Numerical modelling of pillars with weak alteration layers using the TEXAN code

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ABSTRACT: At Everest Platinum Mine, pillar failure occurred in 2008 owing to a weak alteration layer in the pillars. A numerical back analysis was conducted to ascertain design parameters for the ground conditions. The displacement discontinuity code, TEXAN, proved to be useful to simulate the pillar failure. The capability of the code to simulate irregularly-shaped pillars on a large scale was indispensable for this analysis. Furthermore, the built-in limit equilibrium model allows the pillar spalling and failure to be simulated. The model contains a parting at the hangingwall and footwall contacts which appears to be attractive to simulate the effect of the alteration layer. The model was calibrated using data, observations and other information from Everest Platinum Mine. This calibrated model allowed for the study of possible layouts when similar ground conditions are encountered in future.

Keywords: Pillar design, pillar strength, weak alteration layer, limit equilibrium model, displacement discontinuity numerical modelling.

1 EVEREST PLATINUM MINE

The Bushveld Igneous Complex (BIC) in South Africa is the world's largest layered igneous intrusion. It hosts the world's single largest deposit of platinum group metals (PGMs), with three main mining areas namely the western, eastern and northern lobes. The eastern lobe is located predominately in the Limpopo Province, but also in the Mpumalanga Province. Everest Platinum Mine is situated on the southern tip of the eastern lobe of the BC in the Mpumalanga Province. The mafic rocks of the BC are known as the Rustenburg Layered Suite (RLS) that sub-outcrop around the periphery of the complex and dip towards its center. The RLS is subdivided into five zones, of which the Critical Zone (CZ) is the most important as it contains the economically important horizons that include the PGMs and chromitite. The two mineralized layers, which contain the economically important PGMs, are the Merensky reef and the Upper Group 2 (UG2) chromitite layer. Only the UG2 reef was mined at Everest Platinum Mine. The perimeter of the BIC lobes is prone to contain the weak alteration layers formed during cooling. These layers comprise the overall stability of the mines.

Hartzenberg et al (2020) defines alteration layers as follows: “The hangingwall contact of the UG2 Chromitite Reef at these sites consists of pyroxenite. The pyroxenite layers have been exposed to hydrothermal fluid flow, serpentinization and layer-parallel shearing. The resulting clay-like material (weak partings) is defined as the alteration zone.” These layers are illustrated in Figure 1.

Figure 1. Underground photographs of the alteration layer present in the pillars at Everest Platinum Mine. Close up of the alteration layer (left). Pillar showing the presence of the alteration layer on the top contact of the chromitite pillar (right) (after Couto, 2022).

In November 2006, pillar spalling was observed at Everest Platinum Mine and monitoring instrumentation was installed to monitor the overall mine stability. Following high rainfall and the continuation of mining, pillar failure occurred at the mine on the 8 December 2008. Contributing factors to the failure were undersized pillars and the deterioration of the alteration layer due to water and weathering over time. Figure 2 illustrates the extent of the pillar failure across the entire mine as described by Lombard (2008).

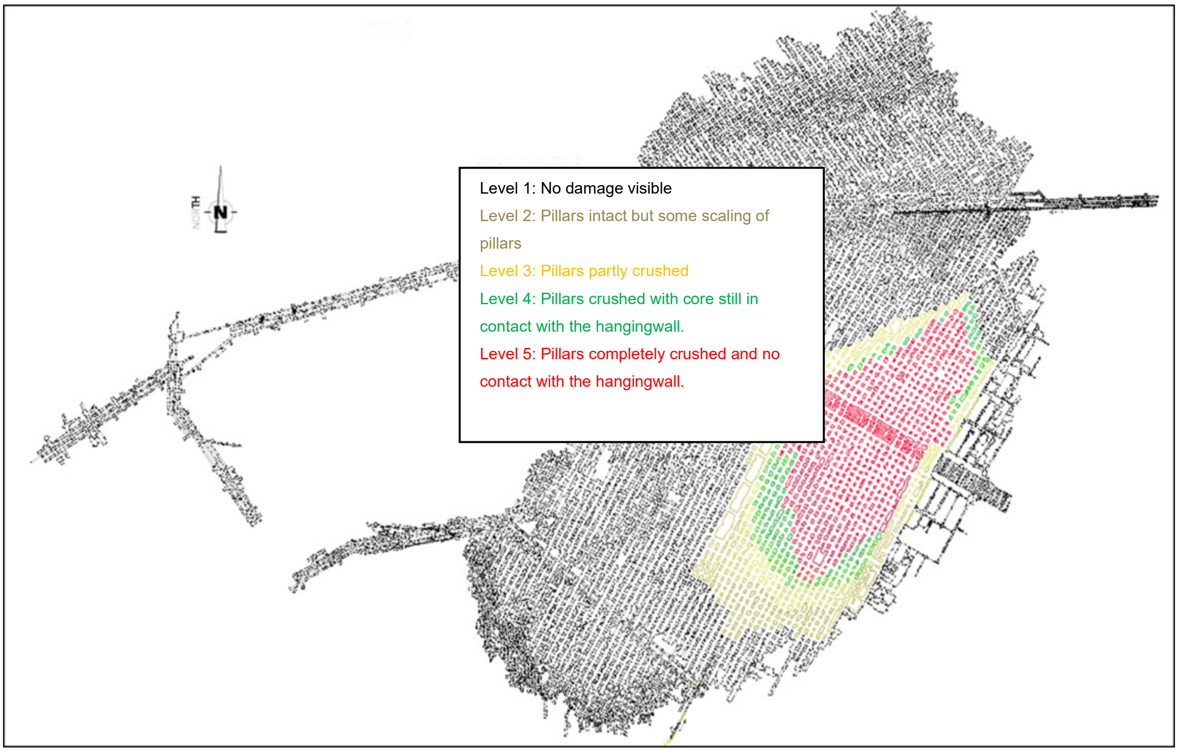

Figure 2. Plan view of Everest Platinum Mine showing the extend of the pillar failure and the conditions of the pillars after failure in 2008 (after Lombard, 2008).

2 NUMERICAL MODELLING – TEXAN CODE

2.1 *Introduction*

In the displacement discontinuity boundary element method (DDM), mining layouts are approximated as irregular shaped planar cracks (or slits) where the ‘width’ of the crack, corresponding to the excavation height, is assumed to be negligible compared to the lateral dimensions. This approach has been successful to simulate the tabular layouts of the deep gold mines in South Africa and early codes using this approach were MINSIM and BESOL. The TEXAN (Tabular EXcavation ANalyser) code (Napier & Malan, 2007) is an enhanced approach in which triangular or quadrilateral element shapes can be used in conjunction with higher order variations of the displacement discontinuity shape functions. This facilitates a more accurate evaluation of detailed stress and displacement components close to excavation surfaces and allows for the assessment of tabular layouts which includes many irregular-shaped pillars.

2.2 *Calibration of the Limit Equilibrium Model*

Initial modelling results indicated that the limit equilibrium model (LEM) in TEXAN will be a useful tool to simulate the pillar failure at Everest Platinum Mine. Details of the model are given in Couto & Malan (2023). Numerous models were run to determine suitable model parameters to simulate the stable and failed areas. Figure 3 illustrates two such areas.

Small element sizes (≈0.5 m) were used to ensure that the LEM is a realistic approximation of the depth of failure in the pillars. Owing to the limitation of the number of elements that can be used in TEXAN and the requirement of small element sizes, the entire mine could not be simulated. An intact and failed area were selected and these two are referred to as “Collapsed” and “Intact” (Figure 3).

Ideally, larger areas than those illustrated in Figure 3 should be modelled. The version of TEXAN used was limited to 60 000 elements. The total number of elements used to simulate the layouts shown in Figure 3 was 52 366 (Collapsed) and 55 679 (Intact). Currently, a new TEXAN code allowing up to 350 000 elements is available and larger runs can be considered in future. The models used nevertheless gave good insights into the applicability of the limit equilibrium model and first estimates of calibrated parameters could be obtained.

The simulated areas were 160 m x 160 m in size and were selected following underground visits to the mine in 2019 and 2020. If the same set of parameters indeed predict pillar failure in the collapsed area and no failure in the intact area, then these parameters can be used with some degree of confidence for future pillar design in similar ground conditions. The depth below surface for both areas does differ, however, and the models were simulated at the different depths.

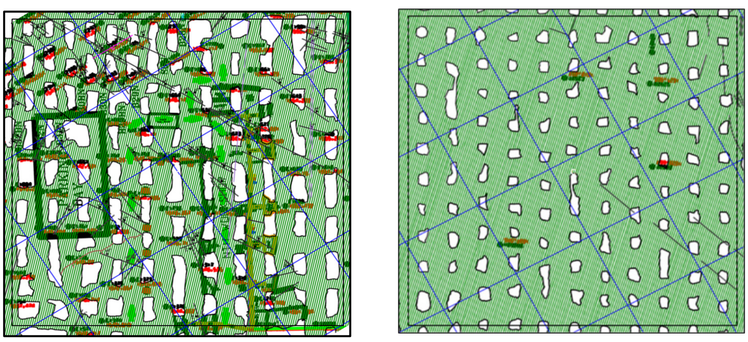

Figure 3. Enlarged views of the two areas simulated. Intact area (left - Extraction ratio = 67.11%) and Collapsed area (right – Extraction ratio = 87.84%) (after Couto and Malan, 2023).

2.3 Model parameters

For the LEM simulations, the parameters in Table 1 had to be calibrated. The initial values were selected to represent a very weak rock mass material to test the model geometries and failure of the pillars. Similar properties were used for the initial models of both areas, even though the interface friction angle was lower in the collapsed area owing to the presence of water and the resulting weathering of the alteration layer. It was noted that friction angle values as low as 17° were recorded for some clays (Couto, 2022). Further calibration of the model was conducted to determine appropriate parameters based on underground observations of the different behaviors of the two areas (see Section 2.5).

Table 1. Input parameters for the initial TEXAN modelling.

Parameter		Value
Depth below surface, h	[m]	113 (collapsed) and 217 (intact)
Overburden density, ρ	[kg/m³]	3 000
Intact Strength, σ_c^i	[MPa]	25
Intact rock slope, m^i		4.6
Crushed Rock Strength σ_c^f	[MPa]	4
Crushed rock slope, m^f		4.6
Interface Friction Angle, ϕ	[°]	10
Seam Height, H	[m]	2
Seam Stiffness Modulus	[GPa/m]	45

2.4 Modelling results

Figure 4 illustrates the failed pillars for the collapsed and intact area as simulated by TEXAN using the parameters in Table 1. The orange colour indicates failed portions and the yellow indicates intact portions of the pillars. For these parameters, most of the pillars have failed for both geometries, even the area that is still intact underground. For the intact area, more of the pillars have an intact core compared to the collapsed area. This is to be expected as the pillars are larger with reduced stress levels. The simulated amount of pillar failure for the intact area is nevertheless greater than that observed for this area underground and the model parameters therefore did not appear to be appropriate. A few pillars in the corners of both models, where the stresses are the lowest, were still intact. This is to be expected as only a finite size model could be simulated and the code treats the material outside the model area as a solid abutment.

Of interest is the amount of closure simulated for the models as a significant amount of closure was recorded in the mine. The closure measured during the underground visit varied between 0.7 m and 0.8 m at the center of the collapse. These were not accurate as the measurements were not done with closure instrumentation, but with a tape measure and by estimating the original stoping width (2.1 m). The height of the opening after the collapse was approximately 1.3 m. The TEXAN modelling seems to predict a larger amount of closure (2.5 m) although it is encouraging that it is of the same order as the measurements. The residual strength of the crushed pillars may therefore be larger than that predicted by the parameters in Table 1.

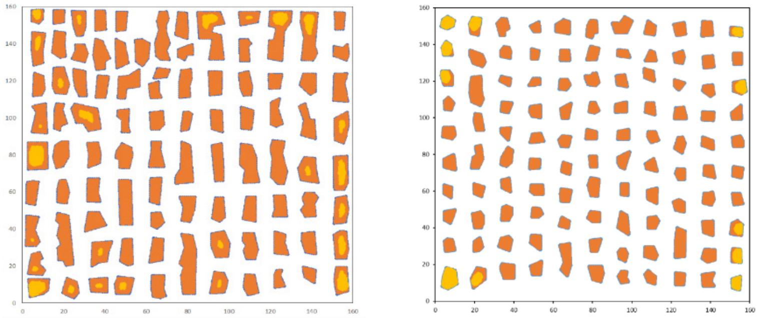

Figure 4. Simulation of pillar failure (left - Intact area; right - Collapsed area). The orange colour denotes failure and the yellow denotes intact portions of the pillars.

2.5 Model calibration

Additional calibration runs were conducted for each area. The parameters used are shown in Table 2. The pillar failure percentage was calculated as the ratio of the total number of failed elements divided by the total number of pillar elements.

To select the most appropriate parameters, it was considered that the presence of water was a key difference between the intact area and the collapsed area. The alteration zone was dry and hard in the intact area and wet and slippery in the collapsed area. The effective friction angle of the pillar contact with the hangingwall seemed to be substantially lower in the collapsed area compared to the intact area. No laboratory test results of these friction angles were available, and it needs to be investigated in future. The other rock parameters are considered identical for both areas. Based on these arguments, and the simulations, the parameters of "Set 9" for the collapsed area and the parameters for "Set 10" for the intact area (Table 2) are the best calibration. The parameters are identical except for a friction of 10° for the collapsed area and 25° for the intact area.

Table 2. Model input parameters for calibration of the intact and collapsed areas.

Parameter	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12
Intact Strength (MPa)	60	25	30	30	30	30	30	30	30	30	30	30
Intact rock slope	7	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Initial crush strength (MPa)	4	4	4	5	7.5	10	4	4	4	4	10	5
Crushed rock slope	7	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Seam height (m)	2	2	2	2	2	2	2	2	2	2	2	2
Seam Stiffness Modulus (GPa/m)	45	45	45	45	45	45	45	45	45	45	45	45
Interface friction angle (Collapsed model geometry)	30	10	20	20	20	20	25	15	**10**	5	15	15
Pillar failure percentage (Collapsed model geometry) (%)	0	73	31	23	11	5	21	50	**72**	91	11	36
Interface friction angle (Intact model geometry)	30	10	30	40	50	20	20	20	20	**25**	15	10
Pillar failure percentage (Intact model) (%)	0	82	14	6	2	26	21	14	9	**19**	44	81

The simulated condition of the pillars in the two areas with the calibrated parameters are shown in Figure 5. These are encouraging results as the pillars in the centre of the collapsed area are completely failed and there is only minor scaling in the centre of the intact area. This agrees with the underground observations The pillars on the edges of the collapsed area are still intact, but this is only caused by the fact that these pillars are next to the simulated abutment.

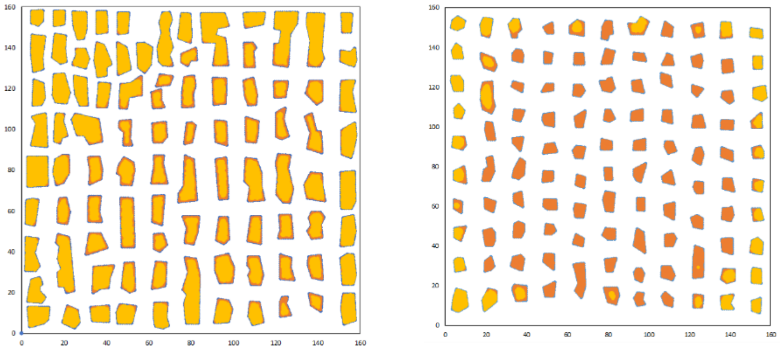

Figure 5. Simulated failure for the calibrated parameters. The intact area ("Set 10") is on the left and the collapsed area ("Set 9") is on the right. The orange colour denotes failure and the yellow denotes intact pillars.

3 CONCLUSION

The effect of weak layers on pillar strength is not clearly understood. This paper describes a case study of the collapse of the Everest Platinum Mine caused by weak layers in the pillars. The TEXAN code, with a limit equilibrium constitutive model, proved to be useful to simulate the observed pillar failure. This modelling approach, with an appropriate calibration of the parameters, can be used in future to study alternative layout designs when similar ground conditions are encountered.

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