Modelling of Large Open Pit Stability Using ABAQUS

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Abstract: The Largest, Deep Open Pits are steadily approaching depths of a kilometre. The complexity of the mining process and damage phenomena for these pits are amongst the most challenging applications of finite element simulation. Although significant advances have been made in the many areas related to mechanics of pit slopes, computer resources have limited the use of numerical modelling for open pit problems to two-dimensions or overly simplified 3d models.

With safety and productivity of future mega-pits depending on new design rules for pit slope stability, better tools are required. In recent times, the emergence of very large models with up to ten million degrees of freedom and advances in parallel solvers have allowed a step change in the simulation precision for slope movements and rock mass damage. The model size allows global and local effects to be realistically simulated in the one model with small excavation steps, more correctly re-creating the stress-deformation history in the slope. Some examples of calibration and forecasting of very large open pit (LOP) models are shown that demonstrate the challenges of modelling large slope behaviour.

Keywords: Slope failure, Large Open Pit, Slope stability, Faults, Geology, Rock Mechanics, Geotechnical.

1. Introduction

There is a trend for open pits to be mined to greater depths than ever before. The greater depths are leading to higher underlying strains in the slope and failures arising from rock mass instability have become more prominent. These failures include instabilities resulting from the combined effects of induced slope damage and structure, as well as structurally controlled failures that pure kinematic analysis does not predict.

It is well known that large slope failure mechanisms aren't simulated well by legacy finite difference and discrete element modelling packages owing to practical limitations including low order or nodal mixed distribution elements, small model sizes and a crude representation of the stress path due to excessively large excavation steps. The common effect of these problems is the difficulty representing realistic scale rock mass movements and damage. The mechanisms also cannot be properly appreciated using 2D models, which are still common in the mining industry.

The emergence of large 3D FE modelling tools with higher order elements and the inclusion of faults and geological contacts with an improved capacity to simulate dislocation and block movements allows much better simulation of many of these mechanisms.

2. Requirements for successful large open pit slope analysis

Successful slope modelling requires simulation of the complete stress path for every slope as well as an appropriate representation of the geometry of the problem. Naturally, the governing physics of the slope response must also be captured. There is also a requirement that the simulated displacements are correct; if a non-linear model of a slope is unable to replicate displacements, it will not have captured the extent and magnitude of yield in the slope, and vice-versa.

These fundamental requirements suggest:

- a 3D representation of the mine geometry
- incorporation of all geological structures and domains on scales relevant to the problem
- the correct consideration of initial stress field conditions
- the use of material models and higher order elements able to simulate the stress-strain behaviour of rock from the intact to significantly yielded states.

The recent step changes in non-linear FE model size and speed immediately translate to an ability to build more detailed geometries that capture the true geometry of the problems and an ability to more properly simulate the complete stress-strain path.

Compared to previous non-linear modelling, the improvements allow significantly more realistic estimates of the nature and extent of yield, so deformation is forecast more accurately and with better reliability. As deformation is forecast more accurately, energy terms and simulated rock failure modes are also more realistic. This significantly simplifies model interpretation, as the quantities that are interpreted are more directly related to observations of the pit.

Large and detailed FE models of large open pits (as shown in Figure 1 for the Debswana's Jwaneng Pit in Botswana) allow detailed analyses and direct calibration of slope movements, caving processes from initiation to propagation, growth of the fracture zone and deformation in underground workings and surface subsidence.

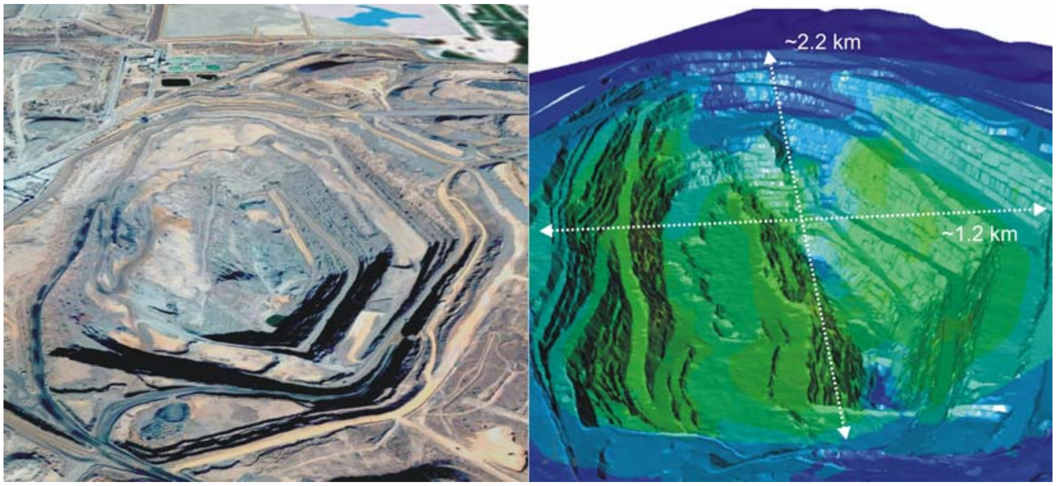


Figure 1. Picture (Google Earth) of a large open pit (Debswana's Jwaneng Pit, Botswana) and the model geometry

2.1 Discretisation and Element Types

Some basic information about the discretisation of the models is listed below.

- Quadratic tetrahedral elements are used. Mesh convergence studies using a representative volume for a typical mine-scale model (10km+) show that quadratic tetrahedral elements represent the far field deformation extremely well even with large surface elements.

- Linear elements or the reduced integration method are not used. These lack the precision necessary for estimation of slope stability for most problems.

- When sub-modelling techniques are applied, the donor model is completely non-linear, the excavations and geology inside the sub-modelling area are still represented in some detail in the donor model, and the complete load deformation path is matched perfectly to the sub model boundary at each model step.

2.2 Material Yield

To properly replicate slope behaviour, the modes of material yield and slope failure must be able to be simulated. Figure 2 shows some conceptual slope failure modes and the yield mechanisms that contribute to them.

Slip on discontinuities is simulated by discretising discrete bands/discontinuities approximating the width of the structure and applying an appropriate material model and properties.

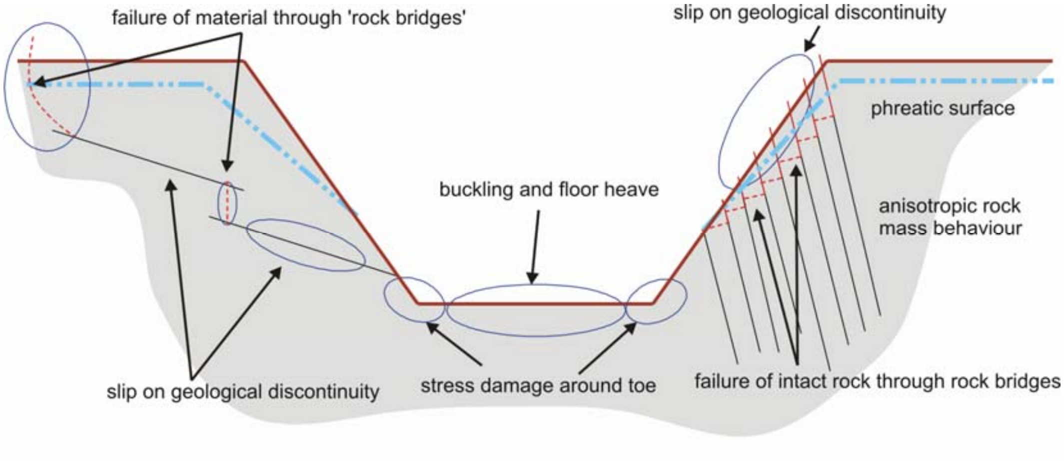


Figure 2. Failure modes to be simulated in proposed conceptual model (Haile 2006)

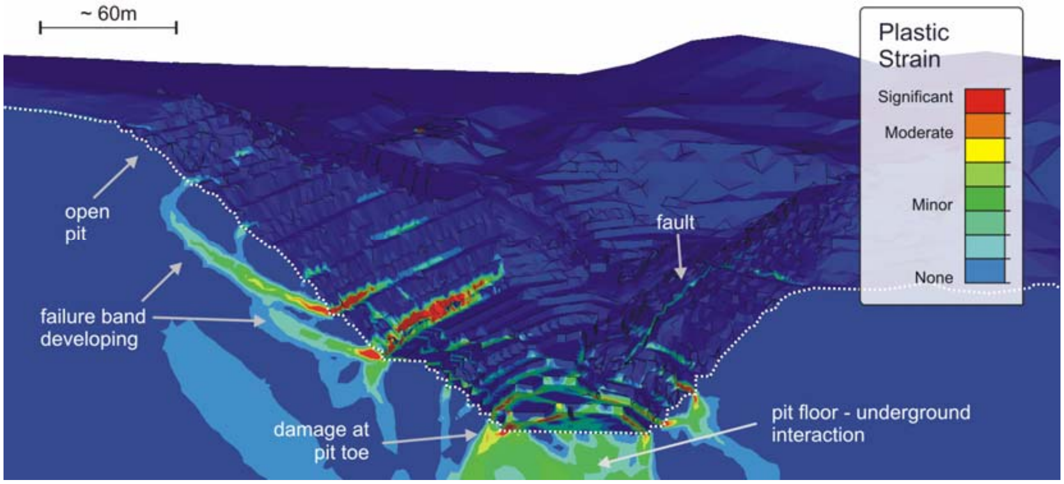


Figure 3. Example of a LOP FE model with ~ 2 million DOF : Plastic strain distribution on the surface and along a vertical cutting plane

In Figure 3, the plastic strain distribution on the surface and along a vertical cutting plane of a large open pit model is shown. The FE results reproduce the phenomena listed in Figure 2. A comparable example is shown in Figure 4, where the extent of fault slip is very large. The purpose of showing these extreme examples is to highlight the very large strain capabilities of modern NL analysis, to demonstrate that the most relevant instability phenomena can be replicated and to show the influence of structure on the damage around the open pits and underground mines.

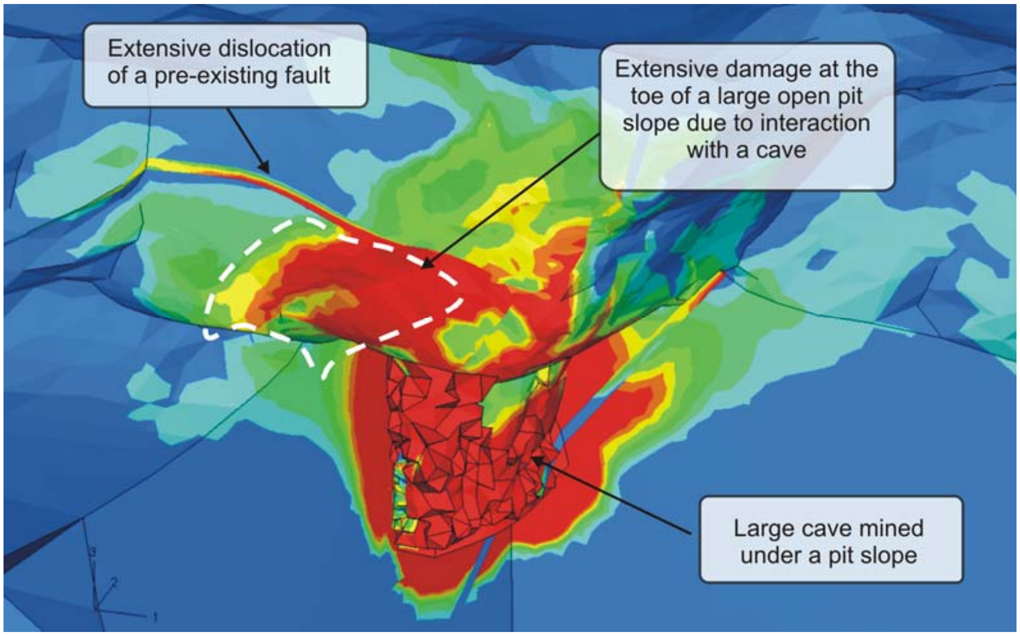


Figure 4. Plastic strain showing intense damage at the toe of a large open pit slope

2.3 Geometry and Material Assumptions

Model geometries are based on orebody models, as mined models and digital terrain models (DTMs) provided by the mines. A view of the geological detail incorporated into an example model is shown in Figure 5. An example of a discretisation of some geological features in the model is shown in Figure 4, highlighting the near exact re-creation of the structural model.

When modelling extraction stages for the pit and any planned, future underground mining, the stress path in the area of interest has been simulated using the complete mine geometry, which was extracted in small increments from the virgin, pre-mining state up to each relevant mining step. Some basic material assumptions are:

- In the models material strengths or properties are calibrated by comparing observed behaviour and measured deformation to the model results, or the material properties are benchmarked against properties from mines where calibration has taken place. This means that large-scale rock mass properties have been derived.

- The inelastic, non-linear, dilatant material model (MOHR-COULOMB) assumes that each material has peak and residual strengths and dilates and softens as a result of yield. Once the peak strength is exceeded, residual strength and material properties are introduced utilizing the UVAR subroutine to define user field variables.

- In cave-pit interaction problems, the cave is represented as a low friction material. The cave material provides important confinement to the walls and floor of the cave and this is simulated in the model.

- The model uses geological wire frames to represent all geological features. Where fault models do not extend far enough, the simplest interpretation has been used to extend them.

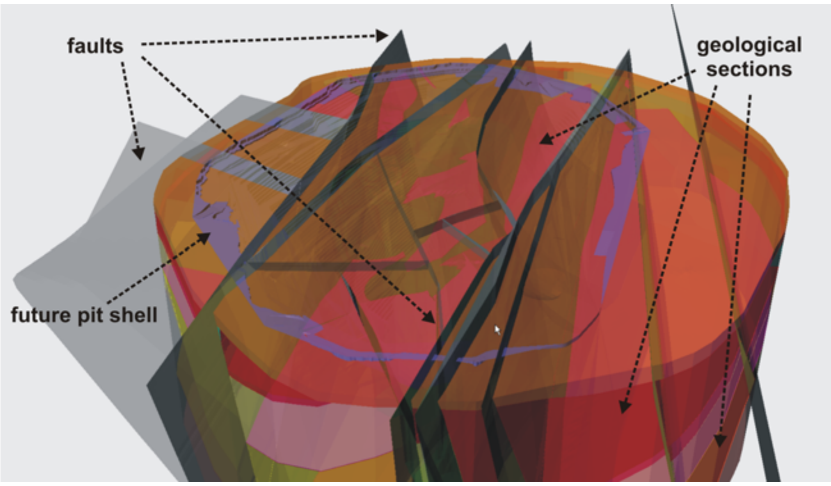


Figure 5. Visualization of some geological data sets used in an example model

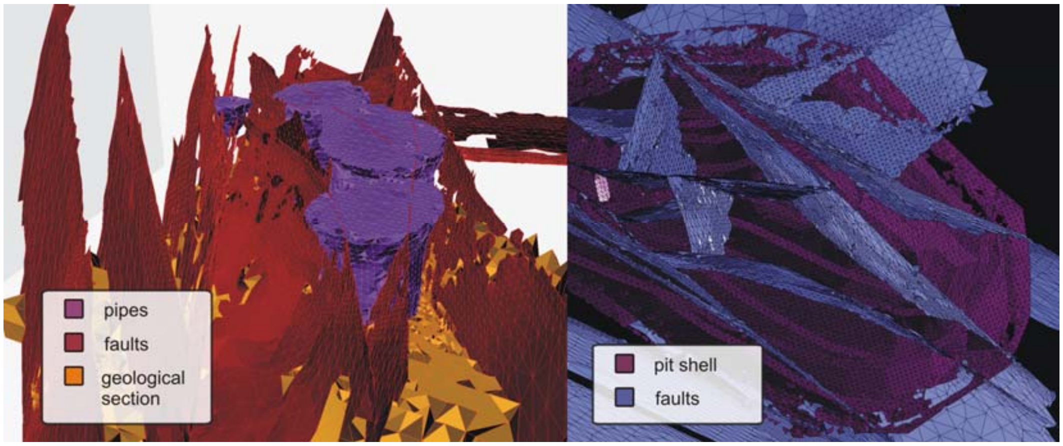


Figure 6. Example of the discretisation of some geological features in a LOP model

2.4 Simulating the stress field

The stress field used to apply boundary conditions to the model with the ABAQUS subroutine SIGINI is based on measurements and a simulation of the geological history, which ensures that a realistic pre-mining equilibrium is reached between the known geological structure and the pre-mining stress field.

An example of the results of simulating geological history at a mine is shown in Figure 7 for the σ_{33} component of the stress field.

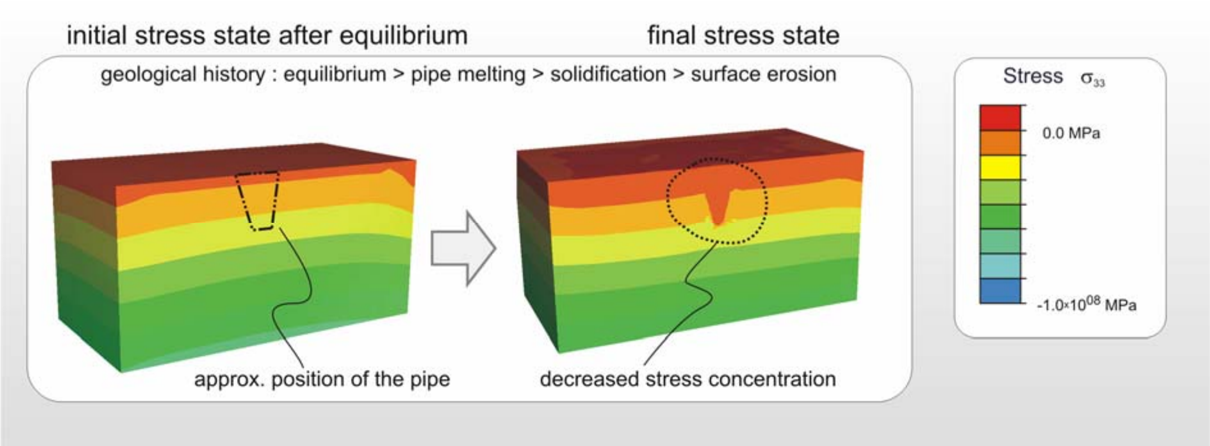


Figure 7. Example of the simulation of the geological stress-strain path

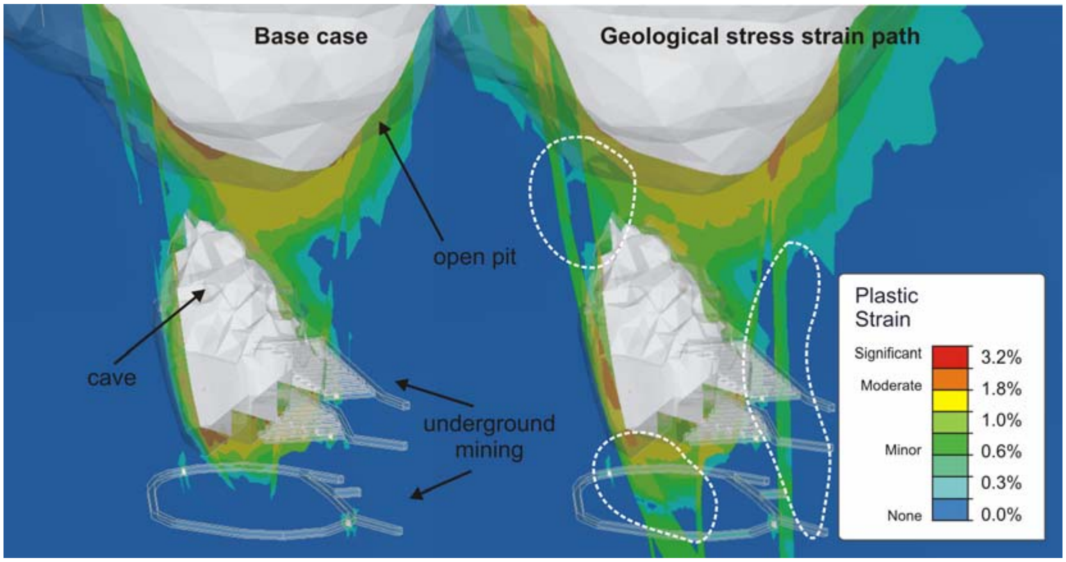


Figure 8. Plastic strain induced in the vicinity of an open pit by caving operations for a base case and the case with the simulated geological stress-strain path

At this example mine, stress measurements suggested that the stress conditions varied significantly. The extinct volcanic pipe is the orebody, and it was believed that the geological history contributed to a low stress state inside the pipe. This was simulated in the equilibrium steps for the model, with results as shown in the Figure 7. The model results not only closely matched measurements at the mine, but the nature of the damaged pipe boundaries were also simulated directly. Figure 8 shows the modelled rockmass damage at a mining step for this special stress case and a ‘standard’ stress field. The simulated stress path, with a better match to measurements produced more realistic interaction phenomena, and importantly shows an increased interaction with the pit.

2.5 Calibration and material properties

The recent increases in model size and speed have more significant effects than just short run-times and improved model complexity. The rapid run times allow economic simulation of large numbers of model cases. The potential for calibration is improved because a large number of material property cases can be tested in the same time as single model runs for comparable ‘status quo’, historical non-linear analysis.

Small time steps also give more opportunities to match model data to field measurements. Most data hasn’t been collected for the purpose of model calibration, so without small time steps it is less likely that the measurement dates will correspond to model time steps. It is usually possible to utilize a very high percentage of the collected deformation data at client mines. Some case studies have utilized up to 20000 measurements in the calibration phase to achieve true statistical quantification of the model calibration.

The calibration of the model is usually based on measurements of movement in the pit slopes and interpretation of a number of slope failures, damage and instability in the model using a number of factors and experience. Stability, failure and damage are all different things, and understanding these modelled performance indicators in pit slopes is critical for understanding the results. In an open pit context, damage or yield is simply degradation in material properties. Failure implies that a feature or aspect of a design isn’t performing its planned function. Damage in a pit slope can occur for a number of reasons and by a number of mechanisms. The damage can be on existing structure or through a rockmass, or by a combination of damage on structure and in the rockmass. In deeper slopes, the contribution to overall damage from rockmass degradation will increase.

Damage in the rockmass and to structures is modelled very well by the large ABAQUS models using plastic strain, which is a measure of the damage or distortion of the rock based on the Common Damage (Beck and Duplancic, 2005). Increments of damage, for example occurring over a particular time period are also sometimes measured by the amount of energy released due to damage. The energy released this way is called the Dissipated Plastic Energy or DPE. DPE is also the best factor for correlating with seismic event probability. Even in seismically quiet environments, DPE is worth considering as it can help understand how the rockmass is adjusting to mining. The most important point about damage is that it doesn’t automatically imply instability or failure. It is quite possible to have a stable pile of completely broken material. The best measure of stability is actually velocity, so changes in displacement in a model are very relevant. In many models of pit slopes where the extent and magnitude of failure is not replicated, movements and the nature of damage in the slope are not captured, so these direct measures of instability cannot be relied upon.

An example of a well constrained model can be seen in a plot of plastic strain and displacement shown in a section of a wall of Debswana's Jwaneng Pit, Botswana in Figure 9 and Figure 1.

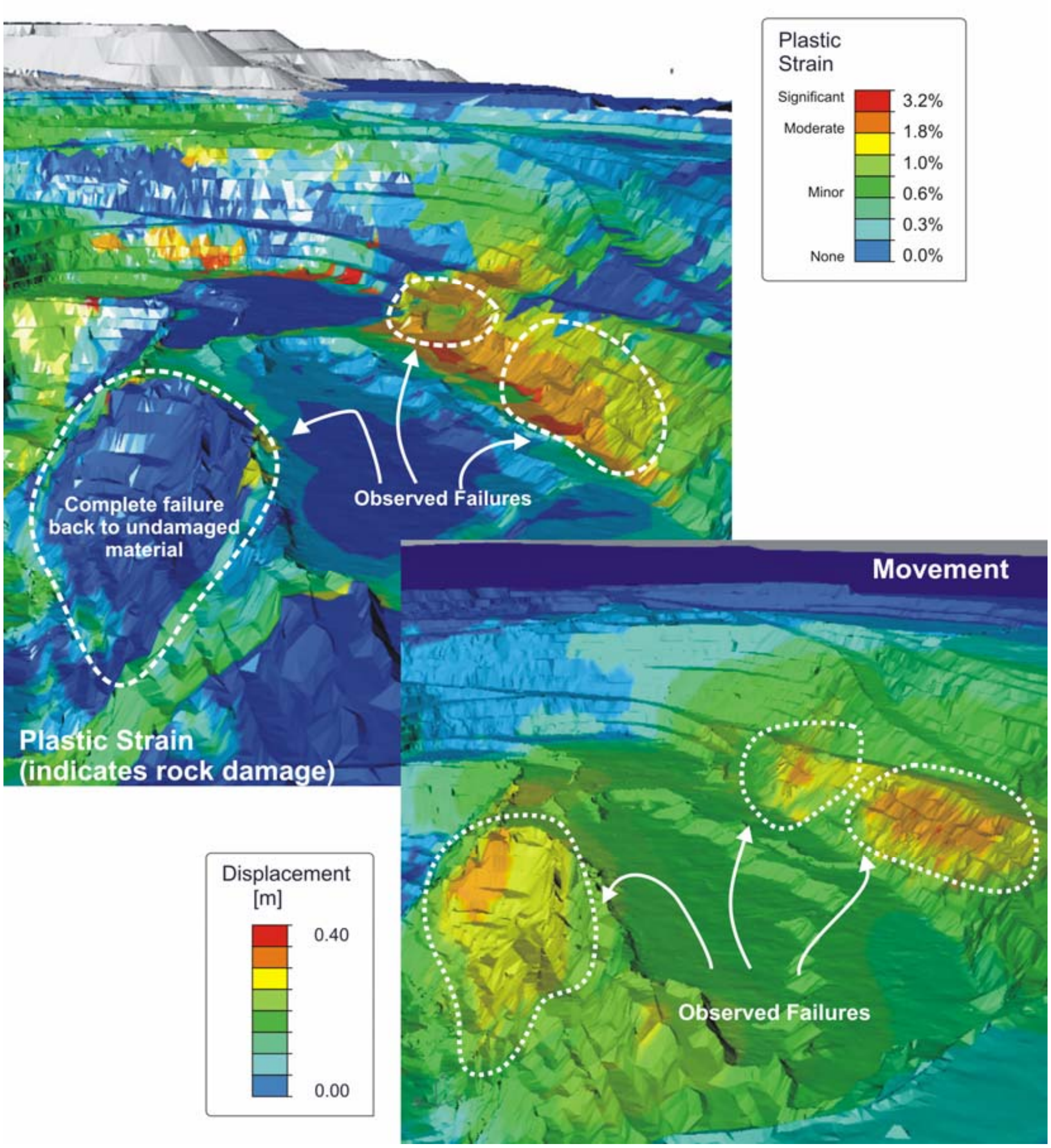


Figure 9. Modelled plastic strain and displacement in a portion of the east wall of an example pit

Three observed failures are indicated in the Figure.

- Two of the significant failures correspond very well to significant but shallow plastic strain and high displacements. Large displacements and high plastic strain correspond to an upper bound for stability; that is, where there are large movements and high underlying plastic strain, instability of some form should be expected.

- A third failure in the plots only has plastic strain on its margins, and the displacements are highest there too. For that failure, the collapse has already occurred in real life as well as in the model and a stable equilibrium has been reached inside the ‘scar’. This stable equilibrium was achieved when the slope broke back to a stable shape. The model would have to be rebuilt with the pre-failure geometry to properly assess this incident.

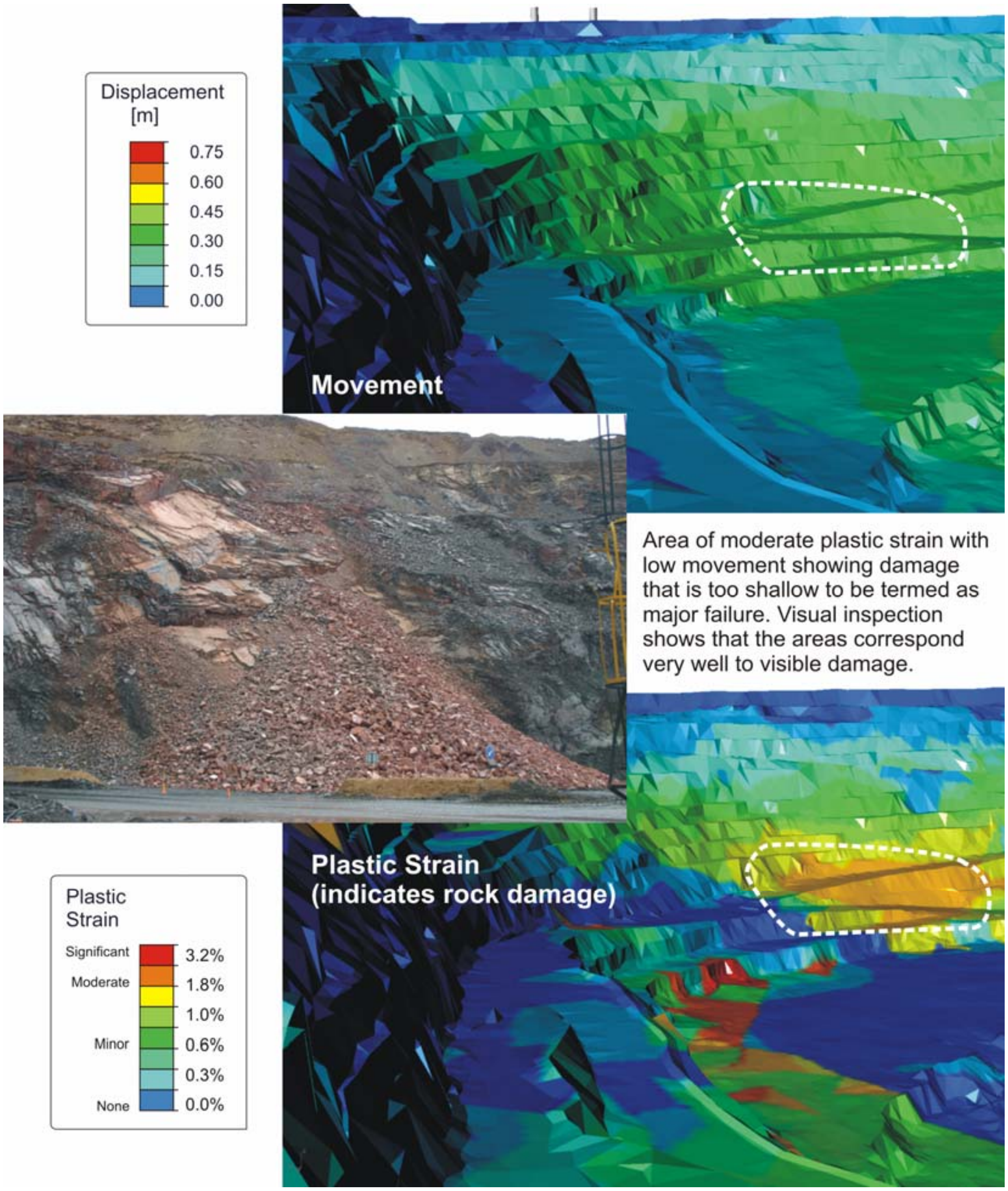
- The fourth interesting observation is that there are a number of other locations in the modelled pit with high plastic strain where no failures have been reported. Visual inspection shows that these areas correspond very well to visible damage in the pit, but instability on a scale that would be termed a failure hasn’t yet occurred. Areas of high plastic strain with low displacement are either stable, show damage that is too shallow to be termed a failure or else represent a lower bound for stability, that is, they will be taken to represent a lower estimate for instability potential and might be most commonly associated with slumps of finely fragmented material or other shallow damage mechanisms.
  Confounding factors such as local conformity of the bedding, blast damage, water or weathering would strongly affect whether these areas of high strain became unstable and should be considered carefully when assessing the stability of these areas.

The failures used for the calibration of this model are shown in Figures 10 to 12. The correlation that has been achieved can be summarized as follows:

- Figures 9 to 12 show failures for which the model indicated both high levels of rock damage and large displacements. The presence of both indicators is a upper bound for stability – i.e. instability is the only interpretation of such a model result. In these cases it is the depth of the damage that controls the size of the failure.

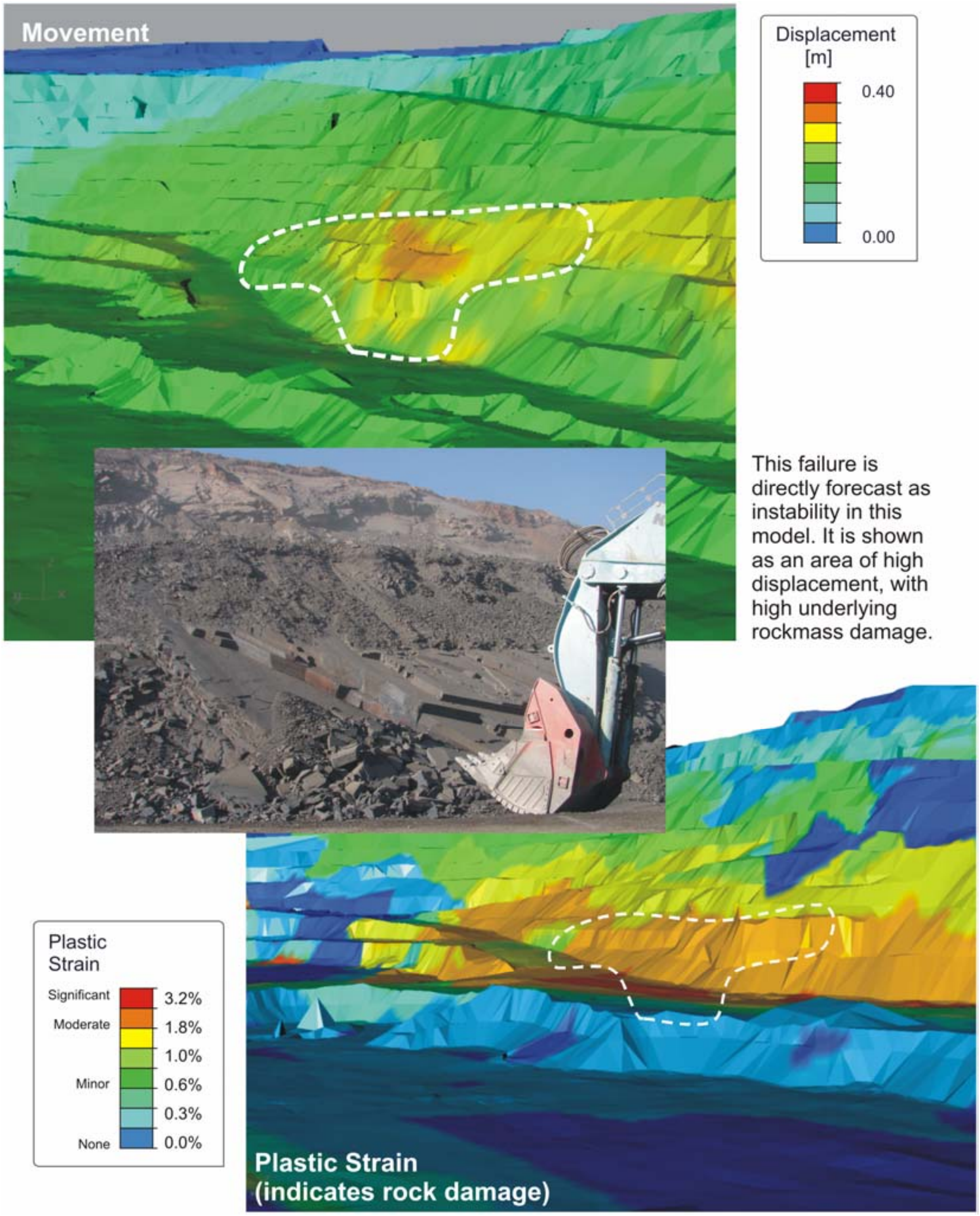
- In some of these cases blast damage was considered a factor. It is likely that blast damage simply influenced the expression of these failures, especially since the ground was already damaged.

It is concluded that there is a very good match between the modelled and actual conditions in the pit. Importantly the model described the conditions in relatively stable areas of the pit as well.



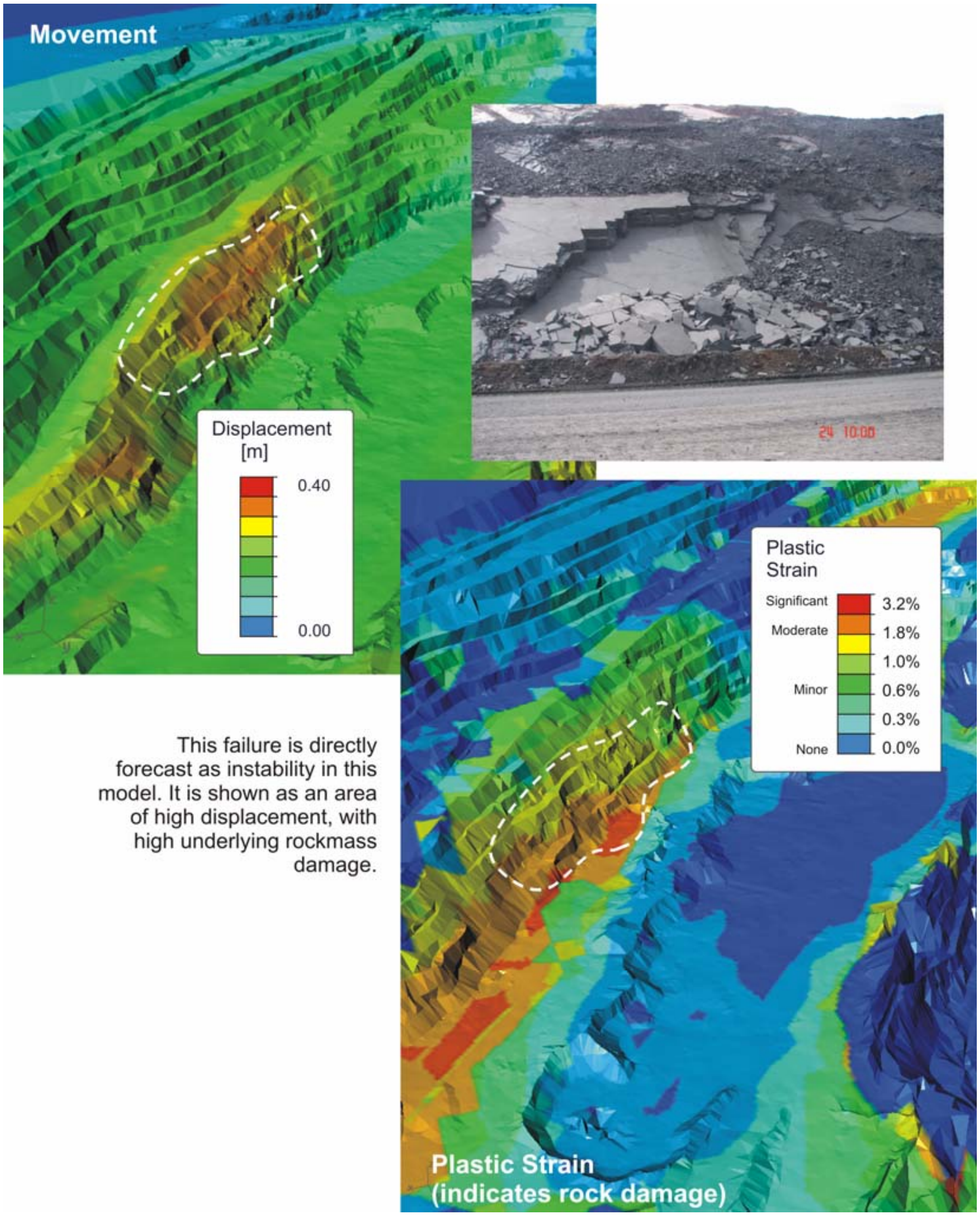
Area of moderate plastic strain with low movement showing damage that is too shallow to be termed as major failure. Visual inspection shows that the areas correspond very well to visible damage.

Figure 10. Modelled Failure in Dry, Weathered Material



This failure is directly forecast as instability in this model. It is shown as an area of high displacement, with high underlying rockmass damage.

Figure 11. Modelled Failure in Moist, Fresh Rock



This failure is directly forecast as instability in this model. It is shown as an area of high displacement, with high underlying rockmass damage.

Figure 12. Modelled Planar Failure in Fresh, Moist Rock

2.6 Some reliability and confidence limitations

The main limitations encountered for open pit FE modelling projects is the lack of data. This arises due to the monitoring philosophy employed in most open pit mines and the lack of precise geological information. The problem with monitoring and geological information arises because most data collection is undertaken with a tactical objective, and for measurements of movement, each survey location is maintained for only a relatively short period before being discontinued. This data is difficult to use for systematic back-analysis for many reasons. Some examples are:

- Only observations of failure events are recorded – very few non-failures are positively recorded.

- The timeframe of the measurements is limited. Model steps sizes chosen to 6-12 months, so the monitoring must span at least this time frame.

- There is a habit of recording surface effect failures instead of underlying slope movements. Measurements of underlying slope movements are required for rockmass and structure calibration.

The problems are simply overcome by undertaking a program of systematic radial and future pit crest traverses in addition to normal measurements.

The continuum assumptions of the code are also becoming less important with developments in ABAQUS. Where continuum assumptions are no longer valid, for example where blocks or wedges have been formed by a combination of structure and induced shear zones, a factor of safety approach incorporating limit equilibrium analyses would need to be applied. Generally, three categories of failure can be identified for the purposes of stability interpretation using the model:

- Failures directly interpreted from deformation in the model as discussed above. These can be plotted directly and are easily visualized within the modelling package. These failures usually affect global stability of the pit, though some small scale failures are able to be simulated.

- Conditions indicated by the model to be compatible with failure, but requiring further kinematic/limit equilibrium analysis. This category of failures is usually smaller than wall-scale. ‘External’ analysis is required because numerical models either don’t incorporate structures of this smaller scale, or else because the interpretation of failure is purely based on kinematic potential for movement.

- Surface effect failures, limited to kinematic analyses, but where model results can be used to derive the evolving rockmass conditions for analysis. These are failures that wouldn’t occur, except that the rockmass has been affected by the stress and deformation induced by the pit. For example, conditioned rock at the toe of a slope may not provide enough confinement to prevent sliding of material above. In this case, the NL model can provide an estimate of the conditioning of the toe and this can be used to adjust input parameters for the kinematic analysis.

For all three categories, it is likely that certain quantities drive the failure, dispose the slope to instability, or directly measure the magnitude of instability (for example velocity). If the quantity is a measure of deformation and the relation with stability is known, it is possible to apply the Alternate Point Estimate Method to true regional scale, non-linear, Life-of-Mine (LOM) numerical models to assist in quantifying the likelihood of failure. A special case applies to tensile or extensional failures, such as toppling. For such modes of failure, strength criteria are not completely developed and need more attention in the future.

3. Summary and Conclusions

Step changes in non-linear FE modelling capabilities allow models as large as 10 million degrees of freedom and a large number of detailed mining steps with a solution time practical for mining engineering problems. This immediately translates as an ability for specialised engineering teams to economically build more detailed models that capture the true geometry of the problems, and for the first time in any mine modelling to properly simulate the complete stress-strain path of the entire mine history.

Compared to previous non-linear, predominately Finite Difference modelling available to the mining industry, the improvements allow significantly more realistic estimates of the nature and extent of yield, so deformation is forecast more accurately and with better reliability. The accuracy and precision is quantified using measured field data. This represents an improvement in calibration data quantities of several orders of magnitude compared to normal slope modelling.

The immediate impact for mines is the availability of an accepted analysis technique (FE modelling) but now with unparalleled quantification of the precision and fitness for purpose of deformation forecasts. The application of large models together with the ABAQUS FE simulation package, coupled with accepted rock mechanics principals and clever mining engineering will be a significant enabling technology for deep open pit excavations.

4. References

1. Beck, D.A and Duplancic, P. 2005. Forecasting Performance and Achieving Performance Indicators in High Stress and Seismically Active Mining Environments. Proc. of the 6th Intl. Symposium on Rockbursts and Seismicity in Mines.

5. Acknowledgements

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