Developing rules of thumb for groundwater modelling in large open pit mine design

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ABSTRACT
A research program has been undertaken to establish guidelines for hydrogeological modelling of large open pits. For this study, it is assumed that fractures are closely spaced such that the rock mass can be approximated by an equivalent continuum. A two-dimensional model of a typical mining scenario is constructed and tests are conducted in which the porosity and permeability in the model are varied. The model results are analyzed to determine under what conditions it is suitable to perform only a steady state analysis, when a transient analysis is required and when full coupling (i.e. undrained) solutions should be considered. Guidelines are presented in terms of a dimensionless rate metric, *R*, that includes the mining rate and the rock diffusivity. Values of *R* are determined to delineate steady state, transient and undrained conditions.

RÉSUMÉ
Un programme de recherche a été entrepris pour établir des directives pour la modélisation hydrogéologique des grandes mines à ciel ouvert. Pour cette étude, il est supposé que les fractures sont étroitement espacées de telle sorte que la masse rocheuse peut être approximée par un milieu continu équivalent. Un modèle à deux dimensions d'un scénario typique d'exploitation minière est construit et des simulations numériques sont effectuées dans lesquelles la porosité et la perméabilité dans le modèle sont variées. Les résultats du modèle sont analysés afin de déterminer dans quelles conditions il convient d'effectuer une analyse découplée avec écoulement permanent, quand une analyse découplée transitoire est nécessaire et quand un couplage plus serré des solutions (ie incluant le non drainé) devrait être envisagés. Les directives sont présentées en termes du taux , R, de mesure adimensionnel qui fait intervenir le taux d'extraction minier et le coefficient de diffusion de la roche. Les bornes de R sont déterminées pour identifier les conditions d'équilibre, transitoires et non drainées.

1 INTRODUCTION

In large open pits, accurate knowledge of the pore pressure conditions is crucial when calculating stability of the slopes. Water flow is affected by rock properties, rock fractures, solid-fluid coupling behaviour, degree of saturation, rate of mining, rate of fluid recharge and discharge, etc. Simulating the pore pressure conditions with numerical models can be a challenge, since to accurately consider all of these factors, a fully coupled model of a discontinuous medium should be used. However, in many cases, this level of complexity is not necessary. For closely spaced fractures (relative to the scale of the excavation), an equivalent rock mass can be assumed and continuum modelling can be performed. For rocks with high equivalent permeability, or very slow excavation rates, transient analyses are not required and a steady state pore pressure distribution can be assumed. Alternatively, in rocks with very low permeability, undrained conditions may be assumed.

Similar types of analyses have been attempted before. Hoek and Bray (1977) show the increase in slope angle that can be attained through dewatering. Brown (1982) calculates the drop in pressure that can be expected for different slope geometries and different diffusivities. Unfortunately, simplified one-dimensional models were used that sometimes can drastically overestimate the pressure drop when compared with a two-dimensional model with a phreatic surface.

In this paper, a two-dimensional model of a typical mining scenario is constructed. A series of numerical models are run with different fluid flow properties. Factors of safety (FOS) are then calculated for each model. Relationships between FOS, porosity and permeability are presented. In each case the accuracy of assuming steady state pore pressures or undrained conditions is assessed. Rules of thumb are then proposed to help decide what type of analysis needs to be performed for different mining scenarios.

2 NUMERICAL MODEL

2.1 Model Geometry

A model of a typical mining scenario was created with the two-dimensional finite difference program *FLAC* (Itasca Consulting Group, 2008), as shown in Figure 1. The figure shows the mining sequence with white numbers. Each excavation is 200-m wide. The excavations of particular interest are stages 5 to 10. Stages 1 to 4 are simulated to provide the initial conditions for stages 5 to 10. Stages 1 to 4 are excavated over a period of 18 years. Each of the final excavation increments (5 to 10) is 133.33-m high, and they are excavated 9 months apart.

The initial water table is at 50 m below the surface as shown by the yellow line in Figure 1. The pore pressure is fixed at hydrostatic conditions on the right boundary at a distance of 5000 m from the middle of the pit. The model base is an impermeable boundary, as is the left boundary (symmetry condition).

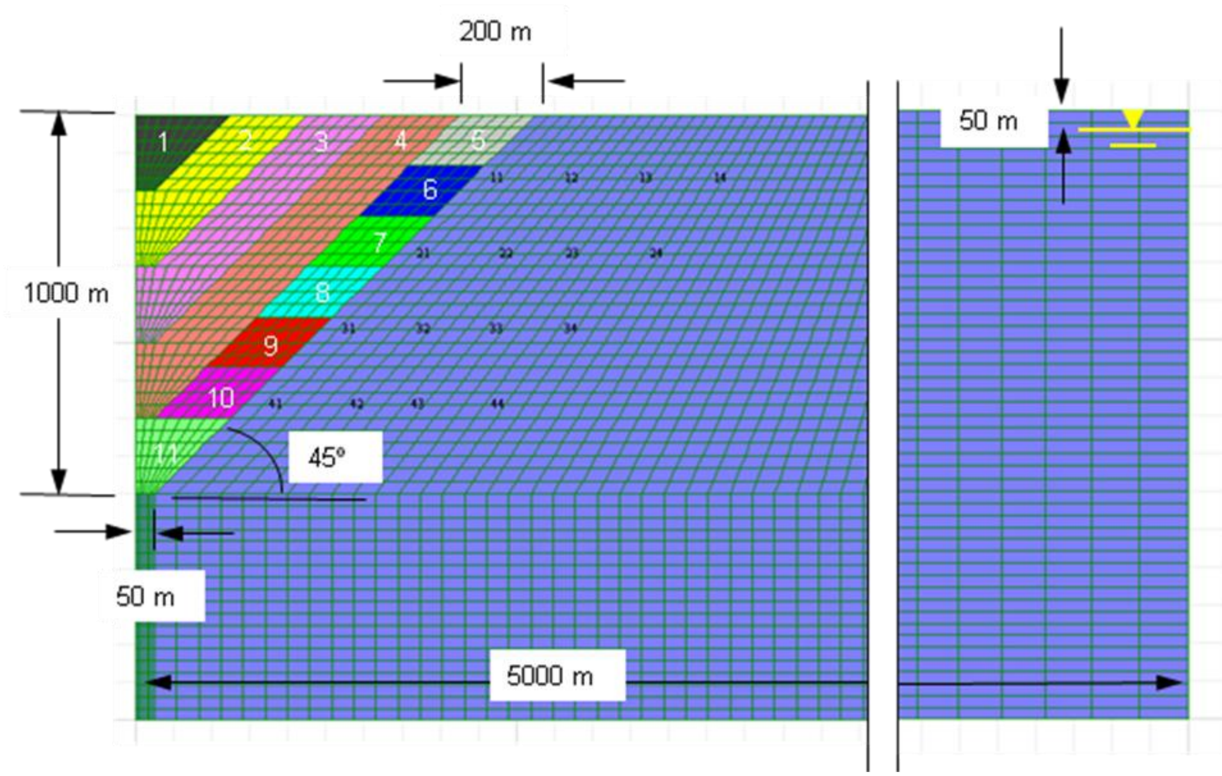

Figure 1. Model geometry. White numbers indicate the mining sequence. Small black numbers indicate locations at which pore pressures are recorded.

2.2 Rock Properties

It is assumed that flow and mechanical behaviour of the fractured medium can be approximated using continuum theory at the scale of the problem investigated. Rock properties are chosen to represent a typical open pit mine. The rock behaves elastically for the simulations, except when FOS calculations are performed, in which case a Mohr-Coulomb constitutive model is considered. The rock stiffness and strength are the same in all models. Permeability and porosity are varied over typical ranges encountered in the field. Rock and fluid properties are shown in Table 1.

Table 1. Rock and fluid properties

Property	Value
Young's modulus, E	5 GPa
Poisson's ratio, v	0.25
Porosity, n	0.1 to 10 %
Density, ρ	2500 kg/m^3
Cohesion, c	0.5 MPa
Friction, φ	45º
Permeability, k	10^{-9} to 10^{-6} m/s
Fluid density, ρ_w	1000 kg/m^3
Fluid bulk modulus, K_w	2.2 GPa

2.3 Modelling Approach

All models are continuum models run with FLAC version 6.0 (Itasca Consulting Group,2008). FLAC is used to calculate both the hydraulic response and the geomechanial behavior (factor of safety). To simulate mining, each block is removed instantaneously, and the model is run for a certain amount of time corresponding to the mining rate (so that changes in pore pressure can be observed). Transient fluid flow solutions are obtained for all models (unless steady state is indicated). Two different approaches to coupling are investigated:

- Simplified one-way coupling — A fluid diffusion equation is solved that accounts for fluid and mechanical storage, and updated boundaries for the stage. A mechanical simulation is then performed to calculate readjustments caused by excavation step, and pore pressure changes. Solid displacements do not affect the pore pressure, but the pore pressures determine the effective stress which influences the mechanical (factor of safety) calculation. The solid stiffness and porosity does affect the diffusivity.
- Simplified two-way coupling — After each excavation stage, an undrained analysis is first carried out to capture the short term response of the model (no fluid flow takes place but stresses readjust, and change in volumetric strain causes change in pore pressure – see Appendix A). This basically assumes that the excavation rate is very fast relative to the rate of fluid flow. Models then are run in fluid-only mode (i.e., simplified one-way coupling) to simulate the recovery of the pore pressure over time, followed by a mechanical calculation to capture readjustments caused by pore pressure changes.

For each model at each stage, factor of safety is calculated using the shear strength reduction method. This essentially reduces cohesion and friction until failure occurs. From the magnitude of shear strength reduction, a factor of safety can be calculated. See Dawson et al. (1990) for details. All models are run in plane-strain mode (2D flow). Similar analyses have been performed for Axisymmetric models but space limitations prevent their discussion here (see Hazzard et al., 2010).

2.4 Dimensionless Excavation Rate

As mentioned in section 2.2, models were run with different permeabilities ranging from 10^{-9} m/s to 10^{-6} m/s. The rate at which excess pore pressure dissipates also depends on porosity, fluid bulk modulus and rock stiffness, so a better measure of fluid flow in the rock is the diffusivity. Diffusivity is the permeability divided by the storativity:

$$c = \frac{k}{S} \quad [1]$$

where the storativity, S, is a measure of fluid storage in the rock. Two possible modes of storage are identified for this problem: elastic storage (associated with water and rock compressibility) and phreatic storage (associated with effective porosity). In this study, elastic storage will be used to calculate diffusivity. This assumes that diffusion (rather than water table movement) is the dominant mechanism for pore pressure adjustment. This may be slightly inaccurate for models with very low porosity, but the error introduced will be small. The elastic storage is given by:

$$S_v = \rho_w g \left(\frac{n}{K_w} + \frac{(1+v)(1-v)}{E(1-v)} \right) \quad [2]$$

where symbols are defined in Table 1. :

The other factor that affects the pore pressures is the rate of mining. The volumetric mining rate (per unit model thickness), M_r, is defined as

$$M_r = L\frac{dH}{dt} \quad [3]$$

Where dH is the height of an excavation and L is the length. In our model, the rate of mining for stages 5 to 10 is M_r = 200 m × 133 m / 9 months. We can therefore propose a *dimensionless excavation rate* metric, based on the mining rate and the diffusivity:

$$R = \frac{M_r}{c} \quad [4]$$

as a number to be used to quantify the effect of different model parameters on pore pressures and slope stability. This rate parameter, R, in principle can be used to determine what type of analysis is required.

One of the work objectives is to identify threshold values for the metric R, such as R_s, R_d to identify when, for stability analyses, steady-state flow is applicable ($R < R_s$), an undrained analysis is sufficient ($R > R_d$) and coupled fluid-mechanical simulation is recommended ($R_d < R < R_s$).

3 RESULTS

3.1 Steady State

The first goal was to determine under what conditions it is acceptable to use a steady-state rather than a transient hydraulic model. The steady state solution was obtained for each excavation stage of the model shown in Figure 1. Then a transient solution was obtained for different values of permeability and porosity. Pore pressures calculated for one excavation stage are shown in Figure 2. It is clear that for this set of parameters, the steady state solution is not a suitable representation of the problem.

Factors of safety were calculated for each excavation stage. An example of the calculated factors of safety are shown in Figure 3. It is clear that the higher pore pressures for the model shown in Figure 2 (top) translate into lower factors of safety (due to lower effective stresses).

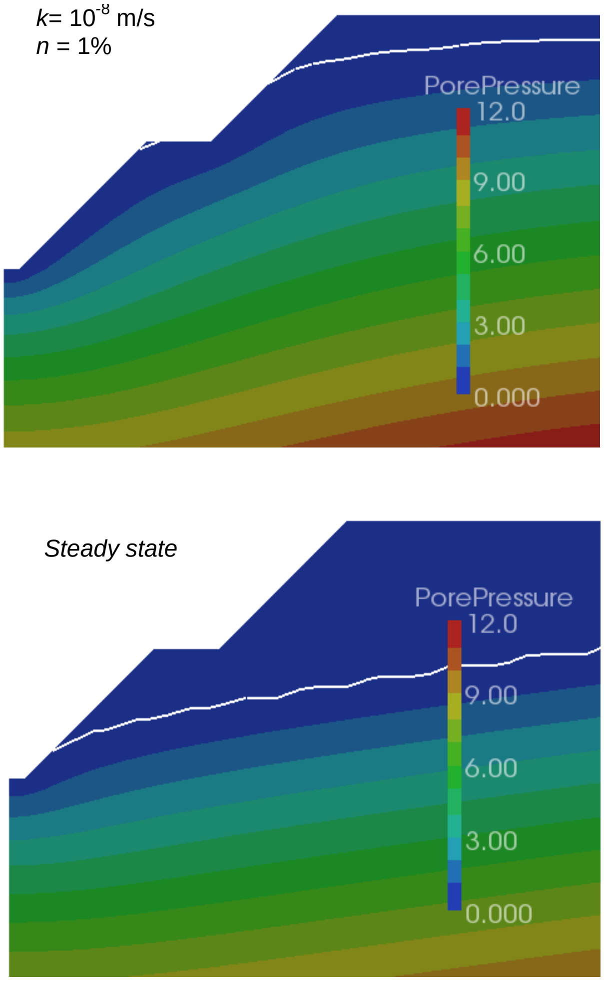

Figure 2. Pore pressures (in MPa) calculated at excavation stage 7 in a model with $k = 10^{-8}$ m/s and n = 1% (top) compared to the steady state solution (bottom). The phreatic surface is shown as a white line.

To evaluate the effect of porosity and permeability on slope stability, the average factor of safety for stages 5 to 10 was obtained for each model. These were then divided by the equivalent factors of safety in the steady state model to quantitatively determine the difference between the transient and steady state models. The results are shown in Figure 4. This shows that the model is well represented by a steady state solution (within 2%) for high permeabilities, slow mining rates and low porosities. If it is assumed that the rock in most open pits has a porosity less than 1%, then the steady state solution is valid for a dimensionless excavation rate of $R <$ 0.005. If the steady state solution is used for scenarios with $R >$ 0.005, then the FOS will be overestimated and the analysis will be unconservative.

This result depends on the location of the vertical, constant head boundary (the right boundary in our model). This will be discussed further in Section 3.3.

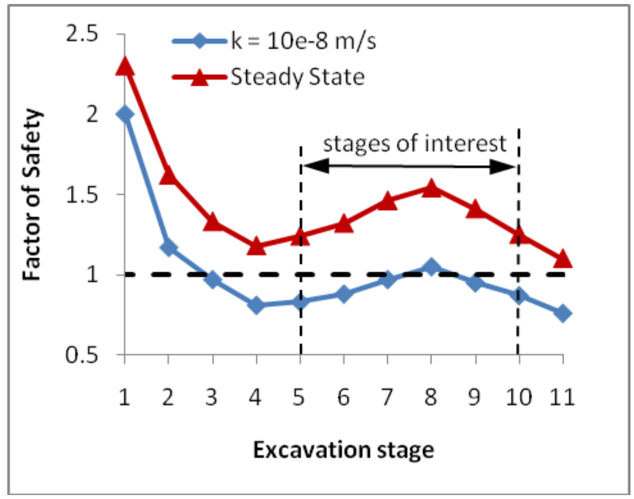

Figure 3. Factors of safety calculated in the model with $k = 10^{-8}$ m/s and n = 1% (top) compared to the steady state solution.

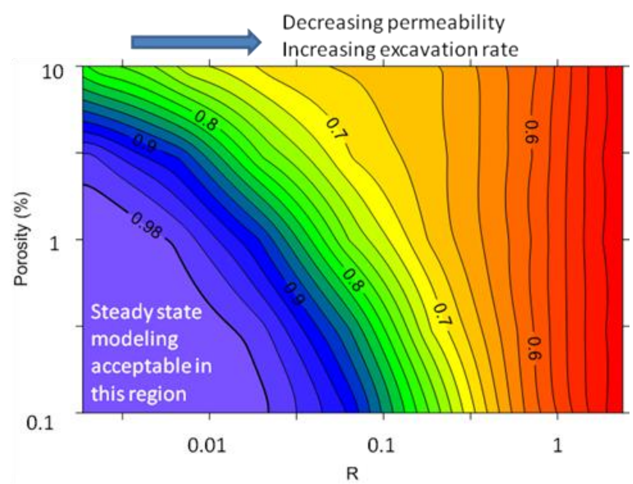

Figure 4. Factors of safety in transient models with different porosities and permeabilities relative to the factor of safety of a steady state model.

3.2 Undrained

When a volume of rock is excavated rapidly, there will be an undrained response resulting from the stress change. Essentially, the stress drop due to unloading results in a very rapid drop in pore pressure. The pore pressure then recovers gradually at a rate that depends on the diffusivity of the system.

In the analysis of the previous section, this effect was not considered, and all models were assumed to drain quickly so that the undrained pore pressures are quickly dissipated. This is obviously not the case for low permeability materials (or very fast excavation rates). To examine the importance of the undrained effect, the same models were rerun taking this into account. Two different analyses were performed:

1. Only undrained. This calculates the undrained response only for each excavation stage. No fluid flow is calculated and the pore pressure remains constant after each excavation
2. Simplified two-way coupled. After calculation of the undrained response, fluid calculations were turned on and one-way coupling was used to simulate 9 months of drainage in order to consider the recovery of pore pressures with time.

Example pore pressure histories are shown in Figure 5. This figure illustrates the different scenarios. For the undrained-only simulation, there is a pressure drop when rock is excavated and there is no recovery of pore pressure. The two-way coupled model shows the same initial drop in pore pressure and then recovery with time. The one-way coupled model (from the previous section) shows no pore pressure drop when excavation occurs, and only exhibits gradual drop in pore pressure as fluid drains from the slope face.

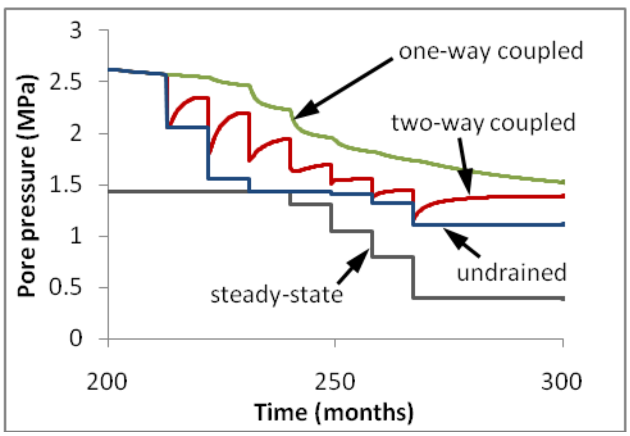

Figure 5. Example pore pressures recorded at a point 100 m from the slope face and 400 m below the ground surface, $k = 10^{-8}$ m/s and n = 1%. For the steady state curve, the time shown is not the true time. Only the final, steady state pressures are shown for each excavation stage.

Using these models it is possible to determine under what conditions the undrained response can be neglected and also under what conditions an undrained-only analysis may be adequate.

Figure 6 shows the factors of safety (average for stages 5 to 10) in models with two-way coupling relative to models with one-way coupling. This figure shows that for the highest values of R (e.g., lowest permeabilities), the FOS is up to 25% higher, but for low R (e.g., large permeability), there essentially is no difference. This makes sense, because for small permeability, the pore pressures due to the undrained response do not have a chance to recover, so the FOS in the two-way coupling models is higher for lower permeability. This plot indicates that for $R > R_s$ (approximately), solving with one-way coupling will be conservative.

Figure 7 shows the relative FOS for the undrained-only simulation compared to the two-way coupled simulation. This plot shows that the two-way coupled simulation results approach the undrained-only simulation results for R ~ 0.7. For R < 0.7, an undrained-only simulation would be unconservative, yielding factors of safety higher than those calculated by the coupled analysis. Figure 7 also shows that for R > 0.7, factors of safety in the undrained-only simulation are less than those of the coupled simulation. This is due to pore pressure increases that occur at the toe of the slope, as a result of mean stress increases (see Figure 8).

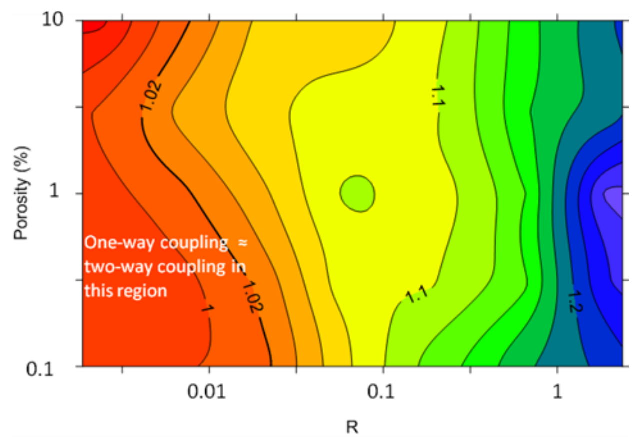

Figure 6. Factors of safety in models with simplified two-way coupling (after 9 months) relative to models with one-way coupling.

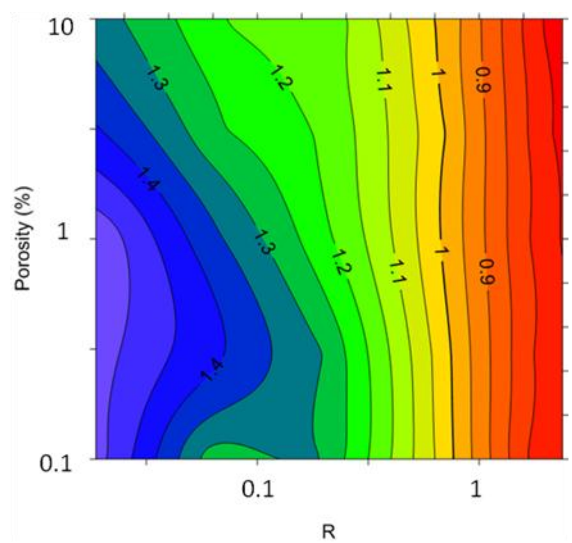

Figure 7. Factors of safety in models with 2-way coupling relative to models with undrained-only simulation

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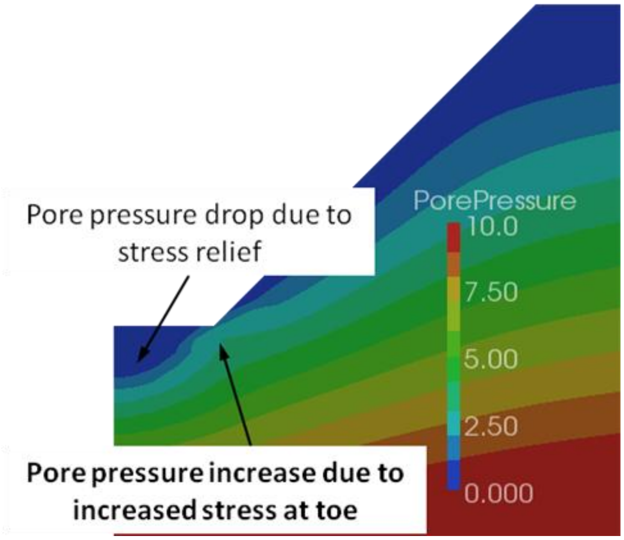

Figure 8. Pore pressures in undrained-only model after excavation stage 10.

3.3 Radius of Influence

The results presented in Section 3.1 show that for $R < R_s$, a steady state solution is sufficient and that for $R > R_s$ one-way coupled analyses will be conservative. However, this result depends on the location of the vertical constant head boundary (the right boundary in our model).

The perturbation to a groundwater system due to mining of a large open pit propagates with time radially away from the pit. Steady state can be achieved only if the recharge boundary is at a relatively small distance compared to the distance to which the perturbation would have propagated. Thus, the parameter influencing the development of steady-state flow is the distance, D, between the recharge boundary and the pit wall. It is expected that the bounding value, R_s , depends on the model size. One useful concept to quantify this dependency is the so-called *radius of influence.*

The model can be assumed to have reached the steady state if the distance, D, from the pit to the vertical model boundary (with fixed head) is a fraction of the radius of influence, or the distance to which the perturbation would have propagated in an infinite domain:

$$D = a\sqrt{ct_t} \qquad [5]$$

where t_t is time elapsed from the start of mining, and a is a dimensionless factor (less than 1). Substituting c from Equation 4 into Equation 5 and realizing that, M_r could be expressed as the ratio of total pit area in cross-section, A_p and time, t_t, then the dimensionless excavation rate, R_s for which the pore-pressure field can be approximated with steady state can be expressed as

$$R_s = a^2 \frac{A_p}{D^2} \qquad [6]$$

From Figure 4, we surmised that for low porosity (< 1 %), the transient solution is within 2% of the steady state solution for $R < 0.005$, i.e. $R_s = 0.005$. For this model, the total pit area $A_p \approx 1\times10^6$ m^3 and the distance from the pit to the model boundary is $D \approx 5000$ m. Solving for a in equation 6 we get $a = 0.35$. We can therefore propose that a steady state solution is satisfactory if

$$R < 0.125 \frac{A_p}{D^2} \qquad [7]$$

To test the robustness of this solution, a second model was constructed with the constant head boundary half as far from the pit (D = 2500 m). Using equation 7, it is expected that the transient solution will approach the steady state solution for $R < 0.02$. Figure 12 shows that this is the case (for $n < 1\%$).

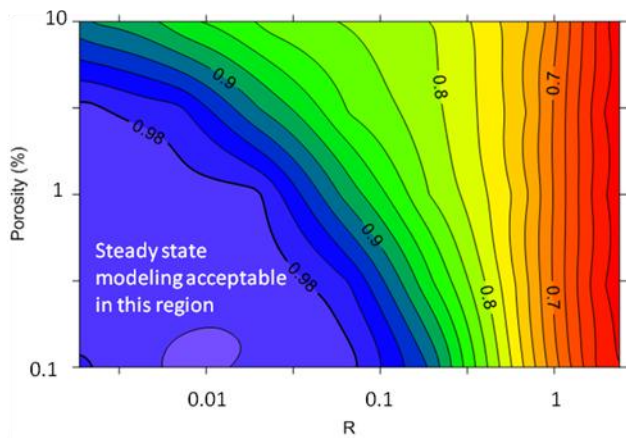

Figure 12. Factor of safety in the transient (one-way coupled) solution relative to the steady state solution for different dimensionless excavation rates, D = 2500 m.

4 CONCLUSIONS

For a model with the vertical recharge boundary at approximately 5 pit radii from the pit centre (5000 m in this example), and porosity ~ 1%, the following recommendations can be made:

a) $R < 0.005$: steady state modeling is acceptable;
b) $R > 0.005$ one-way coupled transient models will be conservative; and
c) $R > 0.7$ undrained-only analysis may be sufficient, but could produce conservative results.

For very low R (i.e., high permeability or low excavation rates), then a steady-state solution will suffice. The exact threshold depends on the porosity and also on the distance of the vertical recharge boundary from the pit.

For most large open-pit operations, R > 0.005. Thus, for low permeability rocks, the pressures predicted by steady-state analysis would almost always be too low for time periods of interest. In other words, steady-state results are unconservative when applied in that range, because they provide a false sense of stability. So, then the choice comes down to one- or two-way coupling. Undrained-only analyses are not recommended since results will generally be unconservative for the conditions of interest ($R < 0.07$).

Two-way coupling probably is adequate for all cases, because it accounts best for the actual behaviour. However, one-way coupling is conservative. Good judgment is needed if we consider a design analysis; advantages of pore pressure drops due to poro-elastic effects can probably be taken, but only if (among other uncertainties) the pit is excavated in the time and manner used in the problem setup. For example, if pit excavation is slowed compared to what is considered in the analysis, different conclusions could be reached.

ACKNOWLEDGEMENTS

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APPENDIX A – TECHNIQUE USED TO CALCULATE UNDRAINED RESPONSE

The following steps were taken to compute the undrained response:

- Set the fluid bulk modulus to 0.
- Set the solid bulk modulus to its undrained value:

$$K_u = K + \alpha^2 M \qquad \text{[A-1]}$$

Where α is the Biot coefficient and M is the biot Modulus. If we assume that the rock grains are incompressible[1] ($\alpha = 1$), equation A-1 becomes

$$K_u = K + \frac{K_w}{n} \qquad \text{[A-2]}$$

where K is the drained bulk modulus, K_w is the bulk modulus of water, and n is the porosity.

- Turn off the fluid calculation and solve the model mechanically.
- Use the change in mean stress to calculate the change in pressure:

$$\Delta p = B \Delta \sigma_{mean} \qquad \text{[A-3]}$$

where

$$\Delta \sigma_{mean} = \Delta \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3} \qquad \text{[A-4]}$$

And B is the Skempton coefficient given by

$$B = 1 - \frac{1}{1 + K_w / nK} \qquad \text{[A-5]}$$

for $\alpha = 1$.

If the change in pore pressure calculated with equation A-3 causes the pore pressure to drop below 0, then the saturation is decreased according to

$$\Delta s = \frac{\Delta \sigma_{mean}}{nK + K_w} \qquad \text{[A-6]}$$

for $\alpha = 1$. In A-6, $\Delta\sigma_{mean}$ refers to the change in mean stress left over after pore pressure has been reduced to 0.

[1] This may not be a valid assumption for very low porosity rocks. Using $\alpha = 1$ in this case will overestimate pressure and underestimate FOS.