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Approach to groundwater and pore water pressure modelling for different geotechnical conditions in open pit slope stability analysis

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Abstract

This paper presents two feasibility case studies related to groundwater modelling for pit slope stability studies at a diamond mine and a gold mine. While both open pit mine projects had a target final pit depth of about 450 m the impacts of groundwater conditions on the slope stability analyses are very different. The former required very detailed analysis and simulation of pore water pressure whilst at the gold mine, both groundwater flow and pore water pressure had limited impact on the slope stability assessment. The two case studies demonstrate that pore water pressure does not always significantly influence the stability of the pit slopes and that it is essential to identify the key controlling factors for slope stability before embarking on detailed modelling of pore water distribution. However, when pore water pressure and groundwater flow are identified as controlling factors due to geotechnical setting, extensive numerical modelling of groundwater flow is required to optimise a dewatering/depressurisation system that achieves the required Factor of Safety (FS) from pit slope stability analyses. A fully integrated numerical modelling analysis of pore water pressure and geotechnical slope stability is an intensive, iterative exercise but the result of such work is very rewarding in terms of optimising pit slope angles.

1 Introduction

Groundwater modelling for mining projects is usually carried out to achieve some or all of the following objectives:

- Estimation of groundwater inflow into the mine.
- Optimisation of the mine dewatering system.
- Assessment of water resources for mine water supply.
- Assessment of potential impacts of mine dewatering on water resources.
- Simulation of groundwater rebound and pit lake formation after mine closure.
- Simulation of pore water pressure distribution for slope stability analysis and/or design of a slope depressurisation system.

A hydrogeological study is required at all stages of pit slope design. However, detailed simulation of pore water pressure distribution for slope stability analysis and/or design of a slope depressurisation system is not usually required for early study stages, unless the initial geotechnical slope stability assessment indicates that pore water pressure is a critical controlling factor in the stability of pit slope design. This is usually the case when the formations around the pit walls comprise low strength, saturated, semi-pervious units such as clayey material that cannot be dewatered using traditional pumping wells. In such case a depressurisation system needs to be considered in place of dewatering.

The difference between depressurisation and dewatering is that in the former groundwater cannot be drained under gravity to an unsaturated condition from the host rock formation. When dewatering is feasible, due to high effective porosity and connectivity of the pores and rock structures, groundwater can freely drain from the rock mass using pumping boreholes or other methods. Under natural conditions, pore water in a saturated, low conductivity material is usually under relatively static pressure that took long enough geological time to be established. During the development of a pit, groundwater in such rock formations cannot drain at a sufficient rate in relation to the deepening of the excavation, and can result in high pore pressures in the pit slope walls.

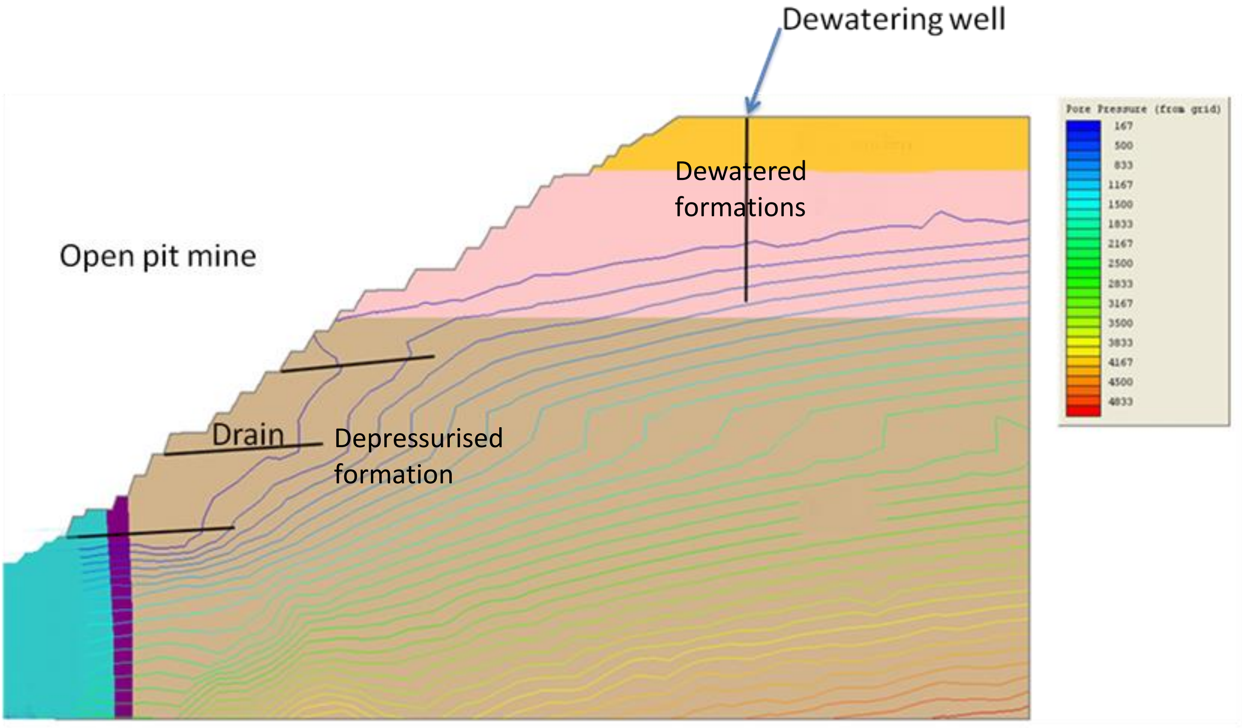

Figure 1 Figure illustrating dewatering and depressurisation of pit wall formations

In depressurised formations, whilst it may be possible to lower the piezometric head, pore water pressure will still remain higher for longer within the more clayey materials (schematically represented by the brown-coloured formation in Figure 1).

It is important to bear in mind that, although the porosity of clays may be higher than coarse grained materials such as sand, the effective porosity of the clay is much lower than that of sand. This infers that dewatering of a geological formation is mainly controlled by its effective porosity and structure rather than its total porosity.

The common factors behind pit slope failure can be summarised as follows:

1. Geological structure.
2. Rock mass strength.
3. Hydrogeological regime and pore water pressures.

In a saturated rock mass pore water pressure exerts a significant control on the effective stress within the rock mass. Dewatering or depressurisation of the geological formations around the pit walls to lower pore water pressures leads to increased rock mass strength and hence more stable (and, from a design point of view, steeper) slopes in the mine. This results in a minimal amount of rock waste with potential for significant cost savings, thus maximising the NPV of a given project.

When pore water pressure is a controlling factor in pit slope stability, using a simple phreatic surface in pit slope, stability analysis as a pit develops can result in either:

- Over-estimation of pore water pressure in the low permeability formations if toe drains or other depressurisation systems are considered, leading to more conservative pit slope angles; or

- Under-estimation of pore pressure in the low permeability formations if no depressurisation system is considered, yielding optimistic pit slope angles that may lead to pit slope failure.

Therefore, when pore water pressure and groundwater regime are identified as controlling factors due to the geotechnical setting of the mine, the most effective way to assess and design a depressurisation system that achieves the required slope design criteria is for an integrated process including groundwater modelling within the slope stability analysis and design.

2 Analysis and results

To optimise the dewatering systems for the two mine projects presented in this paper, steady-state numerical models have been built and successfully calibrated to simulate groundwater flow in the geological formations surrounding the proposed open pits, including any interaction between groundwater and local rivers and lakes. The numerical models have been constructed using Modflow (Harbaugh and McDonald, 1996; Harbaugh, 2005).

Subsequently, the calibrated numerical models have been converted into transient models to estimate the potential groundwater inflows into the proposed pits as they develop, and to determine the dewatering and/or depressurisation requirements to achieve, or exceed, the identified acceptable slope design criterion. In both cases refined groundwater flow models included consideration of regional model results. However, during associated slope stability analyses it became evident that the degree of groundwater model refinement required was different for the two projects.

2.1 Gold mine case study

The site is located in West Africa in a relatively flat area of sparsely vegetated grassland with a final planned pit depth of 450 m.

An extensive hydrogeological investigation programme provided input for the preparation of a water management plan at the open pit. Amongst other investigations, packer testing, spinner testing, pumping tests, slug tests, down hole acoustic televiewer (ATV) survey, geotechnical and geological core logging (8 vertical boreholes and 6 inclined by an angle ranging from 45 to 75°) and water quality monitoring in groundwater monitoring boreholes have been carried out to investigate the hydrogeological properties of the fractured rock mass at the project site. Depth of the 6 inclined holes ranges between 400 and 550 m, while seven of the 8 vertical boreholes have depth between 300 and 425 m, and the shallowest hole is 125 m deep.

The spinner test is used to understand the nature of fractures, and particularly those that are continuous and inter-connected within a wider fracture network, and is achieved by using a downhole impeller flow logging technique. Known as 'spinner' testing, it accurately assesses the variation of hydraulic conductivity with depth through the sequence. The testing takes place under pumped conditions, using a portable submersible pump to quantify the induced flow (Qspin in L/min) from fractures down the hole.

Dynamic downhole spinner flow surveys (carried out simultaneously with pumping at constant low flow rate) and packer tests in 10 boreholes around the proposed pit clearly indicated the top 130 m as the most hydraulically conductive rock mass. The spinner test results indicated the absence of a perched aquifer and/or pressurised confined aquifers in the area. The information from the spinner and packer testing were combined with pumping test results, geotechnical logs and geological logging to create a three layer conceptual model (Figure 2) comprising the overburden, the zone in which inflows were detected ('inflow zone'), and the rest of the rock mass where no inflows were detected.

The results of spinner and packer tests also enabled the transmissivity of inflow structures to be quantified. The addition of geotechnical logging information confirmed the exact depth of inflow structures, as structure depth could be measured accurately by ATV and confirmed in the drill cores. This enabled the thickness of the highly permeable zone to be more confidently constrained in the conceptual model. This has important implications for the estimation of groundwater inflows to the pit and for the design of a more efficient and cost-effective dewatering system.

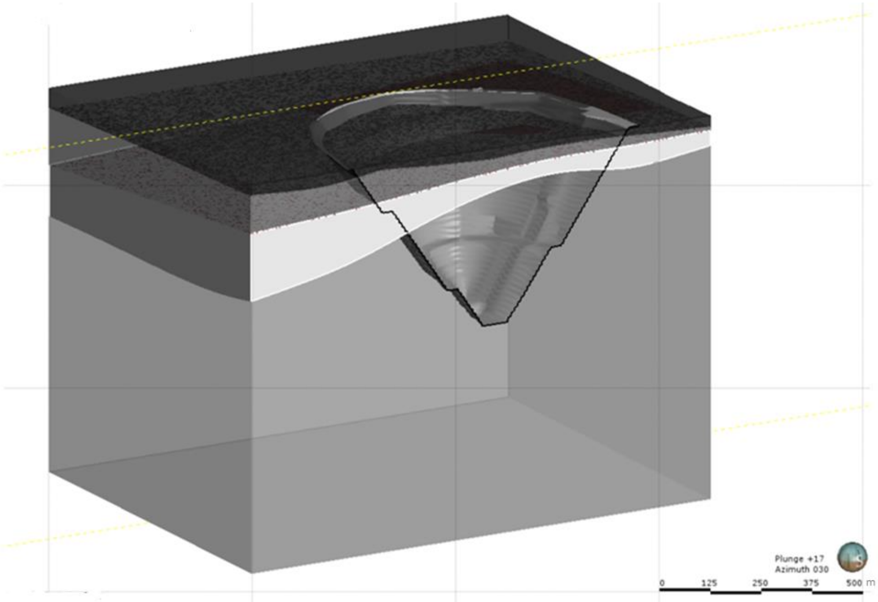

Figure 2 Cross section west–east of the proposed pit shell. Zone in which inflows were detected depicted in white, the weathered zone in black and the remaining rock mass in grey

The rock formations at the project site are sub-vertically dipping and strike to the northwest. The hydraulic testing in combination with core geotechnical logging demonstrated that groundwater flow is not related to lithology but rather to geological structure. Therefore groundwater modelling has been carried out using vertical grid discretisation and using hydraulic parameters based on the results from the hydraulic testing. Hydraulically distinct horizons have been distinguished which comprise the following, with increasing depth: a saprolite and weathered horizon, a fractured rock horizon (major inflow zone with higher hydraulic conductivity), a slightly fractured rock horizon (inflow zone with low hydraulic conductivity), and a fresh rock horizon which comprises the bulk of the rock mass where spinner flow survey did not detect any groundwater flow.

2.1.1 Approach to pore pressure evaluation for slope stability modelling

Initially conservative, nominal phreatic profiles were used in slope stability analyses for the FS. The analysis indicated that pore water pressure does not represent a controlling factor in the slope design. This initial work was then further refined using pore water grids.

The numerical groundwater model developed for the project was made up of 13 layers, each of 35 m thickness. The cell size used for the regional model was 90 × 90 m, however the refined numerical model cell size was reduced to approximately 10 × 10 m to refine estimation of the potential inflow of groundwater into the pit and obtain the phreatic surfaces and/or pore pressure grids needed for the slope stability analysis.

Groundwater models were developed to simulate the likely phreatic conditions once the pit reached the final wall position, assuming no dewatering system was installed. The model results suggested that the phreatic surface runs along the face of the slope to depths of approximately 140 to 150 m below ground level, as shown in Figure 3 for the pit stage at year seven. The contours and colour fill scheme in Figure 3 illustrate the groundwater levels (in meter above sea level) and profile around the pit. The model results suggest more or less similar water table position in Figure 3 for the subsequent years of mining. A phreatic surface mimicking the groundwater model result was applied to each of the sections used in the overall slope analysis.

For the initial stability analysis of the upper domains (saprolite, saprock and weathered zones) the slopes were set to be fully saturated. This was so as to simulate the worst case scenario and to calculate minimum slope angles in these materials so to have a base to work from for the subsequent analyses. For the overall slope stability modelling of the Central Pit (including all lithologies) the modelled phreatic surfaces were utilised, together with a sensitivity analysis on the phreatic surface.

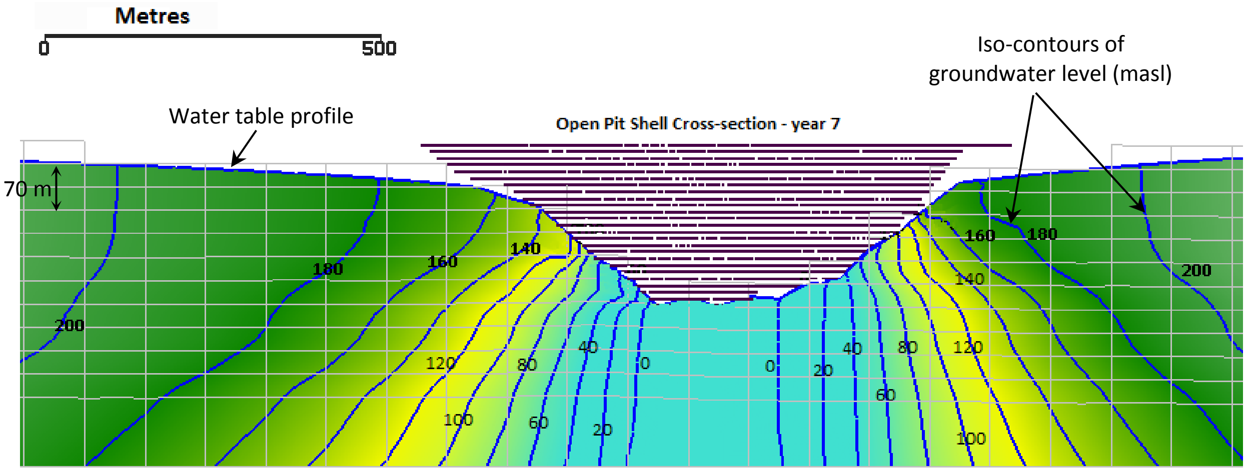

Figure 3 Example of groundwater model results showing cross-section of pit shell and simulated phreatic surface

Figure 4 and Table 1 show the results of the phreatic surface sensitivity analysis undertaken upon the total pit slope height. The results show that, as the phreatic surface is pulled back from the slope, the FS increases; which is to be expected. As the base case simulates the phreatic surface running along the face of the pit, with Factors of Safety >2, there is no concern regarding water pressures on overall slope stability in terms of the rock mass. The geotechnical team was prevented from increasing the slope angles (as these high FS values would usually allow) due to structural constraints.

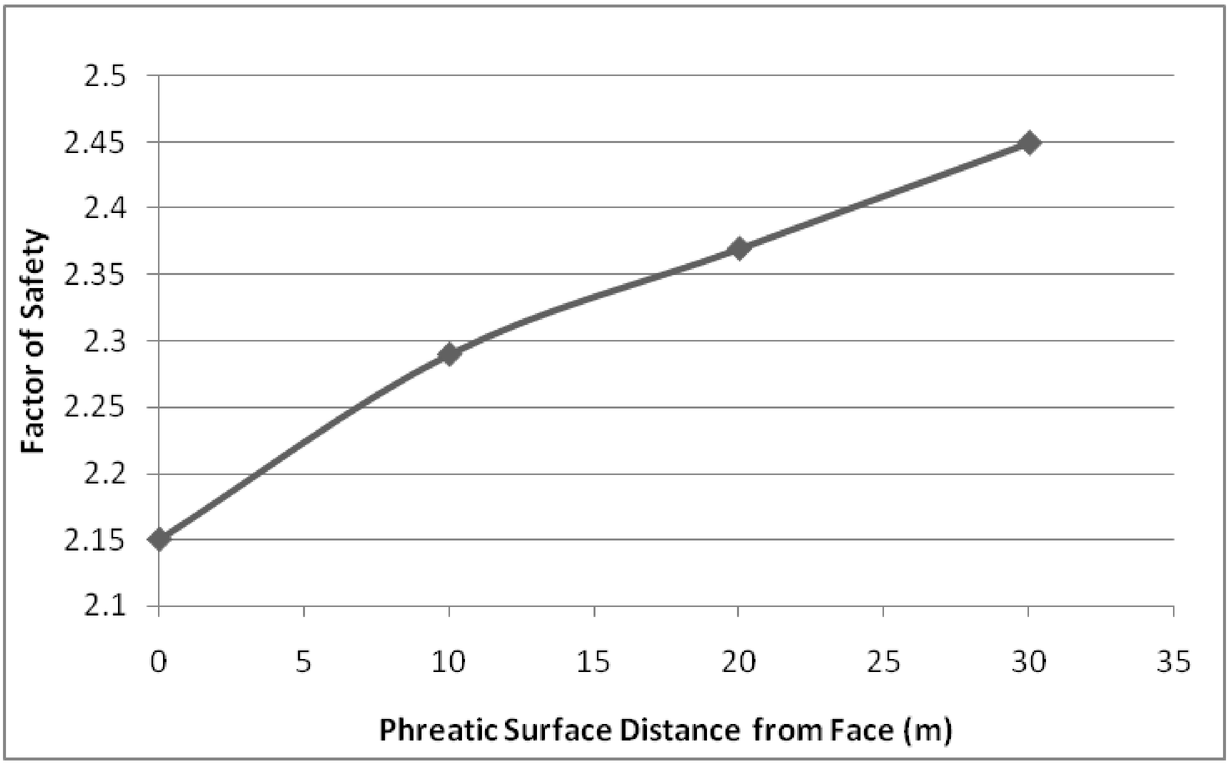

Figure 4 Distance from face of phreatic surface versus Factor of Safety

Table 1 Factor of safety (FS) results for phreatic surface sensitivity analysis

Section	Phreatic Surface	FS
Original value	On face	2.15
Scenario 1	10 m from face	2.29
Scenario 2	20 m from face	2.37
Scenario 3	30 m from face	2.45

2.2 Diamond mine case study

A conceptual hydrogeological model cross-section is presented in Figure 5. In this project the geological formations in the proposed open pit vicinity consist of mostly stratified sub-horizontal marine sediments as follows:

- Group 1 – Middle Carboniferous and Permian formations, comprising dolomitic limestone and sandstone, overlain by thin, Quaternary, unconsolidated sediments.
- Group 2 – late Pre-Cambrian formations of inter-bedded sandstone and mudstone with more dominant sandstone intercalations.
- Group 3 – older late Pre-Cambrian formations of inter-bedded mudstone and siltstone with more common mudstone intercalations.

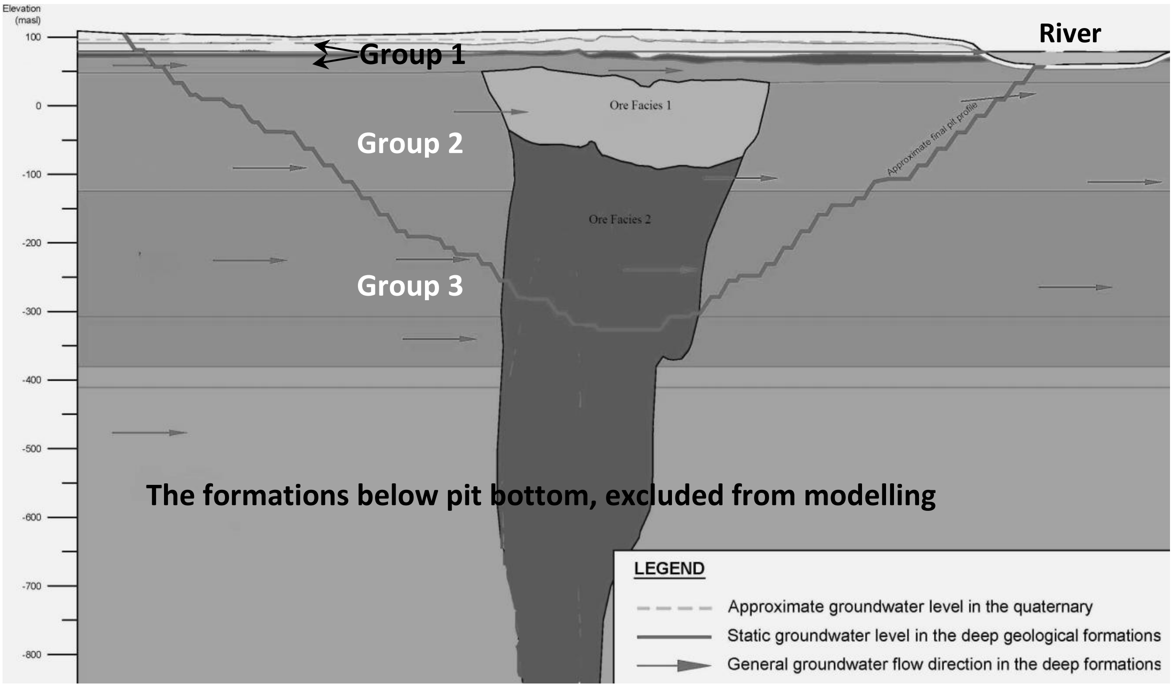

Figure 5 Conceptual hydrogeological model cross-section of the diamond mine

The groundwater flow model developed is made up of fifteen layers to a depth of more than 500 m (nominal elevation was assigned to the lowest mode layer such that the latter is thick enough to prevent impact on model results). Based on investigation drilling with pumping tests and packer tests Groups 2 and 3 rocks were expected to form the main aquifers that would govern the amount of water inflow into the open pit. Before groundwater modelling was carried out the results of pumping tests (five tests as part of the FS and more than ten in previous investigation programmes) in vertical boreholes demonstrated that vertical boreholes were the most appropriate tool for the dewatering of the uppermost (Groups 1 and 2) geological formations down to a depth of 250 m. The pumping tests demonstrated that high pumping rates, water level drawdown and large extent of a cone of depression are achievable in the top layers. Therefore, in the numerical model, vertical boreholes have been considered to dewater the open pit down to such depths. However, pumping and packer tests carried out in the formation below the 250 m depth showed that vertical dewatering boreholes should not be envisaged in these deeper formations due to the very low overall hydraulic conductivity and relatively high vertical to horizontal hydraulic conductivity of these formations. Therefore, dewatering simulation of the deep formations considered the use of sub-horizontal drains only.

Based on the assumption that the Group 1 and 2 geological formations could be effectively dewatered using vertical boreholes, and pore water pressures in these formation were not considered to represent a constraint to pit slope stability, the main focus of intensive groundwater modelling work, was on the Group 3 formation that was assumed best depressurised using sub-horizontal drains.

The key criterion for an optimal depressurisation system for the Group 3 formation was to fulfil the geotechnical requirements of stable pit slopes. Consequently the hydrogeological and geotechnical teams have carried out simultaneous analyses for both pit dewatering and slope stability in an iterative way.

Slope stability analysis has been carried out using Limit Equilibrium Method (LEM) in SLIDE software (non−circular; Janbu Corrected) (Rocscience, 2010), as well as FLAC (Itasca, 2007a) and FLAC3D (Itasca, 2007b) programs. In the former method, various phreatic surface configurations have been used to assess the sensitivity of pit slope stability to pore water pressure within the pit walls. These demonstrated that pore water pressure is effectively a controlling factor, and therefore various depressurisation systems must be simulated to lower pore pressures to acceptable levels.

This led to an intensive iterative exercise of groundwater modelling providing pore pressure grids and slope stability analyses until the required pore water pressure distribution along the pit walls provided an acceptable safety factor. The complexity of the depressurisation system needed to be increased for the pore water pressures to reach the required levels.

2.2.1 Slope limit equilibrium analysis results focusing on Group 3 formation

Table 2 shows the result for pore pressure scenarios with no seepage face on the Group 3 formation slope. As expected, the FS improves as the water surface moves away from the slope face. It was initially considered that there would be a seepage horizon on the face of the Group 3; this possibility was tested at various seepage face heights (Table 3).

It was demonstrated that the height of the seepage face does not affect the stability of the slope significantly; it is the distance that the free water surface is back from the face that is most influential. Following recommendations from the hydrogeological studies, a phreatic surface positioned 30 m back from the face with a seepage face height of 50 m was used to set the initial slope angle for the Group 3, as illustrated in Figure 6. This pore pressure scenario indicated that a Group 3 slope of 24.6° was able to realise a FS of 1.3. This FS value is obviously very low, however as noted in the previous sections, it is considered that phreatic surfaces can over-estimate water pressures and subsequently under-estimate the slope angles that can be achieved. The water pressure grid produced by the groundwater model, reflecting the effect of drainage by the horizontal drain holes, was then analysed. This increased the achievable slope angles and indicated that the pit slope in the formations of Group 3 could be worked at an angle of 31° for a FS of 1.3.

Table 2 FS for Group 3 slope angles – for phreatic water surface distances back from pit face until 50 m above pit bottom

Group 3 – Factor of Safety						
Slope angle	Fully drained slope	Water table surface 10 m from pit face for a height of 50 m above pit bottom	Water table surface 20 m from pit face up to 50 m above pit bottom	Water surface 30 m from face up to 50 m above pit bottom	Water table surface 40 m from pit face up to 50 m above pit bottom	Water pressure grid
22°	1.82	1.32	1.33	1.34	1.36	1.55
28°	1.59	1.19	1.20	1.22	1.23	1.42
30°	1.52	1.15	1.17	1.19	1.20	1.33
32°	1.47	1.12	1.14	1.16	1.17	1.25

Table 3 FS for Group 3 slope angles – simulating differing water seepages at differing pit face heights

Group 3 Formation – Water Surface 30 m from Pit Face to a Height up to 220 m – Factor of Safety						
Slope	50 m Seepage face	75 m Seepage face	100 m Seepage face	125 m Seepage face	150 m Seepage face	220 m Seepage face
22°	1.33	1.33	1.32	1.32	1.31	1.30
24°	1.28	1.27	1.27	1.26	1.25	1.24
26°	1.24	1.23	1.23	1.22	1.21	1.19
28°	1.21	1.20	1.19	1.18	1.18	1.16
30°	1.17	1.16	1.16	1.15	1.14	1.12
32°	1.14	1.13	1.13	1.12	1.11	1.09

2.2.2 Refined groundwater model for depressurisation of Group 3 formation

The initial optimisation of the dewatering system has been carried out using the regional model in which the grid cell size in and around the pit area is 25 × 25 m. This work showed that dewatering of the formation of Group 3 would require a dense network of horizontal drains which cannot be simulated using the 25 m cell size model. Therefore a local model was created and the grid refined to a 10 m cell size in and around the open pit walls. Further optimisation of the Group 3 dewatering system was carried out using this local model which demonstrated that further grid refinement was required to simulate a denser horizontal drain network. Therefore, the local model was further refined to a 5 × 5 m cell size in the pit area to enable simulation of 25 m spaced drains. The refinement resulted in a local model with 472 rows, 468 columns, and 15 layers, making up a total of 3,313,440 cells.

Various sub-horizontal drain configurations were simulated to obtain the optimal drain setting that would enable dewatering of the Group 3 formation to a level that met the slope stability requirements as defined by geotechnical analyses. The various configurations of these sub-horizontal drains used in the model simulations are shown in Figure 6. As shown in the latter, four drain layers have been considered in Group 3 with a vertical spacing of about 50 m, which is approximately the height of two benches.

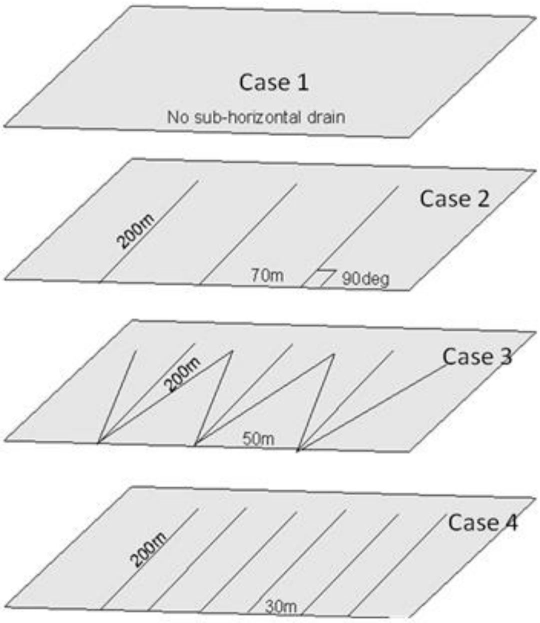

Figure 6 Configuration of the sub-horizontal drains used to simulate depressurisation of Group 3 formation in the model

The refined transient groundwater model demonstrated that dry open pit walls cannot be achieved within the required mine time schedule due to the low hydraulic conductivity of the Group 3 formation. However, the required level of formation depressurisation to a level that ensures pit slope stability was achievable using 30 m spaced drains, as well as the 50 m spaced cross-drains, as shown in Figure 7. However, the most significant depressurisation is obtained in locations where the 50 m spaced cross-drains were used. The highest depressurisation was obtained in the deepest layers (i.e. the lowest Group 3 layer) where a depressurisation of up to 130 m hydraulic head was achieved. The slope stability analysis using pore water grid cross-sections also demonstrated that the required safety factor had been achieved.

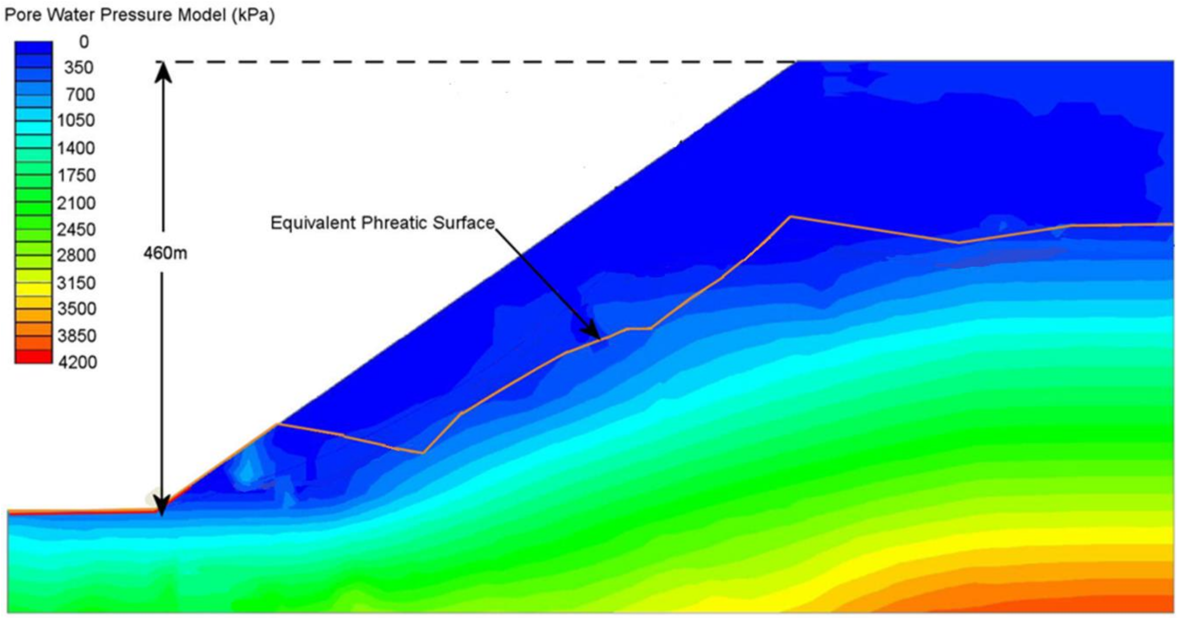

Figure 7 Cross section of the pressure head achieved with the single 30 m spaced drains (vertical spacing of the four drain layers is 50 m)

An equivalent phreatic surface, determined as the equivalent pore water pressure along the failure profile, calculated from the LEM analyses, was superimposed for comparison with the phreatic surface in the upper horizons. This demonstrated that the pore water pressure would have been over-estimated had the pore water pressure grid not been used in the analysis.

In summary the groundwater model results illustrated that the open pit itself is a very good means of depressurisation of the surrounding geological formations. However, the presence of the pit alone was not sufficient to achieve the required depressurisation in the Group 3 formation. The modelling also showed that the effect of the horizontal drains was slow and therefore the installation of the toe drains must go hand in hand with the advancement of the pit excavation. Furthermore, it was recommended that inclined toe drains should be installed in the lowest pit benches, drilled downwards into the bench wall, to enable depressurisation of the Group 3 formation ahead or at least simultaneously with the excavation.

2.2.3 FLAC 2D and 3D analysis

In addition to limit equilibrium analysis, further slope stability modelling was carried out using FLAC programs. The Model setup in FLAC3D is illustrated in Figure 8, with pore water pressure grids obtained from groundwater model being used, including for various toe drain configurations.

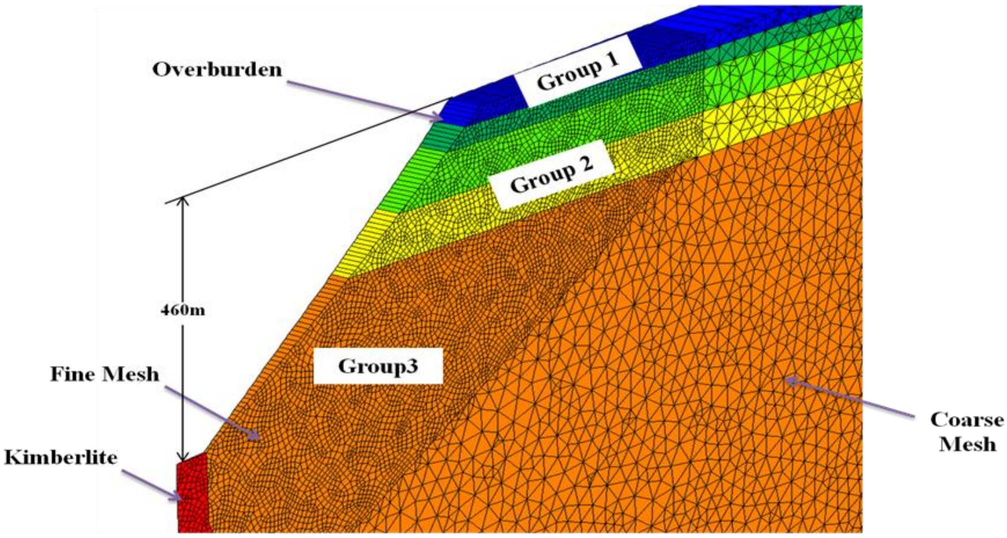

Figure 8 Geotechnical model setup – FLAC3D

Compared to the limit equilibrium method analyses, results from FLAC3D modelling demonstrated that even steeper slope angles could be achieved. The circumferential confining forces of a circular pit simulated by the 3D analysis allowed for 3° steeper slope angles for the overall pit. The slope angle increase was greatest at the base of the pit (5°) as the circumferential forces were more effective due to the smaller diameter.

3 Conclusions

Combined groundwater and slope stability analyses have shown that the level of detail of the groundwater modelling and optimisation for the purpose of providing input to pore water pressure analysis varies dramatically according to the geotechnical setting of the mine and the sensitivity of the mine slope stability to pore water pressure around the pit walls.

In the case of the diamond mine, pit slope angle optimisation required intensive groundwater and pore water pressure modelling. A local groundwater model also needed to be extracted from the regional model and refined to a 5 × 5 m cell size in the pit area to enable simulation of a minimum drain spacing of 25 m. Various sub-horizontal drain configurations, including (1) no drain, (2) 30 m spaced drains, (3) 50 m spaced cross drains, and (4) 70 m spaced drains, were simulated to obtain the optimal drain setting that would enable dewatering to a level that met the geotechnical slope stability requirements. Four drain layers with a vertical spacing of about 50 m, which is approximately the height of two benches, were required.

In the case of the gold mine study, initially conservative nominal phreatic profiles were used in slope stability analyses. The results indicated that pore water pressures do not represent a controlling factor in the slope design. This initial work has further been refined using pore water grids, but not to the same extent as the diamond mine case study. The groundwater model assumed only the effect of the pit excavation itself as the pore pressure dissipation mechanism, without the consideration of a dewatering system. The result of such groundwater modelling provided pore pressure grids that satisfied the geotechnical requirements of the pit slope design.

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