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# Two-dimensional and three-dimensional distinct element numerical stability analyses for assessment of the west wall cutback design at Ok Tedi Mine, Papua New Guinea

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## Abstract

*Detailed evaluations for finalisation of the design for the west wall cutback at the Ok Tedi copper-gold mine in Papua New Guinea have been ongoing since 2010. The geotechnical rock mass characterisation, structural model and conceptual hydrogeological model have been progressively updated since 1997, and have been significantly advanced during recent feasibility studies. The pit is being progressively deepened with ongoing mining, and a cutback of the west wall is being planned that would result in a final wall height of 1,000 m. The wall will be cutback by up to 300 m over a crest length of greater than 1,500 m, which will take place over a period of approximately 13 years.*

*A comprehensive set of 2D distinct element analyses were completed in 2011 for assessment of the stability of the west wall final design. Depressurisation of the cutback slope was indicated to be of great importance, and measures for depressurisation were taken into account in the supporting analyses. Additional field investigations and assessments for confirmation of the design performance were carried out in 2012 and are ongoing in 2013. The key aspect of this work involved further distinct element analyses for assessment of the slope performance in three dimensions, particularly in the context of the effects of major structures, joint sets, pit wall curvature and pore water pressures as the slope cutback is developed. The extreme size and complexity of the 3D model necessitated simplifications to the geotechnical domains and structural inputs in order to create a practical working model. As expected, the 3D analyses provided Factors of Safety for slope instability significantly greater than those obtained from the original 2D analyses. However, it is most important to understand the context and limitations of these results when making final decisions on design outcomes. For this reason, selected additional 2D analyses were carried out in order to assess the sensitivity of the results to simplifications in the geotechnical domains and structural inputs and to the coarser block size necessary for the very large 3D model.*

## 1 Introduction

### 1.1 Overview

The Ok Tedi copper-gold mine operated by Ok Tedi Mining Limited (OTML) is situated in the remote highlands of Papua New Guinea. The terrain around the open pit is rugged, and rainfall is 9 to 11 m per year. Earthquakes of 4 to 6 on the Richter scale occur in the region, and the geology and structure within the mine is complex. As part of the mine life extension (MLE) project, a cutback of up to 300 m is proposed for the west wall, which will occur over a crest length of greater than 1,500 m. The final slope will be almost 1,000 m high. This cutback and others within the pit will take approximately 13 years to achieve the final pit limits and will be completed in parallel with mining operations in the existing pit.

From 2010 onwards, the suitability of the proposed cutback slope design for the west wall has been assessed by OTML and SRK Consulting Australia (SRK) using a range of two dimensional modelling methods for evaluating slope stability and depressurisation requirements. Distinct element analyses using UDEC software (Itasca, 2004) were carried out in 2010 and 2011. These analyses were detailed and comprehensive, with investigation of the effects of: structural fabric; a blast and unloading disturbance zone; a target groundwater pushback (depressurisation) to 250 m behind the proposed cutback face; appropriate seismic loading (pseudo-static analysis); and alternative options interpreted for in situ stress conditions.

Considering the complex three dimensional geological, structural and hydrogeological conditions as well as the curvature of the pit wall, it was recommended upon review that 3D modelling be undertaken to investigate and contextualise the potentially conservative results obtained from the detailed 2D analyses. 3DEC software (Itasca, 2007) was selected as most appropriate for this modelling largely as a result of the need for inclusion of large faults and structural fabric within the model.

An attempt at calibration of the 3D analyses was then made by means of selected additional 2D analyses using UDEC. This was done by assessing the sensitivity of the results to necessary simplifications in the geotechnical domains and structural inputs and to the coarser zone size necessary for the very large 3D model. This work was carried out with the intent of achieving a meaningful comparison with the original comprehensive 2D analyses, and was important in order to gain an understanding of the context and limitations of the 3D modelling results when making important decisions concerning the cutback design.

### 1.2 Geology

The geology at Ok Tedi consists of siltstones and limestones, into which large monzonite porphyry and monzodiorite bodies have been intruded. The pit is centred within these intrusive bodies, as the monzonite porphyry has formed the major ore type and makes up the majority of economic mineralisation tonnage. Skarns have been formed on the eastern and western margins of the intrusive bodies, and are of two main types. The endoskarns are of igneous protolith, and have only minor ore grade mineralisation. The skarns of sedimentary protolith lie immediately outside the endoskarns and form major skarn orebodies, and these are a principal target of ongoing mining operations. The endoskarns and skarns present highly variable, often weak rock, except the skarns that are magnetite-rich which present very strong and sparsely-jointed rock.

Two major thrust zones are recognised within the mining area: the Parrot's Beak Thrust and the Taranaki Thrust. These are well exposed in the west wall of the pit. The thrust faults contain highly fractured and altered fault gouge, pyrite, magnetite skarn lenses, brecciated monzodiorite, and brecciated siltstone hornfels. A fracture zone of generally 20–30 m thickness is associated with each thrust; however the Parrot's Beak thrust has been modelled with a thickness of up to 80 m in places. Mineralisation is truncated by a lower basal thrust, which includes a zone of fractured material that appears to be narrower than the Taranaki and Parrot's Beak thrust zones. Recent mapping studies have identified a steeply-dipping major fault on the west wall of the pit which has been termed 'The Gleeson's Fault'. An associated fracture zone of brecciated siltstone and highly fractured limestone is present to the immediate west of this fault. The geology and structure is illustrated in Figure 1 in Section 3.1.

## 2 Programme of analyses

The rock mass characteristics, groundwater levels and design final pit wall heights and configurations vary across the west wall. Therefore, analyses were conducted as necessary to assess the slope performance in its North, Central and South regions separately, as summarised in Table 1. The primary area of focus is the Central region, where the final pit wall is at its highest. The South region has also been assessed in detail, although the lower wall height and more favourable groundwater levels result in a more stable condition. After preliminary analysis of the North region by means of limit equilibrium (LE) analyses, it was decided not to perform UDEC analyses for this region as the pit slope is broken by several in-pit features, and the stability is indicated to far exceed the slope design criteria (Factors of Safety 1.3 or greater). All three regions were assessed as part of the 3DEC modelling, however.

The very large size of the 3DEC models meant that successive analyses were conducted with joint sets included within only one of the regions at a time. Although the analyses provide results for stability of the entire wall, the focus for each analysis should be on the region where the joints are included. The performance of the pit wall in the regions without joints is also of interest, as a means of assessing the sensitivity of the slope performance to structural fabric (as described in Section 2.5).

**Table 1 Summary of stability analyses conducted for the west wall**

| Analyses | Central Region | South Region | North Region |
|---|---|---|---|
| Initial UDEC (2011) | One section | One section | No analysis considered necessary following LE analyses |
| 3DEC (2012/13) | Overall model, joints in Central region only | Overall model, joints in South region only | Overall model, joints in North region only |
| Additional UDEC (2013) | One section | Additional analyses not considered necessary for South region | Additional analyses not considered necessary for North region |

A number of different scenarios have been considered for each set of analyses, as described in the following Sections 2.1 through 2.6. These scenarios have been carefully selected based on the results of previous analyses and the need to obtain a clear understanding of the main controls on slope performance.

## 2.1 Stress regime

The analyses were performed using the Mills (2010) stress regime, which was obtained from in situ stress measurement in the existing drainage tunnel using the ANZI cell. In this regime, the east–west horizontal stress is equal to 0.5 times the vertical stress and the north–south horizontal stress is equal to 1.8 times the vertical stress.

## 2.2 Groundwater

Limit equilibrium stability analyses conducted by OTML in early 2010 identified that a groundwater level pushback to approximately 250 m behind the slope face is generally necessary to maintain slope stability within the west wall. This was confirmed by SRK using 2D finite element stability and seepage modelling conducted in late 2010 and early 2011 (de Bruyn et al., 2011). A hydrostatic pattern of pore water pressure (pwp) distributions for this target pushback was inputted into the UDEC and 3DEC analyses.

Current drilling investigations in the pit are providing information for update of the conceptual hydrogeological model. 3D seepage modelling using FEFLOW software (DHI-WASY GmbH, 2006), incorporating the preliminary revised conceptual hydrogeological model, is allowing for the detailed calculation of pwp distributions throughout the west wall. However, the designs for the underground and in-pit depressurisation measures have not yet been finalised and therefore the results of the modelling have at this time not been incorporated into the stability analyses.

Further stability analyses using the pwp distributions achieved from 3D seepage modelling of the final planned depressurisation measures will be conducted at a later date once these measures and the groundwater model have been finalised.

## 2.3 Blast disturbance zone

In the initial UDEC analyses, a blast disturbance zone was defined to 50 m back from the pit wall, in which the rock strength properties were reduced for analysis purposes. This was done by incorporating a disturbance (D) factor of 0.5 for this zone, and a value of zero for the remainder of the rock mass. The inclusion of this zone in the model provides a crude, indicative representation of the potential effect that the blasting at Ok Tedi would have on the rock mass, as well as the potential effect of unloading and rebound resulting from excavation. However, it does not provide an accurate distribution of variability of rock mass conditions behind from the pit wall resulting from the disturbance. In light of this, the value of this indicative disturbance zone in the already very large and complex 3DEC model was considered not to be worth its inclusion. It was therefore also not included in the models for additional UDEC analyses.

### 2.4 Basal thrust zone

In the initial and additional UDEC analyses, sensitivity analyses were conducted in order to assess the effect of the Basal Thrust (which was expected to outcrop at the base of the final west wall excavation) on the overall failure mechanism and Factor of Safety for the west wall. It was considered that in reality its actual orientation (dipping to the southwest) and limited length of outcrop at the base of the pit meant that the effect of the Basal Thrust was potentially being overstated in the 2D modelling. The Basal Thrust was effectively 'removed' in some analyses by assigning it the same properties as the underlying rock.

### 2.5 Rock fabric and major structures

The first order structures, including the Parrot's Beak, Taranaki and Basal Thrust zones and the Upper and Lower Gleeson's Faults, were included as zones in all models. The 3DEC and additional UDEC models also included several large (second order) fault structures modelled as discrete planes.

As a means of assessing the effect of the rock mass joint fabric on pit wall stability and failure mechanisms, selected UDEC and 3DEC analyses were run where the joint fabric has been omitted, i.e. where the rock mass is modelled as a continuum.

### 2.6 Seismic loading

In the initial UDEC analyses, all modelling scenarios were analysed under static conditions and with seismic loading. The seismic loading was simulated by incorporating a horizontal ground acceleration out of the pit wall which is one third of the peak ground acceleration of 0.07 g under pseudo-static conditions. This approach was used as it was at the time considered too time-consuming and impractical to include true dynamic loading in the model. The subsequent 3DEC and additional UDEC analyses have not been performed with seismic loading, as it was felt that the initial analyses provided an indication of the effects of seismic loading.

## 3 Models

### 3.1 Initial UDEC model

Within the UDEC sections developed for the Central and South regions, the excavation from pre-mining topography to the final cutback slope was simulated using four excavation stages with appropriate groundwater levels assumed for each excavation stage. These stages were defined to better simulate the stress path, whilst balancing the efficiency of the model run. The performance of the final proposed mining excavations were analysed.

The zones of different material properties (material zones) in the model were defined by the distribution of the major lithology types and the five geotechnical domains (A to E) identified according to rock mass quality. These regions, and the blasting disturbance zone, are shown in Figure 1, illustrating the complexity of the model. The Hoek–Brown rock shear strength model (Hoek et al., 2002) was applied for the majority of the rock mass, except for the large fault and thrust zones of very poor conditions for which the Mohr−Coulomb model was considered more appropriate. Properties were defined for each material based on investigation data (core logging, mapping and laboratory testing data) and engineering judgement.

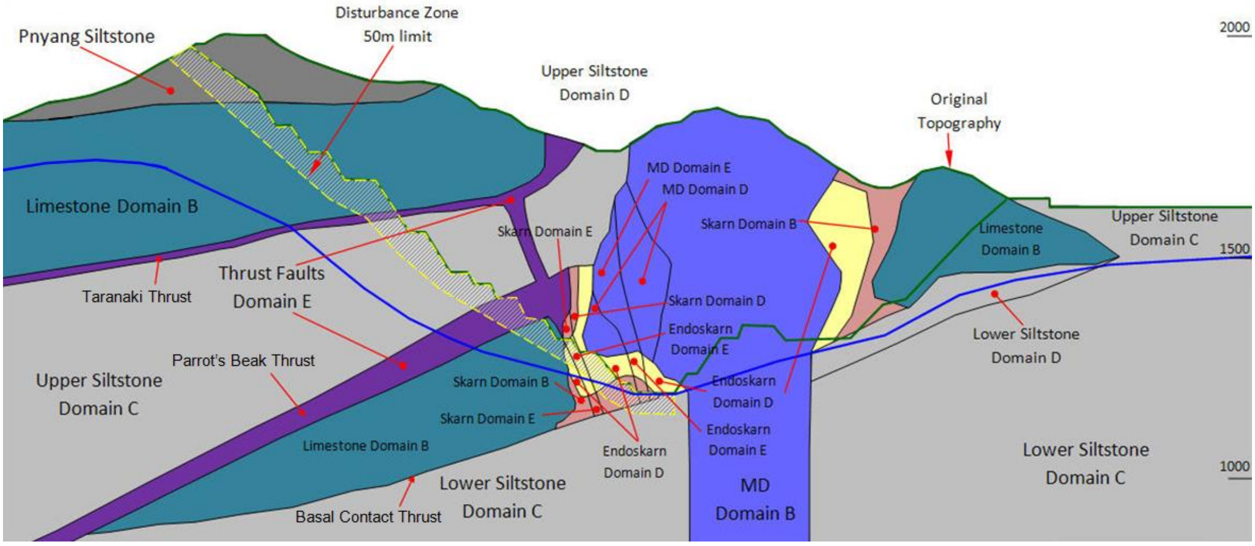



**Figure 1 Pre-mining distribution of materials, and final pit wall and groundwater profiles for the south section**

Simplified (dominant) joint set patterns were selected for modelling within each of the material types. Only four joint sets were assumed to significantly control the failure mechanism in the analysis. A Coulomb slip (joint area contact) constitutive relationship was assigned for the joints. The joint spacing's within each material for the model were selected so that the greatest amount of detail could be included whilst still allowing for efficient models to be created that were compatible with UDEC. The joint spacing's used were thus adjusted to be significantly larger than the actual spacing however, on a model of the scale of the Ok Tedi west wall these are more than adequate to allow for assessment of the role of structural fabric on slope instability mechanisms. It is recognised that the inclusion of explicit joint sets whilst using Hoek–Brown parameters for the rock material between them (which takes into account the effects of structural fabric), might appear an 'over-counting' of the effects of the joints. However, the spacing of the joint sets used in the model are approximately an order of magnitude larger than is the case in reality and thus the approach allows for assessment of the effect of the more persistent joints within each set on the mechanisms of instability. It was also believed that the anisotropy of the rock strength is accounted for in this way. The structural fabrics adopted for the various material zones are illustrated in Figure 2.

The stability of the west wall was assessed in terms of Factors of Safety (FS) for slope failure, as interpreted using the strength reduction factor (SRF) technique. In this technique, Hoek–Brown strengths were first converted to equivalent Mohr–Coulomb parameters, according to the confining stress in each zone. Then cohesions, friction angles and tensile strengths for rock mass and joints were uniformly reduced by the same factor, which was progressively increased until initiation of failure.

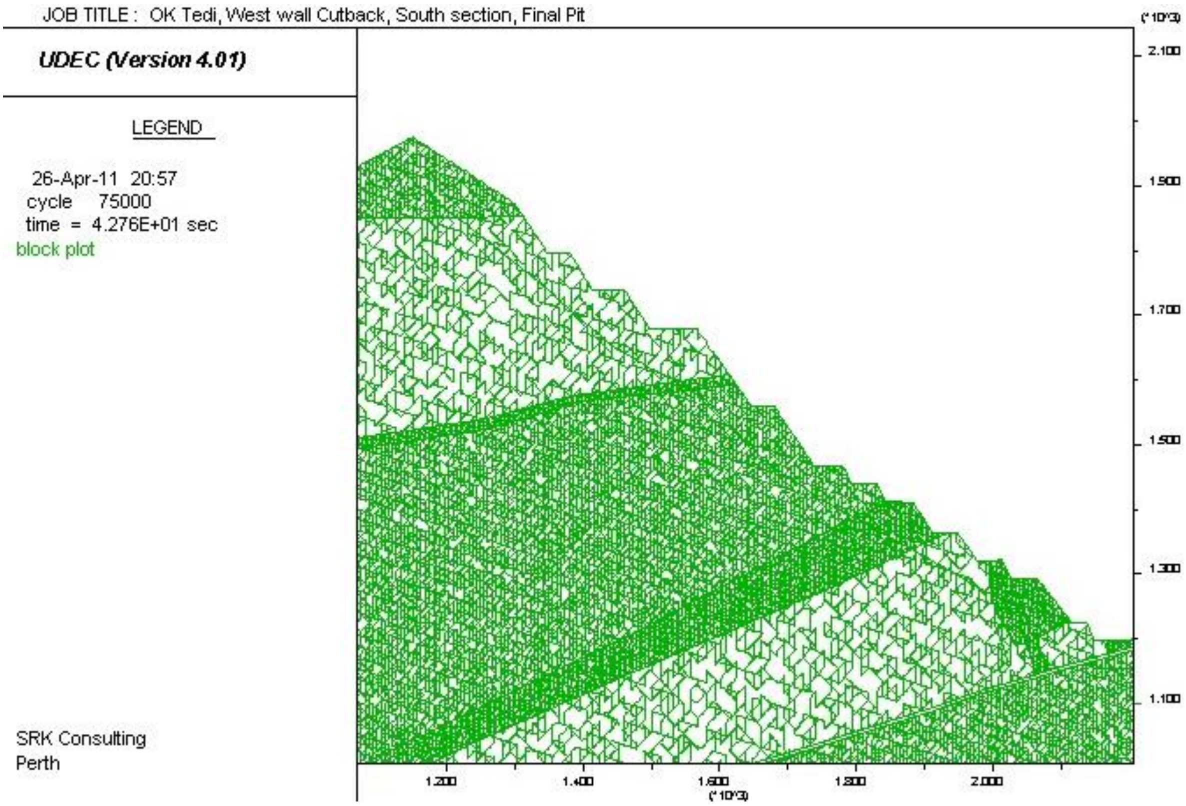



**Figure 2 UDEC plot illustrating structural fabrics for the material zones in the south section**

## 3.2 3DEC model

The 3DEC model was constructed to include the entire pit. In order to best simulate the stress path, the excavation of the final pit from the pre-mining topography was simulated in 3D using six excavation stages. The size and complexity of the 3DEC model necessitated simplifications to the material zones and structural inputs from those used in the initial UDEC analyses, in order to create a practical working model. The distribution of material zones within the 3DEC model is illustrated in Figure 3. As for the UDEC model described in Section 3.1, the Hoek–Brown shear strength model was used for all material zones in the 3DEC model, except for the large fault and thrust zones (for which the Mohr–Coulomb model was used).

A much coarser model zone size needed to be utilised than for the initial UDEC modelling. It was found that building blocks of less than 50 m in each dimension were too small to maintain a viable model size. Whilst building blocks of 50 m cubed were used for the inner non-linear region of the model which focuses on the west wall, it was considered adequate for the outer regions of the model (including the East Wall) to be constructed with blocks 100 m cubed in size.

The extremely large 3DEC model files sizes meant that it was not practical to construct and run a single model complete with all the structural fabrics (joint sets). Separate analyses were conducted for the west wall in which joint sets were included within only one of the Central, South and North regions at a time. Major (fault) structures were included within all regions for each analysis, however. It was difficult to exactly mimic the UDEC joint set patterns within 3DEC for the following reasons:

- A maximum of four joint sets could be practically included in the 3DEC model, only three of which corresponded to joint sets in the original UDEC model.
- Joint sets are generated in 3DEC and UDEC in dissimilar ways.
- In the original UDEC analyses, joint set spacing's were varied for different geotechnical domains, however the size and complexity of the 3DEC model meant that these had to be simplified to a single characteristic set of joint spacing's throughout the 3DEC model across all material zones.

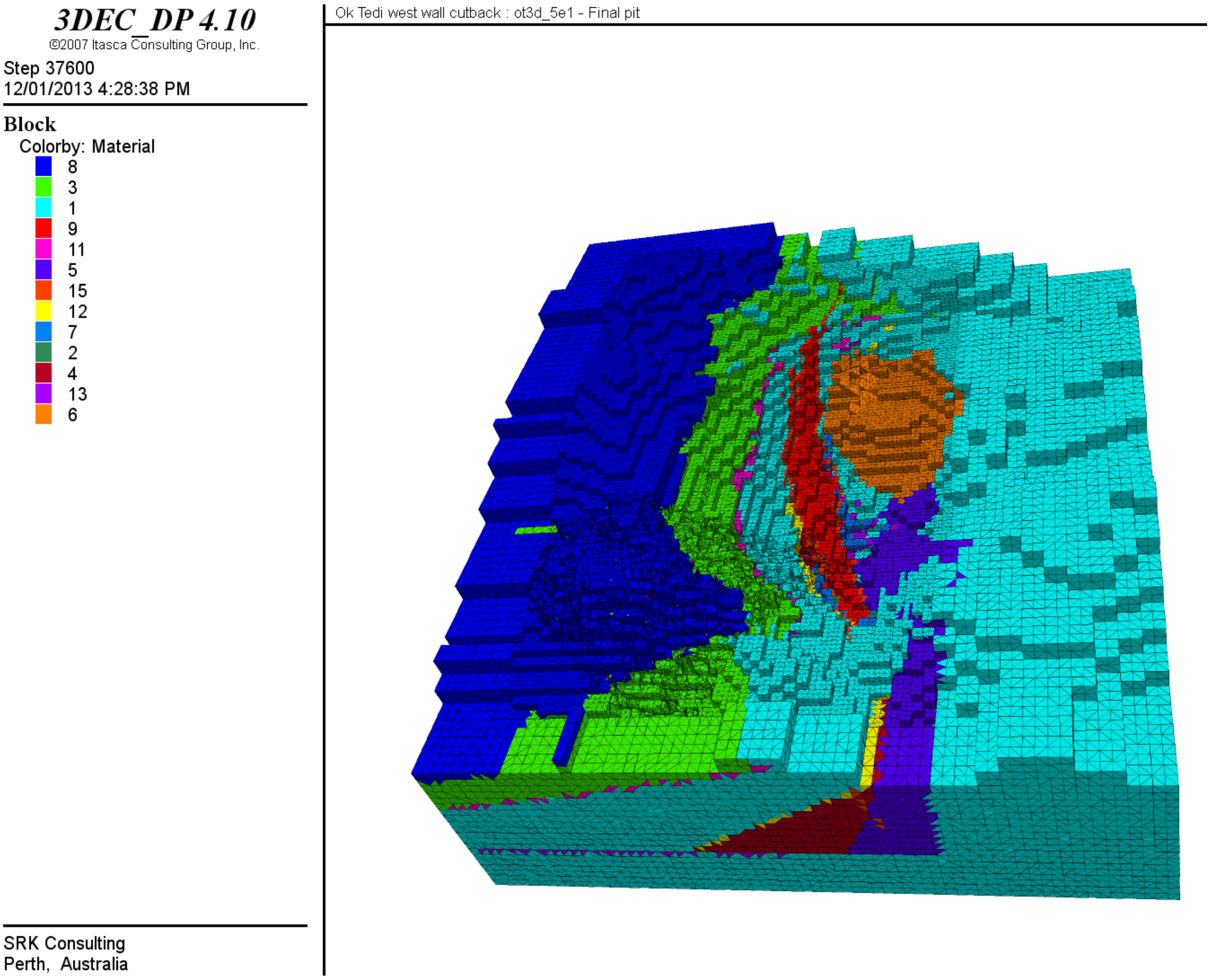



**Figure 3 Isometric view from the south of the entire 3DEC model, showing the block size and the material zones**

A number of vertical sections have been selected within the west wall 3DEC model for assessment of slope performance as the model is run. These include 13 sections in which history points have been situated and 28 sections used for plotting of displacement and velocity contours and plasticity indicators for stability evaluation. The positions of these sections are shown in Figure 4. In this figure, the Central, South and North pit regions have been delineated by blue lines superimposed over the 3D final pit design shell.

As for the UDEC analyses described in Section 3.1, the stability of the west wall was assessed in terms of FS for slope failure, as interpreted using the SRF technique.

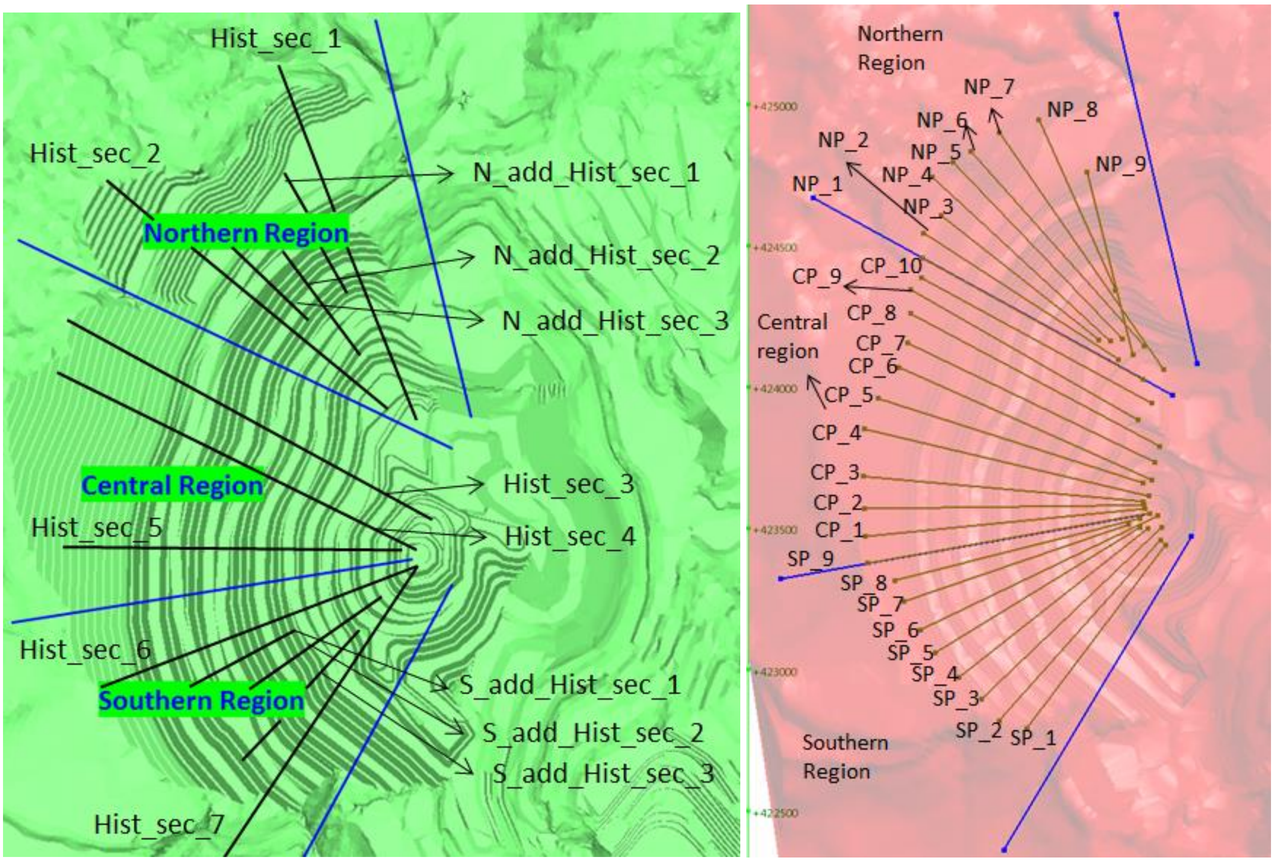



**Figure 4** Plan view showing position of sections including history points (left) and sections for plotting and stability evaluation (right) with regards to the pit regions

## 3.3 UDEC model for additional analyses

From the initial UDEC analyses and the 3DEC analyses, it was apparent that the Central region of the west wall is the most important in terms of stability. The additional UDEC analyses therefore focussed only on a section within the Central region, in exactly the same position as the central section used in the initial UDEC analyses. The position of the section is shown in Figure 5.

The model section was constructed so that it would be as similar as possible to a corresponding section through the 3DEC model. Therefore, the somewhat simplified material zones from the 3DEC model were incorporated and the material properties from the 3DEC model were also adopted (which had been slightly rationalised from the original UDEC model).

Because of the dissimilar ways in which joint sets are generated in 3DEC and UDEC, it was difficult to exactly mimic the 3DEC joint set pattern within the UDEC section, however this was attempted. The same joint sets were used in the creation of the UDEC structural fabric as were used in the 3DEC model, with the obvious omission of the joint set parallel to the section. The major (second order) structures present within the 3DEC model were included in this section.

Models were constructed that had both a fine zone size equivalent to that used in the original UDEC analyses, and a coarse zone size equivalent to that used in the 3DEC analyses, in order for analyses results to be compared.

As for the 3DEC analyses, no blast disturbance zone was incorporated into the new UDEC model, and the Hoek–Brown shear strength model was used for all material zones, except the first order fault and thrust zones (for which the Mohr–Coulomb model was used). However, the slightly different Basal Thrust properties used in the original UDEC model were incorporated for selected analyses for the purposes of sensitivity assessment.

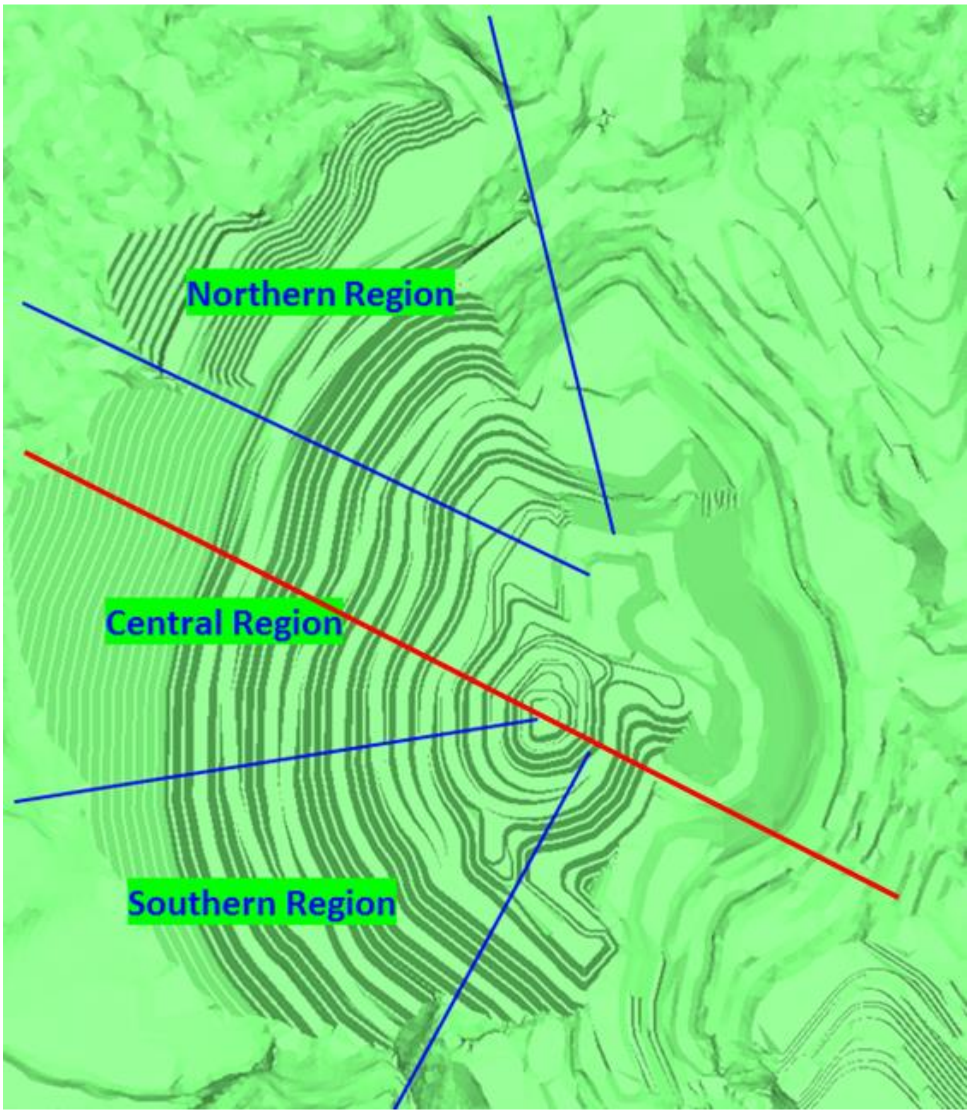



**Figure 5 Plan view of the position of the UDEC central section relative to the west wall pit design shell**

# 4 Results of analyses

## 4.1 Initial UDEC analysis results

The results for the initial UDEC stability analyses are listed in Table 2. The interpreted FS values have been based on:

- The displacement history plots of the large number of selected observation points.
- Displacement magnitude plots.
- Velocity magnitude plots.
- Plasticity indicator plots (showing zones that are yielding/have yielded in shear and in tension).

Several distinct zones of shallow failure become evident in the sections with progressive strength reduction, which are especially pronounced under seismic loading. An example of such zones from the South section is shown in Figure 6 (in this case best illustrated by X velocity contours). FS for failure of the overall slope, and the lowest FS (earliest development of failure) for the many inter-ramp failure mechanisms identified, are listed in Table 2. The overall slope failure mechanism is illustrated in Figure 7.

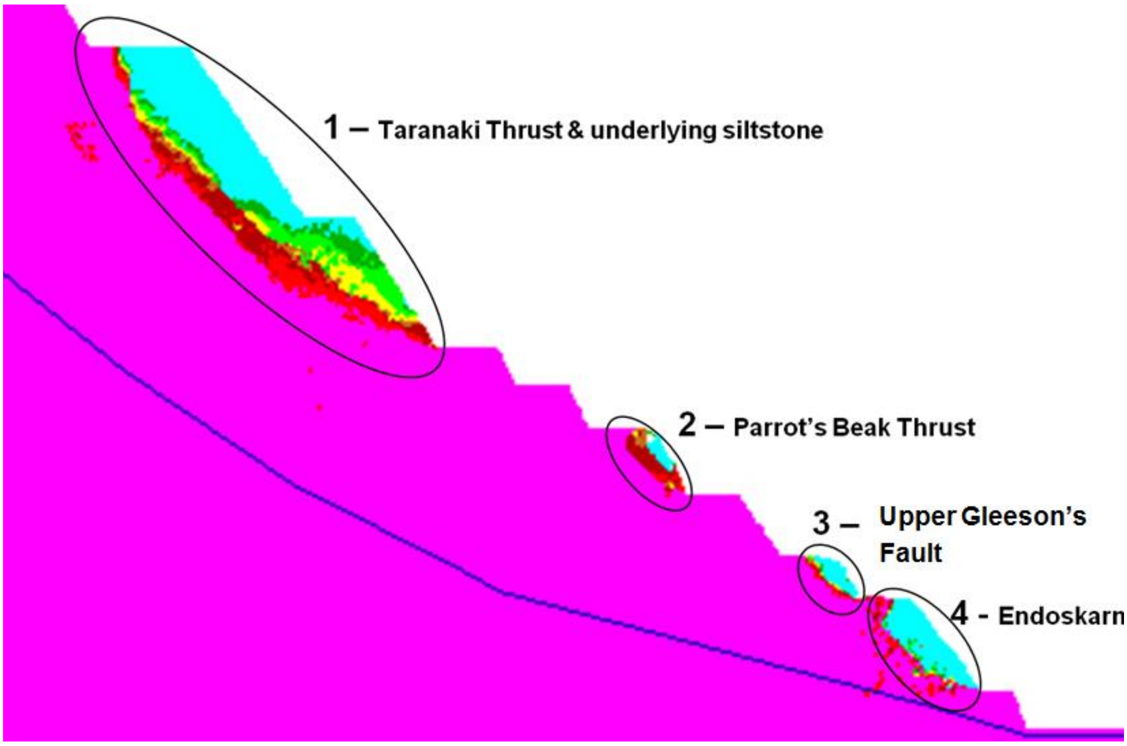



**Figure 6 Main zones of potential failure (low FS and developing instability under seismic loading) in the south section slope face, as illustrated by X velocity contours**

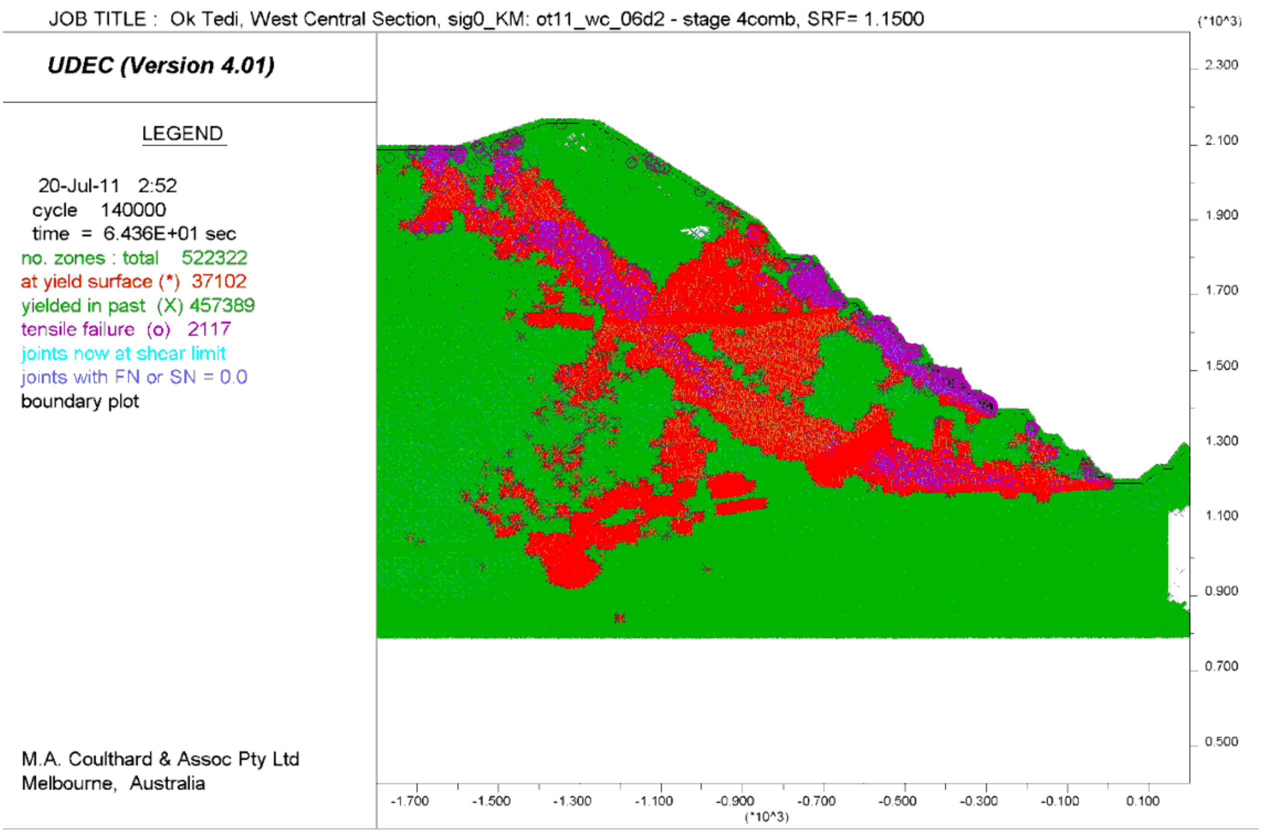



**Figure 7 Plot of plasticity indicators showing the failure mechanism occurring with the central section under static conditions (SRF = 1.15)**

For large scale or overall slope failure, the following is evident:

- The majority of the west wall cutback design would be suitably stable with regard to overall slope failure, with the target FS of 1.3 achieved with intended pit wall depressurisation to approximately 250 m behind the slope face. The exception is the important Central region, where a FS of around 1.15 is indicated.
- Under simulated seismic loading, the target FS of greater than 1.1 was achieved, except for the Central region which is indicated to be potentially unstable (FS of less than or equal to 1).
- FS values of less than 1 were also achieved for localised inter-ramp failure within the Parrot's Beak Thrust and Upper Gleeson's Fault under seismic loading.
- Inclusion of simulated seismic effects reduces FS by 0.1–0.2.
- The presence of the basal thrust zone reduces FS by 0.10–0.15, and failure extends to the toe of the slope.
- The structural fabric (explicit joint sets) reduces FS by 0.10–0.15.
- Inclusion of the blasting disturbance zone immediately behind the pit wall has little effect on the FS for the overall slope. The FS for shallow failures encompassing localised sections of the slope were marginally reduced in some scenarios.

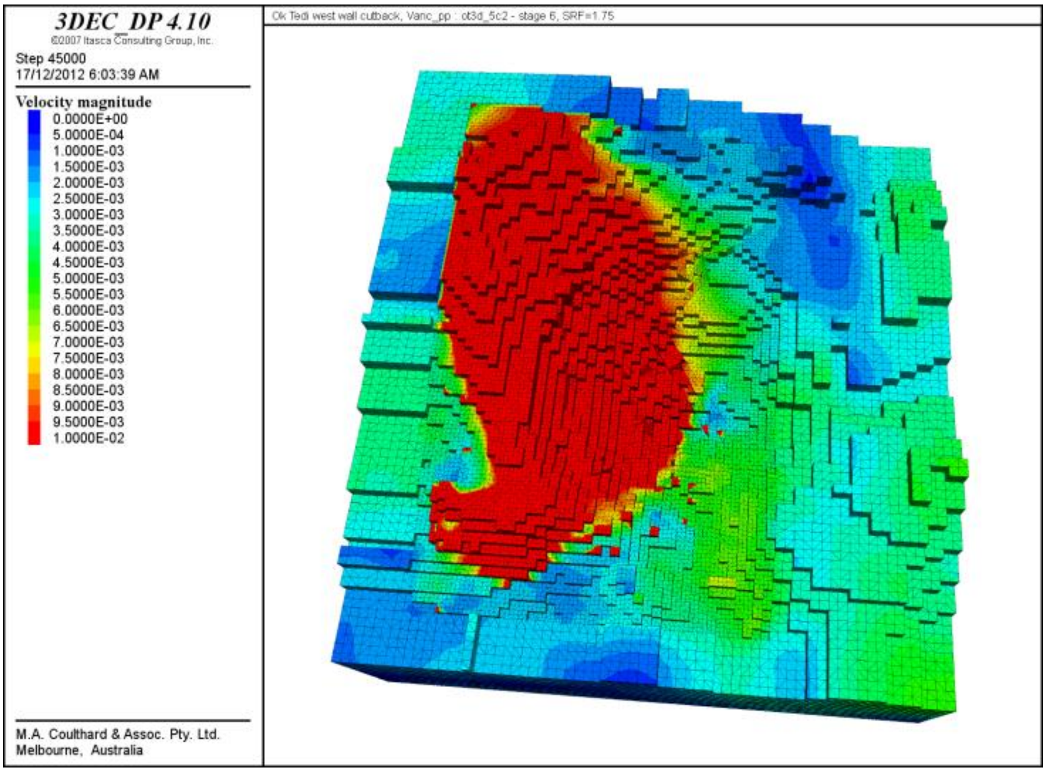
**Table 2 Summary of initial UDEC analysis results, for target groundwater level pushback of 250 m**

| Section | Seismic Loading | Disturbance Zone | Basal Thrust Active | Overall Slope Failure | | Earliest Inter-ramp Failure | |
|---|---|---|---|---|---|---|---|
| | | | | Without Rock Fabric | With Rock Fabric | Without Rock Fabric | With Rock Fabric |
| Central | No | No | No | >1.40 | 1.30–1.35 | 1.15–1.20 | ~1.05 |
| Central | No | No | Yes | ~1.30 | ~1.15 | 1.15–1.20 | ~1.00 |
| Central | No | Yes | No | >1.40 | Not run | 1.15–1.20 | 1.00–1.05 |
| Central | No | Yes | Yes | ~1.30 | ~1.15 | 1.15–1.20 | ~1.00 |
| Central | Yes | No | No | 1.20–1.25 | Not run | 1.00–1.05 | Not run |
| Central | Yes | No | Yes | ~1.15 | ~1.00 | ~1.05 | <1.00 |
| Central | Yes | Yes | No | 1.20–1.25 | Not run | 1.00–1.05 | Not run |
| Central | Yes | Yes | Yes | 1.10–1.15 | <1.00 | 1.00–1.05 | <1.00 |
| South | No | Yes | Yes | Not run | 1.35–1.40 | Not run | 1.0–1.05 |
| South | Yes | Yes | Yes | Not run | 1.20–1.25 | Not run | <1.0 |

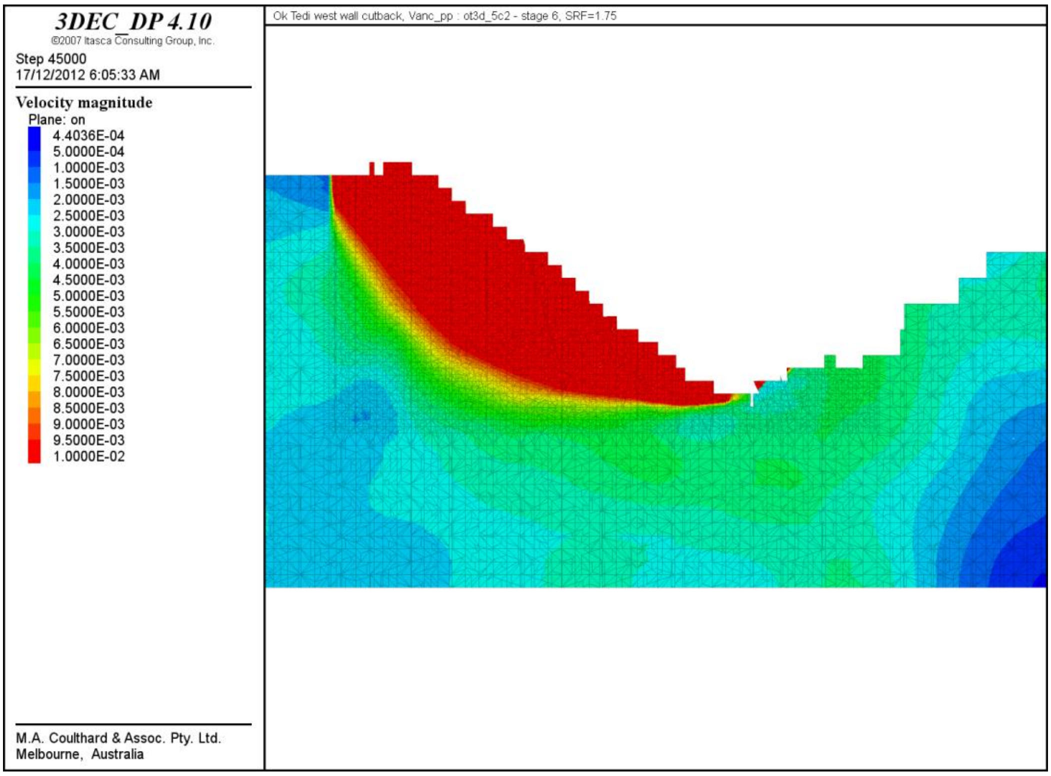
Note: The rock mass strength model revision subsequent to the completion of the initial UDEC analyses is likely to improve the tabulated FS values for the overall slope by approximately 0.05.

## 4.2 3DEC analysis results

The 3DEC analysis results for models run with jointing in the Central, South and North zones are presented in Table 3. For comparison, the slope performance in the key Central zone without inclusion of rock fabric has also been analysed and the results included in the table. As for the UDEC analyses described in Section 4.1, the interpreted FS values have been based on plots of displacement history and magnitude, velocity magnitude and plasticity indicators along the numerous vertical sections as shown in Figure 4. The velocity magnitude plots in Figure 8 have been provided here as an example to illustrate the failure mechanism within the Central region.




(a)




(b)

**Figure 8 Total velocity magnitude at last calculation step at SRF = 1.75 shown (a) in isometric view from the upper south; and (b) in section along CP_5**

**Table 3 3DEC analyses results**

| Analysis Focus | Groundwater | Interpreted FS |
|---|---|---|
| Central zone – without structural fabric | 250 m pushback | 1.75–1.80 |
| Central zone – with structural fabric | 250 m pushback | 1.70–1.75 |
| South zone – with structural fabric | 250 m pushback | 1.80–1.85 |
| North zone – with structural fabric | 250 m pushback | >2.0 |

As expected, the 3D analyses provided Factors of Safety for slope instability significantly greater than those obtained from the original 2D analyses. The results show that the FS is lowest in the key Central region, as expected, with a FS of between 1.75 and 1.8 calculated where the target depressurisation has been achieved. The inclusion of structural fabric (joint sets) does not have a significant impact on stability in the 3D model, with a reduction of only approximately 0.05 in FS, as compared with a reduction of 0.10 to 0.15 in the original 2D analyses.

The South region is indicated to be slightly more stable than the Central region, with a FS of between 1.8 and 1.85 calculated where the target depressurisation has been achieved. The improvement in stability is the result of lower wall heights and groundwater levels in the south, even though rock mass conditions are poorest. The difference in FS is less pronounced than that indicated from the original UDEC modelling, in which there was a marked difference in apparent dip of the Basal Thrust (which played a significant role in overall failure mechanism development) between the Central and South UDEC sections.

The North region is indicated to be most stable, with a FS of greater than 2.0 calculated where the target depressurisation has been achieved. This was expected because although the groundwater levels in the west wall are highest in the North, the rock mass is of best quality in this zone and the pit design has several features (including ramps and an in-pit low grade stockpile) that break the slope angle significantly.

The inclusion of large (second order) fault structures appears likely to have only a marginal effect on overall slope failures mechanisms, providing dislocation planes allowing for earlier, greater displacement within the lower half of the pit slope in the Central and South regions.

## 4.3 Additional UDEC analysis results

The results of the additional UDEC analyses are summarised in Table 4. The results of the comparable analyses during the initial UDEC modelling have also been included in the table. The aim was to use these results to try and place the 2D and 3D analyses in a common context, by assessing the effects that the simplified material zones and coarse zoning in the 3D model have had in the significantly increased FS calculated during the 3DEC analyses. The following is indicated:

- The inclusion of the simplified geotechnical model as used in the 3DEC model has little significant impact on the FS.
- The inclusion of the coarse zoning as used in the 3DEC model serves to increase the FS by 0.1.
- The interpreted FS are below the target design criteria of 1.3 where the Basal Thrust and joints sets are included (the realistic scenario), as for the initial UDEC analyses.
- The structural fabric (joint sets) result in a small decrease in FS, of approximately 0.05.
- The presence of the Basal Thrust decreases the FS for overall slope failure by approximately 0.2.

**Table 4 Results of Additional UDEC analyses for central section**

| Model | Groundwater | Basal Thrust | Interpreted FS of Additional UDEC Analyses | | FS From Corresponding Initial UDEC Analyses | |
|---|---|---|---|---|---|---|
| | | | Without Joints | With Joints | Without Joints | With Joints |
| Material model as for 3DEC but with fine zoning of original UDEC model | 250 m pushback | no | 1.35–1.4 | 1.30–1.35 | >1.40 | 1.30–1.35 |
| | | yes | 1.15–1.20 | 1.10–1.15 | ~1.30 | ~1.15 |
| Material model as for 3DEC but with fine zoning and Basal Thrust properties of original UDEC model | 250 m pushback | yes | Not run | 1.15–1.20 | Not run | ~1.15 |
| Material model and coarse zoning as for 3DEC | 250 m pushback | no | 1.45–1.50 | 1.45–1.50 | >1.40 | 1.30–1.35 |
| | | yes | Not run | 1.20–1.25 | ~1.30 | ~1.15 |

# 5 Synopsis

The areas of lowest stability are the Central region of the wall in the vicinity of the Parrot's Beak Thrust and the lower wall where the Gleeson's Faults and fracture-fault zone form a large part of the rock mass. Following the initial UDEC analyses, it was considered that the 2D model was unlikely to be fully representative with regards to predicting overall slope failure. The extra confinement arising from concave curvature of the pit wall (particularly strong towards the toe of the slope) is likely to render the actual pit wall in three-dimensions more stable than the UDEC analyses would suggest (i.e. these analyses have probably under-predicted the FS for overall slope failure). In light of this, it was considered likely that a suitable FS of 1.3 or greater may actually be achieved across the entire west wall design in reality, with a FS of greater than 1.1 achieved under pseudo-static seismic loading. The localised inter-ramp failures which have been identified in the 2D analyses could be considered more representative, however, as the curvature of the wall will have less of an effect, especially with increasing height up the slope.

The FS indicated from the 3D analyses were considerably higher than those achieved from the 2D analyses, with an increase in FS within the Central and South regions in the order of 0.5 (40%). The FS within the key Central region is 1.7 or greater. However, it is not expected that the results of the 3D analyses alone are representative of the true FS and most significant failure mechanisms within the west wall. It was considered likely that the 3D analyses overstate the stability of the pit slope due to:

- The necessary simplification of the complex geology and structural fabric.
- The coarser zone size necessary for the very large 3DEC model.
- The likelihood that failure mechanisms that do not include the entire slope and that are shallower-seated but that include multiple ramps and inter-ramp sections can still occur at lower FS. This is especially likely in the upper and middle sections of the wall, where there will be less stabilising effect as a result of reduced wall curvature. Such failures have not been the focus of the 3DEC modelling due to time/complexity constraints and the necessary omission of the disturbance zone from the 3D model. These failures, as indicated from the initial UDEC modelling, are of sufficient significance to influence decisions on slope design.

Additional UDEC modelling was carried out in an attempt at calibration between the 3DEC and initial UDEC modelling, in order to contextualise the 3D modelling results and for interpretation of the most likely FS.

The calculated FS for overall slope failure mechanisms during the additional UDEC analyses of the most realistic scenarios (and under static conditions) are still less than the target FS of 1.3, even with inclusion of the coarser zone size and simplified geotechnical model incorporated in the 3D modelling.

The FS as indicated from the 3D analyses can be decreased by 0.1 based on the coarse zone size used for the 3D modelling alone. The nature and disposition of the Basal Thrust is of significance in the overall stability of the west wall and care must be taken that it is well defined and characterised now that it is being progressively exposed in the lower west wall.

# 6 Conclusions

It is evident that the stability of the west wall is variable across its breadth and height. Minimum Factors of Safety for large scale or overall slope failure within the key Central zone are 1.15 from 2D modelling and 1.7 or greater from 3D modelling. It can be considered that the 3D modelling overestimates the FS by at least 0.1 (based on coarse zoning alone), and this is probably still a less than realistic measure of the stability of the cutback design considering the variety of mechanisms for significant slope failure that may be possible within the wall, in which the positive confining effect of wall arching in 3D may be less pronounced, especially in the mid to upper parts of the slope.

It is understood that the stability of the west wall is sensitive to complex interactions of many factors, the combinations of which are difficult to understand precisely in the context of the complex geology and geometry.

It is therefore considered that the 2D and 3D analysis results most likely present the respective upper and lower bounds for the west wall stability. It is proposed that a FS for overall or large scale slope failure in between 1.4 and 1.5 is probably most representative.

Although this FS is significantly higher than the target of 1.3, it was recommended that initiatives for steepening of the final west wall design from that currently proposed are explored with considerable caution and are well considered and evaluated from the point of view of:

- Changes in performance based on the amended position of any pit wall design relative to the major fault/thrust structures and poor rock mass zones.
- Sensitivity of slope stability to key factors such as the nature and position of the Basal Thrust and the achieved depressurisation.
- The potential for increased risk of inter-ramp instability in areas where the inter-ramp angles are steepened to allow for overall slope steepening.

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