Use of Three-Dimensional Distinct Element Numerical Modelling to Determine Ultimate Pit Slope Stability in Areas of Highly Dense Relict Underground Openings: Super Pit, Kalgoorlie

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Abstract

The large Super Pit operation is famous for mining the remainder of the Golden Mile deposit through development of a large open pit. However, prior to development of the pit, the Golden Mile was extensively mined for more than 80 years using a variety of narrow-vein underground mining methods. The resultant relict void network is both extensive and voluminous with approximately 3500 kms of equivalent drives/openings. Development of the final western wall cutback (Golden Pike) will result in a 700 m high wall being formed in highly stope ground. As a result, the owners of the Super Pit have been interested to assess the affect that the relict void network will have on ultimate pit wall stability.

In order to better assess the final pit wall stability, a program of three-dimensional numerical modelling was considered to properly assess the affects of the relict void openings contained within the final wall. An important deliverable was the development of a technique to enable the importation and mechanical representation of the relict void openings within the significantly larger matrix of the 3D numerical model. Using the technique, more than 100 discrete void openings were able to be mechanically represented within the full 3D model.

The resultant model will enable KCGM to confidently assess final wall stability and demonstrate this to external stakeholders. To the authors’ best knowledge, this is the first time that such an extensive network of underground voids have been modelled in 3D using distinct element methods.

1 Introduction

The Kalgoorlie Super Pit (Fimiston) operation is a major contributor to the economy of the Kalgoorlie-Boulder region of Western Australia and operates with a high degree of external visibility from regulatory and community stakeholders. The final pit will be approximately 3560 m long, 1450 m wide and up to 700 m deep. The design includes some relatively steep inter-ramp slope angles, and several bullnose geometries exist, generally below the location of haul ramp switchbacks. The operator of the Super Pit has recently commenced a final cutback on the western pit wall, which lies immediately adjacent to the city of Boulder. As such a high level of interest in the ultimate stability of the western wall exists.

The geometry of the Golden Mile deposit, which is being mined by the Super Pit, dips steeply westwards. As the Golden Mile was previously mined using narrow-vein underground methods there now exists an extensive network of stopes, drives and other openings in a complex mesh within the developing open pit (Figure 1). As a consequence this ‘mesh’ of openings also dips westwards and as such results in numerous intersections with the final western pit wall. The orebody effectively remains open to depths of 1400 m. As a result, stability assessments of the western pit wall are not considered to be complete without some consideration of the effect that this extensive stope network will have on slope stability.

The remnant stopes are generally relatively narrow, with a typical width of around 3 m. Some of the stopes are filled, while most are open voids. The stopes could contribute to slope failure in many ways, including:

- providing a reduction in the shear strength of the materials forming the pit walls.
• providing an upper release surface allowing shear or toppling failure below.
• providing a void into which excessive slope movement (or failure) from upslope can occur.
• allowing additional inelastic strain and therefore rock mass weakening to occur behind the excavation face.
• creating unfavourable stress concentration and redistribution behind the excavation face.
• creating localised unravelling of a batter face, which in turn may undercut the batters above and propagate up the slope.

Figure 1. Plan and side views of final pit dxf and all known stopes.

Assessment of the stability of the western wall is an important task for the operator, KCGM, as the ultimate western pit wall lies immediately adjacent to the satellite city of Boulder. The mine, regulator and community require confidence in the proposed geotechnical design for the pit walls, both during the planned remaining 10 years of operation and following closure. As a consequence, modelling of the pit wall that does not include appropriate representation of the extensive void network provides only limited confidence in the geotechnical design.
1.1 Geotechnical setting and previous investigations

The Super Pit is hosted within strongly metamorphosed and deformed Archean greenstones (meta-dolerite/meta-basalt) of the Eastern Goldfields terrane. The host rocks exhibit high rock mass strengths (RMR values for the west wall typically exceed 70) and the resultant pit wall deformation is low. Regional stresses in the area exhibit a relatively high horizontal stress level, with the horizontal to vertical stress ratio approaching 3:1. Failure mechanisms and pit wall stability are controlled more by discrete structures than the rock mass. The resulting geotechnical designs focus more on inter-ramp and overall slope stability, and both these issues are effectively addressed using numerical modelling techniques.

Given the extensive three-dimensional (3D) array of geological structures, an artefact of the long-lived tectonic history and ore development, distinct element numerical modelling methods have been the preferred choice for slope stability analysis at the Super Pit. For many areas of the pit wall, modelling has been undertaken using two-dimensional (2D) distinct element codes such as UDEC (Itasca, 2004). These methods have typically worked well, especially when geotechnical uncertainty is addressed using scenario and simulation estimation (e.g. monte carlo) methods. There is also confidence in applying 2D methods to laterally extensive pit walls where curvature is minimal.

The issue of open pit mining through abandoned underground workings has been discussed by several authors, including Walton and Taylor (1977), Watters et al. (1989), Watters et al. (1990), Loubser (1994) and Jiang et al. (2005). Stewart et al. (1996) and Stead and Benko (1998) endorse the use of numerical modelling as a tool to enhance understanding of possible slope failure mechanisms associated with underground workings.

Several of the previous 2D numerical analyses performed for the Super pit have incorporated remnant stopes as open voids. No large-scale failures have been predicted by the models with best-estimate properties assigned, however sensitivity analyses with lower material properties have identified some potential failure mechanisms associated with the remnant stopes. Current face exposures of up to 500 m height containing numerous void intersections suggest that voids do not have as significant impact on pit wall stability as some previous 2D modelling outcomes would suggest. This indicates that 2D modelling, which by nature assumes that all voids included in the analyses are infinite in length, could over-predict the effect that these features may have on slope stability. This is supported by Sainsbury et al. (2003), who performed both 2D and 3D numerical analyses to assess the effects of underground voids on pit slope stability. By comparing the 2D to the 3D modelling results, they concluded that 2D analyses may provide conservative stability estimates where underground voids of finite length exist behind the pit wall.

2 Numerical modelling methodology

To eliminate the uncertainties associated with the assumptions that are required to construct and run a 2D model, large-scale 3D numerical modelling has been undertaken for the Super Pit. As well as providing improved representation of the remnant stopes, 3D modelling also allows improved representation of other characteristics including slope curvature, fault geometry and the 3D in situ stress state. Numerical modelling was undertaken using the 3D Distinct Element Code 3DEC (Itasca, 2011). Throughout rock mechanics literature, there are many examples of the application of 3DEC to solve complex slope stability problems (including Board et al., 2000, Brummer et al., 2006, Corkum and Martin, 2004, Grenon and Caumartin, 2007 and Sainsbury et al. 2007). 3DEC was selected for analysis of the Super Pit because a.) it allows an accurate representation of the 3D problem geometry, b.) it allows a large number of geological structures to be discretely defined in the model and c.) narrow remnant stopes can be incorporated into the model based on the individual 3DEC zones. The methodology adopted for the analyses is described below.

2.1 Model construction

A large-scale 3DEC model has been constructed to incorporate the full current and proposed final pit shells. The model consists of 136,418 blocks and 13.78 million zones. Thirteen geotechnical domains were defined in the
model. The overall geometry of the 3DEC model and the exposed domains after excavation of the final pit are shown in Figure 2.

More than 60 faults were explicitly defined in the 3DEC model. The 3D fault interpretations are shown in relation to the final pit dxf in Figure 3a. Three structures behind the east wall were of particular interest. These are the Oroya Shear, the Ayoro Fault and the Reliance Fault, each of which is shown in relation to the final pit shell in Figure 3b. Each structure dips steeply to the west, and the Oroya Shear and Ayoro Fault both daylight in the final eastern wall. Based on its interpreted location, the Reliance Fault is not expected to daylight.

![Figure 2](image1.png)

Figure 2. (a) Oblique view showing overall geometry of the 3DEC model used for slope stability analysis of the Super Pit current and final pit shells, and (b) exposed geotechnical domains after excavation of the final pit.

![Figure 3](image2.png)

Figure 3. Oblique views of final pit dxf showing (a) all fault dxfs, and (b) Oroya Shear, Ayoro and Reliance faults (looking approx. north).
Remnant stopes have been incorporated in the 3DEC pit model to assess their influence on slope stability. Due to the large number and small size (particularly width) of the stopes, it was impractical to incorporate all of the known stopes into a full pit model. As such, those stopes that will exist at or behind the final pit slope on the western side of the pit to the north of the large bullnose have been incorporated into the model. The stopes have been defined in this region because this is the major cutback area for future mining and the township of Boulder is located immediately adjacent. Much of the southern and eastern walls have already been excavated to the final pit shell, as has the southern end of the western wall. Those stopes included in the model are shown in relation to the final pit shell in Figure 4a. The plan area in which these stopes exist is approximately 2000 x 500 m, as shown in Figure 4b. It is seen that the majority of the stopes are steeply-dipping and have a north-south orientation.

Figure 4. (a) Plan and side views of final pit dxf and those stopes incorporated into the 3DEC model and (b) plan view showing extent of remnant stopes included in the model.

The remnant stopes have been defined using 3DEC model zones. Constructing a numerical model for open pit slope stability analyses is typically a relatively straightforward process, however incorporation of remnant stopes creates significant complications that are not normally encountered. On the one hand the model is aiming to assess the medium to large-scale slope behaviour. However, the relatively small-scale of the individual stopes (particularly the width) means that a small model zone size is required in the immediate vicinity of the stopes in
order to properly represent the behaviour of these openings in the modelling process. As such, we require a model capable of representing and analysing both small-scale stope and large-scale slope behaviour.

The size of a 3DEC model, and therefore the computer requirements and time required to run the analyses, are related to the total number of zones in the model. Given that the entire pit was included in these analyses, it was critical that the number of zones be minimised in order to construct a model that was practical to run. The key to minimising the total number of zones in the model was to restrict the smaller zones to only those areas surrounding the remnant stopes. This was achieved using the following process:

- **Stage 1** - A large rectangular mesh was constructed with a constant 2.5 m zone size, and an in-house Itasca model construction tool was used to identify those zones that were located within the stope dxfs. Using 3DEC’s in-built programming language FISH, a function was written to export the centroids of these identified zones to a text file.

- **Stage 2** - In the 3DEC pit model, the regions of the west wall where remnant stopes were to be incorporated were cut into 18 m³ blocks. Another FISH function was written to identify those 18 m³ blocks that were located within a specified distance of the centroids that were identified in Stage 1 above. These blocks were assigned a 3 m zone size, while the remaining 18 m³ blocks were assigned an 18 m zone size. Areas remote from the remnant stopes were assigned a 30 m zone size. This allowed the zones to be progressively graded depending on their proximity to the remnant stopes.

After zoning the 3DEC pit model, the in-house Itasca model construction tool was used to identify those zones that were located within the stope dxfs. These zones were assigned a unique material number. The resulting mesh and stope definition after excavation of the final pit is shown in Figure 5. The relatively small 3DEC zones adjacent to the remnant stopes are evident, as are the larger zones in surrounding areas.

### 2.2 Material Properties, in situ stresses and groundwater

The best-estimate rock mass parameters defined for each domain are shown in Table 1. These properties have been used to estimate the modulus and strength values for the rock mass domains. Young’s modulus and Poisson’s ratio for the rock mass were estimated based on the Geological Strength Index (GSI). The shear strength (cohesion and friction angle) and tensile strength for each rock mass domain were estimated using the empirical Hoek-Brown failure criterion as described by Hoek et al. (2002). The shear strength for the materials was estimated by fitting a bilinear Mohr-Coulomb envelope to the non-linear Hoek-Brown curve. Due to the relatively shallow depth of most pit slope failures in a hard rock environment, the maximum confining stress used for the determination of these shear strength parameters was limited to 2 MPa. To analyse the effects of the rock mass parameters on the modelling results, various analyses were performed with different disturbance factors applied, and both with and without strain-softening assigned to the rock mass. For the base case model, a linear-elastic perfectly plastic Mohr-Coulomb constitutive model (i.e. no strain-softening) was used to represent the rock mass domains.

A Coulomb slip criterion was adopted to represent the behaviour of the faults. The shear strength values used by the model reduce from peak to residual levels when the peak strength of a structure is reached. *In situ* stresses were incorporated into the model based on the results of HI Cell measurements. Pore pressures were assigned to the model using a 3D phreatic surface, which was defined using piezometer data.
2.3 Modelling sequence

Excavation of the remnant stopes was simulated in the model prior to pit excavation. Using the 3DEC code, individual zones cannot be deleted, therefore excavation of the stopes was simulated by a.) removing all stresses from the zones and b.) reducing the material properties assigned to these zones. This includes reduced density and modulus values and a cohesion and tensile strength of zero. The zones were assigned a Mohr-Coulomb constitutive model to allow yielding to occur, which ensured that large stresses could not develop in these zones.

After stope excavation, bench by bench excavation of both the current and final pits was simulated. Including the current pit shell in the model allows comparisons to be made between the modelling results and observed pit behaviour. Excavation of the pits was simulated one bench at a time, and removal of each bench was simulated gradually to ensure that the influence of transient forces on material failure was minimised. During pit excavation, stresses within the stopes were continually reset to zero. After complete excavation of the final pit, shear strength reduction analyses using the technique described by Dawson et al. (1999) were also performed to provide Factor of Safety (FoS) estimates for large-scale stability.
Table 1. Properties used to estimate rock mass modulus and strength values.

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<tr>
<th>Rock Mass Domain</th>
<th>Major Rock Type</th>
<th>Density (kg/m³)</th>
<th>UCS (MPa)</th>
<th>GSI</th>
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3 Numerical modelling results

After initial excavation of the remnant stopes (prior to pit excavation) only minor displacements and very minor yielding was seen in the models. This includes minor yielding in the rock bridges between the stopes. Some stress redistribution was also seen in the rock mass surrounding the stopes. After excavation of the current pit, the slope behaviour predicted by the base case model was generally consistent with pit observations. Cumulative displacement magnitudes produced by the model after excavation of the current pit were generally less than 0.5 m, which is consistent with cumulative movement recorded by slope monitoring.

Numerical velocity, active yielding and cumulative displacement plots are shown after excavation of the final pit for the base case model in Figure 6a. The velocity and yielding plots provide a good indication of areas of potential instability in the model, while the cumulative displacement plots provide an indication of relative displacements in different areas of the pit. No large-scale instability is predicted for this base case model. As discussed, shear strength reduction analyses were also performed using various FoS values. An example of the results produced by the base case model with the shear strength reduced by a factor of 1.5 (i.e. the Factor of Safety = 1.5) is provided in Figure 6b. Note that for this modelling scenario, the shear strength of the rock mass and faults is reduced below actual levels to assess confidence in the adopted design. Again large-scale instability is not predicted and the modelled pit wall stability is observed to be within acceptable limits. Some increased deformation is seen in the model along the Ayoro Fault on the east wall, however this area has been successfully excavated without any signs of instability.
Figure 6. Plans showing numerical velocity, cumulative displacement (in metres) and active plastic yielding for base case model (a) after excavation of the final pit and (b) with shear strength properties reduced using a FoS = 1.5 (i.e. the shear strength for the rock mass and faults is reduced below actual levels).

Several simulations with varied input parameters were performed to analyse final pit stability and these identified several potential multi-bench failure mechanisms. All of these mechanisms are associated with sliding along faults, with some component of rock mass failure. Potential medium to large-scale instability involving only rock mass failure was not identified, reflecting the high quality of the rock mass that will form the final pit walls.

The model predicted localised instability around the remnant stopes on the west wall. This instability is restricted to the immediate vicinity of the stope intersections with the excavation face. Despite this, predicted instability associated with the stopes is relatively small. An oblique plot showing localised displacements on the west wall in relation to the stope dxfs is provided in Figure 7a. An oblique view of numerical velocities on the west wall in relation to the stope dxfs is provided in Figure 7b for the base case model after shear strength reduction using a FoS = 1.5. The figure also illustrates one area of localised instability whereby a remnant stope beneath the excavation face results in a weak zone along which small-scale slope failure could occur.
Remnant stope provides weak zone along which shear failure can occur.

Figure 7. (a) Oblique view showing cumulative displacement (in metres) after excavation of the final pit in relation to stope dxfs, for base case model with no shear strength reduction, and (b) oblique view showing numerical velocity after excavation of the final pit in relation to stope dxfs (above) and cross section showing localised instability associated with remnant stope (below), for base case model with shear strength parameters reduced using a FoS = 1.5.

4 Conclusions

Three-dimensional numerical modelling has been performed to analyse final pit slope stability at the Super Pit in Western Australia. The pit lies immediately to the east of the city of Boulder, and as such a high level of interest in the ultimate stability of the western wall exists. 3D modelling allows improved representation of the true characteristics of the model input parameters. For the Super Pit, 3D analyses were particularly valuable to assess:

- the effects of slope geometry on pit wall stability, particularly the concave geometry at the northern and southern ends of the final pit and the convex nature of several bullnoses that exist in the pit design.
- the behaviour of the geological structures in three-dimensions, with several known structures dipping into the excavation and striking sub-parallel to the excavation face.
- the effects of the relatively high horizontal in situ stresses in three-dimensions.
- the effects of remnant voids associated with abandoned underground workings.

This last point is particularly relevant at the Super Pit, where the Golden Mile has been continuously worked using underground methods for more than 100 years. As such, several hundred abandoned stopes exist in the mining area.
A complex 3D numerical model was successfully constructed and run to analyse the behaviour of the full final pit shell. The model included more than 60 discrete geological structures, 13 geotechnical domains and incorporation of remnant stopes at and behind the final western wall. Due to the complexity of the analyses, and that fact that a relatively small zone size was required adjacent to the remnant stopes, this resulted in a very large model. However given recent advances in computer capabilities, several model runs with varied input parameters have been performed using desktop computers with off-the-shelf hardware.

The main technical challenge addressed was that of incorporating numerous small-scale elements with sufficient model resolution within the context of modelling a significantly large open pit. The results of the modelling now provide KCGM with a full 3D assessment of the pit slope stability that takes into account the potential stress effects induced by the relict voids. The model predicts stable slope conditions despite the extensive void network present in the wall. Limited instances of localised instability surrounding the remnant voids are identified, which is to be expected. These results are consistent with the historical stability at the mine, where no large-scale slope failures have occurred in the past due to the presence of voids in the pit walls. The model now provides KCGM with a tool from which additional sensitivity studies can be undertaken to more fully examine the stability of the western pit wall.

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6 References


