3D Hydromechanical discontinuum simulation for pit slopes

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ABSTRACT

The assessment of slope stability does not frequently account for the interaction between stress, rock mass damage and water pressure and flow in a rigorous manner. Owing to improvements in computer capacity, it is now possible to undertake fully coupled or partially coupled, 3d hydromechanical Finite Element simulation of mines, including explicit representations of large numbers of discontinuities. The analysis requires fewer assumptions than uncoupled analysis or 2d analysis, but may require a change in how hydrological data is collected. The way hydrological data is incorporated in stability assessment and the approach to uncertainty in hydrological information also requires discussion.

The current procedures for this type of analysis are discussed, along with some practical difficulties and learnings from early applications. A work flow for integration of 3d hydromechanical modelling with pit planning and some considerations for the management of uncertain data are also proposed.

1 INTRODUCTION

There are a number of options for numerical analysis of slope stability.

Mathematically simple analysis is most common but the cost is an increased number of assumptions. Frequent simplifying assumptions used in slope models include that the rock mass is fully drained or that discontinuities can be ignored. Naturally, models which assume things that are definitely untrue - such as that strength is infinite (elastic models) or that structure has no effect (continuum models) cannot be correct. The usual justification for these assumptions is lack of information or understanding. Either the available data or the available tools do not allow a more sophisticated accounting for water or structure.

The most sophisticated slope stability analysis is coupled, 3D discontinuum, non-linear hydro-mechanical analysis. This form of analysis has not been common owing to historic computational limitations, but is now employed by some of the world's largest mines. These models incorporate very large numbers of discontinuities, a non-linear constitutive model for the rock mass and the consideration of pore water pressure is governed by theories of porelasticity. The benefit of this analysis is that the physical laws governing interactions between solids, structures and water are accounted for explicitly for the particular geometry of the problem.

The conflict between the simple approaches and more sophisticated analyses is a complex dilemma. Ignoring the issues caused by faulting and Pore water pressure, for example will result in a potentially wrong answer, while there is often insufficient data for a model with a high-resolution, explicit representation of these parameters to be modelled explicitly.

The problem needs debate; overly simplistic analysis is potentially dangerous and mines need long term stability forecasting to design and engineer their slopes.

2 NUMERICAL EXPERIMENT

To demonstrate the reasonableness of certain assumptions, a series of numerical experiments has been conducted on a model of a fictitious pit which is faulted and is mined in a rock mass with a shallow phreatic surface (i.e. a high water table). The same 3d geometry is simulated with various faulted/unfaulted and drained/fully drained assumptions so that the results can be compared.

The intent of the experiment is not to prove or disprove that modelers should never undertake one or another type of analysis as all modeling approaches have a place. The intent is to show that if water and strength and structure matter for a particular problem, the effect of certain simplifying assumptions can be to create an incorrect impression of the likely outcomes.

This matters very much in the typical mine planning and modeling process that is followed in many mines. In this example, for instance, modelling at the mine may start with a much simplified model. The intent of the simplified model - possibly a 2D model - in a typical modelling project might be to aid in identifying vulnerabilities or to bracket certain design parameters, such as the slope angle or timing of pushbacks. If vulnerabilities are identified, the analysis will be escalated to a more sophisticated approach, possibly 3d with structure for example, with fewer assumptions and greater cost.

A problem would occur if the original simple stage was unable to capture the mechanisms of a real problem, or to offer some hint of it, so that the identification of the vulnerability was entirely up to the modelers imagination. Another problem occurs if the effect of the assumptions is so severe that there is no correlation between the model results and the future slope behavior. It might be incorrectly concluded that no more detailed analysis is necessary, or else the initial design might be grossly insufficient.

There should be general concern that most of the simplifying assumptions discussed so far (elasticity, continuum or fully drained) are likely to be non-conservative.

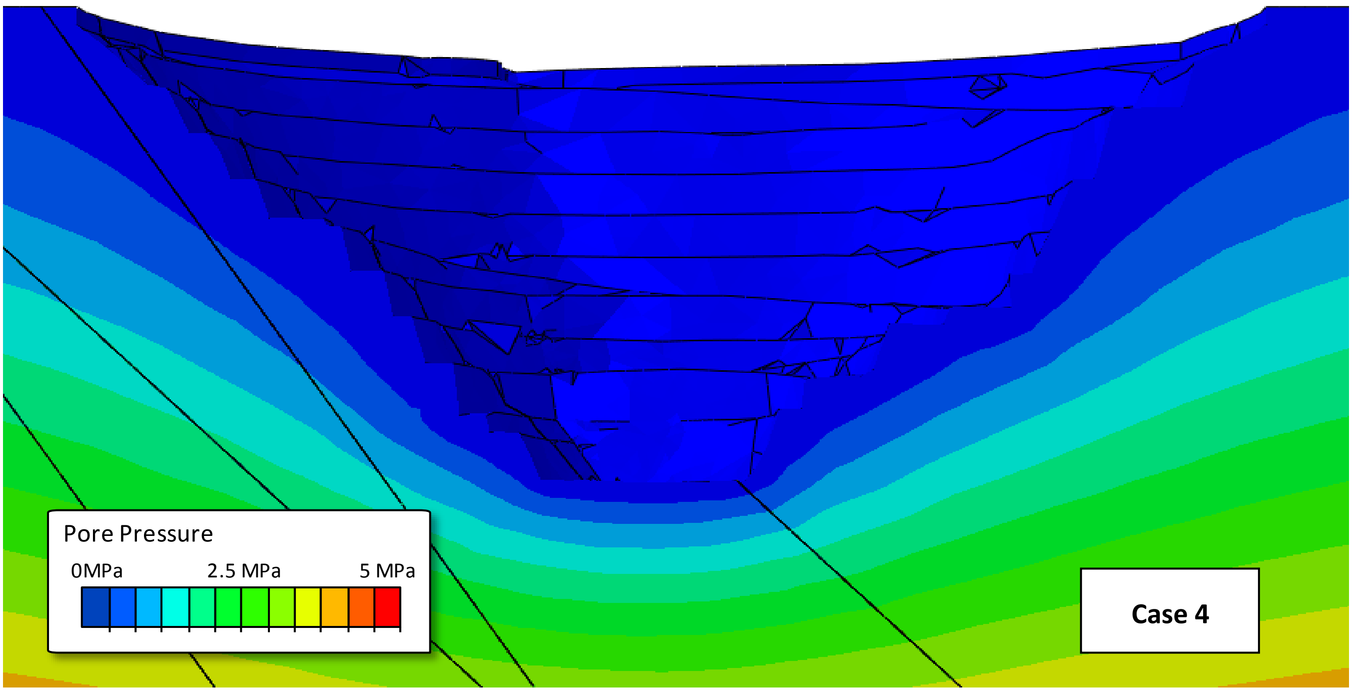

Fig. 1. Pore water pressure distribution for Cases 4 and 5 at end of mining

The experiment consisted of 5 separate models, each using the model geometry shown in Figure 1, and each a typical model as employed for similar problems in mines around the world:

- Case 1: A 2D, Strain Softening Dilatant (SSD), Finite Element (FE) model. The rock mass is fully drained (0kPa Pore Water Pressure, or PWP throughout) and the faults are turned off
- Case 2: A 3D, SSD FE model, fully drained rock mass, faults turned off.
- Case 3: A 3D, SSD FE model, fully drained, faults turned on in the model, but having similar hydraulic conductivity to the rock mass.
- Case 4: A 3D, SSD FE model, coupled hydro-mechanical simulation, faults turned on, but having similar hydraulic conductivity to the rock mass
- Case 5: A 3D, SSD FE model, coupled hydro-mechanical simulation, faults turned on, but in this case acting as direct fluid pathways having higher conductivity than the rock mass, and related to the deformation and stress on the structure.

In order, four cases represent increasing numerical complexity, but a decreasing number of assumptions about the slope. Each additional feature also represents a small upgrade in model costs, as the transition from 2D to 3D to faulted to coupled models frequently involves purchasing additional software or licenses and requires additional engineering skill. Naturally, even more realistic models are possible than Case 5, which in this case makes the least assumptions of all those in the experiment; the intent here is to test the most common and basic assumptions.

2.1 Material properties and assumptions

In each case the material properties for the rock and for the faults (where applicable) were the same. The constitutive model for faults and the continuum components are detailed by Reusch and Levkovitch, (2010) and the material properties are listed in the Appendix.

In summary:

- The continuum parts (ie, the unfaulted rock) are modelled as a strain softening, dilatant Hoek Brown material. This means that as strain increases the material softens, weakens and dilates.
- Discrete structures that are explicitly represented in the models are represented by cohesive elements. In FE simulations cohesive elements allow simulation of the discrete behavior associated with faults or shears and can be used to construct a rock mass compromising discrete rock blocks separated by discontinuities. Using this technique, faults and shear zones are free to dislocate and dilate and the fault surfaces themselves can dilate and degrade.
- In the hydro-mechanical models, conventional equations governing fluid flow and PWP (Darcy, 1856) are solved simultaneously with the equations for deformation and damage inside 3D, strain softening, dilatant, discontinuum models. A typical PWP cross section is shown for Cases 4 and 5 in Figure 1.

There are several other key assumptions:

- The stress field was: $\sigma_h=1.3\sigma_v$. PWP at boundaries is steady state gravimetric hydraulic head.
- The pits were extracted in horizontal slices approximating the height of a single bench
- Only a very small number of discontinuities were simulated. The spacing of structures in the model relative to the pit size means that only global scale (i.e. wall scale) interpretation is possible. This does not reflect current computational capacity; these models were designed to run very quickly on a personal computer.
- In case 4 the faults are modelled with the same hydraulic conductivity as the rock mass. In Case 5 the faults are modelled as offering potentially open fluid paths depending on the dilation and stress.

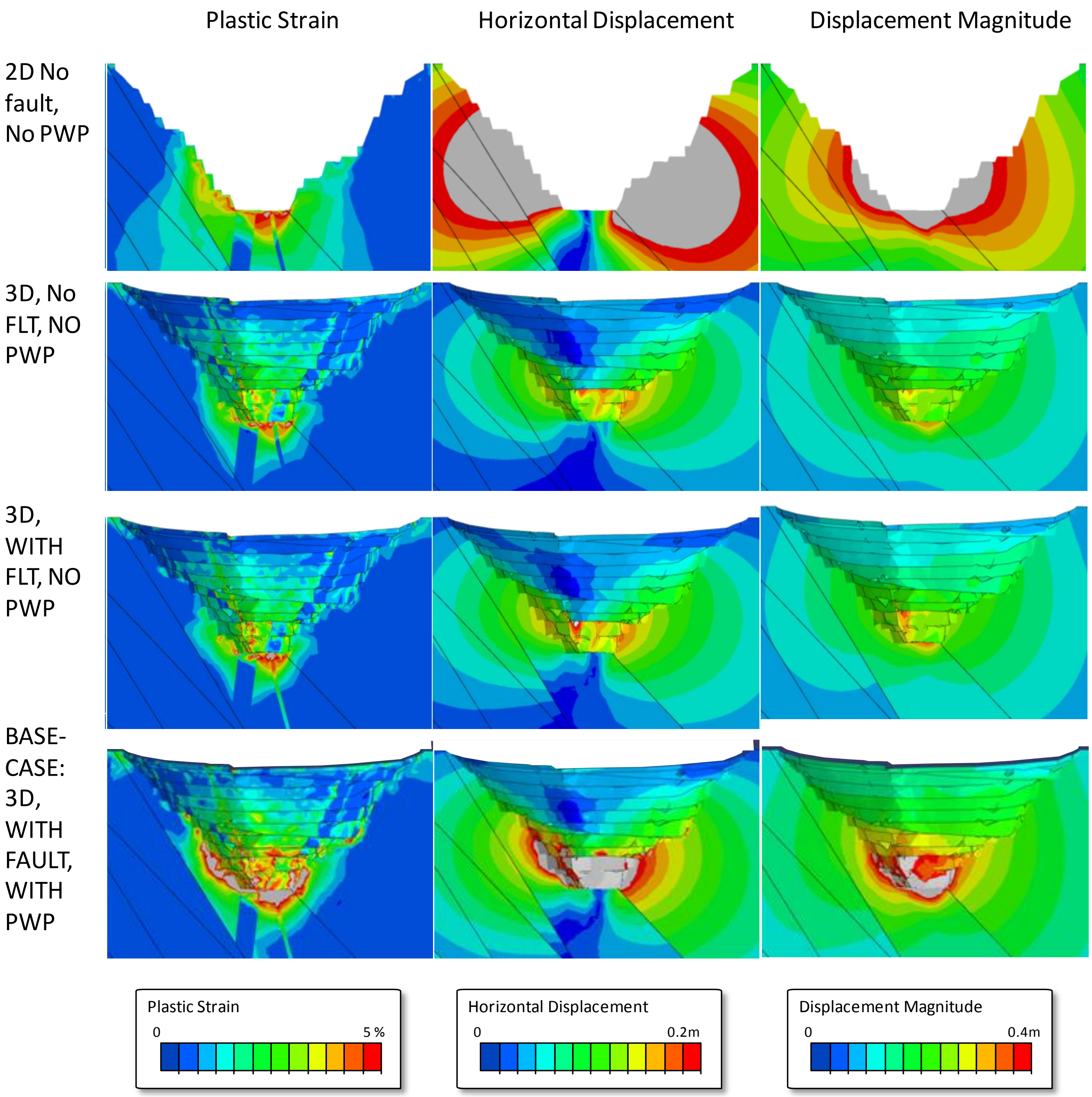

Fig. 2. Simulated plastic strain, horizontal displacement and displacement magnitudes for all four cases. In the no fault cases, the fault traces are visible even though they are turned off.

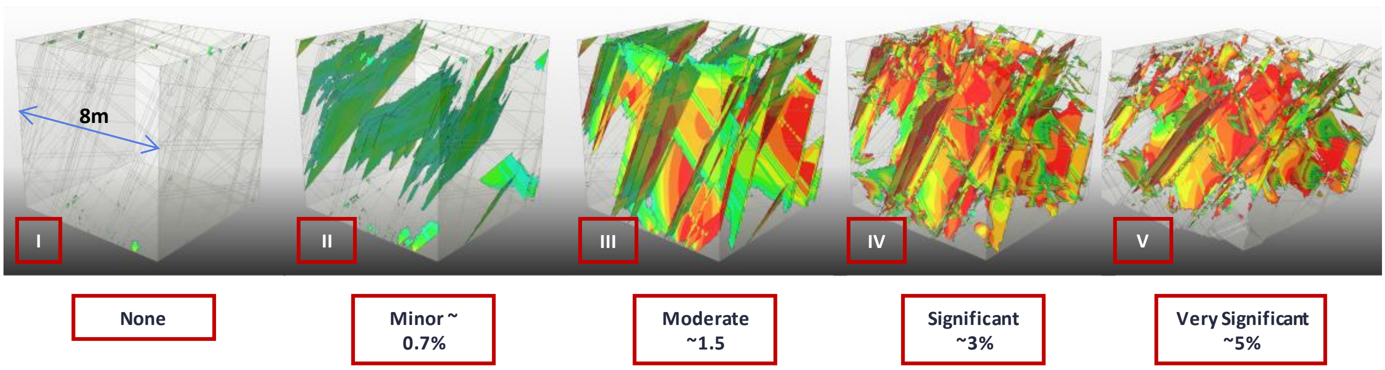

Fig. 3. Simulated rock mass scale specimen depicting an intepretation of the physical meaning of plastic strain in SSD FE models

3 EFFECTS OF VARIOUS HYDRO-MECHANICAL ASSUMPTIONS

The model simplifications are omissions that introduce error; the rock mass is not fully drained and it is faulted. This means that the faulted, hydro mechanically coupled Case 5 - which makes the fewest assumptions - would have the least error, all else being equal and this is the base case against the other cases can be compared.

Figure 2 compares the cases in terms of rock mass damage (plastic strain) and horizontal and total displacement. Figure 3 shows the physical interpretation of plastic strain based on a discontinuum FE simulation of rock mass scale numerical specimens, after Beck, Reusch and Arndt (2009).

3.1 Case 1: 2D SSD FE, un-faulted, fully drained

The 2 dimensional case has the most deformation for this small pit and significantly more deformation than the base case (Case 4) despite the lack of faults and PWP. In contrast, this model also has low wall damage. The reason for this is that the circular pit shape is clearly not able to be represented with high similitude by a 2D model. The effect of the 2D model is the same as assuming the pit is very long compared to its depth, and with the assumed properties a long slope of this steep gradient would indeed fail. The stress path predicted by the 2D model is simply incorrect.

The modelled scenario may well be an extreme case of the unsuitability of2D modeling, but in any situation the only way to properly quantify the effects of the 2D assumption is to simulate the correct 3D geometry. In some documented cases, attempts have been made to adapt material properties in 2D simulations to account for the omission of a spatial dimension, but this akin to assuming properties are dependent on the geometry of the slope.

Take for example a case of a pit at an early stage of extraction. The effective radius of curvature of the walls (a positive effect) is smaller than it will be at a later stage of extraction.

At this stage, a 2d model may be able to show instability or stability as observed in the pit, but the material properties that are back-calculated will be modified because the walls are affected by the confinement and favorable geometry afforded by the compactness of the pit and proximity of the other walls. Now imagine the outcome a later stage of extraction, when these same properties are used? The model was never calibrated in the first place, and now the material properties will produce the incorrect result.

3.2 Case 2: 3D, SSD, un-faulted, fully drained

Assuming that the rock mass is un-faulted and fully drained results in a significant underestimation of the potential for instability for this scenario.

For the base case, instability is clear as a zone of yielded, significantly displaced material in the lower half of the left hand slope, but for Case 2 neither the damage or displacement are significant. The shape of the deformed zone is similar to the shape of the failed zone in the base case. However displacement and plastic strain have physical meanings that cannot be scaled and the levels of movement for Case 2 and the nature of the deformation is not consistent with the instability predicted by the base case.

As damage is of course cumulative, or path dependent, the lack of damage at this stage of the model also means that future forecasts of damage, at later stages of the pit would probably represent an even greater underestimation.

It can be concluded that a 3D model with un-faulted and fully drained assumptions offers a significant improvement over the 2D case but its uses as a predictive tool are limited.

3.3 Case 3: 3D, SSD, faulted, fully drained

This case is faulted, but without the effects of PWP the depth of damage in the walls is still very small and the instability does not occur.

If as is assumed in this case, PWP does contribute to eventual failure, a model with these assumptions would have proven insufficient despite being closer to the base case than the other scenarios. With increasing depth, as PWP becomes more important for stability, the model with these assumptions would have been even less useful.

3.4 Conclusions regarding the effects of various model assumptions

The hypothesis that was tested by the experiment is whether an experienced engineer might reasonably be able to derive useful conclusions from much simplified models.

The result was that none of the simplified models could be interpreted to match the results of the hydro-mechanical models which in this case make the fewest assumptions and have the minimum capabilities required to represent the mechanics of the slope. The simplified models showed deformation in similar places but did not show conditions that were unambiguously able to indicate instability in places that were clearly unstable in the coupled model.

A possible conclusion is that without a sufficient representation of structure, water and geometry the predictions can, and are likely to be in some cases wrong. The effect of ignoring the effects of PWP in this case, was perhaps as significant to the overall model error as ignoring faults and either case would have been sufficient in a real world scenario.

The modeling also shows how each additional simplification introduces error that is not easy to account for using intuition and experience alone. This makes using the simplified models very difficult unless their assumptions can be proven by field observations.

There are some considerations for similar problems.

Generally:

- There is not more uncertainty in a 3d model than a 3d model. A 3d model can use exactly the same data as a 2d model to improve understanding and certainty in the area the data covers
- There are not fewer assumptions in a simpler model, such as an elastic model. These models have make more assumptions, and make more assumptions which are known to be untrue. They are also incapable of testing the effects of these assumptions.

Specifically related to hydromechanical problems:

- Pit models that ignore, or over-simplify poroelastic effects when they may be relevant are hard to justify.

  In the absence of data excluding the importance of PWP, stability analysis without consideration of poroelastic effects may not be sufficient for planning.
- A common approach to the modeling of open pits is to stage the analysis, progressing from 2D, to 3D, adding faults then water. However, in this experiment the progression showed that such an approach would have cost time and run the risk of inappropriate conclusions.

  Mines should carefully consider whether the staged approach adds value as in some instances, it may not. In many cases it may enhance the understanding for the modeling process, but the conclusions may not be sufficient for mine planning purposes.
- Most slope models use a representation of PWP derived from 2D analysis. Given the sensitivity of some slopes to PWP, this approach requires great care and needs to be validated whenever it is applied.

3D analysis is not significantly more complex or costly, so 2D analysis may be hard to justify.

- Un-faulted simulations of open pits are common, even though the spacing and persistence of the smallest structures which are modelled is a limitation on the resolution of the analysis.

  The numerical experiment shows that un-faulted analyses result in an underestimate of damage and deformation even in locations where instability is not occurring due to dislocation on faults alone. This is an obvious and predictable outcome, but it suggests that it is hard to justify persisting with un-faulted analyses except in very occasional circumstances.

- The conclusions regarding un-faulted and fully drained analysis also extends to surface subsidence simulations for caving mines

4 IMPLEMENTING REALISTIC HYDROMECHANICAL ASSUMPTIONS IN REAL-WORLD SITUATIONS

Ignoring faulting and PWP will result in a potentially wrong answer. The dilemma is that fault and PWP data may not be available, certainly in the earlier stages of a project, so the problem needs debate; overly simplistic analysis is potentially dangerous and mines need long term stability forecasting to design and engineer their slopes.

The problem should not be intractable. Mine planning and design in adverse environments is always a data limited problem and it not just hydrological parameters which are uncertain. As a result, mines have developed many procedures for managing uncertainty.

Common to these approaches is some sort of trigger and response philosophy: multiple courses of action are identified ahead of time, and the eventual decision of the correct way to proceed will be made prior to some pre-determined last safe moment to act. The game between planning and this last safe moment is used to collect information, either as a trigger or to assist in making a better decision.

One appreciation process for mine planning has been proposed by Beck (2008). That process wass an adaptation of the MDRP, which was developed by the United States Armed Forces to ensure that the operational environment and situation are properly appreciated when making complex data-limited decisions. Descriptions of the MDRP are widely available on the internet and are not classified. The process is frequently taught in business schools and by business consultants, so its application here is not unique or necessarily original.

Beck 2008 discussed the procedure in detail. In this paper, an example is used to demonstrate how to manage a lack of hydrological data

4.1 Example Application: Open Pit Concept Analysis

4.1.1 Situation:

An open pit is in Stage 1 of production. A partially calibrated numerical model shows that high levels of deformation occur in a wall above the planned Ramp. Stage 2 shows minor problems but easily observed deformation, Stage 3 shows some chance of ramp failure and Stage 4 shows significant wall failure.

The calibration of the model is good by accepted standards but the level of uncertainty means there is a chance that the failure will not occur. The aim is to engineer a pit that will remain stable at a high surety of production until the end of Stage 4.

It is known that to achieve a flatter pit angle by Stage 4, the new design must be implemented by Stage 2.

4.1.2 Mission Analysis:

The Mine Managers mission is to maximise the return on investment in the pit. The Technical Services Managers mission is to ensure that technical issues are managed so that budgets are met. The Geotechnical Engineer mission is to ensure that the pit design results in a stable pit excavation.

Freedoms:

- The Geotechnical Engineer is allowed to change the pit design and design the monitoring program.

Constraints:

- Instability is unacceptable.

The ramp is considered a centre of gravity as is continued production as the pit is used for blending with another mines product.

4.1.3 Concept Development:

Concept 1: Assume forecasts are correct and design a flatter pit wall.

Concept 2: Ignore the analysis

Concept 3: Monitor the pit wall to confirm and improve the numerical analysis. Flatten the wall if later analysis concludes it is necessary.

4.1.4 Concept Analysis:

Concept 1:

Selected vulnerabilities for concept 1:

- Reduced economic returns due to conservative plan.
- Re-designed pit wall may still not be stable.
- Ramp may be affected by falling material as early as stage 2
- Other instability may develop

Modification required to concept 1:

- Design a flatter pit wall, but continue monitoring to identify additional instability.
- Move ramp away from the instability
- Monitor for other instability with sufficient detail to allow forecasting of instability while it can still be avoided or managed

Modified Concept 1:

- Assume forecasts are correct and design a flatter pit wall but continue monitoring to identify additional instability. Move the ramp away from the instability and monitor for other areas of instability with sufficient detail to allow forecasting while it can still be avoided or managed

- The modified concept achieves the mission and goes towards successful completion of the higher missions.

Concept 2:

Selected vulnerabilities for concept 2:

- If the analysis is ignored and proves to be correct, a feasible opportunity to achieve the objectives will be lost.
- As any new design would need to be implemented by Stage 2, it is unlikely that this plan could react quick enough if instability continued to develop.
- Ramp may be affected by falling material as early as stage 2

Modification required to concept 2:

- The plan is not feasible as no basic modification could allow mining to Stage 4 if wall instability continues to develop.

Concept 3:

Selected vulnerabilities for concept 3:

- Reduced economic returns due to conservative plan.
- Re-designed pit wall may still not be stable.
- Ramp may be affected by falling material as early as stage 2
- Other instabilities may develop

Modification required to concept 3:

- All data must be collected prior to stage 2. The monitoring plan must be sufficient to allow the decision for re-design to occur prior to Stage 2. Stage 2 will be the Decision Point for this vulnerability.
- Move ramp away from the instability
- Monitor for other instability with sufficient detail to allow forecasting of instability while it can still be avoided or managed

Modified Concept 3:

- Move ramp away from the instability. Monitor the pit wall to confirm and improve the numerical analysis. This will involve traverses and prism surveys on a regular basis to allow more detailed analysis. The wall will be flattened if necessary and all data must be collected prior to stage 2. The monitoring plan must be sufficient to allow the decision for re-design to occur prior to Stage 2.

  Stage 2 will be the Decision Point for this vulnerability. If insufficient data is available for analysis at that time, the flatter wall plan will be adopted.

- The modified concept achieves the mission and goes towards successful completion of the higher missions.

4.1.5 Implementation:

Concept 3 is selected as it retains the opportunity to implement the original design if analysis suggests this is feasible but still can safely achieve the mission if it is implemented with all control measures. The DPs and the control measures must be implemented as part of the concept and strictly adhered to. The monitoring allows detailed analysis to continue and an ongoing appreciation process to involve the best available data. New concepts are developed as new data becomes available to ensure the adopted plan is optimal.

Over time, the plan must continue to be revised, but the adoption of the most resilient plan should place the mine in the best position to take advantage of additional opportunities and manage problems as they arise.

5 CONCLUSIONS

The proposed appreciation process for mine planning has been tested in another form in a very extreme environment where data is limited and rapid decisions are required. It's application in the mining environment provides a more robust methodology for problem appreciation that 'brain-storming' or group based matrix-form risk assessments.

The most important advantage of the system is that it documents clearly all of the considerations that were made in arriving at a decision, and it enforces the consideration of critical vulnerabilities when tasks are delegated.

The answer to the sparse data-complexity problem may lie in probabilistic approaches that test a range of possible scenarios. Measurement and testing programs can be carefully designed to complement such analysis and to assist in managing uncertainty and making better decisions during operations. If this is the case, mines will need to collect more hydrological information and conduct more sophisticated analyses than they do now.

6 REFERENCES

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7 APPENDIX

Table 1 Peak strength parameters for rock

Hoek Brown Classification		
Intact UCS	35	MPa
GSI	36	
m_i	7	
Disturbance Factor	0	
Intact Modulus	12000	MPa
Hoek Brown Criterion		
m_b	0.71	
s	8.2×10^{-4}	
a	0.51	
Failure Envelope Range		
σ_{3max}	8.75	MPa
Rock Mass Parameters		
Tensile Strength	-0.04	MPa
UCS	0.90	MPa
Deformation Modulus	1500	MPa

Table 2 Residual strength parameters for rock, applied progressively between 0.7% and 3% strain

Hoek Brown Classification		
Disturbance Factor	0.4	
Intact Modulus	12000	MPa
Hoek Brown Criterion		
m_b	0.4	
s	3.0×10^{-4}	
a	0.52	
Failure Envelope Range		
σ_{3max}	8.75	MPa
Rock Mass Parameters		
Tensile Strength	-0.024	MPa
UCS	0.51	MPa
Deformation Modulus	830	MPa

Table 3 Fault strengths for faulted cases

Mohr-Coulomb Peak		
c	1.25	MPa
phi	23.5	degrees
Mohr-Coulomb Residual		
c	0.1	MPa
phi	21	degrees