Probabilistic stability criteria for open pit and underground mines

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ABSTRACT

3D Strain softening, dilatant, Finite Element models utilising higher order elements can achieve a realistic simulation of displacement and damage induced by mining. This allows application of rigorous, displacement and velocity based stability criteria for both surface and underground excavations. Using modern computer packages and hardware, rapid simulation times also allow probabilistic estimates of the extent and magnitude of displacement and damage.

Some case studies are presented that describe the application of the displacement realistic models and the Alternate Point Estimate Method (APEM) for the assessment of mine stability problems. The case studies also demonstrate the development and application of displacement, velocity and damage criteria for the assessment of instability potential in a applications for slope and underground excavation stability.

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1 1 INTRODUCTION

Instability can be a serious problem. Large scale instability can render a mine infeasible, while if not foreseen, lesser stability issues can prevent objectives from being achieved. A common problem for engineers is to have to weigh the risks of a potentially higher earning mine plan against a less economic plan that is more geotechnically sound, with only qualitative inferences to guide them .

One common approach is to identify the last safe moment before a decision would need to be made between alternative approaches, and use the available time to collect as much information and conduct analysis to help make a more informed choice to prevent or better manage instability.

An example of this is shown in Figure 1 for an underground mine that experienced serious stability issues. These problems, or vulnerabilities, occurred in stages. The first problem stage, occurring in year 1could be managed tactically with normal mine procedures, while problem stages 2, 3 and 4 could not. These problem stages would have required revisions to the mine plan. Problem stage 5 at this mine was insurmountable.

The problem for the mine is that those stages of instability for which a solution was available but not able to managed tactically, required a change to the mine plan much earlier than the time at which the problem occurred. Problem Stage 2 and 3 required strategic decisions one year before the problems occurred, while Stage 4 would have required a change to the mine plan nearly 2 years earlier.

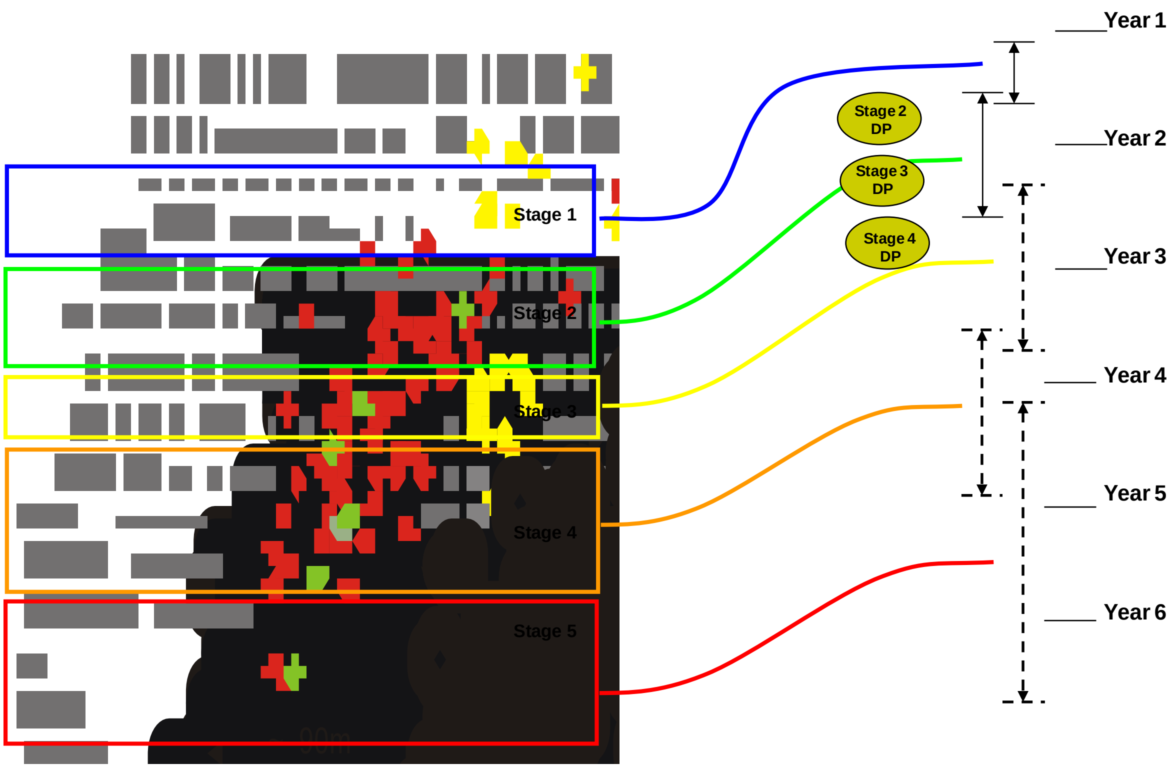


Figure 1 An example of the depth of occurrence of problem stages in a mine, the timing of these vulnerabilities and the last safe moment, or Decision Point (DP) at which the mine would have to act to prevent the problems from occurring. Coloured circle show large seismic events that occurred on a single day when eventually, the central pillar failed.

It simply would not have been possible to avoid the mines' stability problems using tactical approaches alone. Some forecasting of the problems and action to prevent them would have been necessary if they were to be avoided.

If a schedule of instability risks such as that shown in Figure 1 could be developed ahead of time, mine decision making would be simple. However identifying the potential for instability and understanding the timing and uncertainty of risks is difficult.

Apart from human experience and imagination, numerical models are the most frequently used tools used to aid identification of potential stability problems, to forecast the magnitude and timing of problems and to test alternative solutions. If the models are sound, they can assist the mine to identify the potential vulnerabilities and to test the alternative solutions and also to help develop a schedule of risks similar to Figure 1.

The questions then are:

- Is the model sound
- What criteria will be used to identify the timing of mine instability, and the uncertainty around this
- How to manage uncertainty and incorporate variability and probability in decision making

2 MODEL SOUNDNESS AND SUFFCIENCY

The aim of modelling should be to achieve similitude. This requires that the governing physics of the problem is captured and that the physical environment and sequence of events is properly represented. The best, most objective measure of model performance is the models ability to recreate displacements. A match with measured displacements is sufficient because these can only be correct if the extent and magnitude of damage is properly captured in the model. An especially rigorous test of model sufficiency is to measure the correlation between measured and modelled displacement at different length scales over extended periods.

The following is not an exhaustive list of modelling fundamentals required to achieve displacement realistic models as this is not the aim of this paper, however the following are very important requirements:

- Most fundamentally, the geometry of the problem should be represented. This is not usually a data problem as the mine geometry and geology is usually adequately known and fortunately, advances in computational efficiency and capacity mean that 2D modelling and over-simplified 3D models are now very hard to justify. Proper representation of the geometry includes the recreation of the stress path with adequately small excavation steps in the model.
- Equally important is the stress conditions at the boundaries of the model and the material models which are used. For large, multi-scale models (Beck, 2008a) the far-field stresses should be correct, while for sub models boundaries should usually be driven by displacements provided by an equally sound donor model. If the stress field is disturbed, this will have to be incorporated into the model as well.
- The material model should reproduce the fundamental behaviour of the rock, and each model element should perform true to this model. Higher order elements are usually required to ensure that the small volumes of rock in which instabilities initially develop behave appropriately. It is also important to represent the physical consequences of instability (weakening, softening, dilation) in addition to correctly forecasting the timing, location, extent and magnitude, to ensure that the system behaves in the simulation as close as necessary to the way it would in reality.
- If the model fundamentals are wrong, no interpretation, or adjustment of parameters or input can correct the error. If the model fundamentals are sound, the correct input variables will result in similitude. Estimating the correct input variables, all else being sufficient, is a separate topic, but the best estimate will always come from calibration. There are also some reliable empirical and numerical homogenisation techniques for cases where no data is available for calibration. Where a model is unable to reproduce a phenomena which has been observed despite extensive testing of the model inputs, it will usually be because the model fundamentals (geometry, stress path, boundary conditions, material model) are not sufficient.

3 CRITERIA FOR INSTABILITY

The exact definition of instability as related to geotechnical problems is that under constant or reducing load, the part in question would experience indefinitely increasing deformations (Rose and Hungr 2007). This certain critical value at which any further increase, or a maintenance of loads would result in instability, is called the limit state, and the aim of forecasting is to identify what this limit value is and when it might occur. A second goal of stability forecasting is estimate the timing of failure.

Instability, defined as a condition of loads and velocity can differ from failure. A slope can be moving in an unstable way, at constant or varying velocity, over a period of time before the onset of failure, with the condition for instability being that rather than tending towards equilibrium (rest) in its current form, it will continue to displace. Failure on the other hand, is only said to occur once the slope collapses, or is so significantly changed that it can no longer be used as planned.

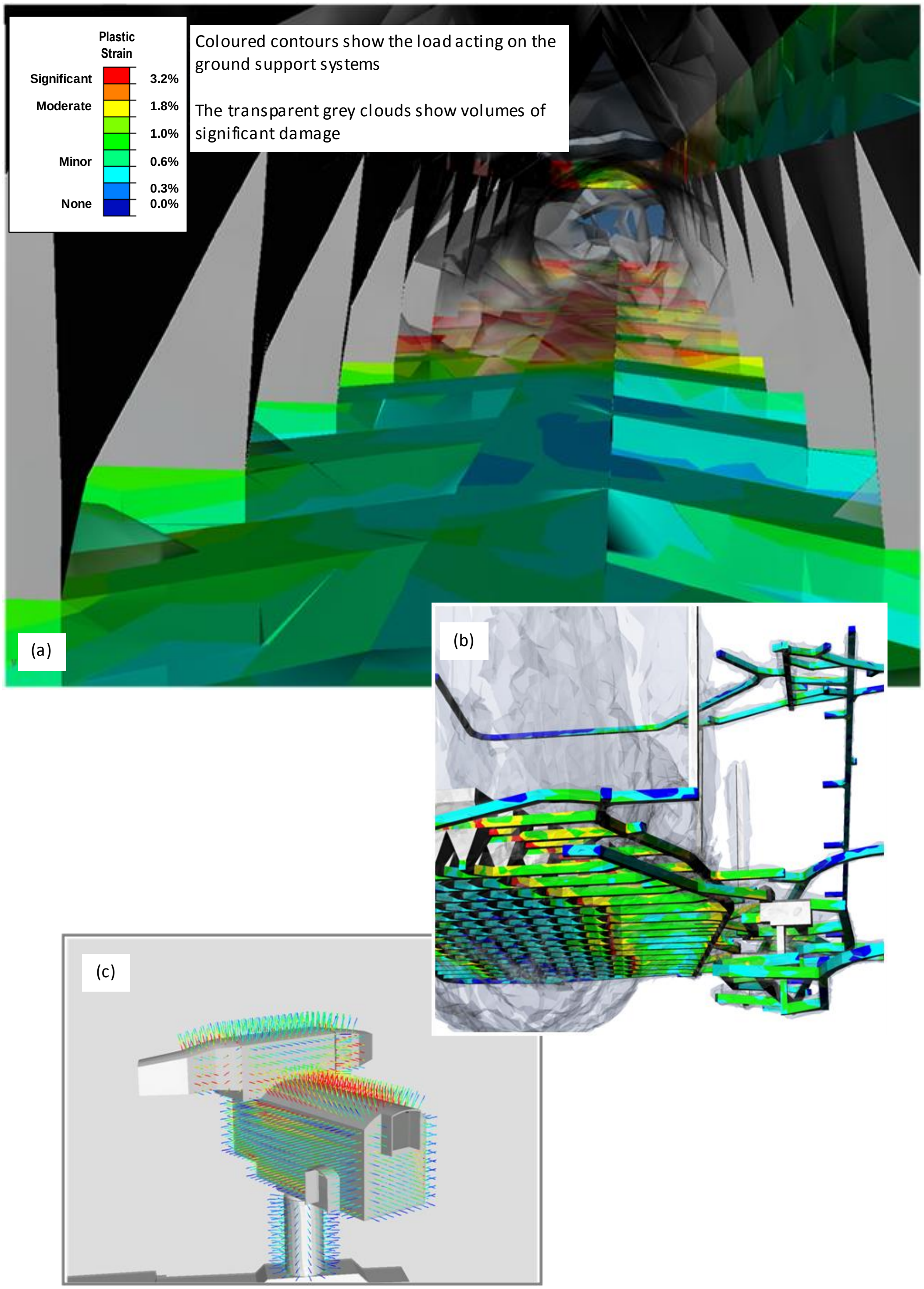


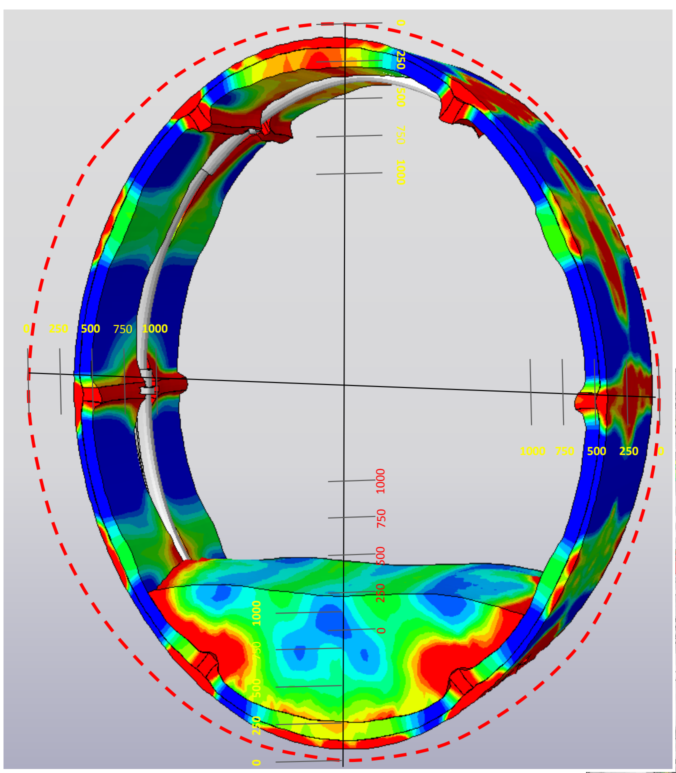
Fig 2 Modelled plastic strain and support load (a) inside a major apex in a block cave, (b) simulated in a life of mine, mine scale model and (c) loads in ground support in a partially coupled sub-model

If displacement realistic modelling is being used, the most useful criteria for stability will be plastic strain, velocity and displacement. A special case exists for ground support, where it is known support failure is likely to result in instability. In this case, support yield can be used to infer instability. Common to all of these is that a critical level for the instability criterion will be met, at which point deformation will continue to occur at constant or reducing load.

Plastic strain is a lower bound for instability, as yielded material is not necessarily kinematically able to behave in an unstable way, or it may be retained by support. For pillars, a critical level of plastic strain in the core would result in instability, while for other excavations, the depth and intensity of damage in a model would be compared to the capacity and geometry of the installed support to determine if the design capacity was likely to be exceeded.

Examples from multi-scale analysis at one mine are shown in Figure 2 after Beck (2008a).

In this model, documented more fully in Beck 2008, achieving a similar level of precision at each successive length-scale confirmed that the fundamental mechanisms of damage and deformation were captured. The Figure shows moderate plastic strain and support load used as criteria for stability for pillars in a major apex and for a major infrastructure excavation. In the case of the pillar, the presence of a level of plastic strain previously correlated with critical instability exists only around the margins of the pillar, indicating stability. Stability of the pillar does not preclude high deformation though, so support load is used to infer stability of the surrounding drives and some areas of excessive support load are indicated.



(i) Complete ovoid drive

(ii) Unexcavated floor

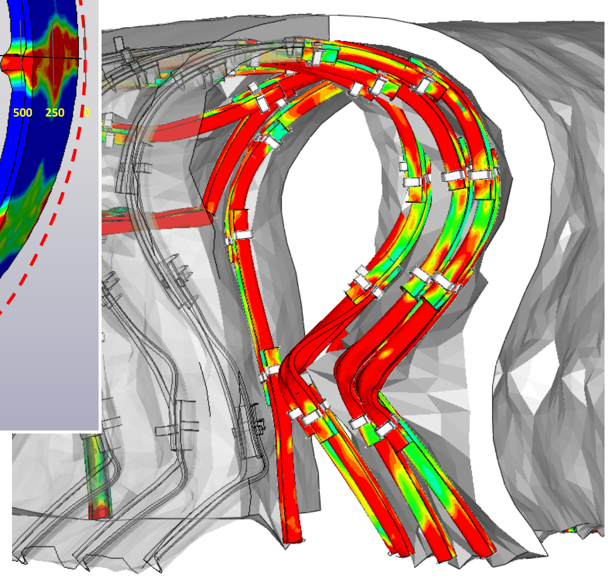


Figure 3 Comparison of high capacity support designs for the same location at the margins of a block cave. The criterion for drive stability here was buckling of the drive surface.

Another more detailed example of drive stability analysis is shown in Figure 3. These very detailed models compare high capacity support designs for the same location at the margins of a block cave. In one case a complete ovoid drive is simulated while in the other the floor is not excavated causing buckling of the yielding arches. The two designs were subjected to identical load conditions, and neither can prevent very significant drive closure, but for the complete ovoid drive, the deformation is managed by the preferable drive shape and yielding surface elements and arches.

This example shows how simply a proper criterion for drive stability can be realised once model similitude is achieved; the criterion for stability in the model would be the same as in practise at the mine.

For open pits, a significantly yielded material may be stable (ie, yielded but not necessarily unstable) so velocity and displacement criteria for stability must be considered as well. Velocity and Displacement are separate indicators of instability, but are both indicators that kinematic constraints for instability have been met and that material is 'actively' unstable.

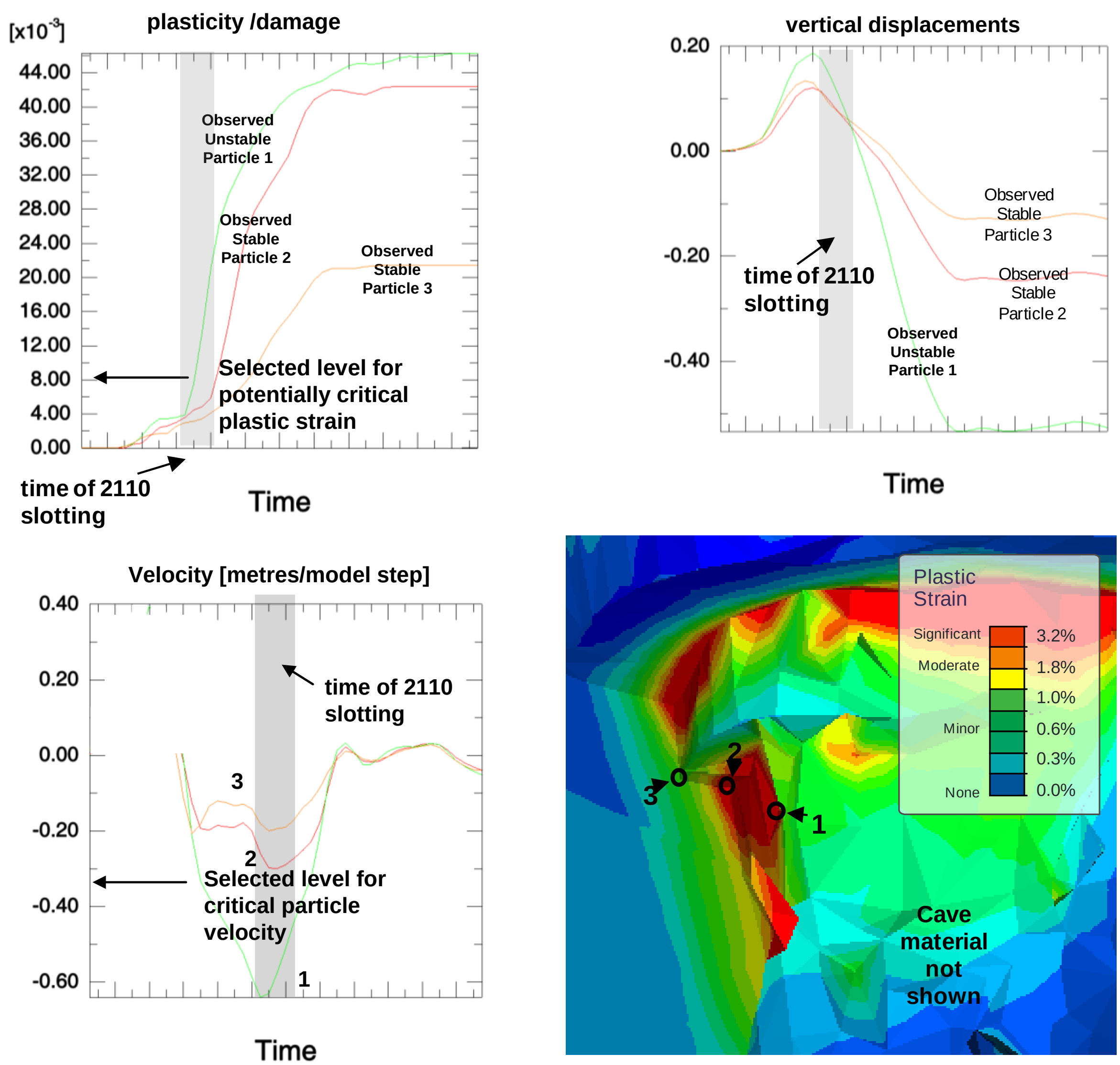


Figure 4 Analysis of stability indicators for a previous failure in the pit. Grey shaded bars indicate the timing of observed failure

Rose and Hungr (2007) describe the failure process for slopes:

- Stress relief associated with mining excavation leads to ground relaxation displacements that dissipate with time by a process that is often referred to as time-dependent deformation (stable deformation).
- As strain levels increase, strain softening may lead to plastic, non-recoverable deformation (the unstable phase) and progressive failure development (active failure).

An example of the assessment of indicators of instability, velocity, displacement and plastic strain at selected points on the underlying surface of a failure and within a failure are shown for a complete model time history in Figure 4. This example and the Figure are discussed in more detail in Beck 2008b.

It is very clear that prior to the failure there was a gradual increase in velocity in the model, which is a clear sign of instability. Around the time of failure there was rapid, step change in acceleration which continued to increase until complete failure.

The graph can thus be divided into 3 phases:

1) An unstable phase: during this phase velocity increases at a near constant rate, or is constant
2) Actively failing: during this phase there is an onset of more rapid accelerations up to failure
3) Failure: this phase is signified by collapse

During the actual failure, Particle 1 was observed to be part of a completely failed zone. It is rubbleised and had collapsed. Particle 2 was rubbleised at the time indicated in the model step in the Figure but had not collapsed and Particle 3 showed only damage and was not part of a collapse.

Interpretation of the velocity, plastic strain and movement indicators for stability for these three stability conditions for a number of failures suggested the appropriate levels of strain, displacement and velocity to use as boundaries for stability.

4 UNCERTAINTY AND PROBABILITY

Even if a model has been proven to have gained sufficient similitude by comparison of modelled and measured displacements there will still be uncertainty and variability.

A family of methods for quantifying uncertainty and estimating probability arising from variability are the Point Estimate Methods (PEMs). Using these methods, any model output can be simulated as a probabilistic range. The value of this is:

- error can be quantified,
- the unique range of conditions under which instability may occur can be identified in a more rigorous and quantifiable way than for discrete sensitivity analysis. Monitoring and measurement programs can target the factors that are most critical
- if the conditions for model sufficiency are met, a realistic estimate of probability is possible

Most PEM approaches are based on two-point estimates but references to third- and higher-order point estimates can be found in the literature such as in Harr (1989).

The Alternate PEM by Harr (1989), or APEM is a rapid means of evaluating the distribution of possible outcomes for a particular, quantitative performance indicator. Run on multiple computers, APEM for a mine scale, life of mine analysis such as this can be completed for complex mine scale problems in a few days, and this is the main benefit of this method. Practically, the approach of Harr is probably the only feasible method for producing a probabilistic estimate of the range of outcomes for a mine-scale problem.

Some examples of APEM results are presented in Figures 5, 6, 7 and 8:

- Figure 5 shows an estimate of cumulative unstable tonnes in the walls of an open pit undercut by an SLC. At this mine, discussed in more detail in Beck (2008b), the actual amount of over break at the end of mining was within about 10% that predicted by that mean scenario. The main value in this case was the reliability of the method. The criteria for sloughing were based on critical limits for plastic strain, velocity and displacement.
- Figure 6 is also from a pit slope. In this case it shows a deceleration and confirms the efficacy of major works to control movement in the slope. The criteria for stability was inverse velocity (see for example Hungr and Rose, 2007)
- Figure 7 (after Reusch et al, 2007) shows wall closure modelling for a crusher. It is clear in the graph that over time this particular excavation experiences significant deformation and towards the end the best and worst case wall closure estimates both reach significant levels. A particularly interesting feature is the step in deformation and the period of accelerated movement in year 3. The step is reflected in all scenarios used to compile the probabilistic estimate, so it is clear it is a geometric issue. APEM often highlights these types of 'inevitable' problem, where only a re-design might influence the result. In this case the criterion was closure, as this can be related to a range of adverse outcomes for a crusher.
- Figure 8 shows an APEM estimate of ranges for deflection in a shaft. Shafts require detailed assessment using a number of criteria, but deflection is a first pass indicator for certain problems. A more detailed discussion of shaft stability criteria can be found in Reusch et al 2007.

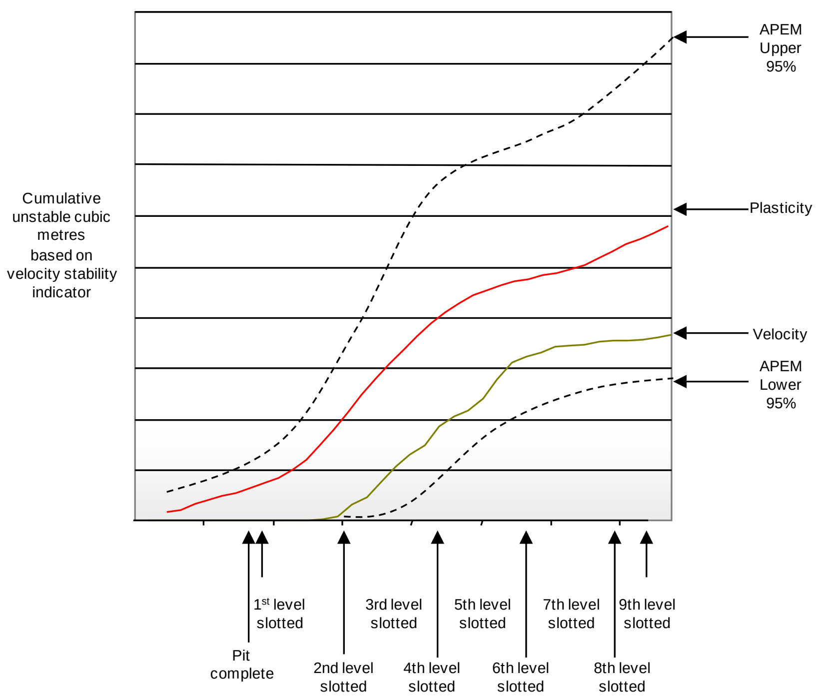


Figure 5 Range of estimates for waste ingress versus time for an SLC under a pit

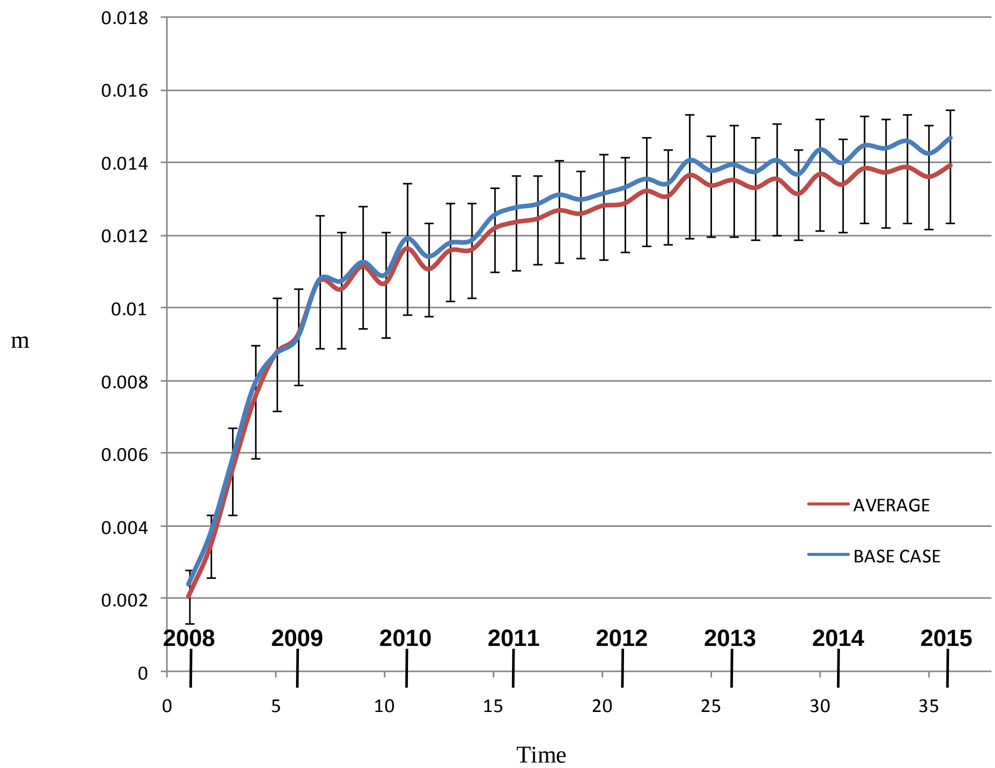


Figure 6 APEM estimate of slope movement

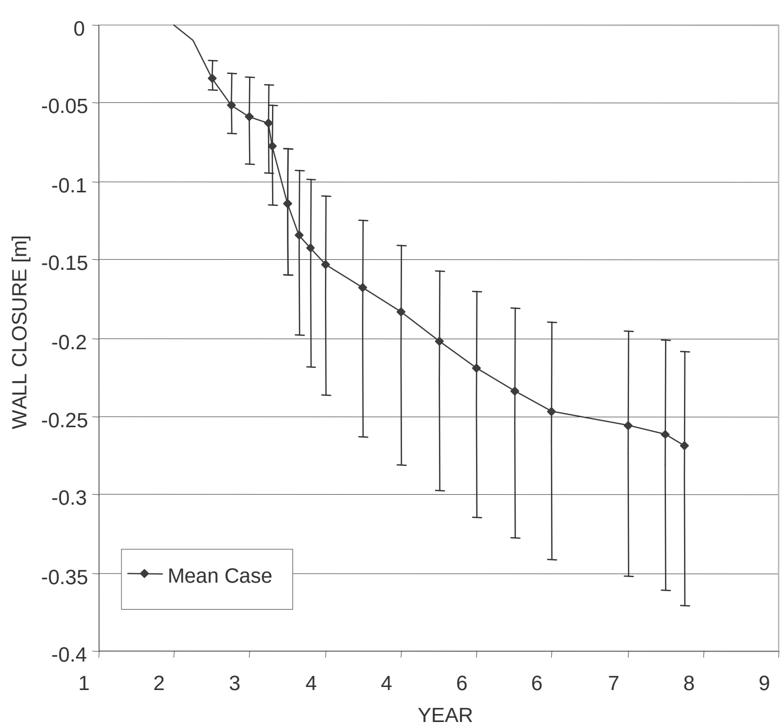


Figure 7 Model based probabilistic estimates of wall closure versus time for a large crusher (after Beck, 2007)

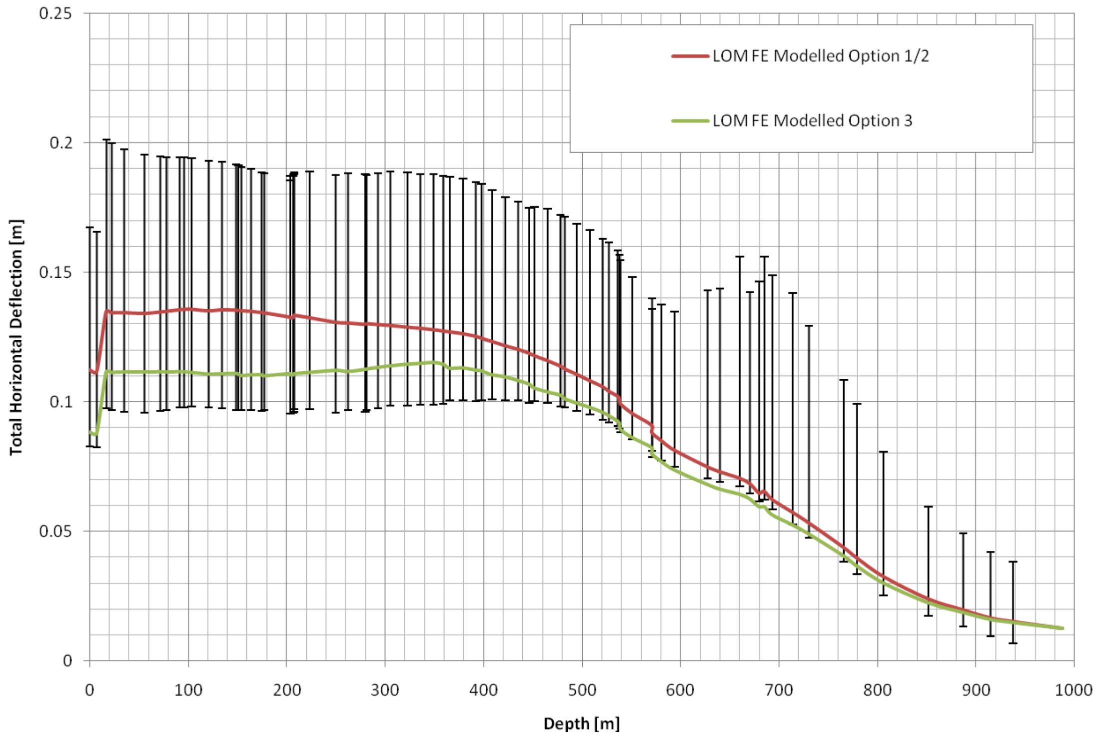


Figure 8 APEM estimate of ranges for horizontal deflection of a shaft

5 CONCLUSIONS

Probabilistic estimates of excavation performance should eventually become a minimum standard for assessment of stability for mines.

Key to this is adequate numerical simulation, with the measure of sufficiency being the attainment of similitude with the problem, measured by the ability of the model to match measured displacements. Not only does this allow confidence in the model results, it facilitates the use of common-sense, practical criteria for interpreting the analysis.

Setting higher engineering standards for numerical modelling of mine stability will lead to better performing and safer mines.

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