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# Stability assessment and slope design at Sandsloot open pit, South Africa

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**Abstract**

Sandsloot open pit is located on the northern limb of the Bushveld Igneous Complex. It is the largest open pit platinum mine in the world. Three major joint sets have been recognized at Sandsloot, which are related to the regional tectonic history. They have an important influence on slope stability in the open pit, notably in terms of planar and wedge failures. Detailed geological and geotechnical data are often a notable unknown factor in the design and operation of an open pit, the lack of which may pose a significant risk to the mining venture. As data are accumulated and used effectively, so the risk of unforeseen conditions is reduced, and accordingly safety and productivity is increased. Usually, the geotechnical work undertaken at an open pit mine is in connection with improving slope stability. At Sandsloot open pit geological and geotechnical data have been obtained by face mapping, scanline surveys, from exploration drillholes and from laboratory tests. Such data have been used to delineate different geotechnical zones in which different types of slope failure have occurred. These are the usual types of slope failure associated with rock masses, namely, planar, wedge, toppling and circular failures. Analysis of the data has allowed optimum design parameters to be developed for these zones which has led to improved slope stability. In other words, this has allowed slope management programmes to be initiated, as well as slope optimization of the hangingwall. The latter resulted in an improved slope configuration and an increase in the ultimate angle of the wall by 7°. This has resulted in substantial savings, as well as an improvement in safety. 

*Keywords:* Discontinuities; Slope stability; Geotechnical zones; Data analysis; Slope configuration

## 1. Introduction

In order to minimize the amount of waste rock, which has to be removed in the recovery of an orebody, the ultimate slopes of an open pit mine generally are excavated to the steepest possible angle. Unfortunately, the economic benefits gained can be negated by major slope failure. Consequently, continual evaluation of the stability of the ultimate slopes is a vital part of open pit planning. As the presence and character of discontinuities have an important influence upon the stability of rock slopes, their assessment forms a critical part of any stability assessment.

Sandsloot open pit (Fig. 1) was commissioned in 1992 and since then a number of slope designs have been developed. The evolution of the designs has not only led to improvements in slope stability and safety but also has given rise to cost savings. The pit is situated on the northern limb of the Bushveld Complex, some 250 km north-east of Johannesburg. It currently is roughly 1500 m long, 800 m wide and trends in a north–south direction. Sandsloot open pit is located at an average elevation of 1100 m and has a projected depth of 325 m. At present, Sandsloot is the largest open pit mining platinum in the world.

In the past the majority of geotechnical work undertaken at open pit mines has focused on the slopes. Detailed geotechnical data are often a largely unknown factor in open pit design and therefore represents a significant risk in any mining venture. As the amount of geotechnical data increases so the risk of unforeseen conditions is reduced, and therefore safety and productivity can be increased. In order to increase and improve the geotechnical data a detailed geotechnical

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Fig. 1. View of Sandsloot open pit looking north.

programme was implemented at Sandsloot open pit. The focus of the project was to make practical use of geotechnical information so as to improve slope stability, and slope configurations, and thereby optimize the final wall angle and so reduce the cost of mining.

Previously, one production and slope design method was applied to the entire open pit, as in the case in many mines. In order to improve production, the open pit was divided into geotechnically similar zones to which empirical slope designs have been applied. These were based on detailed structural and geological mapping which enabled any active or potential instability problems to be detected. The definition of each zone involved rock mass classification, a rock strength testing programme, scanline surveys and slope stability analyses. Five potential failure mechanisms were identified in terms of pit slopes, namely, planar, wedge, toppling, and circular failure zones, as well as a geotechnical "nose" zone. Specific slope design configurations, stability values and sensitivity parameters were estimated for these areas.

A major feature plan and cross sections have been produced based on the structural and geotechnical data collected. The plan has proven very useful for slope design. Five slope designs have been used since the mine started. The changes were due in part to variations in mining method but mostly were due to the use made of the geotechnical data assembled to date. From a slope design perspective there are several configurations, which can be used to give the most stable and economic final wall. The data gathered and designs formulated have been of considerable value in developing a slope management programme, improving safety and optimizing the final open pit walls. The financial benefit associated with optimizing the final walls in terms of extending the life of mine and reducing the stripping ratio is significant.

## 2. Geology of the area

The Bushveld Igneous Complex represents the largest intrusive body in the world. The main period of igneous activity resulted in the emplacement of a mafic phase (the Rustenburg Layered Suite) followed by an acid phase (the Bushveld Granophyre and the Lebowa Granite Suite). The Rustenburg Layered Suite has been sub-divided into various zones, namely: the Marginal, Lower, Critical, Main and Upper zones, and exceeds 9000 m in thickness. At least three large interlinked chambers, with separate feeder pipes, have been identified. A feeder pipe close to Potgietersrus resulted in the Potgietersrus Limb. The Potgietersrus Limb covers an area of roughly 2000 km$^2$ and consists of a north striking trough-shaped body (Fig. 2). It is some 110 km in length and attains a maximum width of 15 km.

A platiniferous horizon, known as the Platreef, is associated with the Potgiertersrus Limb. It forms the base of the Main Zone and hosts economic platinum group element mineralization within a sulphide-bearing pyroxenite body. It has an economic strike length of 40 km. The basal contact of the Platreef is highly irregular and has a transgressive relationship with the underlying sediments of the Transvaal Supergroup and Archaean granites as it progresses northwards. This transgressive relationship with different rock types has given rise to differing degrees of metamorphism, metasomatism and assimilation of the floor rocks. Hence, the interaction of the pyroxenite of the Platreef with different sedimentary sequences has resulted in a highly complex and unique suite of rock types. The Platreef is capped by a sequence of Main Zone gabbronorites, which in turn, is overlain by Upper Zone sequences of ferrogabbros (Fig. 3). Metamorphosed pyroxenite, that is, parapyroxenite hugs the footwall of the Platreef.

At Sandsloot the outcrop of the Platreef exhibits a somewhat sinuous pattern with local changes in strike and dip. There is considerable variation in thickness of the Platreef at Sandsloot, ranging from 70 to 200 m (Fig. 4). The pyroxenites, which comprise the Platreef at Sandsloot, vary in texture from fine to coarse grained and the floor rocks consist of dolomite belonging to the Malmani Subgroup. Indeed, between Tweefontein and Sandsloot there is an embayment of dolomite known locally as the "dolomite tongue", which thins the Platreef. The footwall to the Platreef at Sandsloot is represented by metadolomite referred to as calc-silicate. The dolomite has resulted in appreciable contamination at Sandsloot, with many xenoliths of dolomite being assimilated to form parapyroxenite. The parapyroxenites are essentially contaminated metamorphosed pyroxenite. They are medium grained and contain abundant serpentine, which represents a product of late

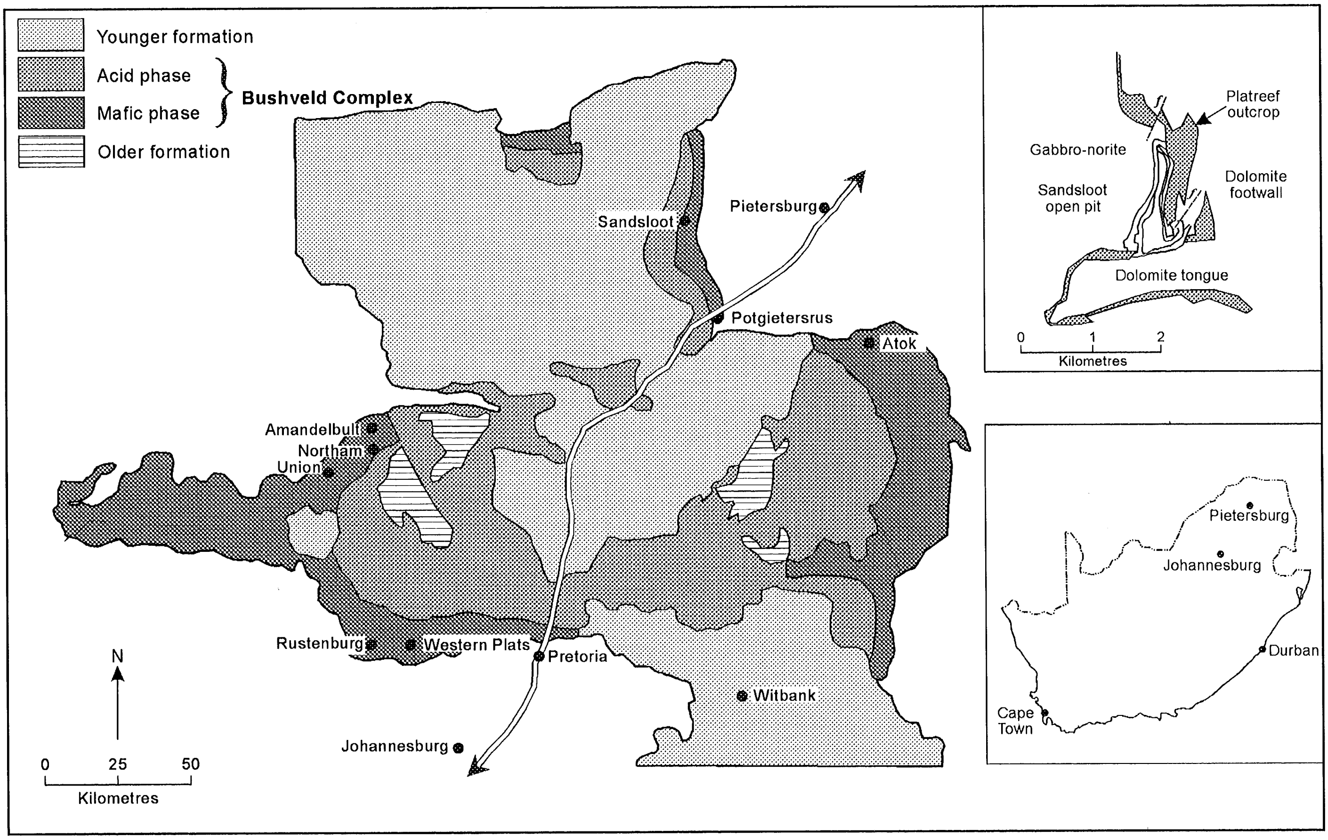



Fig. 2. Regional geology of the Bushveld Complex.

stage alteration. The hangingwall norite unit generally exhibits a medium to coarsely crystalline texture with occasional disseminated sulphides. The norites exhibit a degree of layering and are normally leucocratic.

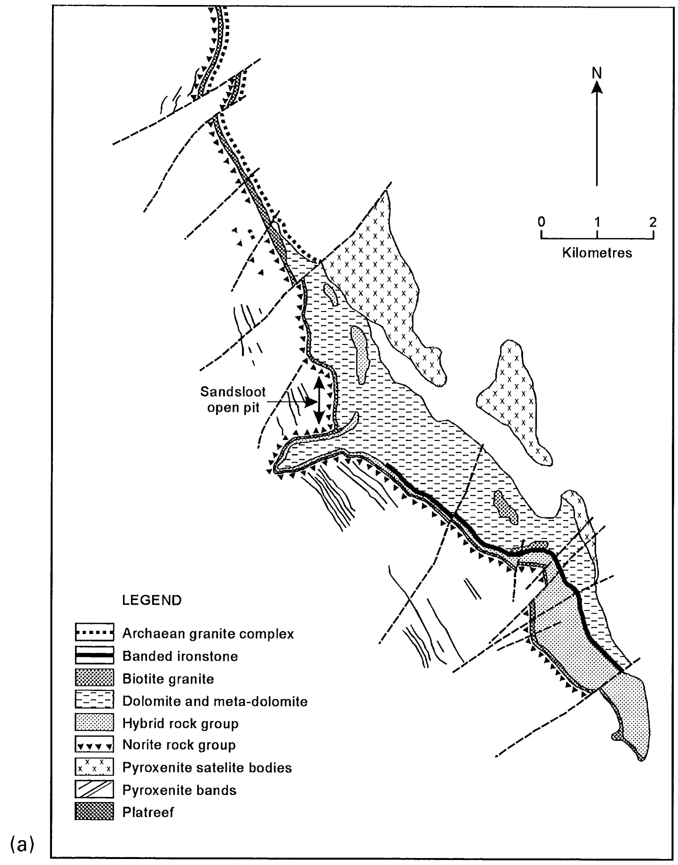
The Platreef has been disturbed by several sets of faults, which strike at 030° and at 080° to the east. Most of these faults have a normal attitude and commonly have a downthrow on the southern limb. A series of strike faults, which trend north north-west also are evident in the region. Indeed, a strike fault marks the basal contact between the Bushveld Complex and the floor over certain sections of the Potgietersrus Limb. The open pit at Sandsloot is interrupted by three major north-east trending faults. There are two normal faults in the north pit, which form a graben structure with a downthrow of 30 m and a major oblique-sinistral fault, which has displaced the ore body to the south-east by approximately 400 m. This fault has caused extensive alteration and deformation in the adjacent rock types. For instance, highly deformed serpentinized pyroxenites occur on the south-east wall of the pit. Such serpentinization has weakened the pyroxenite significantly. A highly sheared zone of pyroxenite, up to 5 m in width and dipping at 45°, separates the hanging wall norites from the pyroxenite ore body. The zone provides a natural drainage path for local groundwater.

## 3. Geohydrology

Sandsloot open pit is situated on the eastern side of the shallow valley of the Groot Sandsloot River, which falls within the catchment area of the Mogalakwena River. The Groot Sandsloot River basin has a mean annual runoff of $1.731 \times 10^6\,m^3$ and contributes 5% of the surface runoff to the Mogalakwena River. The recorded average annual rainfall generally varies from 380 mm to just over 700 mm. Precipitation occurs mainly in the form of thunderstorms during the summer months with a peak in January.

Extensive borehole investigations in the mine lease area and the surrounding catchment indicated that the main water bearing zones lie at the base of the weathering profile at depths of between 2 and 43 m. The annual rate of groundwater recharge within the catchment area is approximately $1.86 \times 10^6\,m^3$.

It has been estimated from boreholes that the open pit at Sandsloot has an influence on the surrounding groundwater system for a radius of only 400 m. There are no groundwater users within this radius. The mine itself is heavily dependent on its well fields for a large portion of the approximately $5.0 \times 10^6\,m^3$ of water it requires per annum for its mining processes. The mine has two well fields, which are hosted within two types of



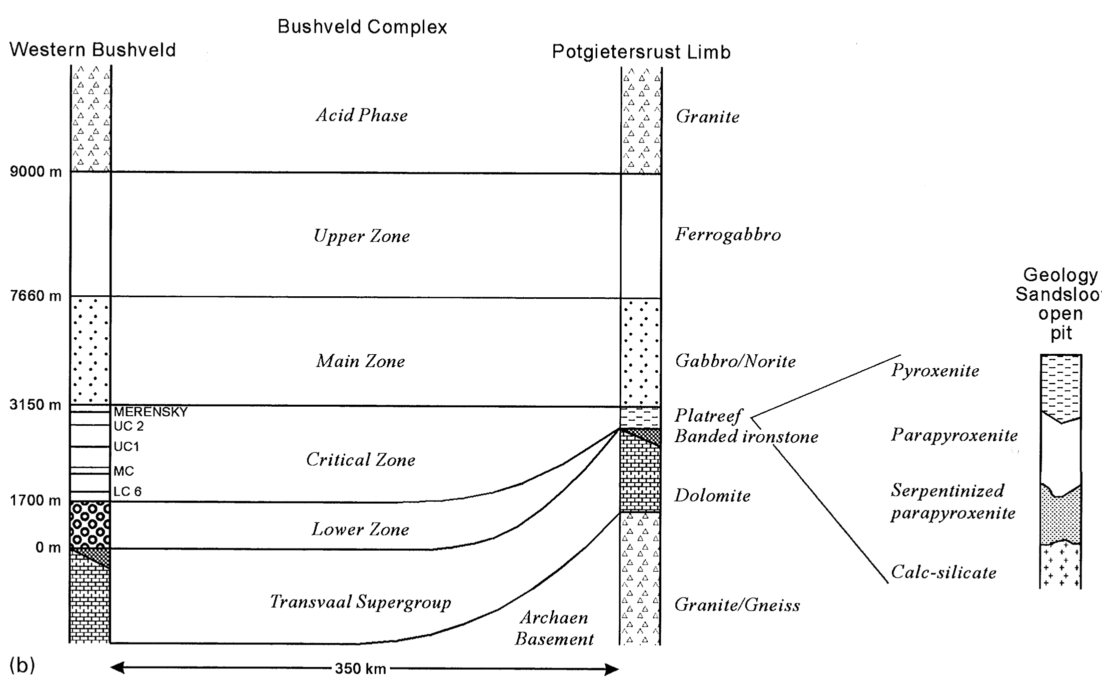




Fig. 3. (a) Geology of the Sandsloot locality. (b) Order of stratigraphic occurrence of the rocks in the Sandsloot locality.

aquifers. The semi-confined, weathered and fractured aquifers are the more frequent. They take the form of a series of elongated troughs approximately parallel to the strike of the Bushveld rocks. Fracturing has enhanced the development of these weathered basins and higher yielding boreholes are associated with them. The

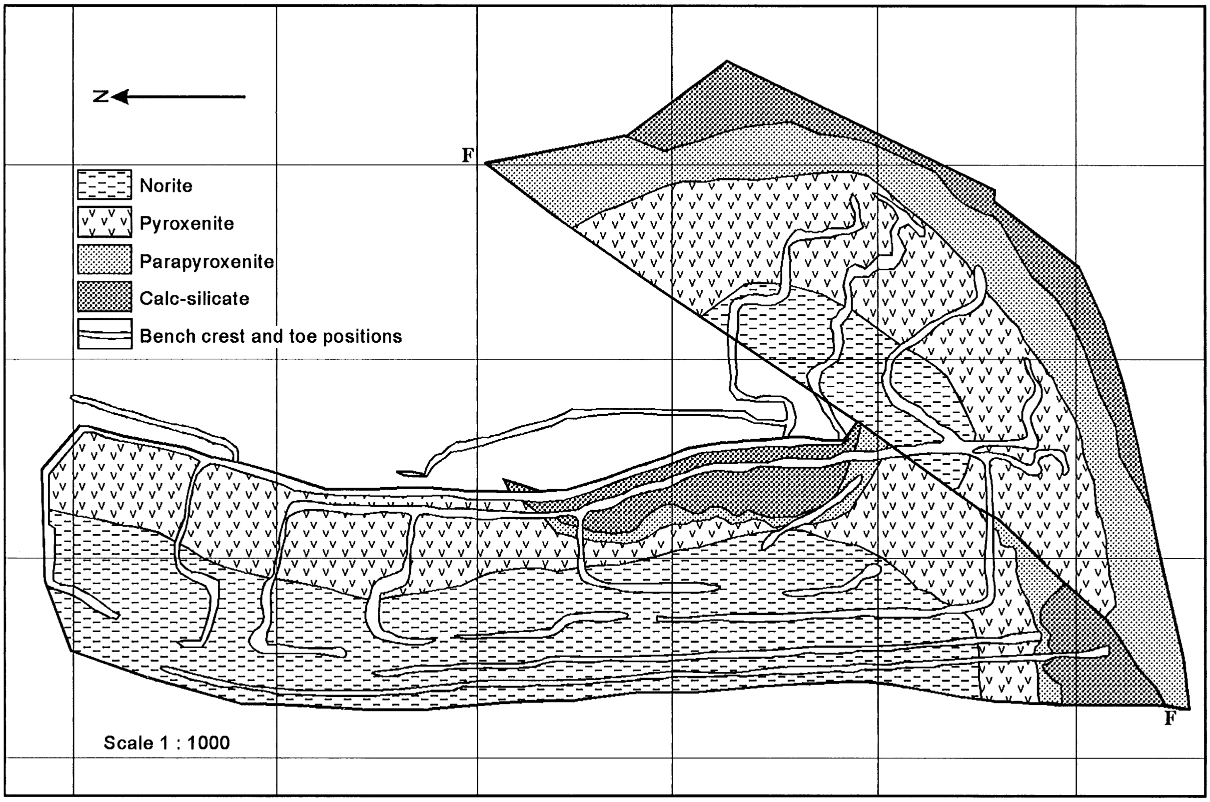



Fig. 4. Plan view showing the geology of Sandsloot open pit. The double lines reflect the crest and toe positions of the active mining benches.

overlying weathered horizon supplies most of the storage, with the underlying fractured zone forming the main transmissive zone. The second well field is located within a highly fractured shear zone associated with north-east–south-west trending faults. Strike depths range between 20 and 45 m.

An initial geophysical survey suggested that the weathered profile could vary from 20 to 35 m in depth within the pyroxenites. From subsequent field observation it appears to be less well developed in the norites, extending to between 5 and 10 m below ground surface. The weathered horizon acts as a perched aquifer. Beneath the weathered horizon water occurs in discontinuities. It has been estimated that the total groundwater flow into the pit is about $112\,m^3\,h^{-1}$, with some $22\,m^3\,h^{-1}$ entering via the footwall, the remainder via the hangingwall.

The phreatic surface exists at approximately 40 m below ground level and could have an affect on the factor of safety of the design slopes in the pit. Therefore dewatering by pumping from sumps is necessary. Fig. 5 illustrates the influence of dry as opposed to wet conditions on the factor of safety of design slopes. A factor of safety of 1.25 was used in the analyses concerned, it allowing a 15–20% probability of failure.

## 4. Discontinuities

Discontinuities play a major role in the design and maintenance of opencast pits, their presence affecting the mechanical and hydrogeological properties of the rock masses. From a slope design perspective three major joint sets can be seen continuously throughout the Sandsloot pit area (Table 1, Fig. 6) and therefore were studied in detail to assess potential failure mechanisms. These three major joint sets reflect the tectonic environment, being related to the emplacement of the Potgietersrus Limb. The remaining minor joints are thought to have formed by randomized contraction jointing on cooling of the Bushveld intrusive phase. The most prominent joint set (JS1) strikes north-west and has pronounced slickensides. Late stage quartzo-feldspathic (felsite) veins are associated with this joint set. They are steeply dipping, and are laterally and vertically continuous over hundreds of metres. As such, they pose slope stability problems.

Scanline surveys were carried out in selected areas of the open pit at Sandsloot either where failure had occurred or where the potential for failure existed [1]. In fact, most of the surveys were conducted around the Satellite pit due to the occurrence of geotechnically poor areas associated with the Satellite pit fault and

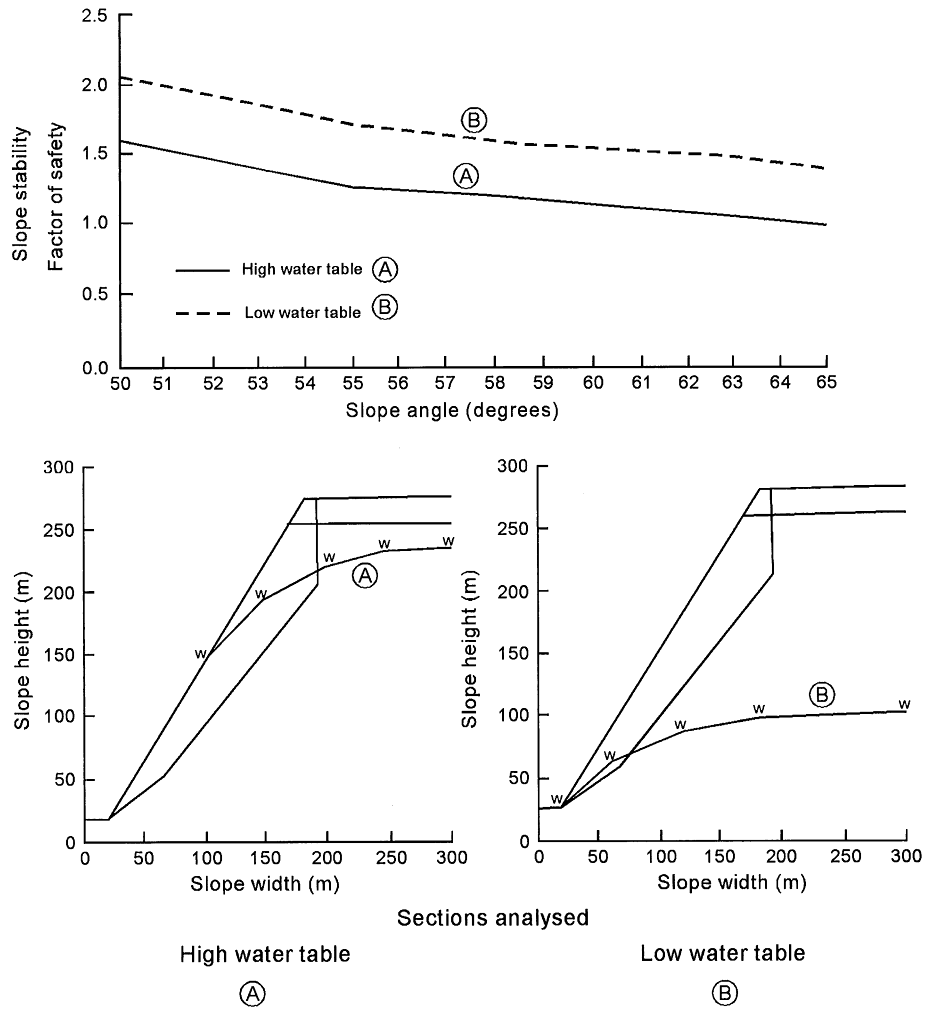



Fig. 5. The effect of dry and wet conditions on the factor of safety of the design of slopes. Line A indicates a lower FOS/less stable slope than line B, for an equivalent slope height and angle, due to the higher level of the water table within the slope. For example a dry slope at 50° will have a FOIS of 2.1 while a wet slope will have a lower FOS of 1.6.

Table 1
Averaged joint set data from Sandsloot open pit

| | Dip | Dip direction | Joint roughness | Joint filling | Joint spacing |
|---|---|---|---|---|---|
| JS1 | 72 | 088 | (IV) Rough Irregular | Calcite | 0.5 m |
| | 73 | 263 | Undulating | Serpentinite | |
| JS2 | 78 | 357 | (II) Smooth Stepped | Calcite | 0.4 m |
| | 82 | 183 | | | |
| JS3 | 70 | 310 | (V) Smooth Undulating | Serpentinite | 0.3 m |
| | 62 | 125 | | | |
| JS4 | 72 | 237 | (VII) Rough/Irregular | Calcite | 0.15 m |
| | 63 | 065 | Planar | | |

serpentinized parapyroxenite. Numerous parameters were measured for each discontinuity such as roughness, dip and dip direction, spacing, continuity, joint aperture, and the presence of gouge. An example of the data sheets used to collect data during the scanline surveys is given in Fig. 7. Joint profile readings were taken [2] with a carpenters comb and compared with the joint roughness profiles of [3]. Detailed structural mapping was also undertaken of each face, the data collected including the lithology, dominant joint sets, critical joint spacing, veins and any faults.

The DIPS software program was used to generate the stereonets from the scanline survey data collected. For each scanline survey a contoured pole data stereonet with joint set windows was constructed. The stereonets then were analysed according to procedures given in [4] in order to assess potential modes of failure, thereby allowing potential failure zones to be identified.

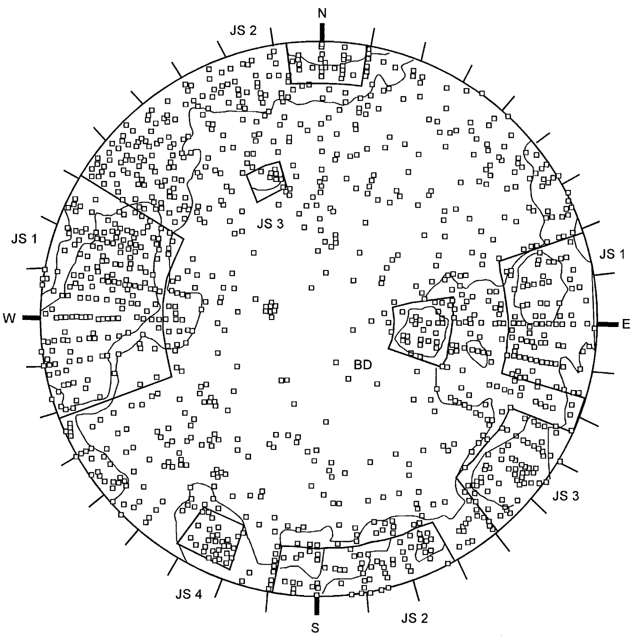



Fig. 6. Stereonet showing the families of joint sets at Sandsloot open pit.

Determination of reliable shear strength values is a critical part of a slope stability analysis because relatively small changes in shear strength can result in significant changes in the safe height or angle of a slope. Differences in the shear strength of rock surfaces can occur because of the influence of weathering, surface roughness, and the presence of water under pressure [4]. At each scanline survey samples were collected for each of the dominant joint sets.

The samples were tested in a Golder shear box [5]. The Golder shear box is designed for testing samples at normal loads up to 2 MPa and the normal load is applied by means of a dead load system. It therefore remains constant throughout the test and is therefore more sensitive than the portable shear box. Moreover, the maximum effective normal stress acting across joints considered critical for stability lies, according to Barton [3], in the range 0.1–20 MPa.

The average peak shear strength parameters for the three rock types primarily involved in slope stability assessments, namely, norite, pyroxenite and calc-silicate, are given in Table 2. Table 2 also gives the range of peak friction angles for normal loads of 0.54 and 1.08 MPa, which correspond to bench heights of around 20 and 40 m, respectively. Generally, the pyroxenite possesses the lowest shear strength along joints.

| | | | |
|---|---|---|---|
| DATE : | 28 - 07 - 1997 | PIT : | SOUTH WEST EXTENSION |
| RECORDED BY : | A. R. BYE | FACE ORIENTATION : | STRIKE 180 |
| BENCH/BLAST : | 17 / 008 | ZONE : | 1 OF 4 |
| FACE : | EAST FACE | GEO POINT : | 17GP-004 |

INTACT MATERIAL STRENGTH

SCHMIDT REBOUND READINGS (R)

| | | | |
|---|---|---|---|
| 1 | 50 | 6 | 50 |
| 2 | 52 | 7 | 52 |
| 3 | 48 | 8 | 49 |
| 4 | 54 | 9 | |
| 5 | 46 | 10 | |

R MPa

| Mean | High |
|---|---|
| 50 | 54 |
| 195 | 250 |

HAMMER ORIENTATION :

| | |
|---|---|
| Horizontal Up : | |
| Horizontal Down : | |
| 45 Up : | |
| 45 Down : | |
| Vertical | * |

SPECIMEN TYPE

| | |
|---|---|
| In situ | * |
| Blasted rock | |

2. ROCK TYPE
PARAPYROXENITE

3. ZONE WIDTH
10 M

4. BLASTING EFFECTS
JOINTS EXTENSIVELY OPENED BY BLASTING

5. RQD FOR ZONE
80%

6a. DISCONTINUITY
1. JOINT 3. FAULT ZONE 5. FAULT
2. BEDDING 4. CRITICAL JOINT

6b. JOINT FILLING
A Non-softening and sheared material (eg. quartz)
1. Coarse 2. Medium 3. Fine
B Soft sheared material (eg. clay)
1. Coarse 2. Medium 3. Fine

6c. DEGREE OF WEATHERING
1. Fresh 4. High
2. Slight 5. Complete
3. Moderate 5. Residual soil

6d. JOINT CONTINUITY (ENDS)
1. Both joint ends extended out of the face
2. Both joint ends end in the face
3. One joint end ends in the face

6e. WATER
1. Dry 2. Moist 3. Wet
4. Dripping 5. Flowing

6. ROCK MASS DISCONTINUITIES

| JOINT SET | JOINT TYPE (6a) | ORIENTATION | | JOINT CONDITION | | | | | WEATHERING (6c) | | JOINT SPACING | | FF/m | JOINT CONTINUITY (6d) | | | | WATER 6 (e) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | JOINT FILLING | | ROUGHNESS | | JOINT WALL | JOINT | ROCK | AVE | CJS | | DIP LENGTH | END | STRIKE LENGTH | END | |
| | | DIP. DIR | DIP | TYPE | NO.(6b) | SMALL | LARGE | ALTERATION | SURFACE | SURFACE | m | m | | m | 1 - 3 | m | 1 - 3 | |
| 1 | 4 | 090° | 72° | Cal&serp | A 2 | 0.95 | 0.80 | - | 3 | 1 | 0.4 m | 1.5 m | | 15 m | 1 | 40 m | 1 | Dry |
| | 1 | 085° | 78° | Calcite | A 2 | 0.90 | 0.90 | | 2 | 1 | 0.3 m | - | | 15 m | 1 | 5 m | 1 | |
| | 1 | 100° | 65° | Serp | B 3 | | | | | | | | | | | | | |
| 2 | 1 | 350° | 85° | Calcite | A 3 | 0.90 | 0.95 | - | 1 | 1 | 0.2 m | 3.0 m | | 10 m | 1 | 1 m | 1 | Moist |
| | 1 | 005° | 83° | Clay | B 2 | | | | | | | | | | | | | |
| | 1 | 355° | 80° | | | | | | | | | | | | | | | |
| 3 | 1 | 040° | 45° | | | 0.70 | 0.80 | - | 2 | 1 | 0.6 m | - | | 8 m | 3 | 3 m | 2 | Dry |
| | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | |
| 4 | 2 | 250° | 30° | Clay | B 3 | 0.75 | 0.75 | - | 2 | 1 | 0.1 m | - | | 20 m | 1 | 0.5 m | 1 | Dry |
| | 2 | 220° | 35° | | | | | | | | | | | | | | | |
| FAULT | 3 | 300° | 75° | Quartz | A 1 | 0.80 | 0.60 | YES | 2 | 4 | 0.4 m | - | | 15 m | 1 | 0.2 m | 1 | Dripping |

Fig. 7. Face mapping checklist for MRMR evaluation.

Table 2
Geotechnical properties of the dominant rock types at Sandsloot open pit

| | Hanging wall | Ore Zone | | | Foot wall |
|---|---|---|---|---|---|
| | Norite | Pyroxenite | Parapyroxenite | Serpentinized parapyroxenite | Calc-silicate |
| Peak Shear Strength (MPa) | 0.93($\sigma_n$ = 0.54) 1.78 ($\sigma_n$ = 1.08) | 0.78 ($\sigma_n$ = 0.54) 1.64 ($\sigma_n$ = 1.08) | | | 1.09 ($\sigma_n$ = 0.54) 1.76 ($\sigma_n$ = 1.08) |
| IRS (MPa) | 190 (150–210) | 160 (120–180) | 200 (180–250) | 270 (200–310) | 140 (100–180) |
| Schmidt Hammer | | | | | |
| RQD% | 80 (40–100) | 65 (25–100) | 75 (55–100) | 70 (50–100) | 55 (20–80) |
| FF | 9 (20–30) | 13 (29–3) | 10 (15–30) | 11 (16–30) | 16 (32–9) |
| MRMR | 53 (48–60) | 48 (35–52) | 56 (50–61) | 61 (51–70) | 42 (32–50) |
| MRMR Class | (III A) Fair | (III B) Fair | (III A) Fair | (II B) Good | (III B) Fair |
| Density (Mg m$^{-3}$) | 2.9 | 3.2 | 3.2 | 3.2 | 2.9 |
| Young's modulus | 10.24 GPa | — | — | — | — |
| Poisson's ratio | 0.2 | — | — | — | — |
| Tensile strength (MPa) | 9.5 (7.5–10.5) | 8.0 (6–9) | 10.0 (9–12.5) | 13.5 (10–15.5) | 7.0 (5–9) |
| $\varphi_p$(°) | 57–64 | 40–58 | 55 | — | 50 |
| $\varphi_b$(°) | 35–38 | 28–32 | 34–36 | — | 32 |
| JRC | 6–10 | 2–12 | 8–10 | 8–12 | 8–10 |
| JCS (MPa) | 87–100 | 62–100 | 75 | 100–150 | 50 |
| Slope angles (°) | 56–59 | 48–50 | 51–59 | 56–59 | 51 |

$\varphi_p$°—Peak friction.
$\sigma_n$—Normal stress.
JRC—Joint roughness coefficient.
$\varphi_b$°—Base friction angle.
FF—Fracture frequency.
JCS—Joint wall compressive strength.
IRS—Intact rock strength.
RQD—Rock Quality Designation.
MRMR—Mining Rock Mass Rating.

Tilt tests were undertaken in the open pit to obtain an approximate value of the basic friction angle for the rock types in the pit. An average value of 32°, with a range of 28–38°, was obtained. In fact, Ref. [6] suggested that tilt tests provided a more reliable means of estimating the joint roughness coefficient, JRC, than comparison with typical roughness profiles. Subsequently, Ref. [7] supported the use of the tilt test, especially in heavily jointed rock masses.

## 5. Delineation of failure zones

Rock slopes generally fail along existing geological defects, notably discontinuities. It is only in very high slopes or weak rocks that failure through intact material becomes significant. Most rock slope problems therefore require consideration of the geometrical relationships between discontinuities, the slope and force vectors involved.

In order to assess the stability of individual benches, so as to aid stack and overall slope design, detailed kinematic failure analyses were undertaken. Kinematic failure zones representing a dominant or critical failure mechanism were delineated for the pit from multiple scanline surveys and detailed field mapping. Five kinematic failure zones were identified, namely, planar, wedge, toppling and circular failure zones, as well as a "nose" zone (Fig. 8). Each zone represented a geotechnically similar part of the pit, the modes of failure being predominantly structurally controlled rather than controlled by rock type. The exception is where circular failure occurs, instability there being due to the weathered rock-soil material. Using the structural data presented in Fig. 6, a kinematic failure analysis [4] was used to define the dominant modes of failure for the various zones of the pit. The dominant modes will vary according to the intersection of the pit slope orientation and dominant joint orientation.

Plane failures are a common type of translational failure and occur by sliding along a single plane. In order for sliding to occur on a single plane the following geometrical conditions must be satisfied.

- The plane on which sliding occurs must strike parallel or nearly parallel (±20°) to the face.
- The failure plane must daylight in the face, that is, the dip of the failure surface must be less than that of the face.
- The dip of the failure plane must be greater than the angle of friction.

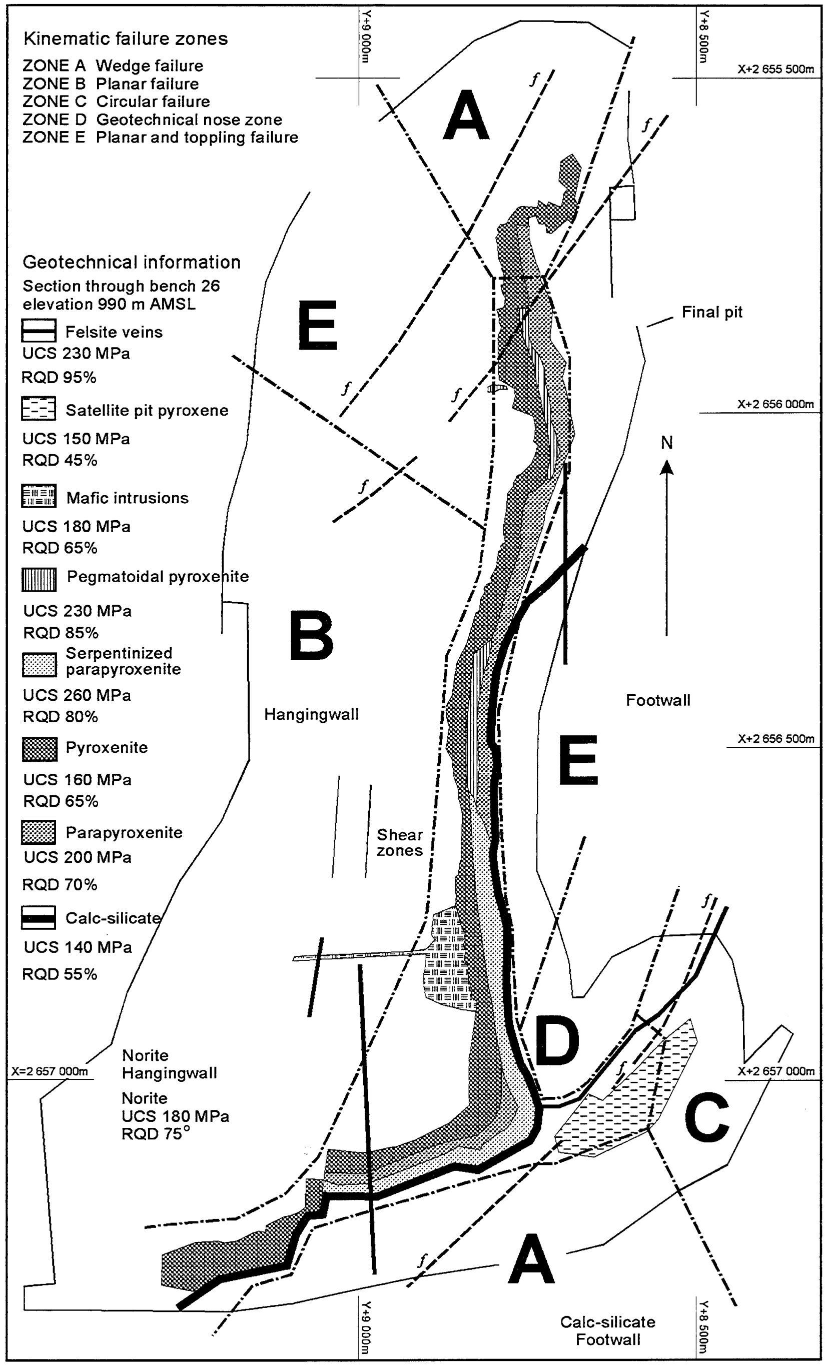



Fig. 8. Failure zones identified at Sandsloot of pit.

- Release surfaces, which provide negligible resistance to sliding, must be present in the rock mass to define the lateral boundaries of the slide.

All these geometrical conditions are satisfied by the major joint sets on the western highwall (Fig. 9). The three critically aligned joint sets are presented in Fig. 10 with joint set one, JS1, trending within 20° of the slope. Joint set one strikes at 352° and dips at 50°, while the face strikes at 355° and dips at 70–75°. It also daylights in the face and is inclined at an angle greater than the friction angle, which is 31°. Additionally, joint sets two, JS2, and three, JS3, provide release surfaces for failure to occur. The relevant data relating to the plane failure attributable to the major joint sets are given in Table 3. The critical joints showed significant water flow after heavy rainfall, which drastically reduces the slope stability. This reduction in stability is evident from the sensitivity analyses given in Table 4. In particular, continuous joints, which are slickensided and contain

Fig. 9. Planar failures on the western highwall.

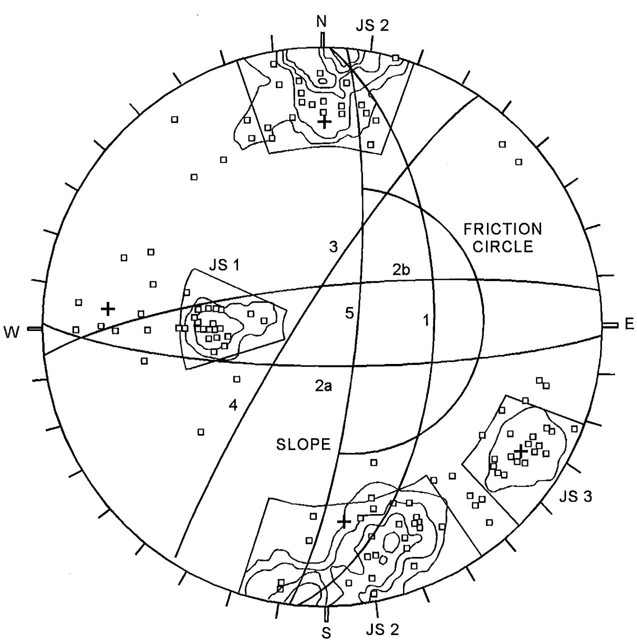



Fig. 10. Stereonet depicting plane failure on the western highwall.

serpentinite and calcite vein filling are potentially critical joints, which may fail, especially after heavy thunderstorms. Water tends to flow along such joints after heavy rainfall.

From field observations and stereographic analyses, it appeared that the hangingwall (western highwall) was prone to planar failures developing from tension cracks whereas in the footwall (eastern highwall) planar failures occurred without a tension crack. As an example, when the following parameter values were used: face height (20 m), cohesion (100 kPa), friction angle (31°), tension crack distance (3 m), inclination of failure plane (50°) and rock unit weight (27 kN m$^{-3}$) to determine the factor of safety of the western highwall, then it was 1.38 dry and reduced to 0.8 wet. The results of sensitivity

Table 3
Data relating to the critical joint sets causing planar failure

| | JS1 | JS2 | JS3 |
|---|---|---|---|
| Dip | 17–55 | 65–90 | 70–90 |
| Dip direction | 073–114 | 329–018 | 291–351 |
| Spacing (m) | 0.2 | 0.3 | 0.4 |
| Critical joint spacing (m) | 1.5 | 4 | 3 |
| Continuity (m) | 1–70 | 4–10 | 4–50 |
| Joint width (mm) | 2–60 | 2–20 | 2–20 |
| Joint filling | Thick calcite, serpentinite, some inactive clay | Calcite, serpentinite, inactive clay | Calcite, serpentinite |
| Joint thickness (mm) | 2–60 | 2–20 | 2–20 |
| Joint roughness (After Barton, 1978) | Planar rough (VII) | (Planar rough) (VII) | Planar rough (VII) |

analyses are given in Table 4 and suggest that the plane failure mechanism is most sensitive to slope height and inclination of the failure plane but insensitive to tension crack distance, cohesion and friction angle. If the failure plane occurs in a double bench with a height of 40 m, then the factor of safety drops to 0.97 dry and 0.27 wet. Therefore, it is unwise to create benches greater than 40 m on the western highwall. The most critical failure plane inclination is 50°, which more or less corresponds with the dip of JS1. Sensitivity analyses also were undertaken to ascertain the nature of the failure mechanisms on the eastern highwall where failure occurred without the development of tension cracks. The results are illustrated in Fig. 11.

Potential wedge failures exist where two discontinuities, which dip out of a face intersect and the line of intersection daylights into the face and is steeper than the friction angle of the joint surfaces. There are two zones in the pit where wedge failure occurs. In the north pit wedge failures develop due to the intersection of the hanging wall contact fault and JS1. In the south pit wedges are formed due to the intersection of the sympathetic jointing related to the satellite pit fault and the relict bedding in the calc-silicate. Observed wedge failures generally occur in association with a nearby production blast and normally are smaller than 100 tonnes (Fig. 12). Wedge failure analysis was undertaken using stereonets (Fig. 13), as well as the SWEDGE software package. The data related to the critical joint sets responsible for wedge failure are given in Table 5. In addition, a sensitivity analysis was undertaken to assess the effect of face height, cohesion and friction angle on slope stability in relation to the factor of safety in dry and wet conditions. The results are given in Table 6. Wedge stability appears to be relatively insensitive to these three parameters with the factor of safety barely

Table 4
Variation of parameters used in sensitivity analyses

| Parameter | | Factor of safety | |
|---|---|---|---|
| | | Dry | Wet |
| Face height (m) | 10–50 | 2.27–0.88 | 1.93–0.16 |
| Cohesion (kPa) | 60–140 | 1.03–1.73 | 0.51–1.08 |
| Friction angle (°) | 30–35 | 1.36–1.46 | 0.79–0.81 |
| Tension crack distance (m) | 0.5–10 | 1.53–1.53 | 0.44–1.47 |
| Inclination of failure plane (°) | 30–70 | 1.81–5.69 | 0.67–5.92 |

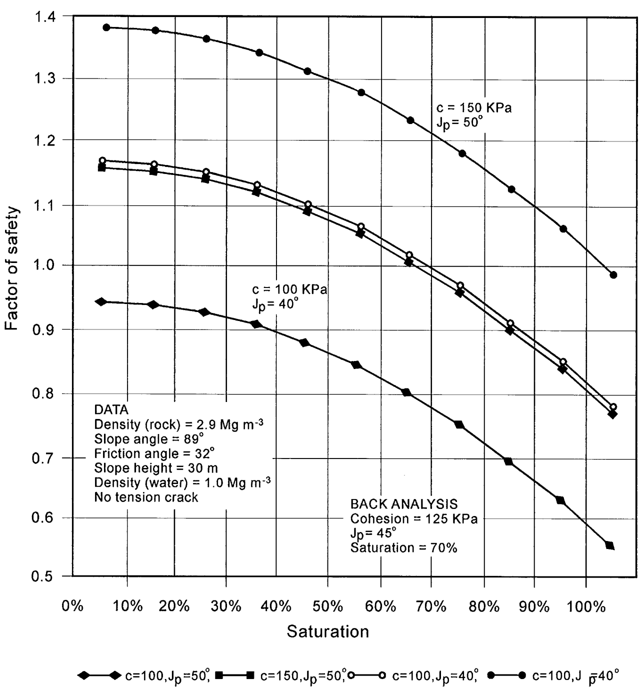



Fig. 11. Sensitivity analysis for planar failure (relationship between factor of safety on the one hand and rock mass saturation, cohesion, $c$, and joint angle, $j_p$ on the other). The term saturation refers to the height of the water table in the slope as a percentage of the slope height. For example, 100% saturation indicates a water table that is at the surface.

changing with parameter variation, suggesting that small wedge failures are inevitable.

Toppling failure involves the rotation or overturning of blocks of rock about some fixed base and is associated with steep slopes and sub-vertical joints dipping back into the slope. The areas in the open pit where toppling failure has been identified are shown in Fig. 8. The joints causing potential failures are associated with JS1. Flexural type toppling most closely approximates the mechanism identified in Sandsloot open pit. In this, continuous columns of hard rock are separated by well-developed steeply dipping joints which break in flexure as they bend forward. Dilation of the joints over time is associated with sliding along shallow dipping joint surfaces. Toppling failures are evident

Fig. 12. An example of a small wedge failure.

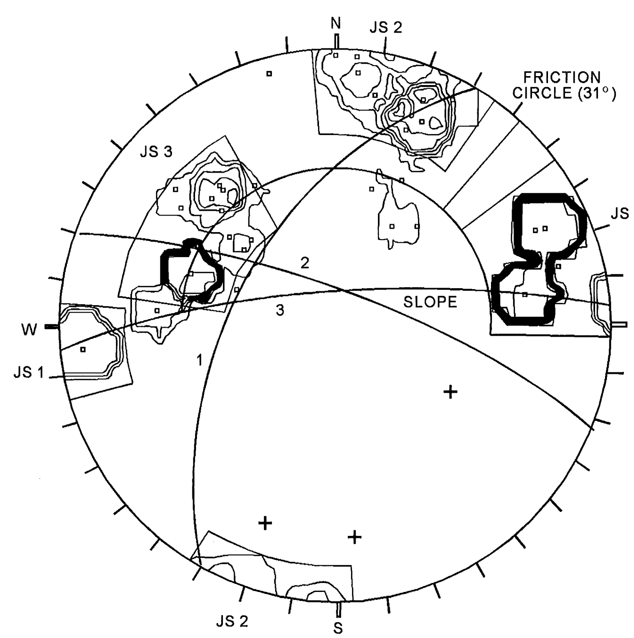



Fig. 13. Stereonet indicating potential wedge failure. Joints 1 and 2 intersect within the friction circle (joint intersection dip angle > friction dip angle) and will daylight within the slope face, resulting in a high probability of wedge failure.

Table 5
Data relating to the critical joint sets causing wedge failure on the footwall ramps

| | JS1 | JS2 | JS3 |
|---|---|---|---|
| Dip | 85° (80°–90°)<br>75° (60°–90°) | 86° (81°–90°)<br>79° (68°–90°) | 61° (42°–80°) |
| Dip direction | 087° (075°–098°)<br>253° (233°–272°) | 014° (355°–032°)<br>196° (177°–215°) | 124° (098°–149°) |
| Continuity (m) | 1–10 | 2–10 | 1–10 |
| Joint filling | Calcite | Serpentinite, calcite | Calcite |
| Joint spacing (m) | 0.40 | 0.50 | 0.30 |
| Joint thickness (mm) | 2–20 | 2–20 | 2–20 |
| Joint roughness (After Barton, 1978) | IV Undulating rough | VII Planar rough | V Undulating smooth |

Table 6
Sensitivity analysis of the pertinent parameters controlling wedge failure

| | | Factor of safety | |
|---|---|---|---|
| Parameter | | Dry | Wet |
| Face height (m) | 10–40 | 0.60–0.57 | 0.15–0.13 |
| Cohesion (kPa) | 5–500 | 0.59–0.87 | 0.18–0.18 |
| Friction angle (°) | 20–40 | 0.40–0.84 | 0.09–0.19 |

along the crests of the footwall and hangingwall. Potential failures are destabilized by crest damage attributable to poor presplit blasting and inadequate crest protection measures. However, owing to the steep nature of JSI (70–75°), and narrow joint spacing, the resultant toppling failures are small in size and are retained by the underlying catchment berm.

Circular failures may occur in rock masses, which are highly weathered or are so intensely fractured in relation to the scale of the slope that they may be considered as randomly jointed and isotropic. Unlike wedge and planar failure in competent rock, circular failure is not defined by discontinuities and the failure surface is free to find the line of least resistance. Along the eastern highwall of the Satellite pit the serpentinized pyroxenite is weathered, slickensided and jointed to such a degree that it approaches the conditions necessary for circular failure (Fig. 14). Indeed, the entire highwall underwent multiple circular failures to the extent that benches were carried away. However, the ore body within the Satellite pit was mined out in June 1998 and back filled with waste to surface elevation.

From a geometrical perspective it can be assumed that concave slopes are more stable than convex slopes. The "nose" zone is therefore potentially a problem area as it has a prominent convex geometry (Fig. 15). Small scale planar and wedge failures occur around the entire "nose" zone. The "nose" zone consists predominantly of calc-silicate material, which is highly jointed. The area therefore requires continual monitoring, as well as bench inspections so that any potential failure can be predicted.

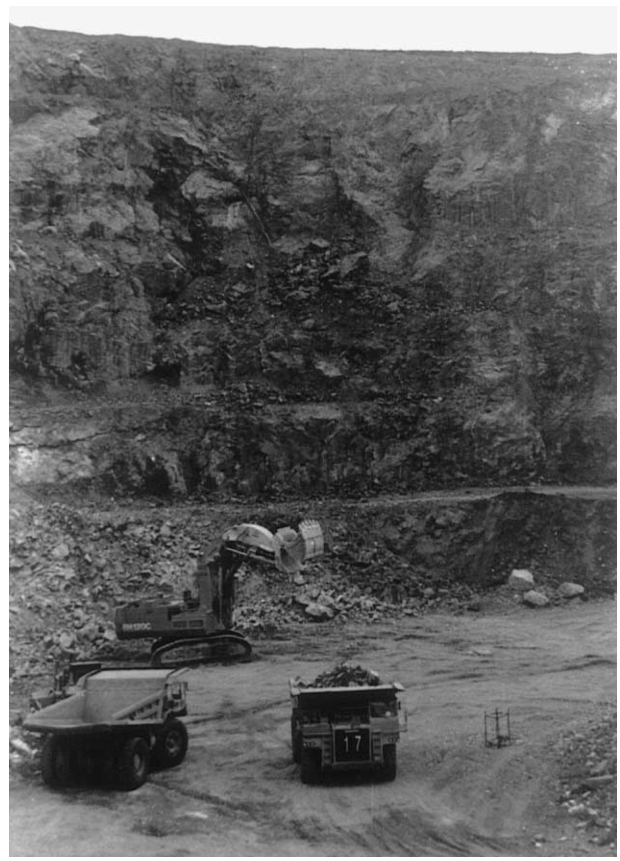


Fig. 14. Circular failure on the south-east highwall of the satellite pit.

Fig. 15. The "nose" zone between the main pit and the satellite pit.

## 6. Design zones

A number of design zones in which the geotechnical conditions are similar were recognized at Sandsloot open pit mine. Their identification was dependent upon the data obtained from extensive scanline surveys, geotechnical face mapping and exploration drillhole logs, which were evaluated in terms of the mining rock mass rating (MRMR), rock quality designation (RQD) and intact rock strength (IRS). Particular strategies and mining methods can be adopted to work each of these zones.

As noted, the mining rock mass rating (MRMR) system of [8] was used for rock mass quality assessment. When compared with the rock mass rating (RMR) system [9] and the Q-system [10] the results were very similar. The comparison was undertaken purely to ensure the MRMR assessments were providing reliable data. The MRMR system is suitable for both face mapping and drillhole logging, which ensures consistency in data capture. The averaged values of the geotechnical data collected are given in Table 2.

The MRMR system involves the assignment to the rock mass of a rating. Each parameter used in the system is weighted according to its importance and the sum of the individual weightings gives the rating. The system is outlined in Fig. 16, which shows the weighting for each parameter. A range of ratings from 0 to 100 is obtained and allows distinction of a number of classes from very poor to very good. Adjustment factors are used in the MRMR system to suit particular conditions. These include adjustments for weathering, mining induced stresses or change in stress field, joint orientation and blasting effects. The site specific mining adjustments for Sandsloot open pit are given in Table 7. The concept of rock quality designation (RQD) was introduced in [11]. It is based on the percentage of core recovery when drilling rock with NX (57.2 mm) or larger diamond core drills and is the sum of the core sticks in excess of 100 mm expressed as a percentage of the total length of core drilled. A Schmidt hammer was used in the field to obtain a rough estimate of the intact rock strength for all rock types within the pit. The point load strength of the rock types also was determined in the field.

Standardized field mapping sheets for capturing rock mass rating, geological and structural data are developed (Fig. 7). The bench face to be mapped was visually divided into zones based on a change in rock type or major structural features. Any structural zones wider than a metre were classified separately. Each individual zone then was mapped using a separate mapping sheet to which all the relevant information was captured. The mapping included a scanline survey and recorded data on joint spacing, orientation, roughness, continuity and condition. As mentioned, Schmidt hammer readings

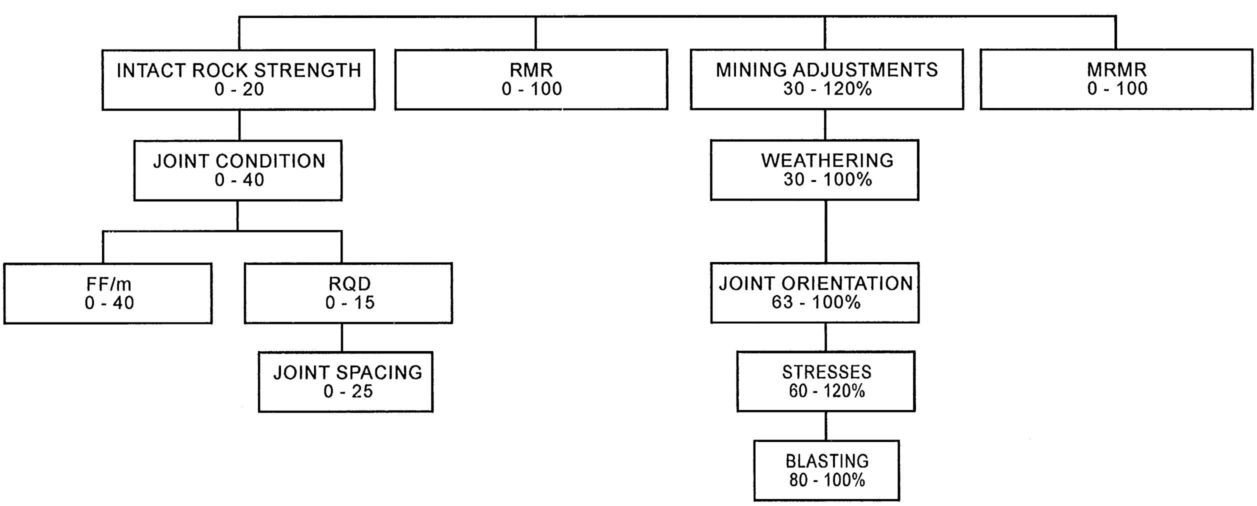



Fig. 16. Flow diagram illustrating the MRMR system of Laubscher [8].

Table 7
Mining adjustments for Sandsloot open pit

| Sandsloot MRMR mining adjustments | | |
|---|---|---|
| Weathering | 100% | All rock types have UCS > 140 MPa and do not weather significantly within a 5 year period |
| Joint orientation | 95% | One unfavourably orientated joint set (JSI) |
| Stresses | 96% | Accounts for relaxation and de-stressing of the open pit slopes |
| Blasting | 95% | Accounts for smooth wall blasting and high blast activity in narrow pit |
| Total adjustment | 87% | The total adjustment is large to ensure a conservative rating |

were taken to obtain an estimated value of intact rock strength.

The data collected in the pit was transferred to computer for digital storage. A customized AutoCAD system was used to image the mapped faces (Fig. 17). In addition, the MRMR rating was calculated by AutoCAD. Structural features, lithologies and RMR zones, then were exported to a plan, which incorporated all relevant information for a particular bench.

Dempers [12] discusses how the MRMR system was customized for a drillhole logging procedure, which allows rapid assessment of core for geotechnical evaluation. In conjunction with the logging technique, a spreadsheet was designed whereby the relevant parameters that are required for input into the MRMR system can be analyzed and interpreted. The results are used to produce final MRMR ratings and preliminary slope angles, from the charts illustrated in [13], for each geotechnical zone.

The principle of this core logging technique differs from conventional logging in which each core-run drilled is individually assessed for each geotechnical parameter required for engineering classification systems. The drillhole is separated into similar geotechnical zones based on rock type and any major structural features wider than one metre. After the drillcore has been grouped into geotechnical zones each relevant parameter required for geotechnical evaluation is determined within a particular geotechnical zone. Relevant geotechnical information subsequently can be exported directly to DATAMINE or AutoCAD for interpretation. The interpreted data are used to estimate stable slope configurations and predict rock mass conditions.

Slope monitoring is necessary to ensure that open pit slopes are safe and that any movements, which do occur are within acceptable limits. It also is important to record excessive slope displacements associated with total or partial failure. Records of displacement data can be used to predict the behaviour of a failure and enable a mine to take steps to minimize production and equipment losses and, most importantly, danger to personnel. A comprehensive slope monitoring network is being installed in critical areas of Sandsloot open pit and monitoring is carried out on a regular basis. Both permanent and temporary monitoring points are used, as well as those that are accessible to GPS monitoring and those that require conventional survey monitoring. The temporary points are on walls that will be removed within two years. Specific monitoring of individual structures as they are exposed in the pit also is undertaken using portable monitoring equipment. Portable monitoring points are located in areas that are below unstable highwalls. These points utilize a telemetry system to relay displacement information in order to help predict any sudden failures.

Traditionally, geotechnical information in an open pit environment has been collected for slope applications, however, using the data to define unique geotechnical zones, to which specific designs can be applied, is becoming standard practice. The information collected has resulted in more stable slope configurations, substantial savings in stripping costs, improved safety and extension of the life of mine.

The data obtained from the geotechnical zones are used in a slope management programme, as well as for slope design. Delineated kinematic failure zones highlight problem areas and allow adjustment of stack configurations in order to contain identified failure mechanisms. The recognition of similar geotechnical zones has afforded the opportunity to move away from one design recipe for the entire pit, and customization of slope designs and configurations has been developed to allow for local variations in the rock mass conditions. Hence, slope stability has been improved.

FLAC was used to model the pit slopes as it can take into account ubiquitous joints and variable water tables. The FLAC modelling of the pit slopes was undertaken based on the data derived from the in-pit geotechnical programme. A rigorous analysis was carried out on the hangingwall in order re-evaluate aspects of stability on bench stack and overall slope angles. A sensitivity analysis was carried out using a number of ubiquitous joint model runs to take into account the effect of critical joints on slope stability. Model runs with variations in joint cohesion and critical joint angle were

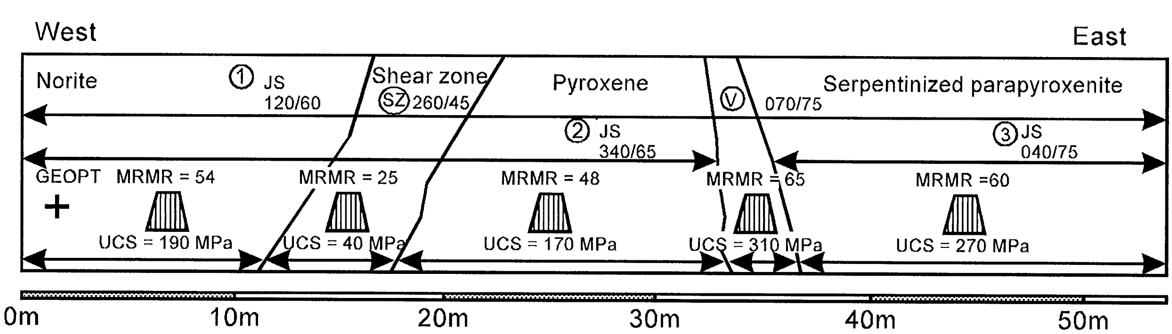



Fig. 17. An example of a geotechnical face map.

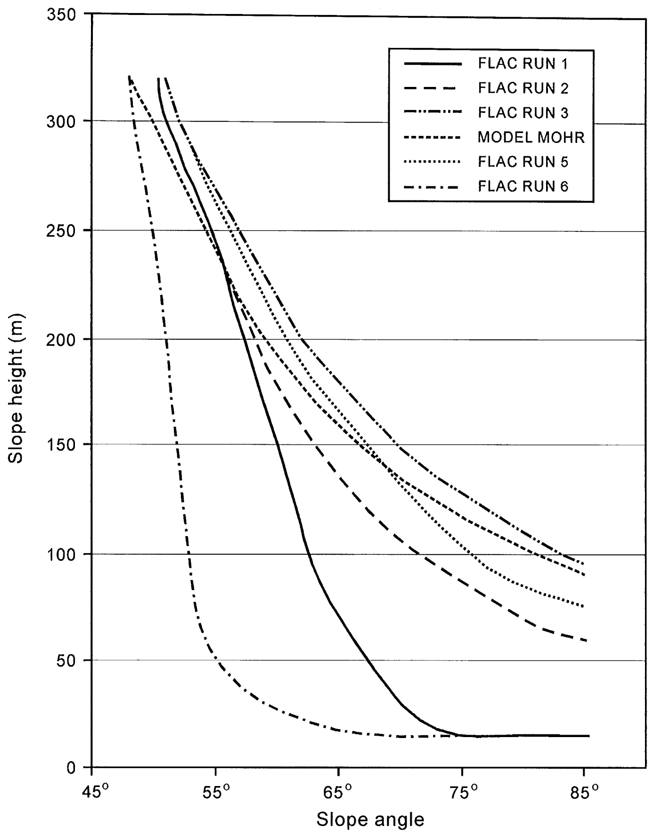



Fig. 18. Stability envelopes for norite of the hangingwall developed by FLAC analyses.

undertaken in order to determine parameter sensitivity and a stability envelope for the norite hangingwall. A critical joint dip variation of 50–65° was modelled, with a range of cohesion from 0 to 300 kPa. Fig. 18 outlines the stability envelopes of the norite hangingwall developed from the series of FLAC analyses. The input data used in the modelling is given in Table 8. It can be seen from Fig. 18 that for a 60 m stack inclined at an angle of 73°, stability can be achieved with cohesion values between 25 and 35 kPa, while for a slope of approximately 200 m inclined at 61°, the required cohesion increases to between 50 and 100 kPa. The results of FLAC modelling showed that the proposed overall angle for a 300 m slope could be increased by 7°, from 51° to 58°. Additionally, the optimized slope design has extended the life of mine by two full benches, thereby allowing the mine to accrue over R1.2 billion in additional income.

Slope configurations at Sandsloot open pit have evolved as more geotechnical data have become available and variations in slope design have been applied to accommodate kinematic failure mechanisms. Fig. 19 illustrates the evolution of the stack configurations at Sandsloot open pit from two angled bench designs to a vertical double bench design. By moving to a double bench presplit design, bench preparation, presplit holes

Table 8
Rock mass input parameters for the FLAC ubiquitous joint model

| Young's modulus | 10 GPa | Poisson's ratio | 0.2 |
|---|---|---|---|
| Friction angle | 35° | Cohesion | 30 kPa |
| Joint friction angle | 43° | Joint cohesion | 0–300 kPa |
| Density | 2.7 Mg m$^{-3}$ | Joint angle | 50° and 65° |
| Run | c (kPa) | Joint angle (°) | Joint tension (kPa) |
| 1 | 0 | 65 | 0 |
| 2 | 100 | 65 | 10 |
| 3 | 300 | 65 | 30 |
| 4 | MODEL MOHR | — | — |
| 5 | 50 | 65 | 5 |
| 6 | 0 | 50 | 0 |

and presplit drilling time is considerably reduced. The double bench configuration has improved slope design at the open pit as the 20 m catchment berms capture any planar failures on the hangingwall.

From the viewpoint of overall slope stability a double bench vertical presplit design is as stable as an angled presplit design. Angled presplits, however, result in less crest damage and cleaner walls, thereby reducing rockfall. The problem of rockfall can be dealt with by designing double benches with large catchment berms as opposed to a 60 m stack, without catchment berms. Double bench presplitting has resulted in an improved batter condition by eliminating the mini-berm, which occurred at the toe of each 15 m bench. The mini-berms could retain some loose material so creating a potential rockfall hazard.

Empirical design charts were developed from the MRMR data obtained from the geotechnical zones for stable slope height versus slope angle for each dominant rock type occurring in the pit. As a result, a unique stack configuration and optimized slope angle can be developed for each geotechnical zone, taking into account practical constraints. For example, Fig. 20 illustrates the stable slope height, with a factor of safety of 1.2, for the different rock types present at Sandsloot. As the variability of measured parameters must be taken into account when using the MRMR data for design purposes sensitivity analyses were undertaken to determine the upper and lower range of MRMR values per rock type. Figs. 21a–e illustrate the range of slope design angles for each major rock type at Sandsloot open pit.

## 7. Summary and conclusions

Sandsloot open pit is the largest platinum mine in the world and it is situated on the northern limb of the Bushveld Igneous Complex. The major discontinuities

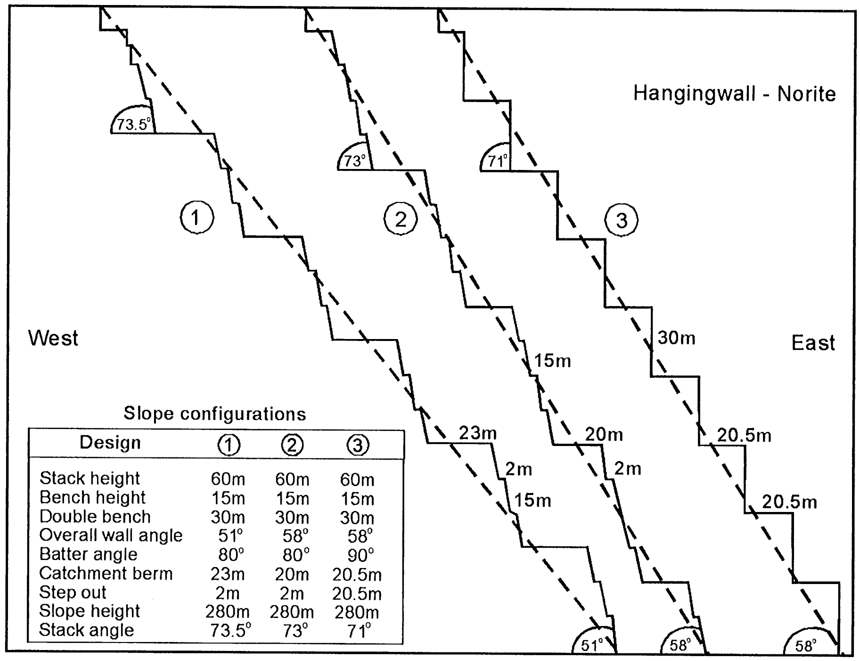



Fig. 19. Stack configuration for the hangingwall.

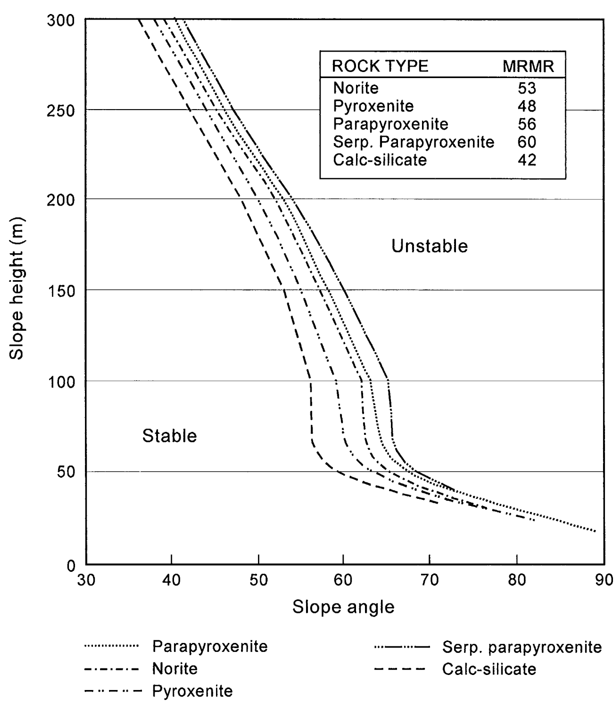



Fig. 20. An example of a slope design chart for rock types at Sandsloot.

at Sandsloot reflect the tectonic history, the three main joint sets having no obvious relation with rock types. The principal joint sets are continuous throughout the pit. Geological and geotechnical data at the pit has been obtained by mapping faces and from exploration drillholes and from blastholes. Once the geotechnical data set is collected, it is then evaluated in AutoCAD and SABLE to give rock mass quality ratings in terms of the MRMR classification system. This has aided the recognition of different geotechnical zones with different slope failure mechanisms within the pit. Hence, a major features plan of the pit together with geological sections has been produced and is continuously updated. Groundwater and its flow through a rock mass, with associated pore water pressures, adversely affect potential failure surfaces lowering the factor of safety of the slope. Therefore saturated joint zones are mapped in detail and incorporated into the major features plan.

Plane failure appears not to be a serious problem unless the slope becomes saturated. Heavy rainfall with a rising water table significantly reduces the stability of potential failure planes. Hence, the critical joints on the western highwall require monitoring. Wedge failures have tended to be small and are only likely to cause failure of a single bench. By contrast, potential multi-bench circular failure poses a threat to production in the pit. Unfortunately, there is little that can be done to stabilize these areas of potential circular failure and so monitoring is important in that it helps to predict slope movement. It also has to be borne in mind that vibrations generated by blasting subject slopes to dynamic loading and that blasting itself can weaken rock masses, especially weathered and/or highly discontinuous rock masses.

Recognition of variations in rock mass quality and different types of slope failure has meant that slope design has been tailored to suit the geological conditions. In this connection, a rigorous analysis of the data obtained from mapping and drillholes, by means of the

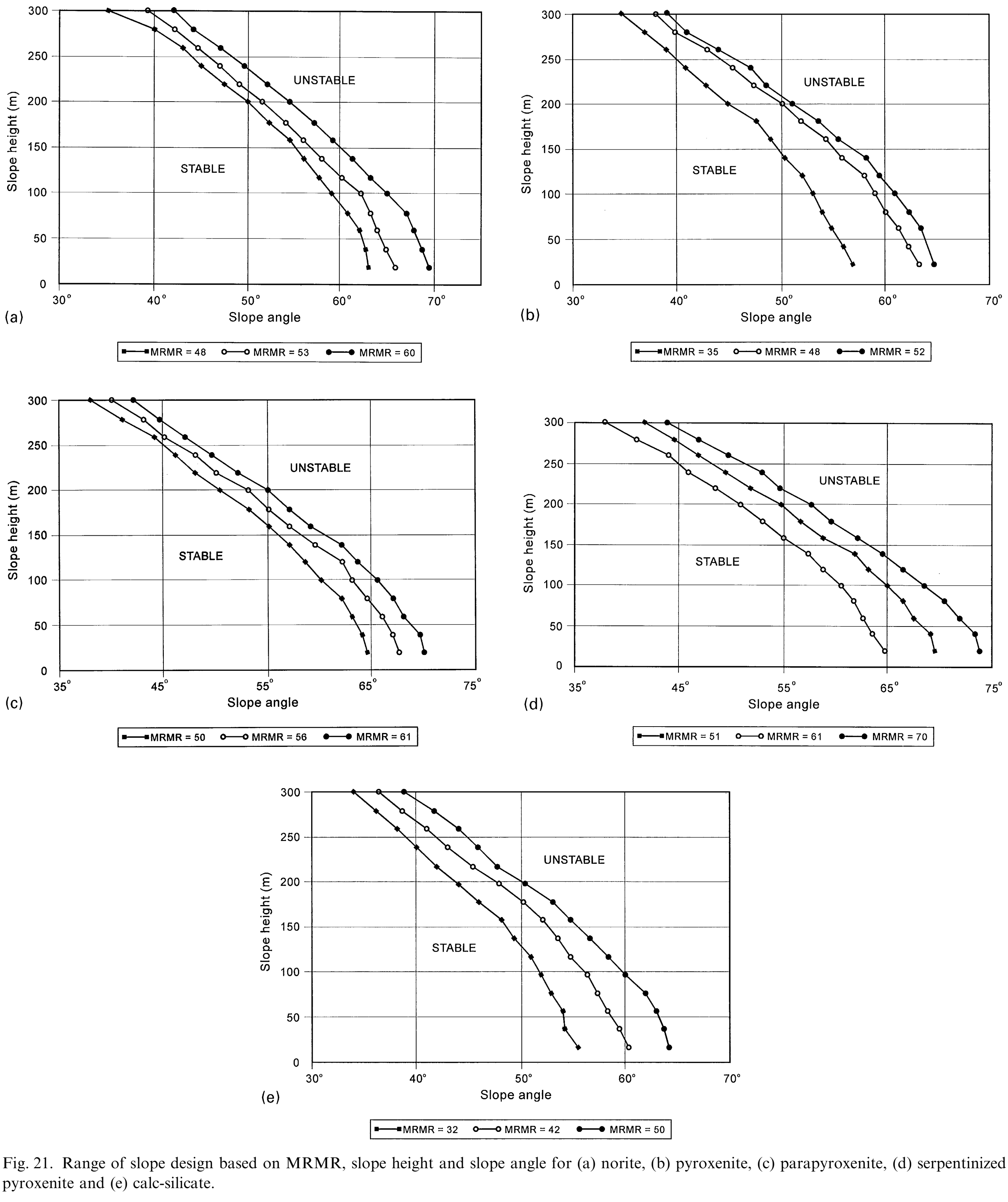



Fig. 21. Range of slope design based on MRMR, slope height and slope angle for (a) norite, (b) pyroxenite, (c) parapyroxenite, (d) serpentinized pyroxenite and (e) calc-silicate.

FLAC modelling, was undertaken on the hangingwall to assess aspects of stability on bench, stack and overall slope angles. This proved that the overall slope angle for a 300 m slope could be increased by 7°, from 51° to 58°. The significance of this is demonstrated by the fact that a single degree saves R12 million in stripping costs. In addition, optimization of slope design has extended the life of mine by two benches, thereby allowing the mine to generate over R1.2 billion in additional revenue. Empirical design charts have been developed for stable slope angle in relation to stable slope height for the geotechnical zones. As a result, stack configurations have been adjusted to prevent or accommodate failures in these zones.

Slope monitoring is necessary to ensure that the open pit slopes are safe and movements are within acceptable limits. A comprehensive monitoring system is being implemented and data gathered therefore helps to provide a rational basis for evaluating stability conditions. In other words, a record of displacement data can be used to help predict the behaviour of a potentially unstable slope.

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