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Effects of Boundary Conditions and Boundary Block Sizes on Inflow to an Underground Excavation – Sensivity Analysis

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ABSTRACT

A coupled hydro-mechanical analysis is carried out for the prediction of groundwater inflow into a mine and to investigate parameters which control total flow to the excavated cavity, using two-dimensional Universal Distinct Element Code, UDEC (Itsca, 1996). In order to evaluate realistic parameters which control the water ingress to a subsurface cavity, two types of joint patterns are analyzed with different stress-hydraulic boundary conditions for various boundary block sizes. Findings of this study show that total inflow rates decrease with increased block sizes, irrespective of the boundary conditions and insitu stress ratios. The sensitivity analysis provides the most appropriate block size to achieve consistent results for a given joint pattern and excavation geometry. The analysis reveals that the hydraulic boundary conditions (eg. permeable boundaries) can greatly influence the water inflow to a subsurface cavity. Moreover, increase of the insitu horizontal stress to vertical stress ratio has a significant effect on water flow through discontinuities.

1 INTRODUCTION

Accurate prediction of mine water inflow to a tunnel is one of the essential tasks of underground work during design and construction stages. In the present days of increased environmental and regulatory controls, the evaluation of the quantity and quality of total inflow to the mine and the procedures of discharging polluted mine water are significant factors in the development and operational stages of mines. The prediction of inflow volumes as discussed in this paper is expected to minimise most environmental hazards (eg. Pollution of water bodies, lowering of groundwater table), damage to equipment and time delay associated with dewatering.

Adverse situations and the risk of inundation can only be mitigated by the correct evaluation of protection measures during the design stages. Therefore planning decisions concerning groundwater control measures such as grouting and dewatering should be implemented in advance, so that the whole operation system would contribute more efficiently towards greater economics of scale within a safer work environment. For rational analysis and design, it is essential to understand the hydraulic and mechanical behavior of rock mass, the response of natural joint system, and how groundwater table responses to changes induced by proposed sequence of excavation. Underground

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openings represent a region of stress release causing mechanical deformation and pressure drop. Depending on the regional stress fields, portion of rock around the opening may experience compression while the other portion is under tension. For hard rocks, mechanical effects will be mainly concentrated in the discontinuities.

The existing ground conditions (eg. joint patterns and their properties, type of rocks and the ground water potential) will determine the method of flow analysis, apart from the availability of computer resources and time. Despite the recognition of the importance of water flow through fractures into an excavated cavity the coupled hydro-mechanical behavior is not still well understood because of the complex behaviour of rock mass associated with the excavation. For accurate evaluation of mine water inflow towards the proposed excavation, one needs to identify: (a) geological structures such as joints, bedding planes, faults and dykes, (b) potential water resources and (c) initial and re-distributed stress fields before and after excavation. Closed form solutions are now hardly employed for flow calculation because real groundwater problems contain a large number of time dependant variables which cannot be handled efficiently by these techniques. Considerable interest has developed in recent years concerning the usage of numerical models for computation of water flow through a rock mass.

2 METHOD OF FLOW CALCULATION

Numerical techniques using boundary element, finite element and distinct element methods have been used to simulate groundwater flow in jointed rock masses. In conventional rock mechanics, most of the above numerical models are based on porous media, discrete fracture flow theory and dual porosity approaches. The rock is assumed to be approaching a porous media by decreasing the fracture spacing or by increasing the fracture density of a mass with at least three orthogonal joint sets. In such a situation, one may select a porous media approach for predicting fluid flow rates (Long and Witherspoon, 1985, and Oda, 1986). In this approach, it is not feasible to incorporate the consequences of shear-related opening of fractures caused by effective stress. Also the degree of connectivity of joints and super-connection with faults are usually overlooked. Consideration of these factors into any flow analysis through discontinuities with impermeable rock matrix is only possible with the discrete fracture theory. It is well understood that if the number of fracture sets are not orthogonal or have different densities, one may apply the discrete fracture model in which the flow is dominated by a number of large through going joint planes, whose location and orientation in the area of interest are assumed to be known. In the past, a number of researches (eg. Long and Witherspoon, 1985, Indraratna, 1995 and Herbert 1996) have employed this approach for flow calculations in a jointed rock mass. In this study, the discrete fracture theory is used to simulate flow through fractures.

3 SELECTED JOINT MODELS

It is understood that the hydraulic behavior of a rock mass is determined by the geometry of the fracture system and the hydraulic potential. Thus, in order to analyse the water flow behaviour of a rock mass, one may need to identify the detailed characteristics and geometric aspects of the individual discontinuities and joint network. Often for simplicity, three basic joint sets can be considered, which are roughly perpendicular to one another and thereby divide the whole rock mass into intact rectangular blocks or cubes. The discontinuities may be closed, filled with some other material such as silt or clay or may contain voids.

In this investigation, two types of joint models, which commonly represent sedimentary rocks, have been considered for fluid flow analysis.

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(a) Horizontal bedding planes with vertical staggered joints, as shown in Figure 1a.
(b) Two continuous joint sets with inclination of 30^0 and 120^0 to the horizontal (Figure 1b).

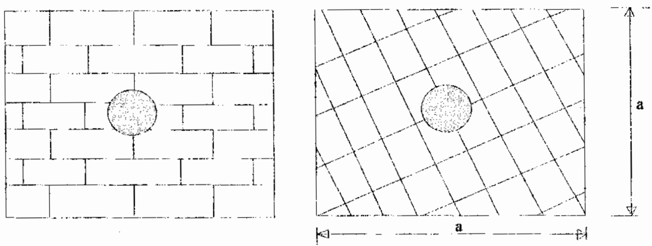

Figure 1a - Joint Model 1

Figure 1b - Joint Model 2

Note: Boundary block size = a x a m^2

Figure 1: Network of joint models analysed

The detailed properties of the two joint models are given in Table 1. The material properties of the rock matrix, discontinuities and pore fluid pressures are presented in Table 2. The joints in the models were generated in two-dimension using UDEC. Two distinctly different analyses were carried out as described below.

Analysis 1: Centers of boundary blocks were selected 50m below the ground surface. The watertable is assumed to be 10m below the ground surface.

Analysis 2: Dimensions of the boundary blocks were selected so that the top boundary of block coincided with the groundwater table.

Table 1: Joint parameters of joint model 1 and model 2

Joint Model 1				
Parameters	Units	Joint set 1	Joint set 2	Joint set 3
Orientation	deg.	0	90	90
Spacing	m	4.0	3.5	5.0
Gap length	m	0	4.0	4.0
Trace length	m	25	4.0	4.0

Joint Model 2			
Parameters	Units	Joint set 1	Joint set 2
Orientation	deg.	30	120
Spacing	m	4.0	3.5
Gap length	m	0	0
Trace length	m	25	25

4 NUMERICAL ANALYSIS

The Numerical analysis was carried out for a 6m diameter circular tunnel. In order to reduce the complexity of the problem symmetry was assumed about the vertical axis for the joint model 1(a). Although this property of symmetry may not always represent the actual field situation, it

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allows for a greater rate of convergence in the model. However, symmetry cannot be applied to joint model 1(b).

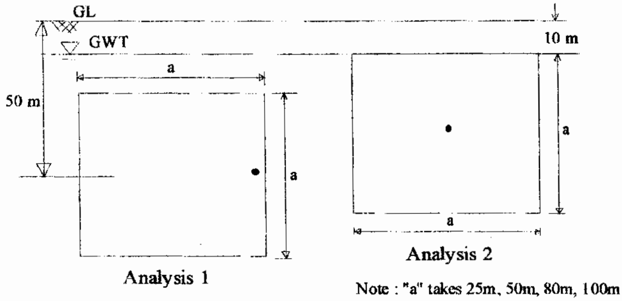

Figure 2 : Selected boundary blocks for analyses 1 and 2

Table 2: Material properties of rock mass and water

Material	Parameter	Units	Rock Matrix	Discontinuities			Fluid (water)
				Joint Models 1 and 2			
				Joint set 1	Joint set 2	Joint set 3	
Rock Matrix	Block modulus	N/m^2	2.26×10^{10}				
	Block shear modulus	N/m^2	1.1×10^{10}				
	Density	kg/m^3	2500				
	Cohesion	N/m^2	6.72×10^6				
	Friction angle	deg.	42				
Rock fractures	Normal stiffness	N/m^2		2.5×10^{10}	1.2×10^{10}	1.6×10^{10}	
	Shear stiffness	N/m^2		2.0×10^{10}	1.0×10^{10}	1.0×10^{10}	
	joint permeability factor	$Pa^{-1}\ sec^{-1}$		100	100	100	
	Friction angle	deg.		44	43	42	
	Initial aperture	m		1.0×10^{-3}	2.0×10^{-3}	2.5×10^{-3}	
	Residual aperture	m		3.0×10^{-4}	4.0×10^{-4}	6.0×10^{-4}	
Fluid	Density	kg/m^3					1000
	Dynamic viscosity	Pa.sec					8×10^{-4}
	Bulk modulus	N/m^2					2×10^9

Two different models, namely the joint area contact model and the Mohr-Coulomb plasticity model (Itsca, 1996) were assigned to represent physical response of joints and intact rock, respectively. Furthermore, rock matrix was assumed to deform elastically under the stress redistribution caused by stress relief.

4.1 Initial and Boundary Conditions

The assumed mechanical boundary conditions (displacement) and applied boundary stresses are shown in Figure 3. The initial compressive stress is defined by the isotropic stress associated with

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gravity represented by the following equations:

$$\sigma_{yy} = \rho_r\, g\, y \qquad (1)$$
$$\sigma_{xx} = \alpha_1\, \sigma_{yy} \ \text{ and } \sigma_{zz} = \alpha_2\, \sigma_{yy} \qquad (2)$$

where, ρ_r = density of rock
y = vertical distance (depth), measured downward from the ground surface.
σ_{yy} , σ_{xx} and σ_{zz} = insitu stress components in x, y, z directions.
α_1 and α_2 = insitu stress ratio factors.
It is assumed that α_1 and α_2 remain constant throughout the analysis.

Three different hydraulic boundary conditions (Figure 3) were considered for joint models 1 and 2 as described below.

Case 1: constant water pressure along top and bottom boundary surfaces while linearly varying the fluid pressures with depth. No pore pressures applied along the right boundary surface, due to axis of symmetry.

Case 2: no pore pressures along the top boundary surface as the groundwater table coincides with top boundary surface. Constant water pressure along the bottom boundary, while linearly varying the fluid pressure along the left and right vertical surfaces.

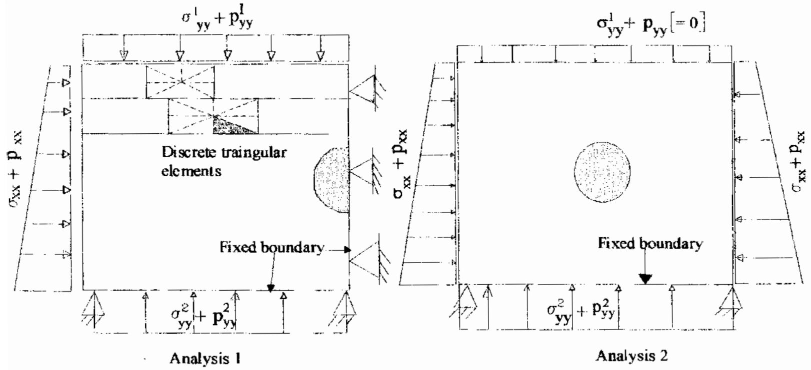

Figure 3: Boundary Conditions applied into the model

Case 3: same as in case 2, except the bottom boundary is made permeable, such that excess pore pressures are totally dissipated. This models a sand aquifer or sand lense underlying the fractured rock.

The fluid pressure(p_{yy} or p_{xx}) is given by $p = \gamma_w\, y$ where, γ_w is the density of water and "y" is the vertical distance from the groundwater table. Initially there is no flow into the region and hydrostatic pressure prevails all around the excavation. Once the tunnel is excavated, a constant atmospheric pressure is applied around the tunnel surface.

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5 RESULTS AND DISCUSSIONS

The relationship between total water ingress and normalised block sizes is shown in Figures 4, 5 and 6, which indicate that increasing the block size will result in a decreasing flow rate irrespective of fluid boundary conditions or insitu stress ratios (ie. insitu horizontal stress/vertical stress). The normalised block area is defined by the total area covered by the mesh boundaries (boundary block) divided by the area of excavation. As verified by this analysis, when the boundary block size is increased, the effects of water pressure on discontinuities that are intersected by the tunnel boundary become less, consequently, a smaller inflow can then be expected due to the reduced hydraulic head. Decrease in flow rate becomes marginal when the normalised block size exceeds 350. This result seems valid for all the fluid boundary conditions and insitu stress ratios tested for the two joint patterns. Therefore, it is realistic to propose that the minimum normalised block size should be taken as 350 for the flow analysis based on UDEC, to obtain consistent flow rate.

Hydraulic boundary conditions can also play a major role on the water ingress to the subsurface cavity as shown in Figures 5 and 6. If one side of the boundary is treated as permeable (Analysis 2/case 3- Figure 6), a greater flow rate can be expected. As shown in Figure 6, The increased flow rate is approximately 1.75 times of the flow rate in Figure 5 for the same normalised block value size of 350.

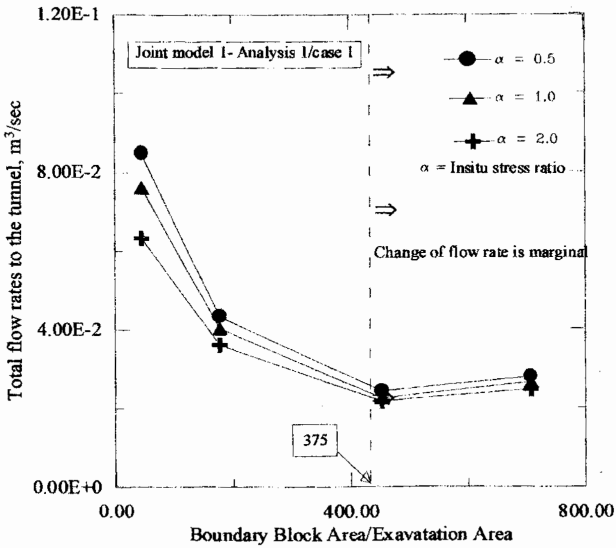

Figure 4: Total flow rate to the tunnel vs (boundary block area/total excavation area)

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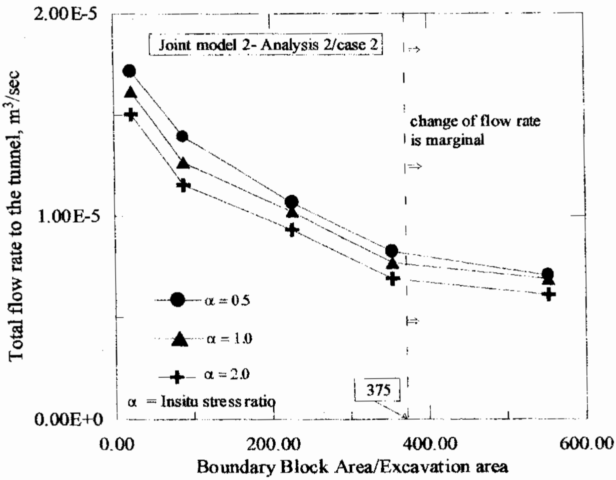

Figure 5: Total water ingress to the tunnel vs normalised bl ock sizes

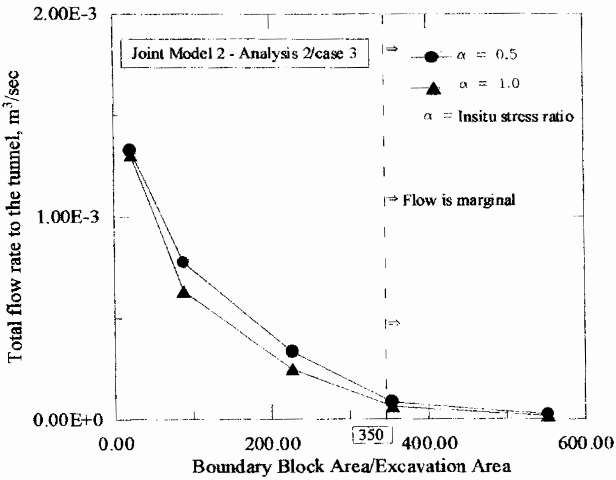

Figure 6: Variation of total water inflow to the tunnel with normalised block sizes

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Figure 7 presents the relationship of the total flow rate into the tunnel against the insitu stress ratio (α). As expected, flow rate decreases with increasing the horizontal stress. As the ratio of horizontal stress to vertical stress increases from 0.5 to 2.0, the reduction in the percentage of water ingress to the mine cavity changes from 5 to 15%. However, the change in flow is marginal (as low as 3 to 5%) when the insitu stress ratio exceeds 1.25.

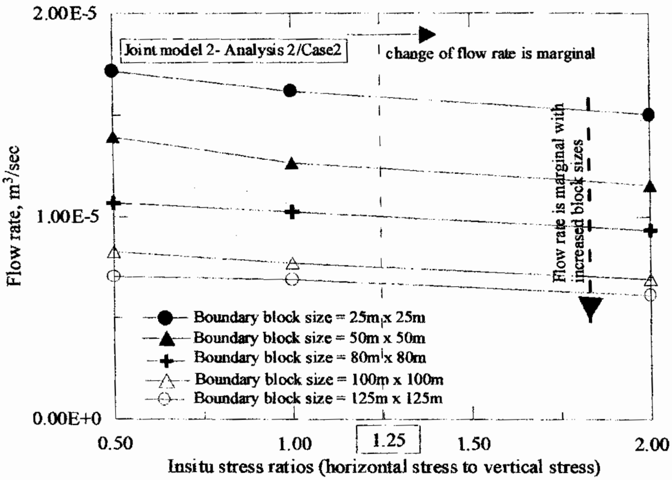

Figure 7: Variation of flow rate with insitu stress ratios

CONCLUSIONS

In order to determine water ingress to a mine, a fully coupled hydro-mechanical analysis was carried out with various geo-hydraulic and joint parameters, which influence the flow rate. It is useful to consider a relationship between total flow and the ratio of block area /excavation area, since it can be used to determine the approximate flow range for mapped discontinuities in a given area. The study reveals that change in flow rate becomes consistent (marginal fluctuation) when the boundary block area/excavation area exceeds 350 for regular joint patterns. Therefore, the recommended boundary block should be 15 to 20 times the diameter (or maximum width) of excavation. The study demonstrates that as the horizontal to vertical stress ratio is increased from 0.5 to 2.0, then the percentage decrease in total inflow lies between 5 and 15%. However, when the insitu stress ratio exceeds 1.25, then the rate of change of flow becomes very small. This is because, most joints have reached their residual aperture at the corresponding stress levels.

As the current analysis is limited to regular joint patterns, the analysis should be extended to include irregular joint patterns also, in order to establish general relationships between flow and block geometry. Furthermore, the effects of shear deformation of asperities on water flow through joints need to be incorporated for improving the numerical analysis.

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