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Using observations and measurements to establish a relation between modelled movement and Probability of Failure in a large open pit

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Abstract

In late 2021, the potential to extend a very large open pit was investigated. The mine has a high-resolution structural and hydrogeological model, permitting construction of a large-strain, discontinuum, closely coupled hydromechanical finite element model with a much better than inter-ramp scale representative elementary volume. In models of this type, the hydrogeological parameters and constitutive model are also non-linear, so that conductivity and the Biot coefficient are expressed as functions of the modelled plastic strain tensor.

Additionally, because extreme seasonal variations occur in surface water flows, the models included simulation of the flow of near-surface water and a novel method for capturing the inflow of this water into the dilated rock mass, joints and faults, thus permitting estimation of active water pressure. Active water pressure in the damaged and dilated rock mass and rock mass defects is a major driver of instability in slopes, but it is not often simulated, especially in models of this scale (30 pit stages, over 100M degrees of freedom).

The addition of this mechanism for water-driven instability and the high-resolution model setup permitted very close calibration of modelled and measured movements, enabled measurement of hydraulic head and failures using many years of data, and facilitated a statistical analysis of the correlation of failure and modelled movement and strain. This was undertaken using a cell evaluation method (CEM; Beck & Brady 2001), resulting in a true probability function using model outputs with an estimate of error and resolution.

The CEM has previously been used to compute the relation between seismic event probability and stress and energy criteria for underground mines, but this is the first known use of its application for an open pit.

The project resulted in a comprehensive validation of the model for the mine, a useable probabilistic criterion for slope failures ranging from small to medium, and a hypothesis ranging from the extrapolation of early slope stability data to the prediction of larger failures. There are also lessons regarding the necessary resolution of hydromechanical assumptions and inputs for high-quality prediction of slope instability, particularly the need to capture the influence of rock mass and rock defect dilation and degradation on flow and pressure.

Keywords: *feasibility study, large open pit slope, hydromechanical coupling, non-linear model, open pit stage, Probability of Failure, active pressure, Factor of Safety, slope failure, pore pressure, near-surface hydrology, LR4, freeze thaw, melt water*

1 Introduction

An essential task of open pit slope design is to achieve a sufficiently low Probability of Failure (PoF), estimated by reliable means. Whether empirical, limit equilibrium or numerical, the forecast relies on models capturing the ‘coupling’ or connectedness of factors affecting strain in the slope: stress, strain, strength, structure, water and the staged slope geometries.

Common sense implies that the choice and composition of model and the target resolution will be governed by the situation. To be fit for purpose, a model must not only simply incorporate geological information in the form of constituent materials and rock mass defects spanning from greater than slope scale to smaller than the length scale of interest but also sufficiently incorporate transient effects of water at every stage, and it must include the stages of excavation with the ultimate effect of sufficiently replicating the pattern of strain. If, for example, a model does not sufficiently capture rock mass defects at a small enough scale, it will be invalid.

For a large slope of great value, sufficient inter-ramp scale models are 3D, necessarily large-strain, discontinuum, strain softening and anisotropic where applicable, and should represent joint sets and other rock mass defects explicitly and consistently at scales from smaller than inter-ramp to larger than pit scale. A discrete fracture network (DFN) will usually be employed to represent all the major joint sets.

It is also strongly implied by observations of the timing of failures that water flowing over or near the surface from any source can enter dilated zones and defects in the slope, resulting in high ‘active water pressure’, driving potential instability, and that as most effects of water on slope stability are localised around the defects that carry the most water, flow-on defects should be simulated.

In 2021, this standard was employed for life-of-mine stability analysis at a very large open pit, resulting in a significant improvement in similitude between modelled and measured displacements and instability and between modelled and measured water pressures.

Significant features of the model, compared to old workflows, include:

- All major joint sets were included in the model explicitly. Previous models by consultants included just one joint set per model.
- Simulation of near-surface water via application of representative flux at surface approximating the spatial and temporal patterns described by the mine’s hydrologists.
- A two-way close hydromechanical coupling of the hydraulic conductivity and the Biot coefficient as a function of the induced plastic strain in the constitutive model to simulate the mechanical effects of ingress of preferential ingress of water into the dilated and degraded rock mass and along rock mass defects.
- An additional critical ingredient for the results interpretation was the elimination of excessive elastic rebound from the model results. In most historical numerical models of large open pits, unrealistic elastic rebound confounds the use of conventional instability criteria, preventing reliable interpretation of the model results. This is a major problem confronting the use of most models of pits that is almost never discussed, but has been solved in models of the type described here.

2 Model details

LR4, coupled hydromechanical, discontinuum, explicit finite element models, as described in Levkovitch et al. (2010), were used in this project. Key features of LR4 are significant computational capacity that enables incorporation of complex DFNs and structural models, and non-linear hydromechanical coupling. This means that that for rock mass and discontinuities across all relevant length scales, the hydraulic conductivity and the Biot coefficient are expressed as functions of the modelled plastic strain tensor. Run as a multi-step simulation, coupled with simulation of the surface flow and fault flow, the LR4 model forecasts the active pressurisation of dilated and damaged rock due to the ingress of water.

Other model features essential for high similitude with this environment were:

1. The model was regional in scale: >15 km × 15–20 km × 5 km deep and used higher-order elements throughout. Higher-order elements are critical to efficiently simulate high gradients of strain.
2. A large-strain, strain softening dilatant material model with a 3D Hoek–Brown yield criterion for the rock mass and Mohr–Coulomb for dumps, soils and narrow rock mass defects was used (Levkovitch et al. 2010).
3. The model used 347 regional faults and a DFN with over 4,000 discrete fracture surfaces built explicitly, spanning regional to multiple bench scales (Figures 1 and 2) plus anisotropy to reflect bedding and foliation. All discrete structures were active as discrete flow paths for the hydromechanical modelling process. Foliation was simulated by defining anisotropic properties for the rock mass domains. We note that this simulation incorporated orders of magnitude more structural defects than is included in typical large models of pits.
4. The DFN and foliation orientations vary on a node-by-node (sub-element) basis according to a 3D joint set block model.
5. The open pits were excavated, and dumps emplaced in the model in >30 stages. Small excavation increments in the model are essential to capture the stress path in the slope. The comparatively large number of pit shells also permits the model results to be compared to the maximum possible number of observations.
6. Other than the non-linear implementation of hydrological properties, we used the internal and external boundary conditions from the mine's hydrological model (conceptual details provided in Figure 3).

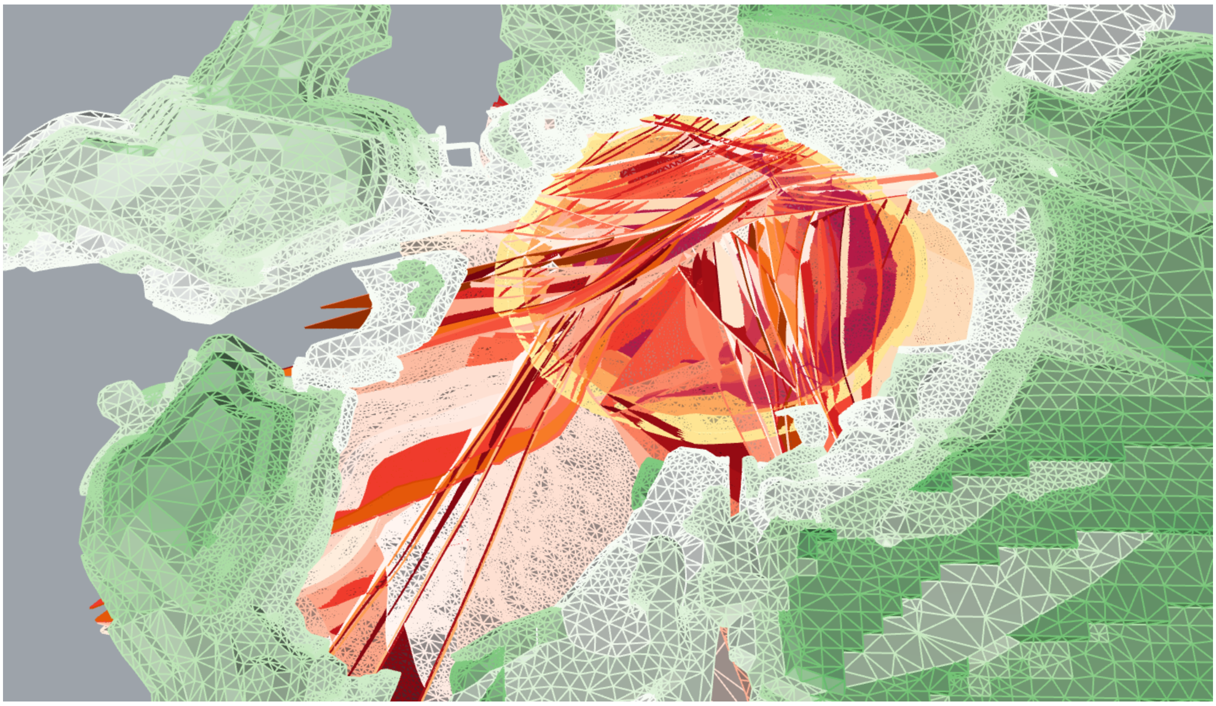

Figure 1 Major faults and dumps as built in the model for one of the projects sites

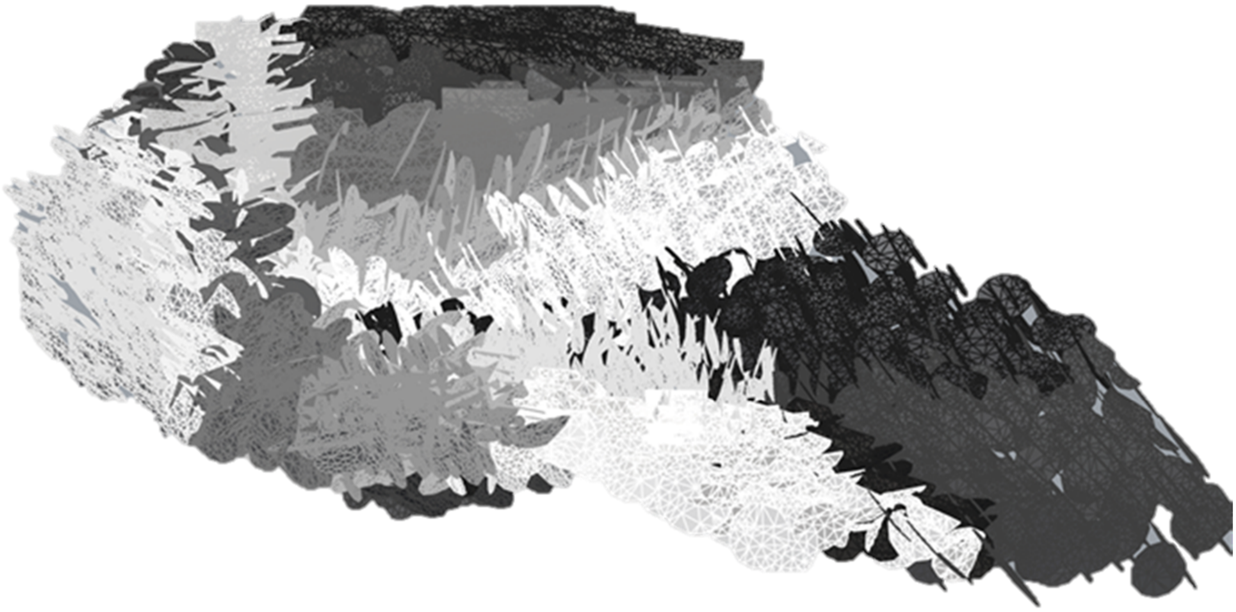

Figure 2 As-built DFN for one of the project sites

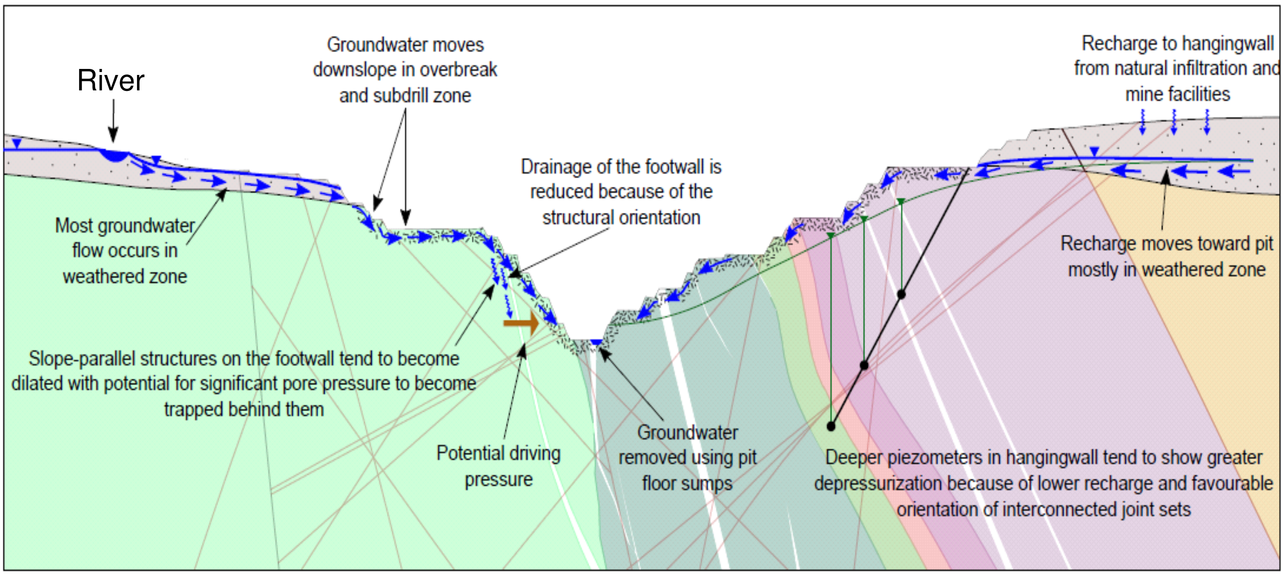

Figure 3 Example conceptual hydrological model for one of the mines, provided by the mine's expert hydrological consultants (Piteau Associates 2022)

The resulting model size and performance statistics for the model were as follows:

- 10,704,213 × 10-node higher-order tetrahedral elements.
- 9,806,660 cohesive elements to model fractures and faults.
- 91,107,075 solution variables (degrees of freedom plus Lagrangian multiplier variables).
- Same spatial resolution throughout the coupled hydromechanical modelling (i.e. no loss in accuracy between mechanical and hydrological data transfer for coupling).
- Model run times of approximately three days.

3 Close, non-linear hydromechanical coupling

Suvorov & Selvadurai (2019) investigated the influence of the development of elasto-plastic yield on the evolution of the Biot coefficient by comparison of numerical models with observations and analytical solutions, and we implemented a similar, close two-way non-linear coupling as a feature for the rock mass and all rock mass defects, including the DFN. This means that effect of damage and dilation on the hydrogeological properties of the rock mass is simulated, and the relevant functions and variables can be calibrated. Further, the simulation of surface flow coupled with this implementation means transient hazards and cumulative effects from seasonal, active water pressures can be captured.

To do this, we applied the initially undisturbed hydrological domains, hydraulic properties and boundary conditions as provided, but these are expressed as functions of damage (inelastic strain) and dilation. For example, the damage-dependent hydraulic conductivity function is expressed as exponential relation proposed by Rutqvist et al. (2009), motivated by work from Mahyari & Selvadurai (1998) and Shirazi & Selvadurai (2005), rewritten as:

$$K_w(d_{rm}) = K_{w0} \cdot \exp\{A_w \cdot d_{rm}\} \leq K_{wmax} \tag{1}$$

where K_{w0} is the undamaged hydraulic conductivity, K_{wmax} is the hydraulic conductivity once the material is fully degenerated and d_{rm} is a logarithmic rock mass damage quantity of the equivalent plastic strain.

$$d_{rm} = \log\left(1000.\cdot \varepsilon_p + 1.\right) \tag{2}$$

For any degraded material, the parameter A_w then follows to be $A_w = \ln\,(K_{wmax}/K_{w0})/1.71$. This relation has been described further in Flatten & Beck (2015) and verified via simulations related to field and laboratory observations in Flatten et al. (2016). Moreover, the far field and surface recharge boundary conditions were applied as provided with recharge fluxes (e.g. Figure 3) according to measured data and advice from the mine's hydrological team based on measurement and analysis. Vice versa, the computed porewater pressures $p_w$are considered in the mechanical constitutive equations via Terzaghi's effective stress concept:

$$\sigma_{eff} = \sigma + \alpha_B p_w 1 \tag{3}$$

where σ and σ_{eff} are the total and effective stress tensors respectively, and α_B is the Biot coefficient and 1 being the unit tensor.

The Biot coefficient is implemented as piecewise linearly varying parameter depending on ε_p:

$$\alpha_B(\varepsilon_p) = \text{LinearInterpolation}\left[(\varepsilon_{p0}, \alpha_{B0}); (\varepsilon_{p1}, \alpha_{B1}); \ldots\right] \tag{4}$$

and here, in particular for this project due to the considerations mentioned before, we utilised the ramping function:

$$\alpha_B(\varepsilon_p) = 1.0 \cdot \min\left(1.0;\ \max\left(0.0; \frac{\varepsilon_p - \varepsilon_{p0}}{\varepsilon_{p1} - \varepsilon_{p0}}\right)\right) \tag{5}$$

where we calibrated the plastic strain values ε_{p0} and ε_{p1} to be small values of 0.01% and 0.50%, respectively. Naturally, these values may vary by domain, and this will take place in future, improved versions of the model. For now, we found this simple implementation resulted in significantly better similitude.

The main benefit of the close non-linear coupling for this project was the ability to capture high near-surface pressures, which are 'lost' when mapping porewater pressures from a coarser hydrological model, as is the most common practice for hydromechanical modelling of slopes. The closer, non-linear coupling in LR4 avoids the non-conservative over-draining that occurs in such models and permits the testing of efficacy of dewatering strategies with higher confidence.

For this project, where applicable, we simulated the planned dewatering holes explicitly, scheduled when they would be implemented step by step to match the staged impact of the program (see for example, Figure 4 from an adjacent mine using the same LR4 model setup). This detailed approach to simulation of dewatering captures the variable performance of the holes across the sectors, permits closer calibration by evolving pathways in the model that can be compared to measurements and observations, and avoids over estimation of the performance of drainage.

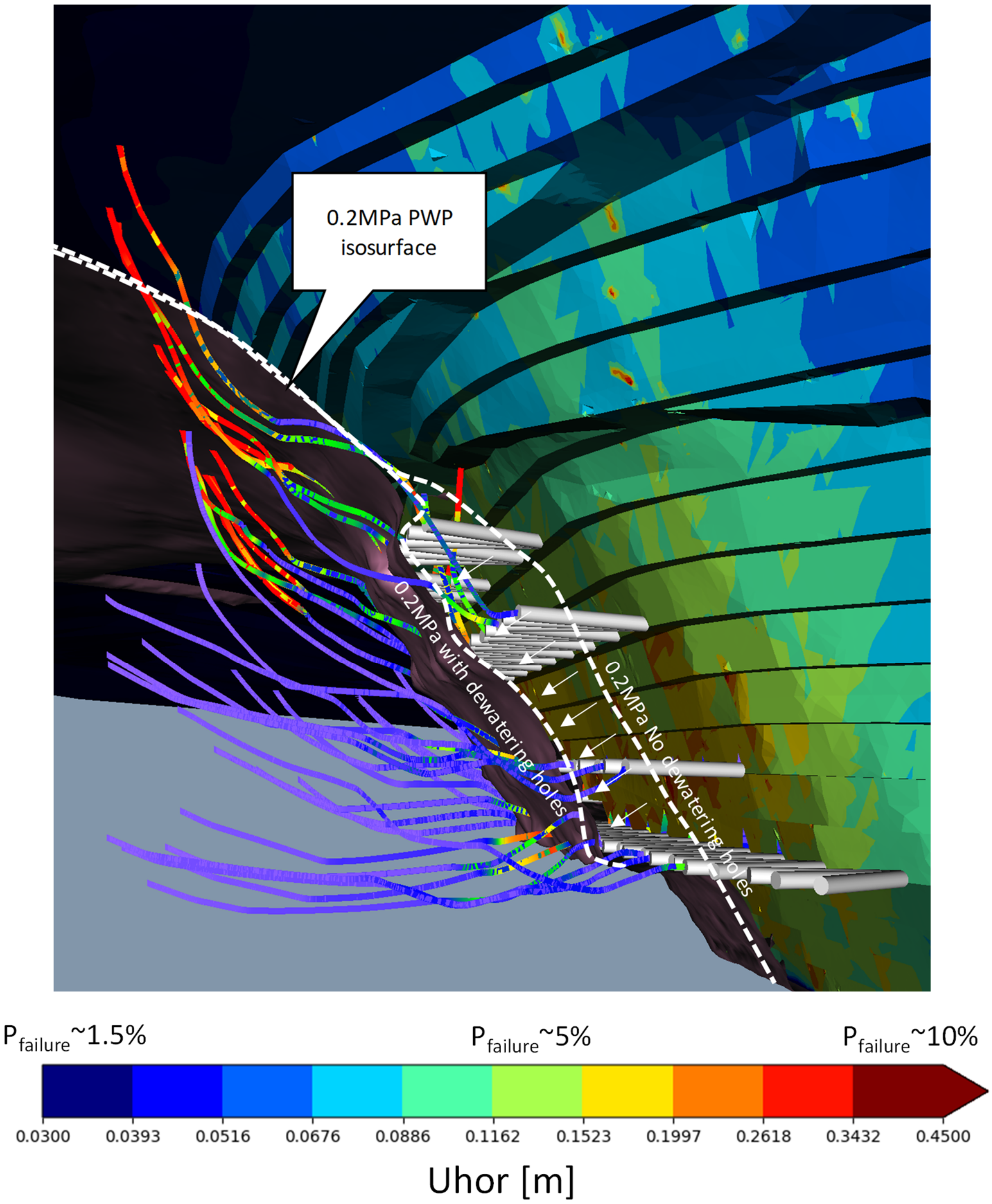

Figure 4 Simulation of explicit dewatering holes for an adjacent mine using the same LR4 model setup and resolution. The flux lines show the simulated source of water recovered from the drain holes

4 Calibration and material property estimation

The first step for estimation of material properties was classification of the various geotechnical domains, considering lithology, alteration and rock mass quality by the mine's geological and geotechnical teams. This comprises significant effort including detailed exploration and geological interpretation with the goal of differentiating rational geotechnical domains with a much smaller than precinct scale (e.g. multi-bench ~50–70 m persistence in this case) resolution. Combined with the DFN, the resolution of the geotechnical domains is a limit on the resolution of any model, and determines the representative elementary volume (REV).

The REV is length scale below which defects and heterogeneity are 'smeared' into a homogenised representation, and is typically described by smallest structures included in the model or the largest defect that is not explicitly represented. Every model has an underlying REV determined by data in this fashion, and this is the length scale for which material properties must be estimated. In this case, the REVs were between 30 m and 75 m, which is greater than the scale targeted by common empirical schemes like the tunnel-face scale Hoek–Brown (HB) geological strength index (GSI) scheme.

The only applicable empirical scaling tool developed for LR4 models is after Beck et al. (2013). This scheme was originally developed using comparisons of successful model inputs and classifications and measured strengths to estimate yield criteria, plastic strain potential and softening rules, but is being extended via projects like that described here to include the inputs for non-linear hydrological models. It is also worth noting that many very coarse models with much larger REVs than the present study do use the HB GSI scheme, which surely results in a poor fit.

We then simulated the past mining and compared modelled pore pressures, displacements and signs of instability to the surveyed data comprising a mix of recorded failures, radar movements and piezometer data, targeting a like-for-like comparison without application of multiplicative factors (i.e. metres = metres, Pascals = Pascals). Where there was a substantive mismatch, we adjusted the inputs for the relevant domain or structures, especially focusing on metre-for-metre comparisons of prisms, radar and InSAR as well as the fit of measured failures to instabilities that emerged in the model and re-ran the simulation.

This process of testing and adjusting inputs was repeated several times for each mine, following these essential rules:

- The rational geotechnical domains classified by the geology teams are indivisible. For example, if we make an adjustment in any area of a domain, the same changes will be reflected throughout the domain. It is not permissible to change properties to replicate a failure that are not carried throughout all the similarly classified areas of the model.
- As we wish to describe the connectedness between areas the modelled displacements and loads must be realistic. For example, it is not permissible to scale modelled displacements by a factor.
- The model used for forecasting must have the same features as the model used for calibration, and in this case, a single multi-stage model was used for each mine.

Example comparisons of modelled and measured movement data for one mine are shown in Figures 5–10, where the indicated movements are horizontal, inwards movement (UHor [m]). There were also numerous explicit comparisons of important failure events in the model (e.g. Figures 6–9), including some with very good piezometer coverage. These indicated the model can reliably replicate most failures or indicate high risk factors were present. The back-analysis also implied a strong correlation between many failures and significant gradients in porewater pressure across known major rock mass defects, suggesting high water pressure on rock mass defects as a significant causal factor.

An example known problem area where near-surface seasonal water flow was suspected as a contributing cause of past problems is shown in Figures 8 and 9, which also show 'mechanically acting', or 'active', pore pressure, $\alpha_B p_w$, in the model. A corresponding mechanism for high active water pressure occurs near the surface where water enters cracks and damaged rock, and LR4's ability to capture this was critical in matching the pattern of failures. The improved resolution of the LR4 models with this unique feature supports the hypothesis that some of the very high measured pressures and gradients at the mine are due to the ingress of surface water into the network of faults, aided by dilation at surface and it supports the need to capture this mechanism in models for large slopes generally.

The correlation is strong enough to suggest that the mechanism of surface ingress into damaged and dilated zones should be captured in stability forecasting wherever the mechanism is applicable.

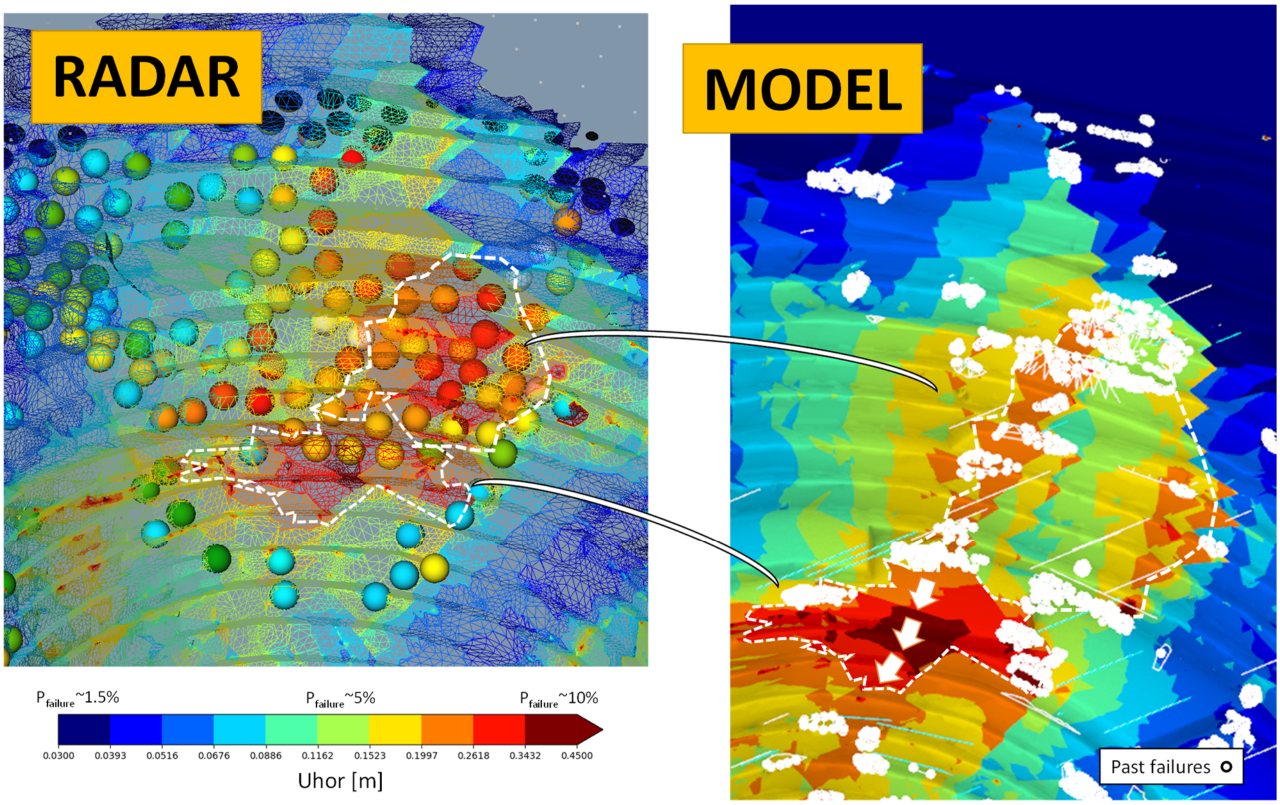

Figure 5 Comparison of modelled horizontal displacements, radar trends and measured failures

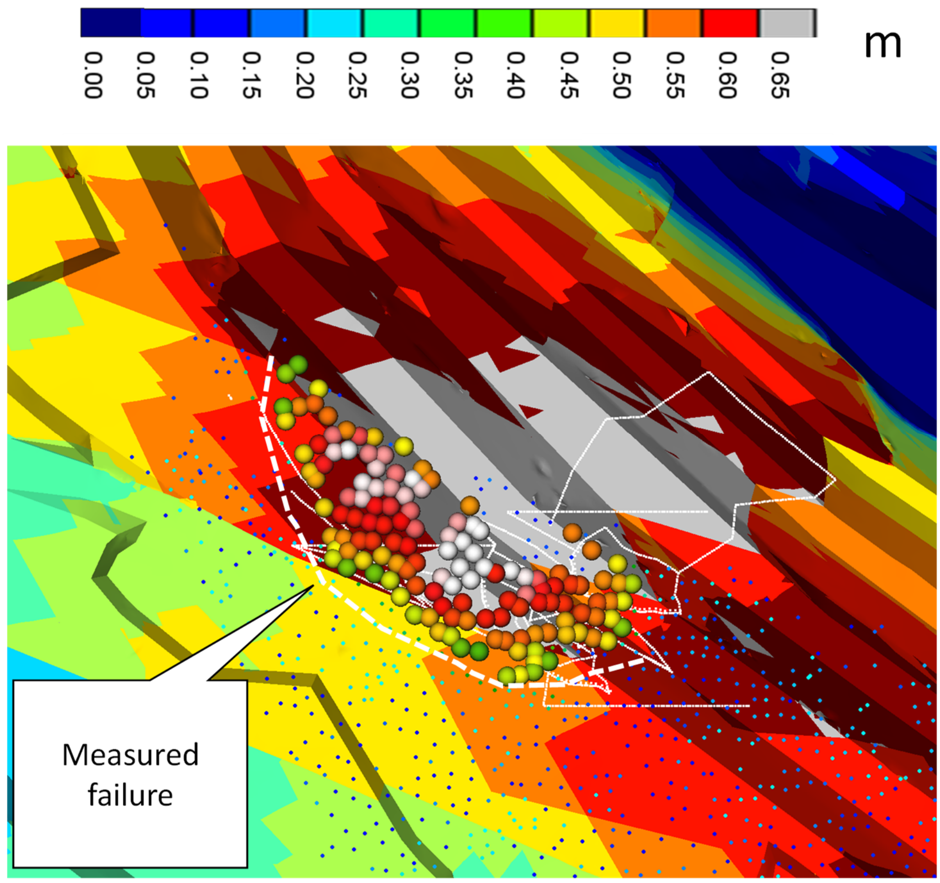

Figure 6 Comparison of modelled and radar measured displacements (spheres and dots) in the vicinity of a failure

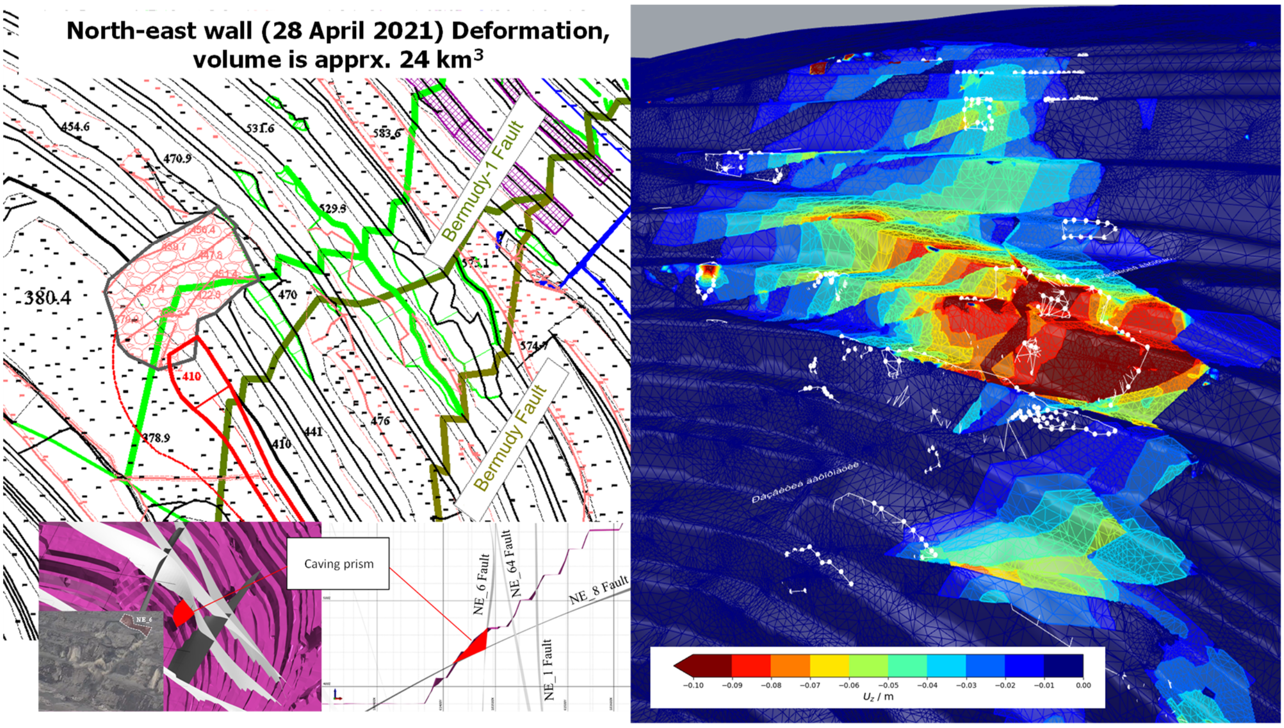

Figure 7 Comparison of simulated rock mass damage and a wall failure. The white dots indicate the extent of the measured instability

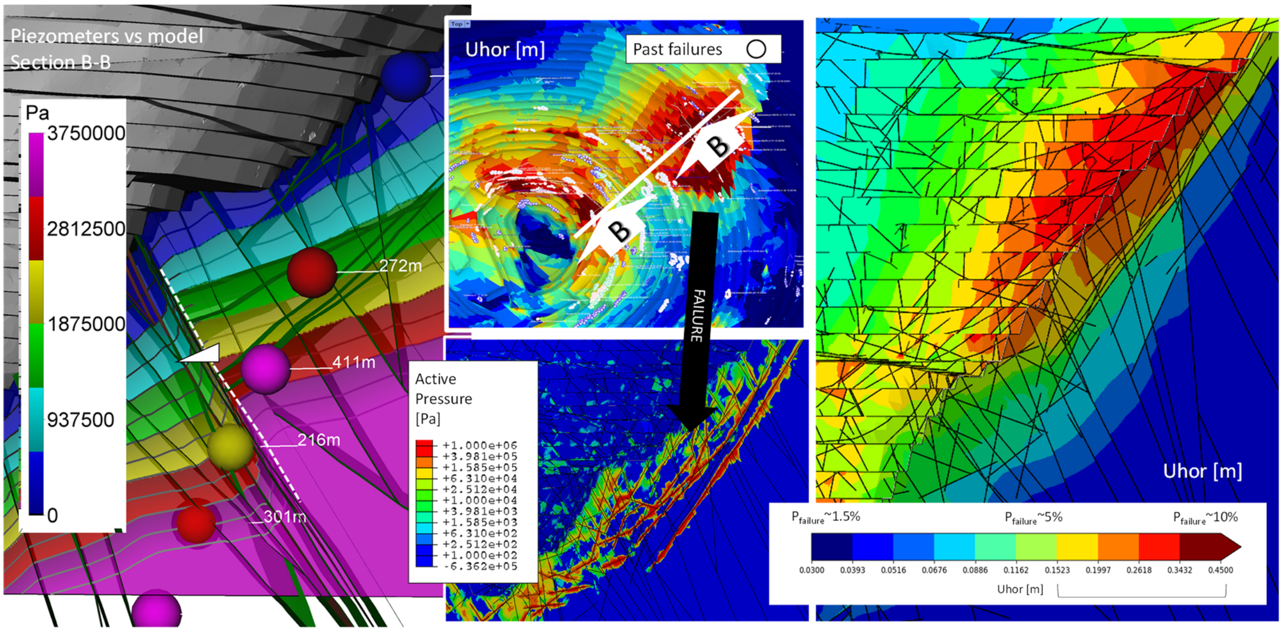

Figure 8 Measured and modelled porewater pressure and failure and simulated active water pressure

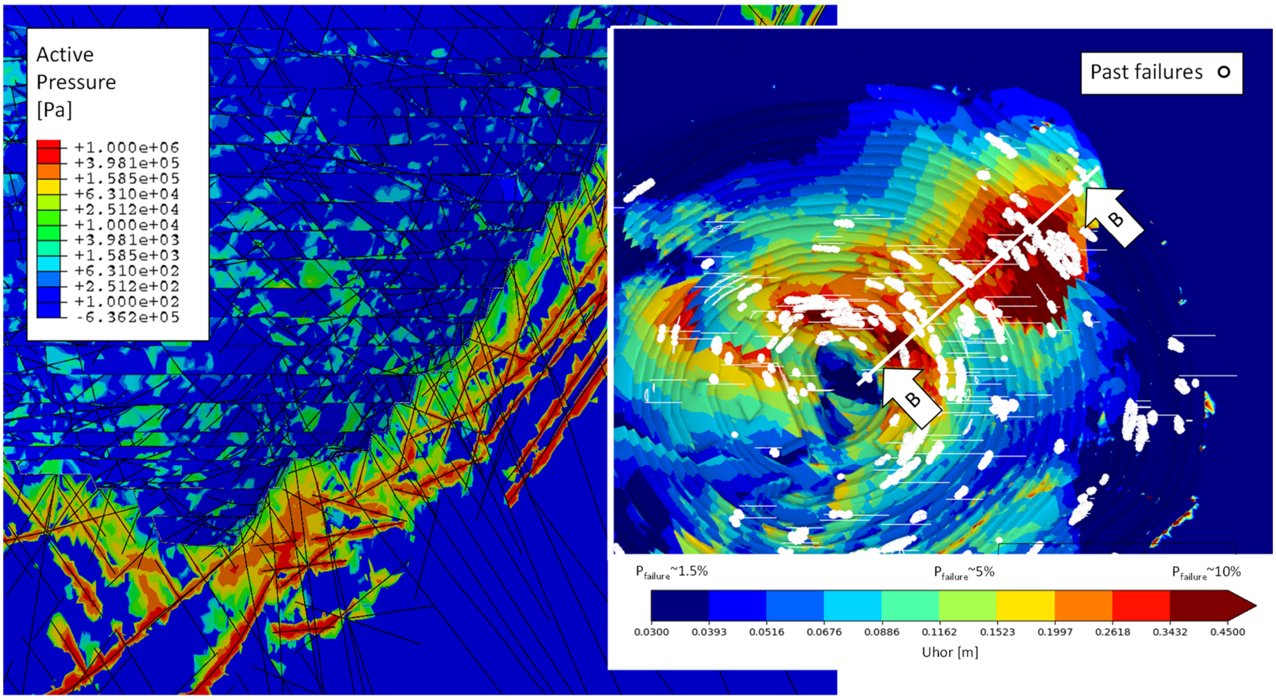

Figure 9 Active pressure, modelled horizontal displacement and past failures

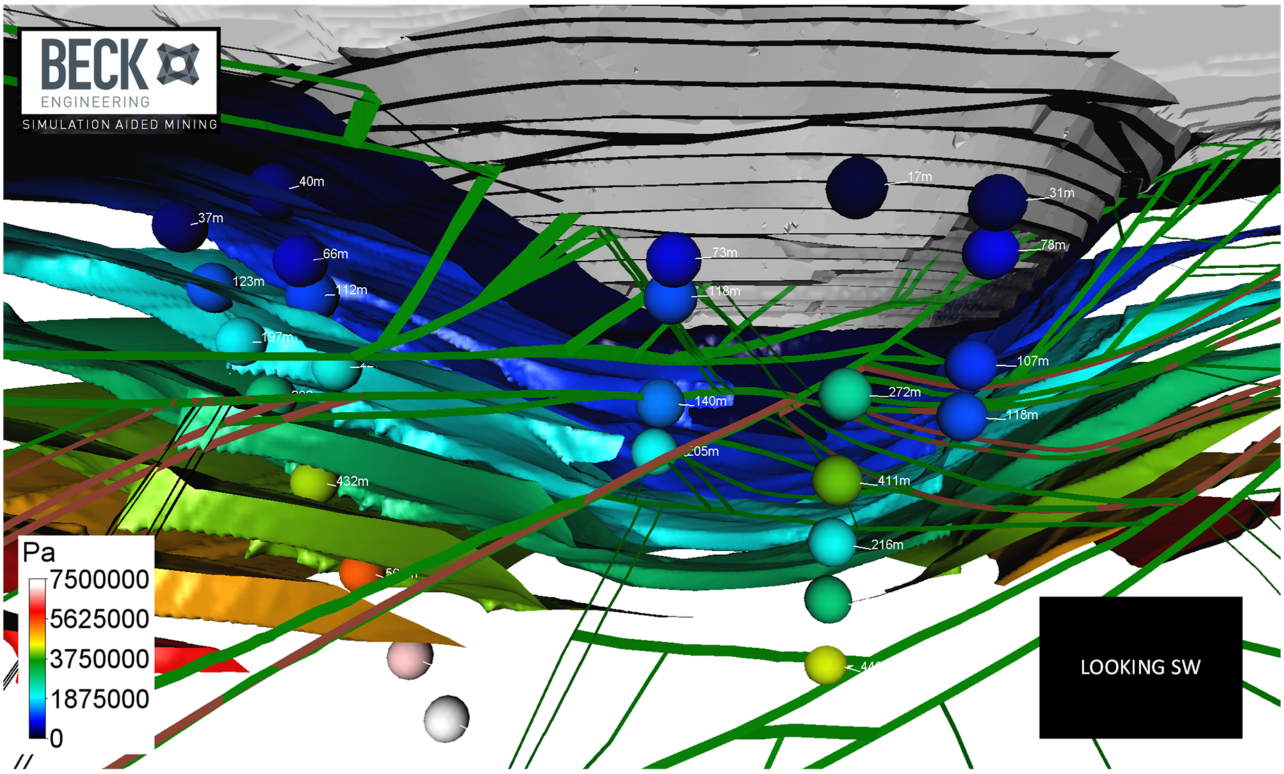

Figure 10 Example correlation between modelled porewater pressure and piezometer reading

5 Correlation between PoF and measured movements

For this project, we measured model reliability by systematically comparing the frequency of past failures to model outputs, using the cell evaluation method (CEM) outlined by Beck & Brady (2001). The technique is described fully elsewhere, but in summary, this technique divides the modelled volume into cells on a regular grid. Since there is a measure of failure or non-failure and a model result forecast for every cell in the grid, the probabilistic relation between measured failure and any modelled output can be computed by comparing the number of failures versus non-failures for every range of the modelled output.

The CEM has previously been used to compute the probabilistic relationship between measured seismic event occurrence and modelled stress and energy criteria for underground mines, but this is the first known application for an open pit.

An example correlation between past failures and UHor (m) in one of the models to establish PoF is shown in Figure 11. It shows that at this example mine, there is a rapid rise above 10–15% PoF for cells at UHor > 0.35 m trending above 20% per cell at >0.45 m. The PoF per cell, measured by comparing modelled movement and measured failures, approaches 0% at 0 m, showing that modelled horizontal movements differentiate zones with frequent failures from zones with low occurrences of instability as required.

After comparison of the movements, probabilities and past experiences we developed added guidance on the use of PoF for the mines in keeping with the legislated requirements for the relevant jurisdiction which is similar to others where regulators impose guidelines. Referencing the various categories of action in Figure 11:

- Manage:
  - The occurrence of failure is low in areas with this level of movement, but failures will still occur from time to time. The end user will observationally manage residual risk.
- Investigate:
  - At an intermediate level of movement, the level of risk is high enough to warrant more detailed investigation to estimate a course of action. Re-design may be required, or observational management may be appropriate, depending on the situation.
- Modify – tolerances significantly exceeded:
  - The occurrence of failure is high enough to warrant improvements to the design, even though not all areas with this degree of movement will fail.

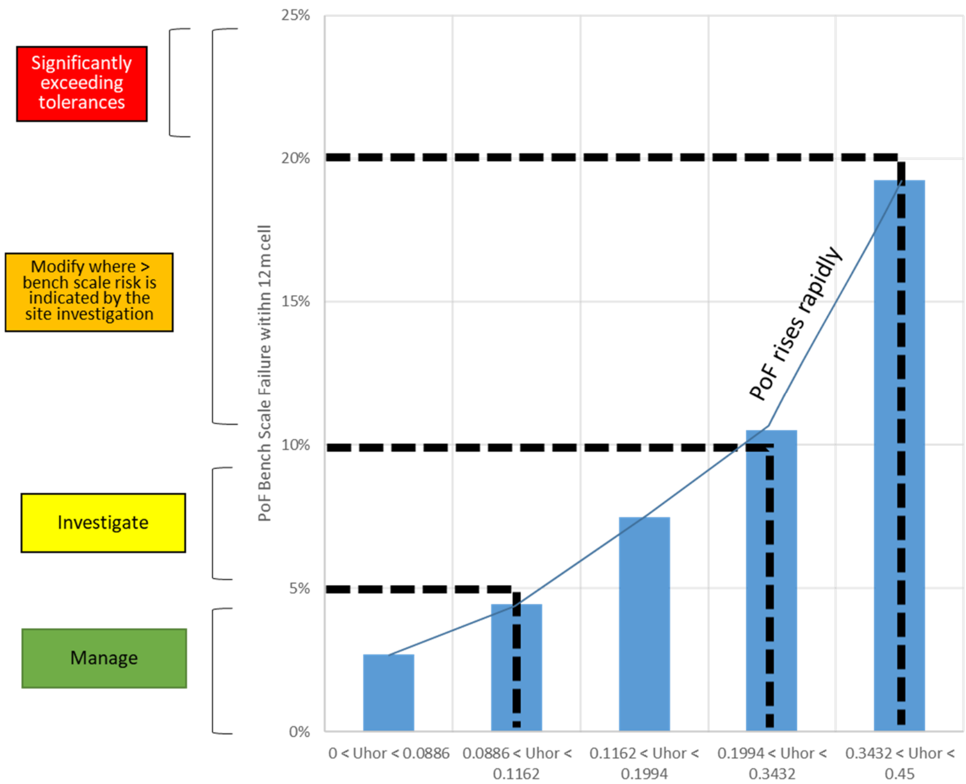

Figure 11 Relation between PoF and modelled horizontal movement at one of the mines in this study

It is important to note that the past failures recorded at the mines were mostly small so to assist with extending the relationship to estimation of the likelihood of larger failures, we considered the distribution of the size of measured failures as shown in Figure 12 at one of the mines. This is only possible because the mine systematically records virtually all bench- and larger-scale stability problems.

The y-axis of the graph shows the fraction of failures exceeding each size range (e.g. normalised for total number of failures, so the y-axis range is one for 100% exceeding, to 0.001 for 1/1,000 failures exceeding). The data suggests a scalable logarithmic distribution for failure size, which is a common feature of many types of instability in natural systems, including natural and induced earthquakes. It has also been observed in fall-of-ground data at large mines by some of the authors of this paper.

It is hypothesised that in such systems, as the 'driving forces' increase (e.g. as the slope lengthens), the exposure to factors necessary for large 'events' emerges and the likelihood of a 'maximum' failure increases. Another feature of such systems is that the early data, projected as shown in Figure 12 is a reasonable guide to the eventual largest 'event'.

The suggestion for a distribution of this kind favours the hypothesis that the PoF correlation can be extended, and the UHor criteria can be used to identify potential for large failures without undue conservatism. If so, the probabilities forecast in individual cells can potentially be integrated to assess a potential failure population, and therefore the likelihood of events of different sizes. This element of the study is ongoing.

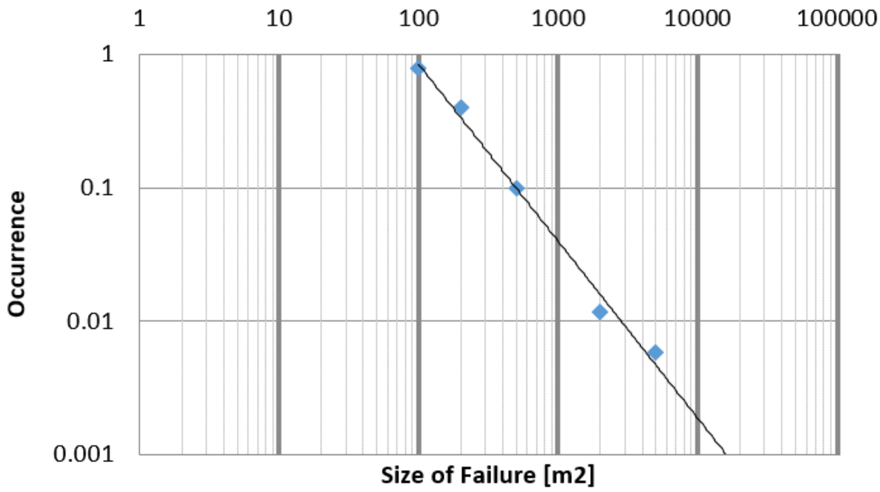

Figure 12 Distribution of measured failure sizes. The 'occurrence' is the fraction of measured failure events exceeding the indicated size. The minimum event size recorded is 100 m^2

6 Conclusion

The purpose of this work was to evaluate the potential for instability for a number of deepened pits. We did this by calibrating an LR4 non-linear, hydromechanically coupled discontinuum model to replicate the nature of deformation and failure, and then by simulating the mine plans in small mining steps. This permitted assessment of the evolution of deformation at intermediate stages to validate the model and appreciate hazards.

We found that without explicit simulation of the rock mass defects to much smaller than inter-ramp scale, including all major joint sets, and without simulation of near-surface water, the correlation between modelled and measured data was poor. Unfortunately, most mine models do not include this combination of information and model features.

With these features, the match to movement, failures and piezometric measurements was very good, and we could define a statistical correlation between modelled movement and measured failures. This is an indication that in similar environments, mines should be similarly hydromechanically coupled, and include at least a similar resolution of rock mass defect information.

6.1 Other lessons

The models use between 100M and 155M degrees of freedom and are probably the largest models ever built for a mine.

To simulate over 40 pit stages in each model requires significant computing power and several days of model run time. As such, the models are a significant investment on top of the massive effort needed to develop best-practice geological and hydrological models.

Key findings from the back-analysis and forward analysis include:

- Water:
  - The model strongly indicates sub-surface and surface water has a significant influence on the size and timing of failures, justifying the investment in close-coupled models and simulation of the ingress of water into dilated and damaged zones.
  - The model strongly indicates great value in practical efforts to reduce water ingress at surface and reduce sub-surface water pressures, justifying the explicit simulation of dewatering options.
  - The results were sufficient to recommend that all future stability models be properly hydromechanically coupled (as opposed to simple mapping of assumed pressures) and include fault flow and the effects of dilation on water ingress and flow characteristics.
  - There is significant value in better representing the availability of surface water.
- Structure:
  - Simulating the structural model in high fidelity and the addition of a DFN were crucial in achieving a close match to past failures.
- Intermediate modelling steps.
  - We concluded that the use of annual pit stages is only just sufficient for simulation of large slopes, and there was benefit in modelling with smaller steps.
  - This is because many steps are needed to evolve a realistic stress path, and most design problems we solved were at intermediate stages of excavation. Past models for this mine, and many large models of large pits include just a few stages, almost certainly insufficient to simulate the stress path and impossible to use to evaluate intermediate stability.
  - Generally, quarterly steps permit a better accounting for seasonal changes in near and sub-surface water and more sufficiently capture the stress path, though this is just a guide. The critical minimum resolution for excavation steps would depend on the circumstances.

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