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Investigation into the location of chromitite plant structures on shallow undermined ground

F. HARVEY
Steffen, Robertson and Kirsten (South Africa) (Pty) Ltd, Illovo, South Africa

When a mine decides to construct surface structures close to, or on undermined ground, it is required in terms of the regulations of the Mine Health and Safety Act to obtain permission from the Department of Minerals and Energy (DME). Apart from the legal requirements, the stability of the structures is crucial as damage to the structures due to surface movements could result in loss in life, equipment and/or production.

This paper deals with the rock engineering aspects of a study that was conducted on one of the chrome mines in the Bushveld Complex (BC) involving the construction of plant structures on shallow undermined ground. The paper addresses the legal requirements and guidelines regarding ground stability of surface structures placed on undermined ground and the assessment of the undermined area with regard to the following:

- sources of potentially damaging surface movements
- safe mining spans
- stability of the pillars
- effect of the loading of plant structures on underground stability.

Due to the irregular layout and geometry of the pillars in conjunction with a changing surface topography, numerical analysis and not the conventional tributary area theory was used to determine the imposed loads on the pillars.

In order to subject the plant structures to minimum movement, the plant should be located in areas where the pillars would remain stable, the elastic deformation of the hangingwall is minimized and hangingwall failure extending to surface is unlikely to occur.

The study indicates that although the depth of undermining is shallow (between 27 m and 60 m), potential damaging surface movements are not anticipated due to the stability of the pillars, competent nature of the overlying strata and negligible effect of the plant structure loading on the underground stability.

Criteria for undermining

Legal requirements

The regulations under the Minerals Act, No. 50 of 1991 also apply to the Mine Health and Safety Act No. 29 of 1996. Regulations 5.3.1 to 5.3.5 provide for the mining under or near surface structures and the construction or erection of surface structures over undermined areas. The regulations make it clear that permission must be obtained from the DME to erect or construct any structure over or within a horizontal distance of 100 m from workings.

Sources of potentially damaging surface movements

Subsidence can be divided into two categories, namely continuous and discontinuous subsidence. If the mining spans are sub-critical and there are no major geological structures present, the hangingwall would tend to deform elastically, resulting in a smooth and continuous surface subsidence profile, which is favourable.

When mining spans are super-critical, progressive failure of the hangingwall may occur. The failure could extend either to some point within the overlying strata or to the surface. Experience shows that the failure profile would probably occur to the angle of break, approximately 70°, and the free span of the overlying strata would gradually reduce as the height of caving increases. When the free span of the overlying strata is reduced to sub-critical dimensions for the strata, failure would stop and only elastic deformation would continue further. Should failure extend to surface, a stepped or discontinuous subsidence profile will result.

Discontinuous subsidence can result from block movement in which the subsided block of ground is defined by the contact planes of major geological features that extend to the surface. Alternatively, hangingwall failure could occur if an unstable block is formed in the hangingwall by the intersection of sub-horizontal and sub-vertical joints with low shear resistance. Failure could occur up to the sub-horizontal joint and would only progress further if the resulting free span, of the exposed strata, is super-critical.

According to Stacey and Baker[1], overloading of pillars and their consequent collapse, associated with major geological features, have been the probable reason for surface subsidence in the BC. It is also a known fact that pillar failure will result in increased mining spans, causing greater elastic deformation, with the critical span possibly being exceeded.

Safe mining spans

Mining spans should be maintained sub-critical to prevent initial failure of the immediate hangingwall. The critical span can be determined from knowledge of the geological structures, rock mass properties of the immediate hangingwall and mining experience. These spans should be reduced if unusual jointing, which may result in the formation of large unstable blocks, is apparent. Bakker[2] has suggested safe mining spans for both a worst-case scenario and a more stable environment in the BC, based on UG2 and Merensky Reef mining as summarized in Table I.

Table I
Safe mining spans for the BC after Bakker

Depth range	Safe mining span	
	Worst case	Stable
50 m–75 m	18 m	28 m
75 m–100 m	20 m	30 m
100 m–125 m	24 m	33 m
125 m–150 m	29 m	36 m
150 m–175 m	35 m	40 m
175 m–200 m	42 m	45 m
200 m–240 m	45 m	

Pillar stability

The stability of pillars depends on the magnitude of the imposed loads relative to the strength of the pillars. The pillar load is usually determined using the tributary area theory, which is often conservative and does not take into account irregular mining layouts. Alternatively, the pillar loads can be determined through numerical modelling.

An empirically derived formula after Hedley and Grant[3] is generally used to determine the strength of pillars in hard rock. The formulas were subsequently altered for pillars of different width to height ratios.

For W:H ratio less than 4.5:

$$Strength = k\frac{w_{eff}^{0.5}}{h^{0.75}} \qquad [1]$$

For W:H ratio greater than 4.5 after Stacey and Page[4]:

$$Strength = k\frac{2.5}{V^{0.07}}\left(0.13\left[\left(\frac{R}{4.5}\right)^{4.5} - 1\right] + 1\right) \qquad [2]$$

Where:

k = cubic strength of the pillar material

w_{eff} = effective width of pillar (see Equation [3])

h = height of the pillar

$V = w_{eff}^2.h$

$R = w_{eff}/h$

According to Stacey and Page[4] and Laubscher[5], the design rock mass strength (DRMS) can be used to estimate k. In the case of rectangular pillars, the effective width (w_{eff}) is obtained by:

$$w_{eff} = \frac{4A}{C} \qquad [3]$$

Where A is the cross-sectional area of the pillar and C is the circumference of the pillar.

The factor of safety (FS) is calculated as the pillar strength divided by the pillar load. Stacey and Baker[1] proposes that the FS for pillars for the protection of surface structures, should never be less than 1.5. However, this is the FS suggested by Hedley and Grant[3] for general pillar stability and it is expected that this should be higher for the protection of surface structures. For coal, Bakker[6] suggests factors of safety for the various surface structures, ranging from 1.6 to 3.0. Based on previous undermining studies conducted by SRK in the area (SRK Report No. 261117/3 and SRK Report No. 261117/4) an FS of at least 2.5 will be considered for the study.

General characteristics of area of interest

Geology

The area where the plant is to be located is at the foot of a hill with a change in topography from the hillside to a flatter landscape. Mining has been conducted on the MG1 chromitite seam, which dips towards the West at approximately 15°. The depth of the undermining in the area of interest ranges from approximately 27 m to 60 m.

The MG1 chromitite seam is relatively competent, with a DRMS of about 35 MPa. The immediate hangingwall is a competent pyroxenite. The overlying strata are predominantly composed of competent pyroxenite and norite. Three chromitite packages, MG2, MG3 and MG4, are found above the MG1. These chromitite packages are intact and will not be mined in the future. Based on borehole data close to the area, surface weathering extends to an approximate depth of 7 m.

The few major geological structures in the mining area have a north east-south west strike. A dyke structure of approximately 8 m wide is present in the area where the drum and cyclone plant structure is to be positioned (Figure 1). From underground observations, the dyke appears to be competent and no ingress of water was observed.

Mining geometry

Regional pillars to the east and south bound the area where the plant structures are to be positioned. The dyke structure to the west was left intact acting as a barrier pillar. The span between the pillars ranges from 2 m to 27 m as depicted in Figure 4. The pillar sizes vary substantially and are expressed in terms of its cross-sectional area as depicted in Figure 5.

All rib pillars in the area of interest are stable and no signs of scaling have been recorded to date. In general, the hangingwall is competent and it appears that mining spans on the MG1 are sub-critical. Large scale hangingwall failures are uncommon on the mine.

The area beneath the proposed new metallurgical plant and associated infrastructure was visited in order to assess the general stability of the area and particularly the pillars *in situ*. The ground conditions in the area are generally very good with only minor falls of ground of less than 0.6 m in thickness have occurred. The chromitite pillars are in excellent condition and show no sign of scaling. Spans between pillars are generally less than 20 m and show no potential large collapses or caving to surface.

Surface structures

The chromitite plant consist of drum and cyclone plant structures, a plant feed bin structure, a screening and crushing structure and four stockpiles that will be located directly above existing pillars, as indicated in Figure 1.

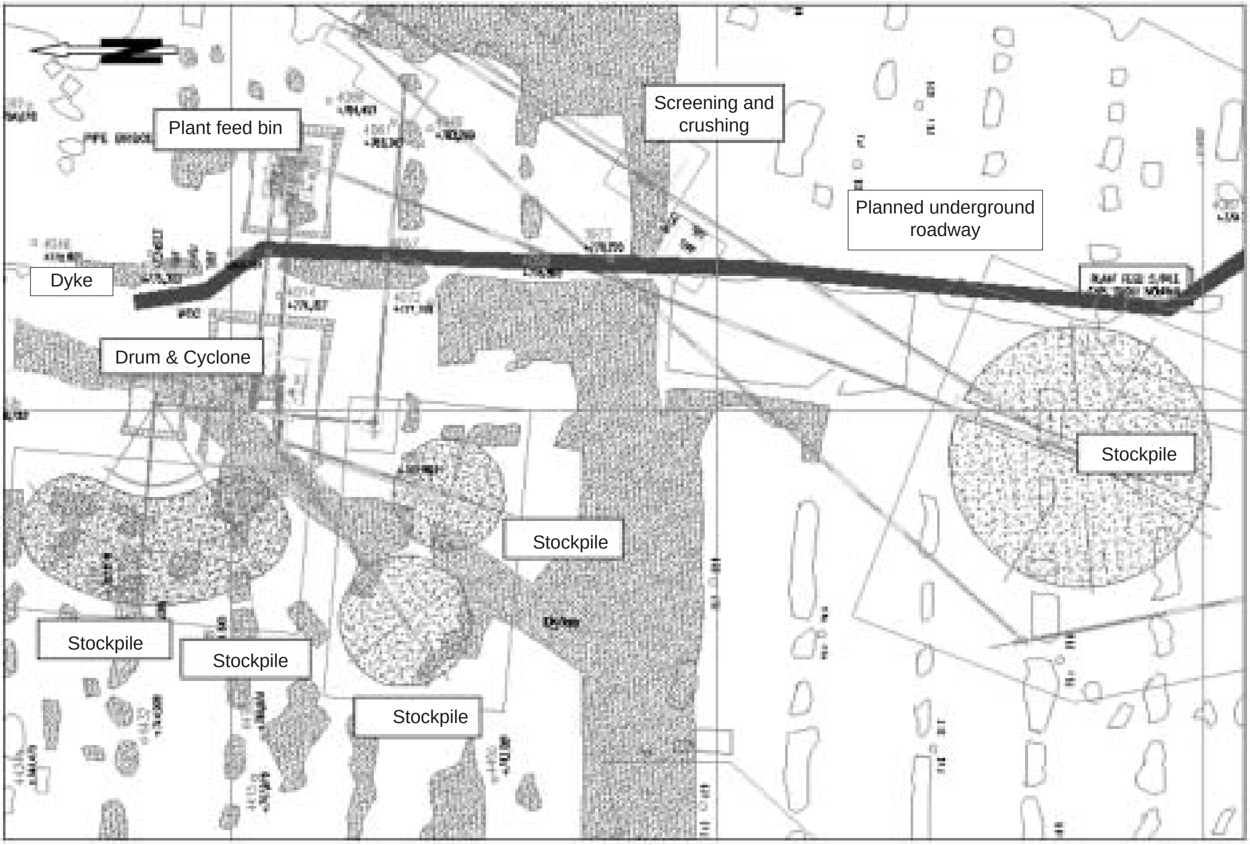

Figure 1. Plan view of area of interest

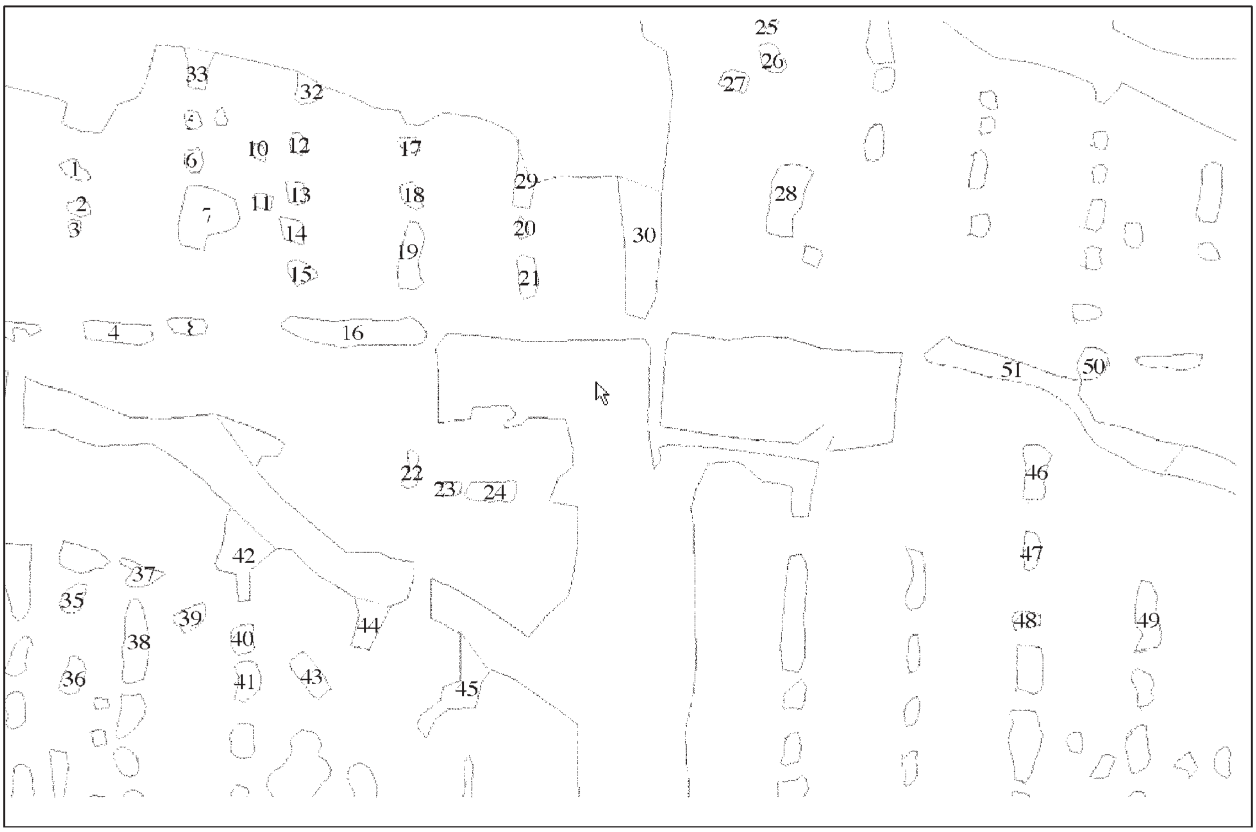

Figure 2. View of pillars that were analysed

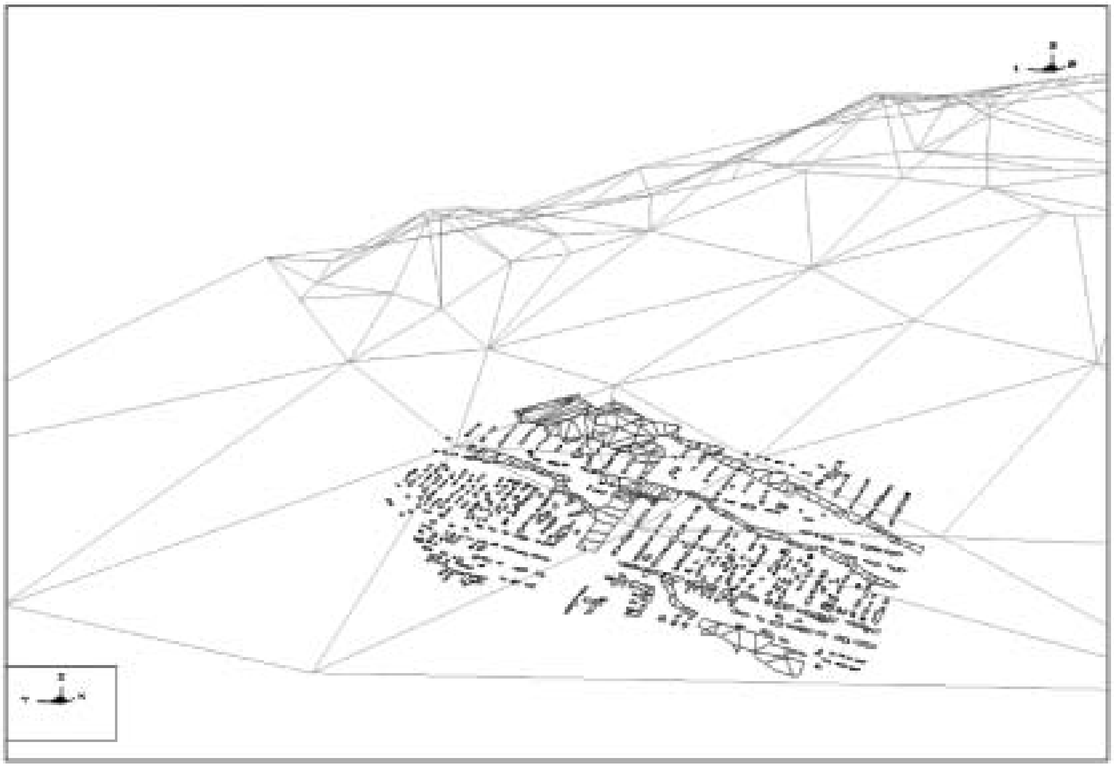

Figure 3. View of constructed model

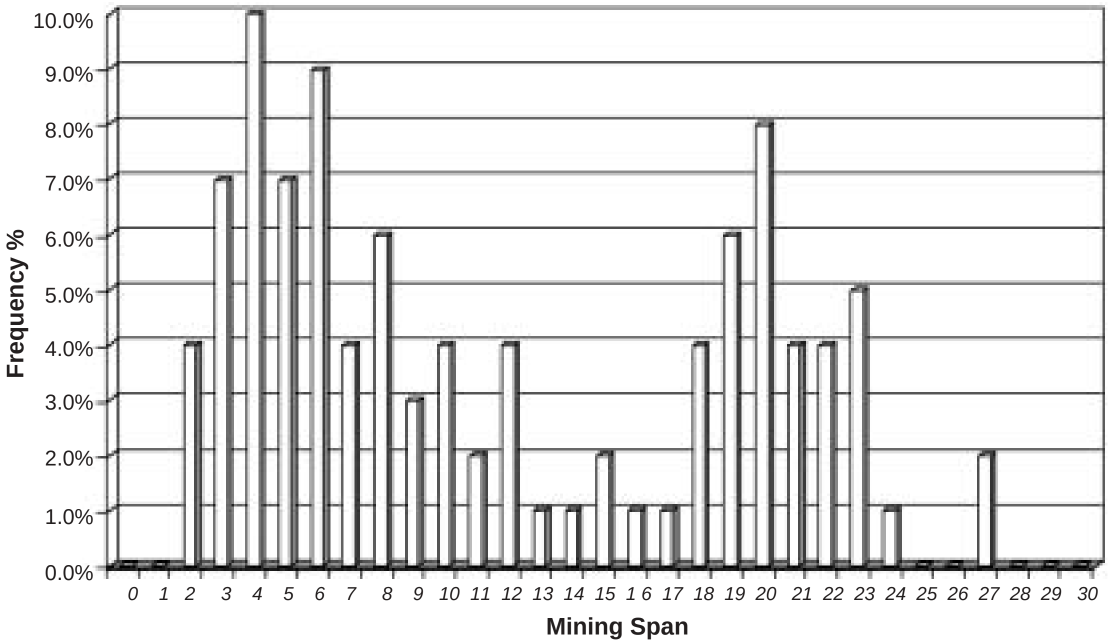

Figure 4. Distribution of mining span

Analysis

Continuous surface subsidence

Due to the relatively small mining spans and occurrence of regional pillars in the area, the probability of continuous surface subsidence over a large area is small. Continuous surface subsidence normally occurs during or directly after mining has taken place. Mining of the area was conducted between 1980 and 1989. The 13-year period after mining was concluded in the area would be sufficient for any significant settlement to take place over a large area.

Discontinuous surface subsidence

Although 13 years have passed after mining was concluded in the area, the possibility of discontinuous subsidence still needs to be considered. Discontinuous subsidence generally results from block movement along geological structures extending up to surface and/or progressive hangingwall failure where critical mining spans are exceeded as previously discussed.

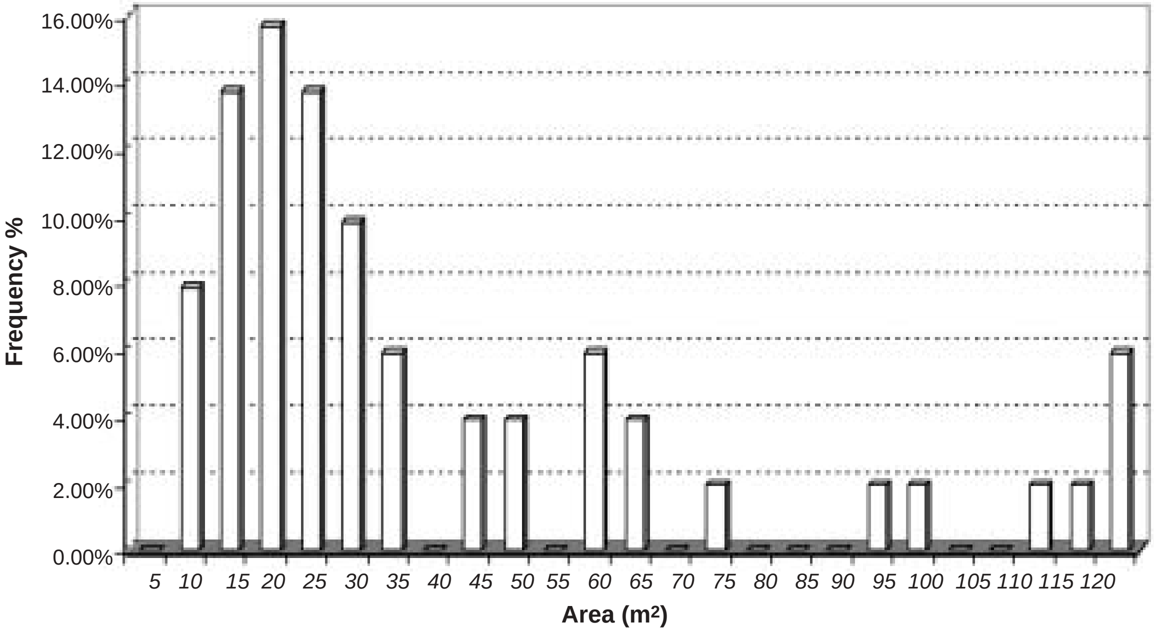

Figure 5. Distribution of pillar cross-sectional area

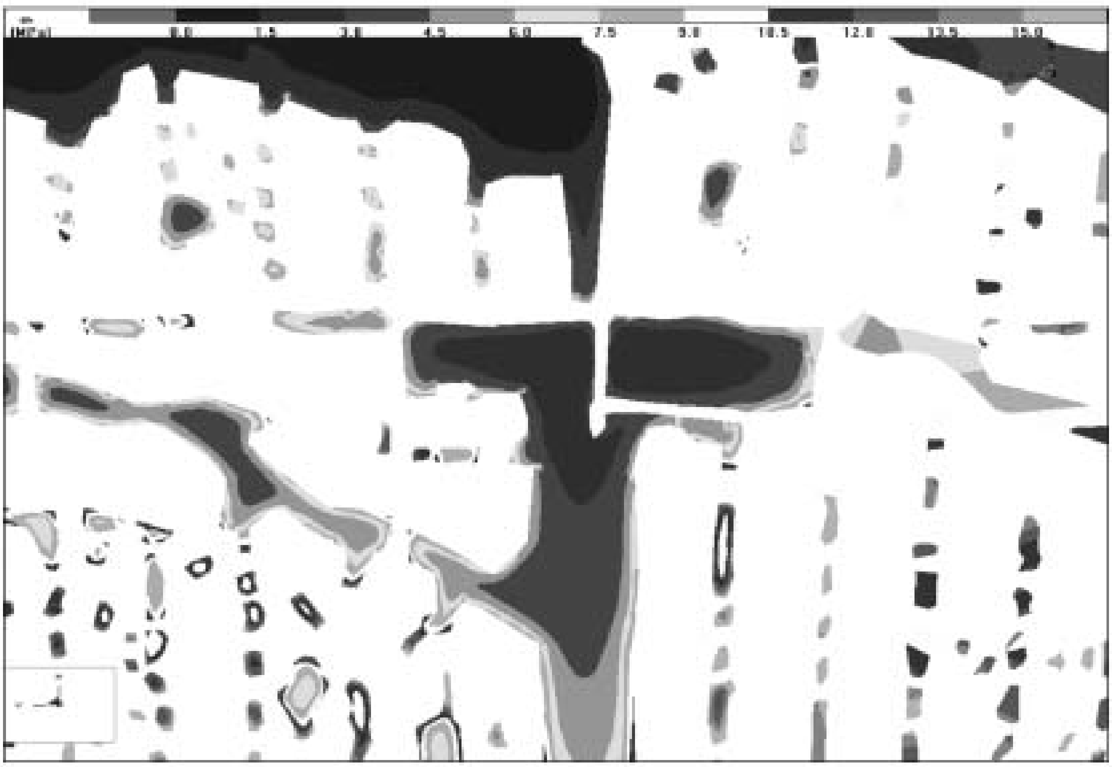

Figure 6. Results—contour plot of pillar stress (MPa)

The immediate hangingwall and overlying strata in the area are competent. From experience, it is apparent that mining spans of approximately 15 m are sub-critical for the current hangingwall conditions. The average mining span in the area is approximately 11.5 m with 65 per cent of the mining spans being less than 15 m. Unstable blocks can occur in the hangingwall, due to unfavourable joint orientations; however, these are infrequent. Additional pillars are normally left when unfavourable jointing is recognized, which further reduces the probability of these types of failures. It is unlikely that these failures would continue to surface, since the overlying strata is of a competent nature.

The few major geological structures in the mining area are generally undulating and irregular and would have a high shear resistance over their full length, so that large-scale slip would be unlikely. The probability of discontinuous subsidence resulting from differential block movement along the dyke structure are minimized by pillars left intact along the dyke structure.

Numerical analysis to determine pillar stability

The stability of the pillars was analysed by calculating the pillar strength (Equations [1] and [2]) and obtaining the average pillar stress from numerical analysis using the boundary element program Map 3D, which is a full three-dimensional rock stability analysis package.

The average pillar stress levels were determined through numerical analysis and not by using the conventional tributary area theory for the following reasons:

- the layout and geometry of the pillars are irregular, making the use of the tributary area theory impractical
- the surface topography changes, resulting in different undermining depths, which cannot be effectively assessed by using the tributary area theory.

The factors of safety for the pillars in the area of interest were subsequently calculated by dividing the pillar strength by the pillar load.

Model construction

The host rock was modelled as a single material with typical properties for pyroxenite or norite. The pillars were modelled with typical properties for a relatively competent chromitite. All materials were allowed to deform plastically, and the Mohr Coulomb failure criterion was applied. Geological discontinuities were not included in the model and the formation of unstable blocks is therefore not taken into account. The constructed model is illustrated in Figure 3.

Results

The 51 pillars that were assessed are depicted in Figure 2. The FS calculated for each of the 51 pillars is graphically presented in Figure 7 with the FS frequency distribution depicted in Figure 8. The FS for the various pillar sizes varies from 2.5 to as high as 13.8. The high factors of safety can mainly be attributed to the small mining spans and the effect of the regional and barrier pillars. The relatively low FS (2.5) calculated for Pillar 22 can mainly be attributed to the larger mining spans in the area and the small cross-sectional area of the pillar. There are no structures planned to be erected over the pillar that could result in an increase in load on the pillar. The pillar should therefore remain stable.

Effect of loading of plant structures on underground stability

The static and dynamic bearing pressures for the structures as provided by the mine and are tabulated in Table II.

It is well known that the pressure increase caused by a structure placed on surface decreases with an increase in depth. For the worst case, i.e. for a 53 m diameter stockpile applying a sustained static load of 250 kPa on surface, will reduce to approximately 105 kPa at approximately 40 m below surface after Das[7]. The increase in load will result in the FS of the pillars directly below the structures decreasing by maximum 1.1% with a minimum FS of 3.4.

The effect of the dynamic loading of the structures on the stability of the rockmass is more difficult to quantify. The dynamic loading can be expressed in terms of the energy being transmitted. If the host rock is subjected to a dynamic load of 5 kPa the energy is in the order 0.00063 J/m^2. Matthews, Hope and Clayton[8] suggest that approximately

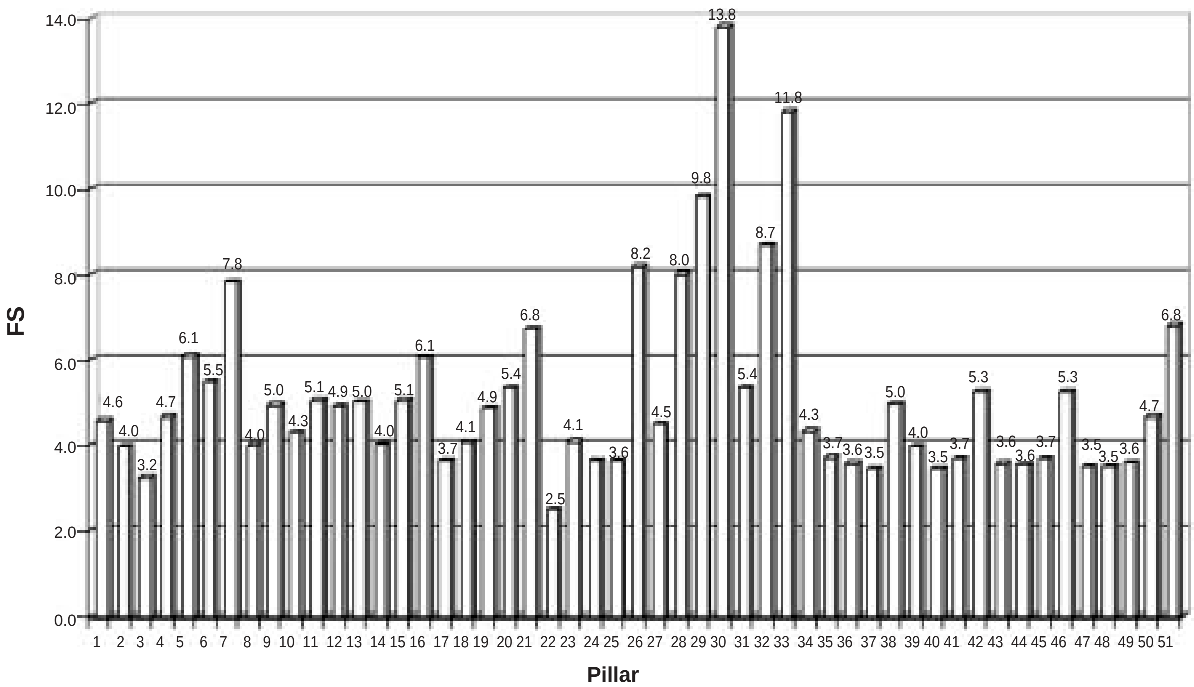

Figure 7. Factors of safety for each pillar of interest

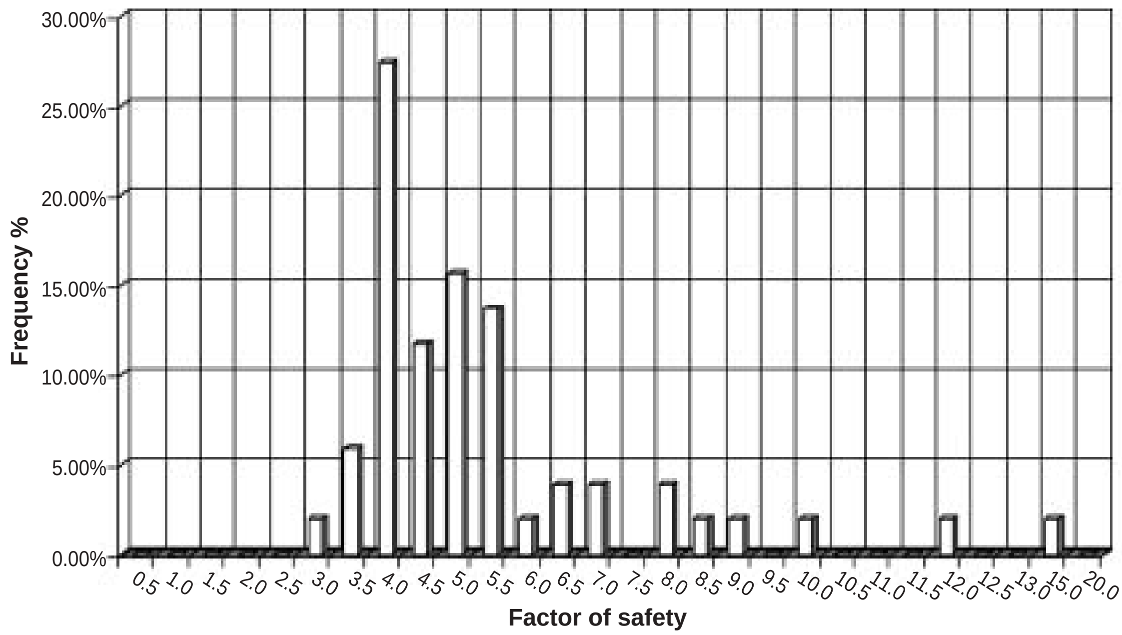

Figure 8. Distribution of factor of safety

Table II
Static and dynamic bearing pressures

Plant structure	Foundation size	Bearing pressure		
		Sustained static	Peak static	Dynamic
Drum and cyclone structure	2 m x 2 m	100 kPa	150 kPa	5 kPa@16 Hz
Plant feed bin structure	2.5 m x 2.5 m	150 kPa	200 kPa	5 kPa@16 Hz
Screening and crushing structure	12 m x 8 m	80 kPa	120 kPa	5 kPa@ 5 Hz
Stockpiles	53 m diam	250 kPa	-	-

half of the energy of a pulse induced at surface is transmitted in the form of Raleigh waves which travel along the surface and will therefore not affect the underground workings. The remaining energy is transmitted as P and S waves through the rockmass. The energy that will therefore be available to affect the rockmass is approximately 0.00032 J/m^2. This energy is available on surface and will further decrease with depth. It can therefore be assumed that the affect of the dynamic loading will be insignificant 27 m below surface.

Although the effect of the dynamic loading of the surface structures on the underground workings is expected to be negligible, precautions still need to be taken. As the areas are readably accessible via the underground roadway (Figure 1), inspections of the ground conditions in the area are to be conducted on a regular basis. If any deterioration of the ground conditions is observed, line management is to be notified.

Conclusions

- Experience and numerical modelling show that the mining spans in the area of interest are sub-critical.
- Unstable blocks formed by unfavourable jointing occur infrequently. Such hangingwall failures are unlikely to cause progressive failure up to surface, since the overlying strata are of competent nature.
- Discontinuous subsidence resulting from differential block movement are minimized by pillars left intact along the dyke structure.
- The pillars in the area of interest have a factor of safety of more than 2.5. This exceeds the factor of safety recommended by Bakker[2]. Underground observations further indicate that the pillars are stable.
- Due to the relatively small mining spans and large regional pillars, continuous subsidence over a large area is not anticipated.
- The increase in load due to the static foundation pressure will result in the FS of the pillars directly below the structures decreasing by maximum 1.1% with a minimum FS of 3.4.
- It is expected that the effect of the dynamic loading of the surface structures on underground workings will be negligible 27 m below surface.

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