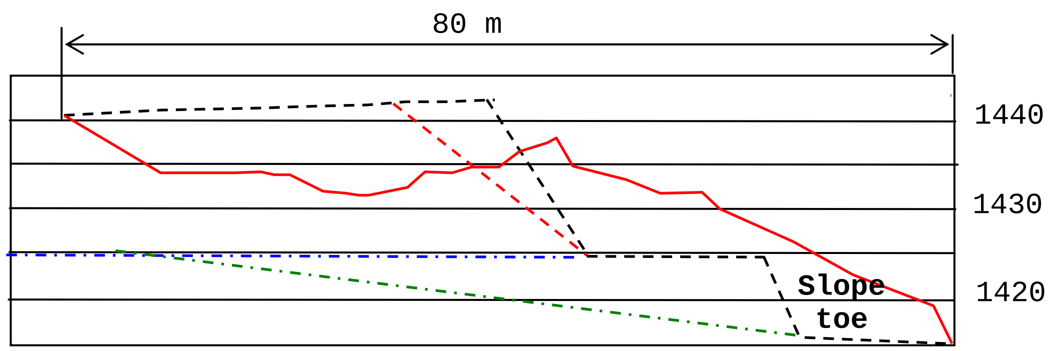
Figure 1.3

Representative stratigraphic column (after Mattushek, 1985)

The geological sequence that appears in Figure 1.3 is reproduced after Mattushek (2005), showing the representative stratigraphic column in which slope failure examples taken from Colliery "A" will be described.

1.1.2 Slope failures in complex geotechnical conditions

Opencast Colliery "A" mines three coal seams with an average total thickness of approximately 16m. Figure 1.3 presents the colliery stratigraphic column. A map of Colliery A showed old coal pillars, left in some areas in the middle coal seam, in other areas, the bottom coal seam, and sometimes superimposed upon one another in both seams. The upper coal seam was never mined.



Legend

---- Slope profile before initial failure
---- Slope profile after initial failure
—— Slope profile after major collapse
-·-·- Bottom contact of the embedded shale layer
-·-·- Bottom contact of the sandy overburden

Figure 1.4

Initial and main failure profile in Pit "A-1" (after SRK – 1995)

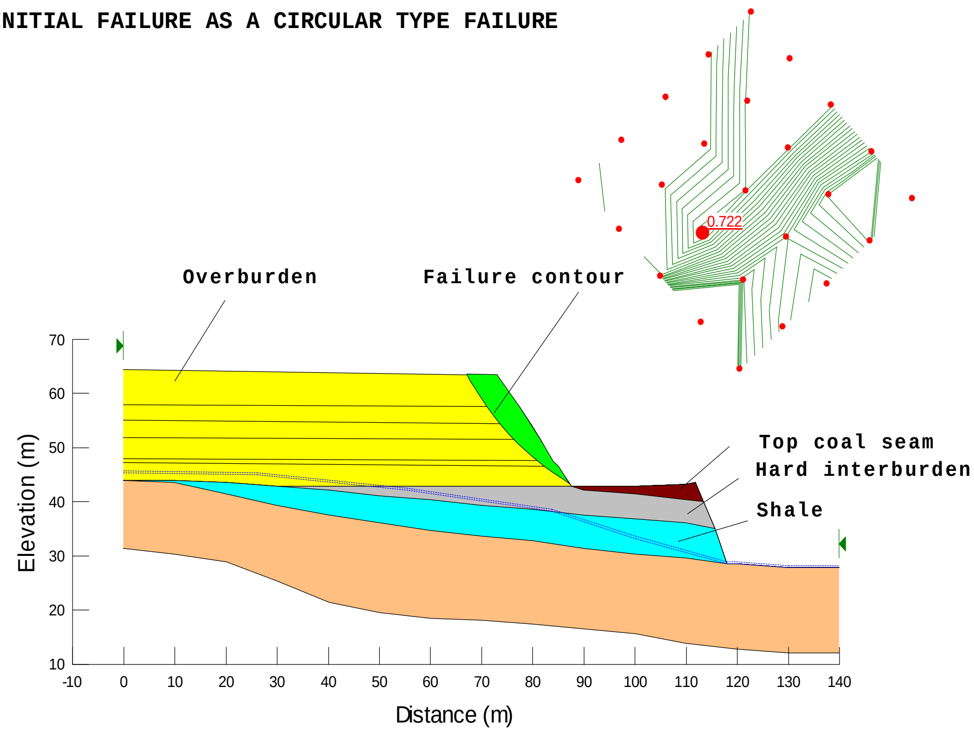
Two slope failures took place during different seasons and in different pits but in both cases the strata dip towards the pit. The widely used computer program "SLOPE/W" developed by Geo Slope International particularly for circular and blocky failure, aided the failure analysis undertaken by the author.

The first case of slope failure took place in pit "A-1" in an undulated stratum at the shaly contact between the shaly interburden and the middle coal seam with a dip angle of 10^0 to 12^0 towards the pit. The top coal seam in the area was very thin (in the range of 1m). The failure took place in two stages: the initial failure (involving only the sandy overburden) and the major collapse, which slipped along the bottom contact of the shale layer above the middle coal seam. The slope profiles before and after failure can be seen in Figure 1.4. Owing to the calculated factor of safety (FOS=0.72), the initial failure can be recognised as probably circular. SLOPE/W outputs showing initial failure profiles for circular and blocky failure appear in Figure 1.5.

The major collapse followed the cleaning operations that took place after the initial failure, when the slope profile had a lower slope angle than it had prior to failure (compare Figures 1.5 and 1.6). The major failure indicates a multi-planar or blocky type of failure, but the applied block-specified technique used for the FOS calculation was not successful, because the calculated FOS value was higher than unity. SLOPE/W outputs are shown in Figure 1.6. Mine plans did not show any underground mining activities in the area underneath the failure.

PIT A-1

INITIAL FAILURE AS A CIRCULAR TYPE FAILURE



PIT A-1

INITIAL FAILURE AS A POSIIBLE MULTI-PLANAR (BLOCKY) TYPE OF FAILURE

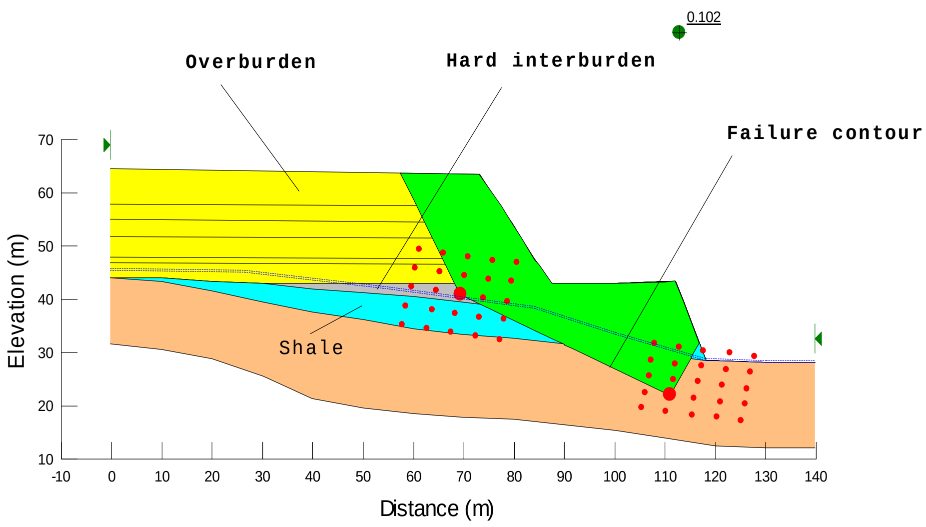
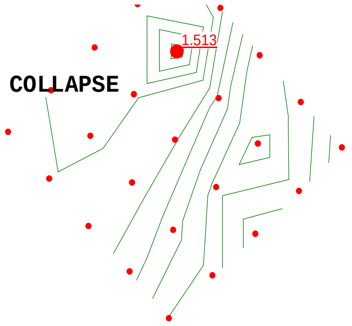


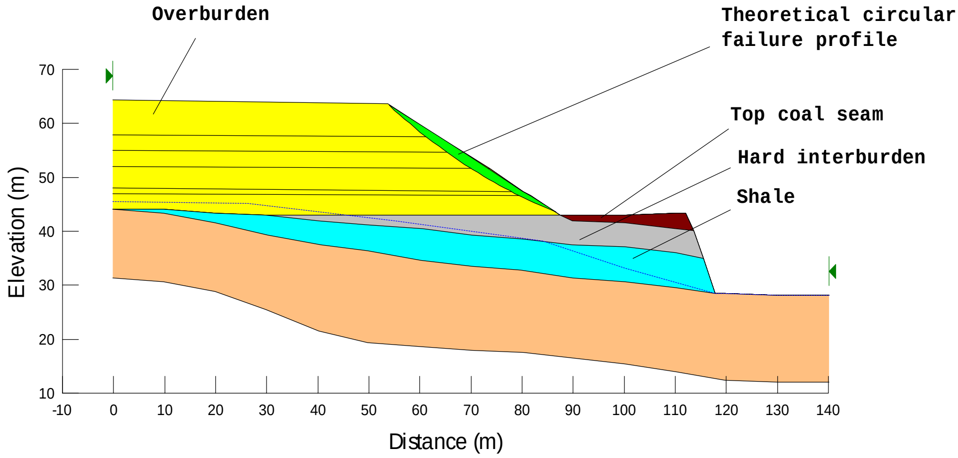
Figure 1.5

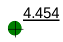
Theoretical failure profiles which resulted in initial collapse of sandy overburden – Pit A-1 (note higher slope angle in sandy overburden compared with Figure 1.6)

PIT A-1

POSSIBLE CIRCULAR TYPE OF FAILURE BEFORE MAJOR COLLAPSE







PIT A-1

POSSIBLE BLOCKY TYPE OF FAILURE BEFORE MAJOR COLLAPSE

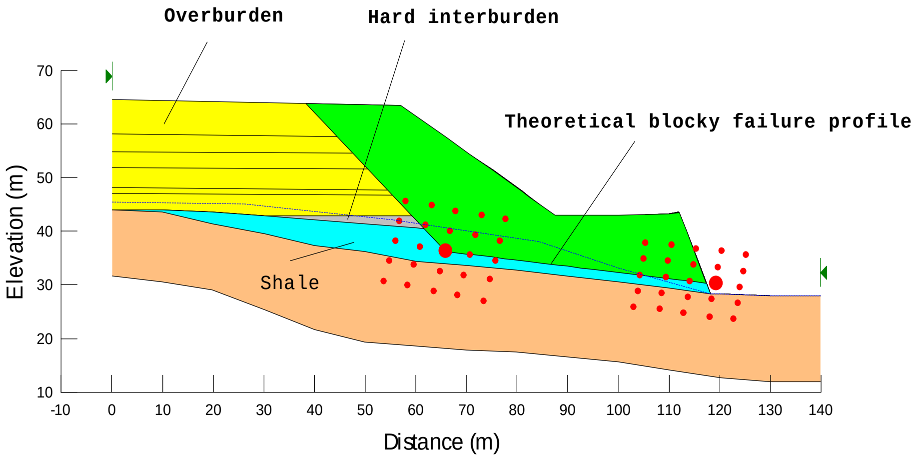


Figure 1.6

Theoretical failure profiles for final major slope collapse after the initial failure had been cleared– Pit A-1 (note lower slope angle in sandy overburden)

The second slope failure took place in Pit “A-2” of the same colliery. Figure 1.7 presents the slope profile before and after the failure, while Figure 1.8 shows possible failure mechanisms. Spoils with heights of 20m to 25m were dumped at a distance of approximately 20m behind the slope crest. Any joints that might have triggered wedge failure were not observed in the area.

Without any visible indications or warnings of impending failure, the slope collapsed, and this failure involved the spoils, overburden, top coal seam, and interburden between the top coal seam and the middle coal seam.

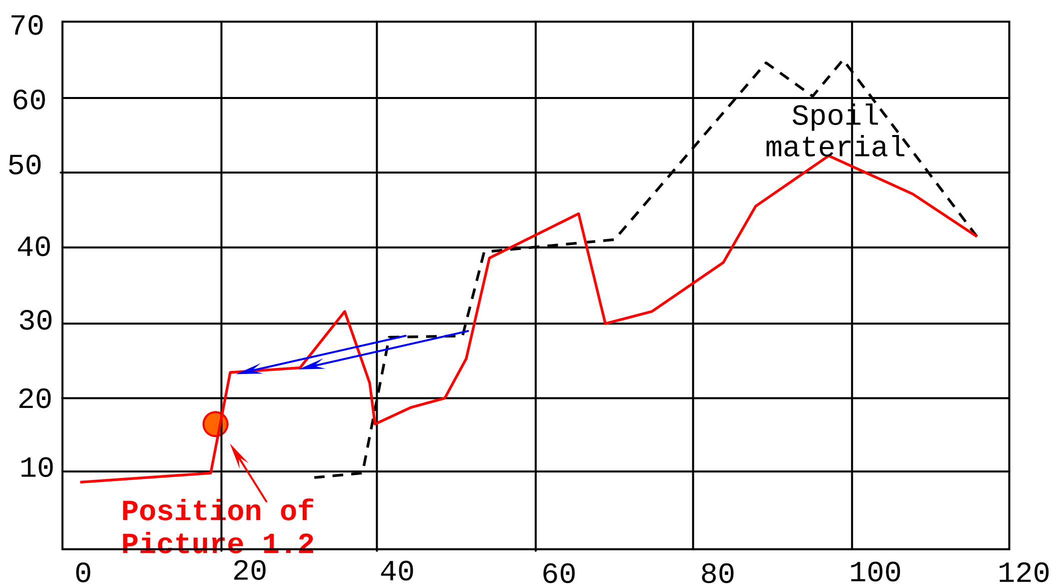


Figure 1.7

Slope profile before failure (marked with dotted black line) and after failure (marked with red line). Blue arrows indicate movements of the face block, while the red line shows valley formation behind the face block

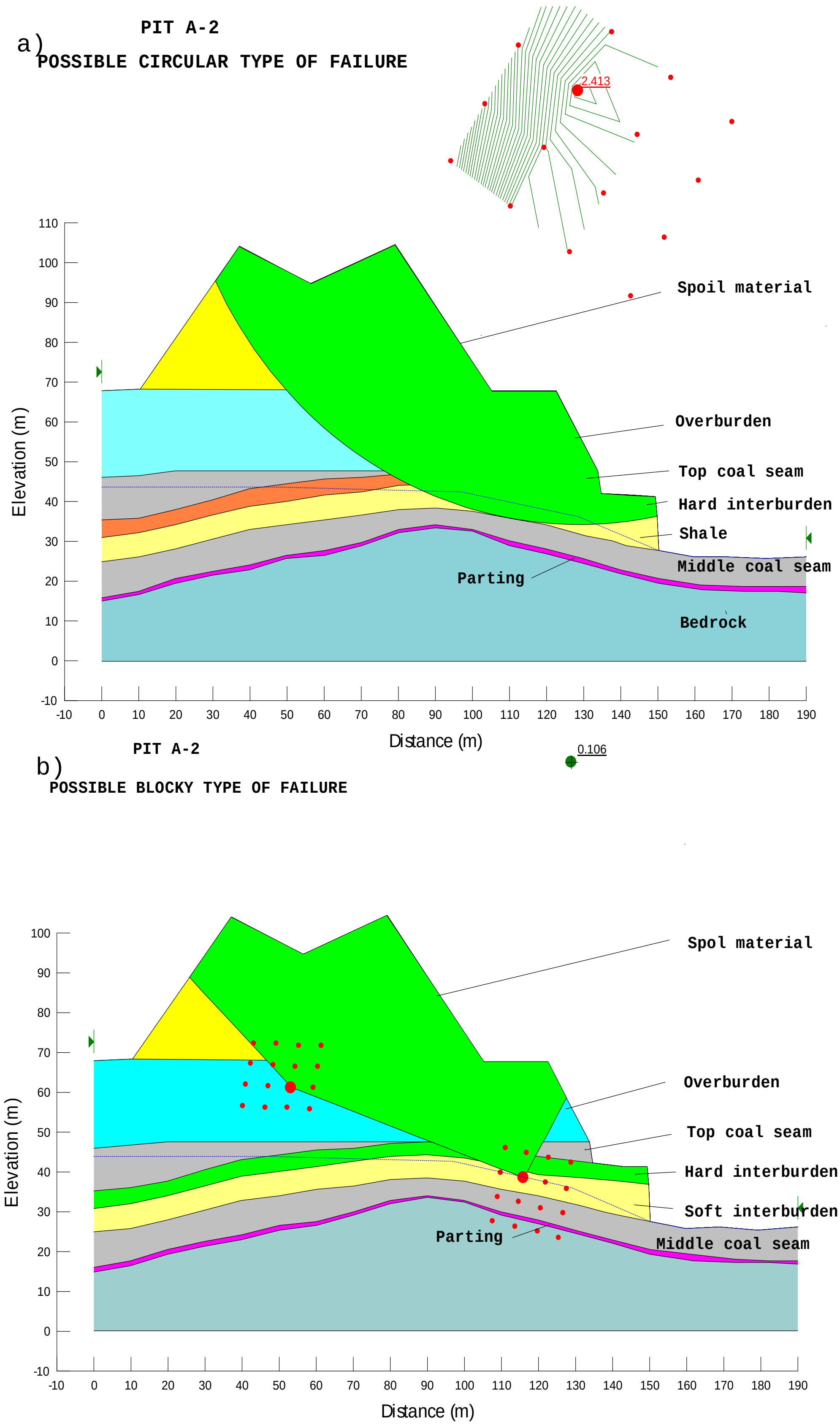


Figure 1.8

Possible circular (a) and blocky (b) type of failure at Pit–A2

After the cleaning operations, the failure surface was clearly observed on the contact between the soft interburden and the middle coal seam (Figure 1.9) which had an average dip angle of 16^0 towards the pit. The estimated FOS for the circular type of failure (Figure 1.8a) was between 2.4 and 2.6 depending on the method of calculation (Ordinary, Bishop, Janbu, Spencer or Morgenstern-Price).

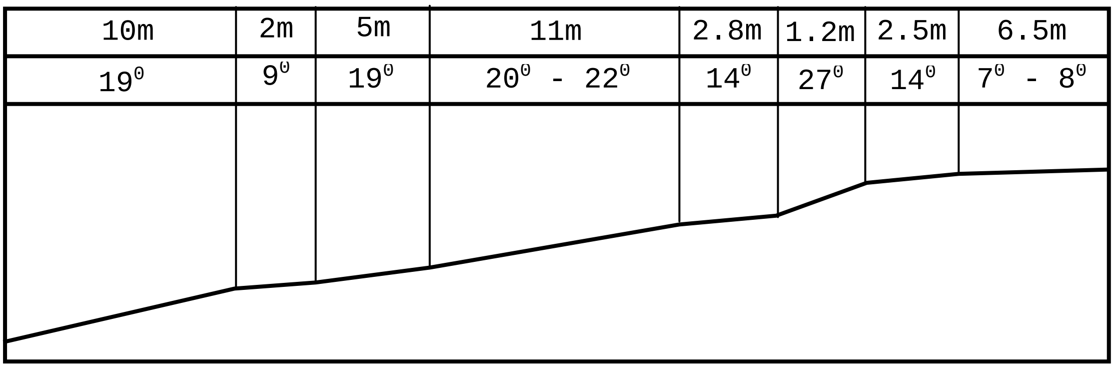


Figure 1.9

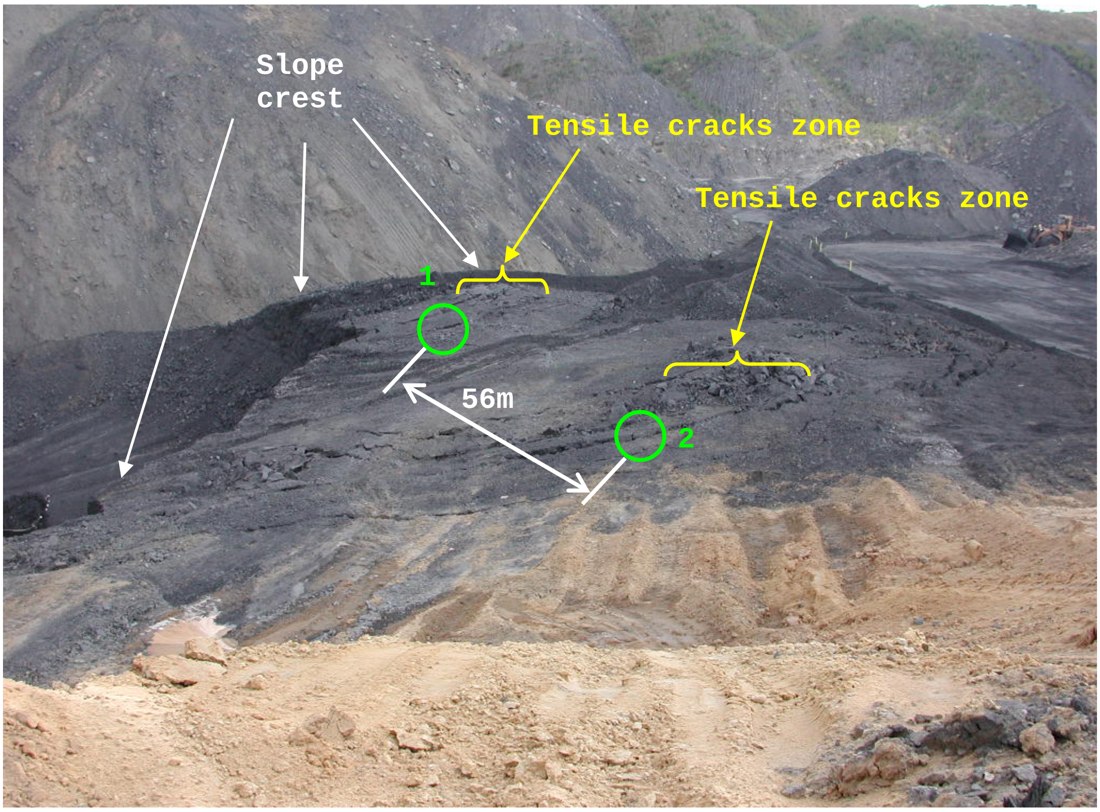
Profile of the failure surface, measured after cleaning operations

The blocky type of failure (Figure 1.8b) had a lower FOS for the profile, varying between 0.2 and 1.2. From these results and the derivative profile of the failure mass the author concludes that the failure must have been of a "blocky" type. As with the previous slope failure example in Pit A-1, there are problems with the application of the "Block Specify" in SLOPE/W because of the complexity of the slope profile. For instance, one of the most reliable calculating techniques, namely the Morgenstern-Price method, for blocky failure calculations, gives a very low safety factor value (FOS=0.11 to 0.14). The other methods, such as the Janbu and Bishop indicated slightly higher safety factors around FOS=0.15, while the Ordinary method yielded a FOS of 1.198. All except the Ordinary Method therefore failed to provide credible slope safety factors, even though it was clear at the mine that some sort of blocky mechanism was responsible for the major collapses in both pits.

Picture 1.2
Face of the failed slope profile in Pit A-2, which does not indicate any significant structural damage to the shale

Picture 1.2 shows the front side of the failed blocks for the second slope failure. There is no significant structural damage, despite the fact that the material is shale, which had been thrust forward some 20m. The location of the picture is shown in Figure 1.7. If there were any joint sets which might have triggered wedge failure, and which were missed by the author, then the downward movement of the spoil material and almost horizontal movements of the other points in the slope profile are kinematically impossible for the wedge failure mode. Furthermore, wedge failure cannot explain the valley formation in the post-failure profile i.e. definite downward movement of parts of the slope behind the forward thrust of the slope face, see Figure 1.7.

The third slope failure took place in Colliery “B” with similar stratigraphic column shown in Figure 1.3. The slope was composed of strata dipping 5^0 to 9^0 towards the pit. This failure was smaller than the previous two, but was notable in that it provided an opportunity to see the failure type between the blocks. The failure occurred in an 8m-thick coal seam at 25m depth with a similar overburden shown in Figure 1.3.



Picture 1.3
Panoramic view of the cleaned coal seam after the movement, showing tensile and shear crack zones

The failure indicated only horizontal movement toward the pit along the contact between 0.6m thick clay layer the coal seam. When the failed overburden was removed, two fracture zones could be seen in the coal seam (Picture 1.3) - a shear zone and a tensile zone. Pictures 1.4 and 1.5 are detailed pictures taken at the shear and tensile zones respectively. Measurements of the slope profile before and after the failure were not made available to the author, so no further analysis of this failure is possible in the thesis.

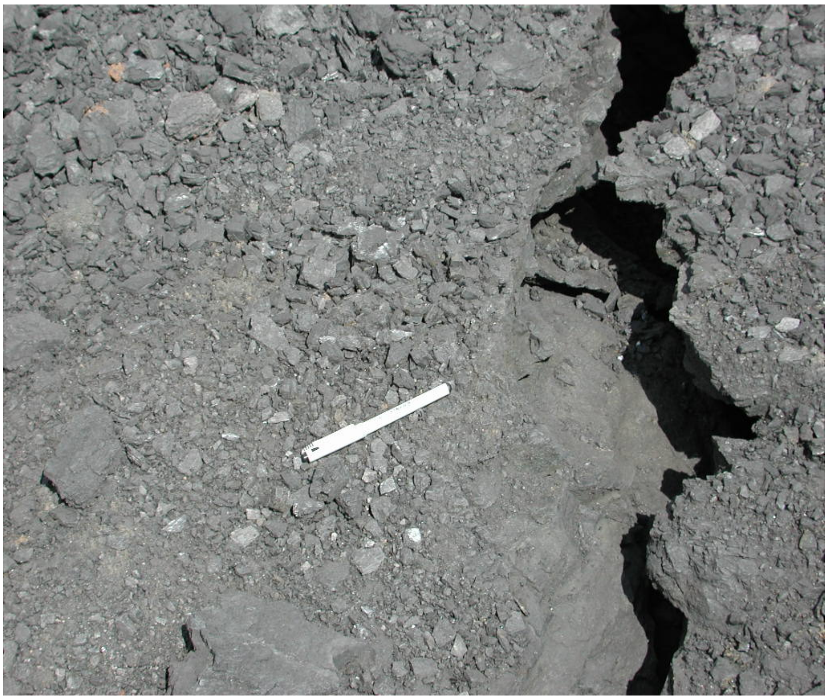
1.1.3 Common features of the failures

There are four features common to the failures. The first one is related to the post-failure profile, similar to that reported by Boyd (1983) in Figure 1.1. The failure mode has horizontal movement towards the pit by an almost undisturbed front block (passive block) and vertically downward movement of the block behind it (active block), with a final elevation significantly lower than that of the original slope profile.

The second feature of the failures is that in all cases the slope is situated on an undulated stratum with strata dipping towards the pit. The failure surface is at the contact between shale that overlies the second coal seam, i.e. the contact between a relatively weak and relatively strong layer respectively.

The third feature is that all failures daylighted at the toe of the slope, unlike the SLOPE/W failure planes for the blocky type of failure, which are predicted not to approach the toe of the slope (see Figures 1.6b and 1.8b).

The fourth feature common to the failures is the presence of almost vertical tensile fractures (indicating tensile failure) above the crest of the undulated strata formations. These fractures are often difficult to see because they are usually covered by debris but, whenever access is available, for example after cleaning operations (as in Picture 1.3), they can be seen. In this case, it appears that tensile fractures may have persisted from surface behind the slope crest, into the middle coal seam.



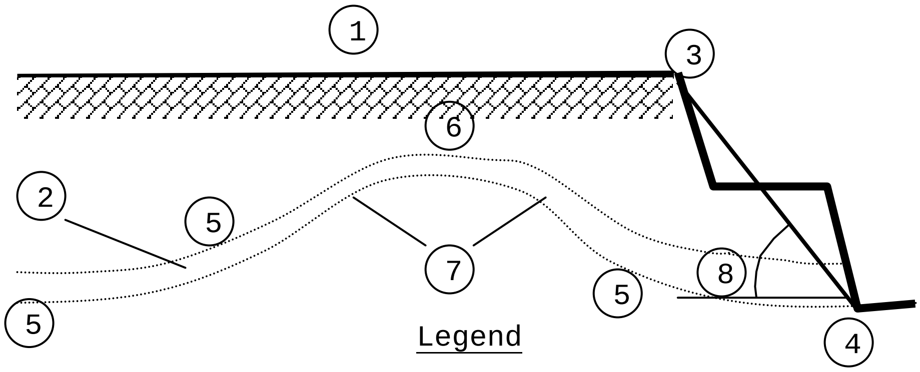
Picture 1.4

Open tension crack in the coal seam on the sheared block side (closer to the slope crest)

Picture 1.5

Tensile type of failure at the coal seam on the sheared block side, further from the formation crest

In this thesis, specific terminology will be used to facilitate discussion. Figure 1.10 presents a visualisation of the terminology that will be used in this thesis. It is necessary because in South Africa, for instance, the term “highwall” refers to the slope where excavation processes have taken place and “lowwall” refers to the dumped overburden debris in a pit, behind the highwall. In Australia the term “highwall” refers to a certain method of opencast mining. To avoid any misunderstanding and confusion the terminology used in this thesis is shown in Figure 1.10.



Legend

1 – Natural ground surface
2 – Weak embedded shale layer, or old coal pillars
3 – Crest of the slope
4 – Toe of the slope
5 – Toe of the undulated strata formation
6 – Crest of the undulated strata formation
7 – Limb of the undulated strata formation
8 – Slope angle

Figure 1.10

Visualisation of the terminology used in this thesis

1.2 THESIS OVERVIEW

The above discussed highwall failures (Section 1.2.2, pp. 10-17) pose some questions:

- What is the role of an undulated strata formation in the slope failures?
- What is the role of the embedded weak layer in terms of slope-stability when an undulated strata formation is present in the slope profile?
- What failure type occurs behind the slope crest in such conditions?
- What failure type exists along the embedded weak layer contact surfaces?
- How does a flatter slope angle cause major collapse in the same geotechnical conditions?

Poisel and Eppensteiner (1988) investigated failure modes at the edges of horizontal hard rock slabs lying on a soft, incompetent base. They found the existence of a tensile stress state in hard rock at the contact between hard and soft layers but they did not investigate the stress state in a multi layered system dipping toward a pit.

The failures discussed in Section 1.2.2 clearly show features that cannot be accounted for by the limit equilibrium methods, which assume far simpler conditions and geometries than are usually encountered in reality. The following features of the failures are therefore investigated in this thesis:

- The virgin stress state in undulated strata;
- The stress changes induced by cutting a slope in the undulated strata;
- The effects of the presence of a weak layer in the strata, either in the form of a shale layer or a mined coal seam in which pillars have been left behind;
- The role that different mineral constituents may play in fracture formation in a weak layer.

Site observations will be combined with the results of research carried out for the purpose of proposing a block thrust failure mode. Slope-stability safety factors will be computed for predicting more accurately the potential of slope failure in complex geotechnical conditions.

The discussion of the investigated features and research objectives is continued in the remaining chapters of this thesis.