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Distinct Element Analysis of Water Inflow to Underground Excavations

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ABSTRACT

A rational analysis of groundwater flow towards mine openings requires a thorough understanding of the coupled hydro-mechanical aspects of jointed or faulted rock masses. Although there has been a significant progress in this field during past 2-3 decades, further computational advances are imperative for predicting water inflow to underground excavations. In this study, after an overview of the fundamental hydro-mechanical aspects related to fluid flow in jointed rock, the application of a Distinct Element Method (DEM) numerical model is elucidated for a number of simplified joint systems surrounding a rectangular mine opening. In order to represent some common mining conditions in NSW, horizontal joints (eg. bedding planes) and vertical joint sets (with stagger) have been analysed. The effect of the insitu stress ratio, joint aperture size, joint stiffness and the joint pattern on water inflow is discussed, and a dimensioneless parameter (product of joint spacing / area of opening) introduced as an indicator of inundation. Based on this preliminary analysis, recommendations for further research have been identified.

INTRODUCTION

Mining or tunnelling underneath sandstone aquifers is common in many parts of the world. Substantial amount of water can be released to mine workings in the case of roof collapse sometimes causing inundation (Singh, 1986). The groundwater level existing within a jointed rock mass is an important factor requiring due attention in many excavation projects. In New South Wales, large reserves of coal lie under tidal waters, reservoirs, rivers and the Pacific Ocean. Sudden inrush of groundwater and the development of large seepage pressures can often cause safety, stability and operational difficulties. Underground excavations such as mines are of great concern because of the restricted work space, limited access and often the lack of proper dewatering facilities. It is anticipated that the development of groundwater inflow models will assist in the prediction of total volume of water flowing into a mine opening, assess the risk of inundation and identify the regions where the inflow rates are particularly excessive. After evaluating the risk of inundation, sufficient protective measures should be provided during the construction and operational stages. For numerical analysis and prediction, it is necessary to quantify the hydro-mechanical response of the rock mass in relation to the natural joint or fault mechanisms that govern the groundwater movements. Furthermore, the inevitable changes taking place in the hydro-geological system attributed to the excavation process must be incorporated in the predictive models. The complex and random nature of discontinuities makes it difficult to quantify the exact hydro-mechanical behaviour of the rock mass and to formulate reliable computational procedures for many field situations.

Analytical or numerical modelling of water inflow to mine openings requires:

a) Evaluation of material properties of both intact rock and discontinuities,
b) Assessment of groundwater conditions including the identification of other potential water sources and sinks,
c) The geometry and storage-conductivity characteristics of aquifers and aquicludes,
d) Identification of structural discontinuities (permeable bedding planes, joints, faults and dykes), as well as their mechanical properties,
e) Determination of the initial in-situ stress field, stress redistribution during and after excavation, displacements and seepage fields induced by the excavation process.

In the application of the distinct element method, the joint geometries, material properties and the initial groundwater and in-situ stress conditions must be prescribed. The data acquired from piezometric levels and bore hole pumping tests can be interpreted to back-analyse or verify the assumed conductivity parameters and to establish more accurate joint geometries. However, the accurate predictions depend also on the assumed boundary conditions which must be carefully assigned with respect to the excavation geometry and the convergence requirements of the stress, displacement, hydraulic potential and flow fields. The numerous factors contributing to water inflow into excavations and the associated risk of failure are highlighted in Figure 1.

HYDRO-MECHANICAL ASPECTS AND NUMERICAL MODELLING OF FLOW THROUGH JOINTS

The most appropriate method of analysis for a particular flow problem is not only influenced by the nature and extent of jointing but also by the availability and limitations of computer resources. The success of any prediction method is undoubtedly a function of the ability to accurately describe the water flow process within a given rock mass under different stress and strain fields. A rock mass essentially consists of intact rock (rock matrix) and discontinuities. While the flow through intact rock can be neglected, the major defects such as faults may often act as super-conductors. Significant flow components through any of these features should be incorporated in the numerical model for accurate prediction. The numerical model should be further calibrated according to the significance of major and minor joint sets, and to include the role of staggered joint sets. The depth of information required for design, the availability of appropriate computer software and iteration time constraints also influence the computational efficiency, hence, a compromise often becomes necessary in terms of simplified models.

The numerical methods of flow prediction can be divided into three main categories according to (a) continuum equivalent approach, (b) stochastic models and (c) discrete fracture network analysis (Long, 1983). The extent of anisotropy and inhomogeneity existing within a representative rock mass volume dictates the viability of this method. The extensive coputer time and storage requirements have often made the stochastic models unpopular. The discrete fracture network concept employed in many computational schemes requires detailed knowledge about the distribution of joints and the constitutive relationships

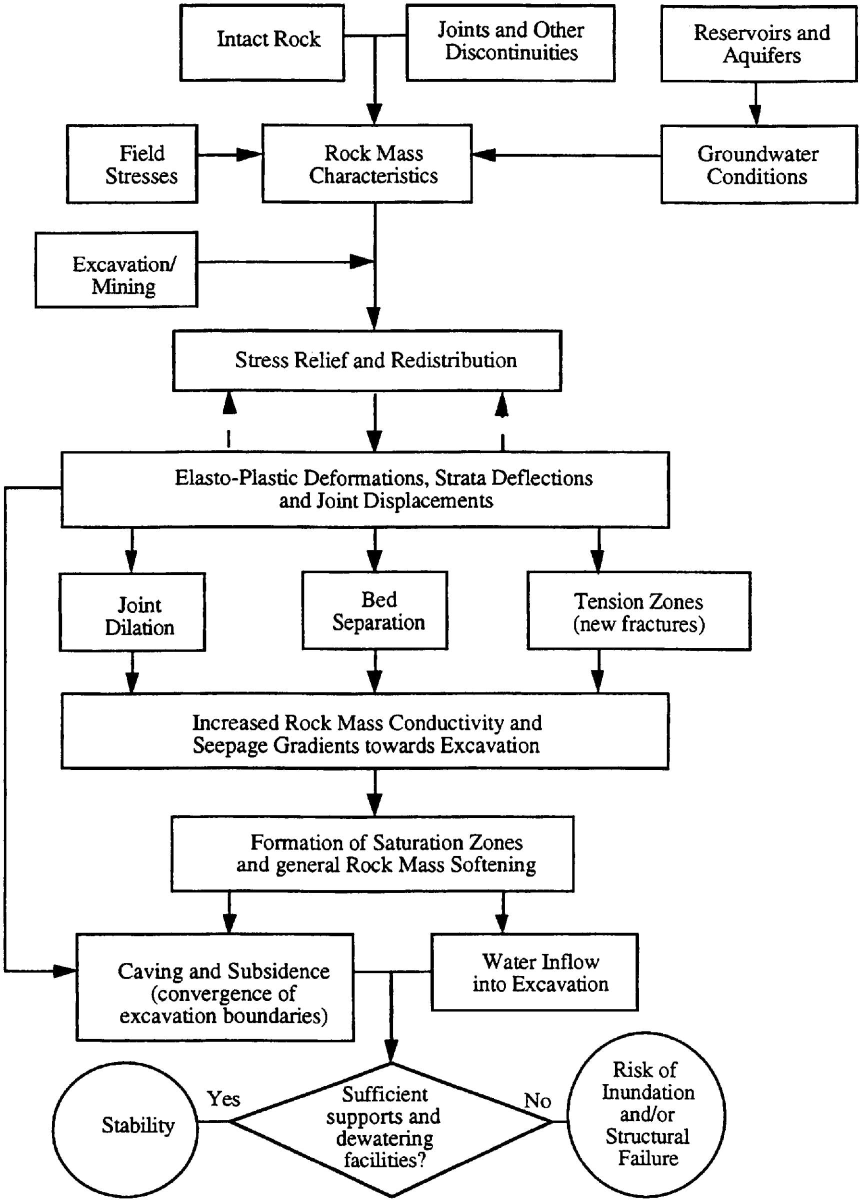


Figure 1 Factors Influencing Inundation of Excavations (after Indraratna et. al., 1994)

describing the flow in individual fractures when subject to various normal stress conditions and hydraulic potential gradients (Elseworth, 1993). Wei (1992) has pointed out that for any given site, an equivalent continuum approach or a stochastic discrete model may be adopted instead of the discrete fracture network schemes, if detailed information on distribution of fractures is difficult to obtain with the available field techniques. The distinct element method (DEM) has become a powerful tool mainly because of its sophisticated capability of handling coupled hydro-mechanical behaviour. The four main phases of analysis include, (a) formulation of governing equations to describe explicitly the deformation and fluid flow processes in a single fracture, (b) assimilation of an array of potential directions to simulate water flow towards a common node from several fractures, (c) integration of the flow response at all such nodes (junctions) to represent the effect of the overall joint system and (d) quantification of the effect of flow on rock mass deformation and vice versa.

Flow through a single fracture

In this paper, based on the assumption of steady laminar (incompressible) flow between smooth parallel plates, a cubic law is used to describe the flow through fractures. This theory is incorporated in the Universal Distince Element Code, UDEC (Itasca Consulting Group, 1993). In the past, a number of investigators have studied the validity of the cubic law for flow through fractures using artificial and natural joints (Witherspoon et al., 1980; Lee and Farmer, 1993). The results of these studies indicate that the cubic law is valid for smooth open fractures, if the correct mechanical aperture is considered. For rough open joints, the cubic law can be employed with a correction factor to incorporate the effect of roughness. For rough and tight fractures, the cubic law deviates from accuracy as the flow through such discontinuities is influenced by the inevitable stress changes. At low stress levels, the joint aperture and the corresponding flow rate vary substantially with the applied normal stress, whereas at relatively high stress levels, no significant change in aperture and flow rate is observed with the stress changes (Cook, 1992). This implies that the residual aperture can be assumed to be constant at high normal stress levels.

The condition of flow can be considered to be non-linear when the flow rate is not directly proportional to the hydraulic gradient. It is well-known that non-linear flow situations take place when the inertial effects (due to acceleration, divergence or convergence) and kinematic effects (due to head losses at high velocity or turbulence) become important under high hydraulic gradients.

Distinct Element Modelling

In explicit hydro-mechanical coupling, two separate models (hydraulic and mechanical) are developed, and the information is transferred between the two models using iteration schemes until convergence occurs. Experience has shown that while this technique is more appropriate for steady state problems, it is less successful in transient problems where the solution procedure often becomes numerically unstable or non-convergent. In UDEC, the solutions for displacements and pressures are obtained simultaneously during each individual iteration. Given the current stress-strain behaviour, the stiffness and permeability matrices can be upgraded for the subsequent iteration and the solution procedure continued until the final convergence is attained.

In this paper, a fully coupled hydro-mechanical analysis has been conducted where the joint conductivity is a function of the joint deformation with stress. Consequently, joint water pressures affect the numerical computations, where the flow through joint domains is based on the following relationship:

$$q = (a^3 / 12\mu)\, \Delta p / L \qquad \text{(eqn. 1)}$$

where, μ = kinematic viscosity of water

a = contact hydraulic aperture
L = contact length between domains
Δp = pressure differential between adjacent domains

Given the pressures of two adjacent joint domains as p_1 and p_2, and the vertical co-ordinates of the domain centres as y_1 and y_2, then the quantity Δp is determined by:

$$\Delta p = p_2 - p_1 + \rho_w g(y_2 - y_1) \qquad \text{(eqn. 2)}$$

The existing hydraulic aperture varies with joint dilation or closure (Δa), ie. $a = a_o + \Delta a$. The quantity a_o is the joint aperture at zero normal stress, and Δa is the joint normal displacement, where dilation is taken as positive. In order to accelerate the rate of convergence, a maximum joint aperture, a_{max} and a residual aperture, a_{res} can be prescribed. The variation between a_{max} and a_{res} is considered to be a linear function with respect to the applied normal stress (σ_n). The change in joint deformation (Δa) with the normal stress (σ_n) is given by:

$$\Delta a = \sigma_n / [k_0 + \sigma_n/a_{max}] \qquad \text{(eqn. 3)}$$

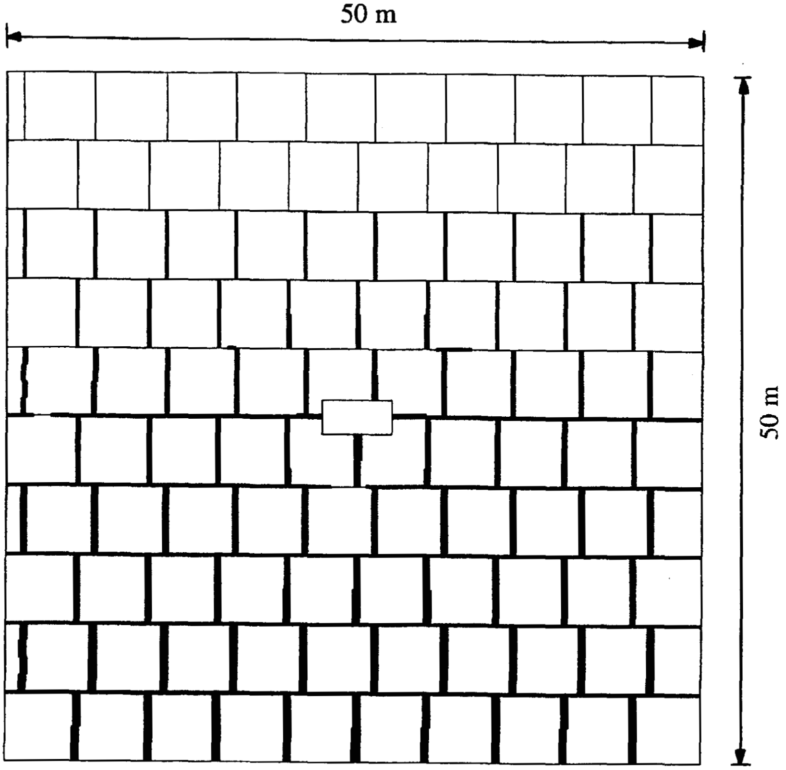
where, k_0 is the joint stiffness at zero normal stress.

NUMERICAL ANALYSIS OF SIMPLIFIED EXCAVATION MODELS

For the distinct element analysis using UDEC, geometric block models containing vertical and horizontal joints were analysed. The horizontal joints representing bedding planes were made continuous, while the vertical joint sets were made either staggered or continuous. The spacing between the vertical joints along a given horizontal layer was kept constant. A simplified rectangular excavation with a cross-section of 5m x 2.5m was analysed subject to an overburden of 200 m. For most models, the water table was maintained at the ground surface, except in one situation where the water level was elevated 0.3m above the ground level. The insitu stress ratio (σ_h/σ_v) was increased from 0.5 to 2.0, the latter being typical of Illawarra coal measures.

Figure 2 illustrates a staggered joint pattern (model s1a1 with a stagger of 1.3 m) surrounding a rectangular excavation. In this model, the principal joints carrying water are spaced at 5m intervals, such that four joints intersect the given excavation boundary at points A, B, C and D. The reduction of the joint spacing obviously increases the number of joints intersecting the excavation boundary, thereby increasing the inflow volumes significantly. An overall block size of 50m x 50m around the opening is shown in Figure 2, where the line thickness indicates the relative magnitude water pressures at the joint domains. In this case, the thinnest line indicates domain water pressures less than 0.1 MPa, while the maximum pressure (bottom of the figure) represents a value of 0.475 MPa. As the static water pressure at a depth of 50m below the phreatic surface should be close to 0.5 MPa, the small error of 5% is attributed to the boundary effects. In the authors experience, beyond a distance of five times the maximum excavation dimension, the effect of excavation boundaries on stresses tends to diminish significantly.

An enlarged section of the flow pattern near the mine opening is shown in Figure 3, where the flow directions are indicated by arrows, where the spacing of arrow heads indicates the magnitude of flow rate. Relatively small flow rates (less than 0.3 litres/sec) are not shown. The aperture of all joints at zero normal stress (a_o) is assumed to be 1.0mm, and the residual joint aperture is prescribed as 0.5mm. In this example, the inflow at point A is the largest, and the inflow at point D is the smallest. Table 1 gives a summary of the joint apertures corresponding to the normal stress (σ_n), the domain water pressures (u_w) and the inflow rates (q) at the four intersecting points around the opening. At points B and D, due to the relatively high normal stress (> 5 MPa), the joint apertures have attained their residual



excavation: 5m x 2.5m
individual blocks: 5m x 5m

line thickness: relative water pressures in joints

Figure 2 Staggered Joint Pattern Around Rectangular Joint Pattern

Table 1 Analysis of Water Inflow to Excavation for Model S1a1

Point	a_o (mm)	a (mm)	u_w (MPa)	σ_n (MPa)	q (litres/s)
A	1.0	0.67	0.10	3.35	3.79
B	1.0	0.50	0.25	5.49	1.62
C	1.0	0.62	0.21	3.84	3.04
D	1.0	0.50	0.4	6.29	1.42
			Total	Flow	9.87

a_o = joint aperture at zero normal stress; a = current joint aperture near the opening
u_w = joint (domain) water pressure; σ_n = normal stress at joint
q = water flow into opening

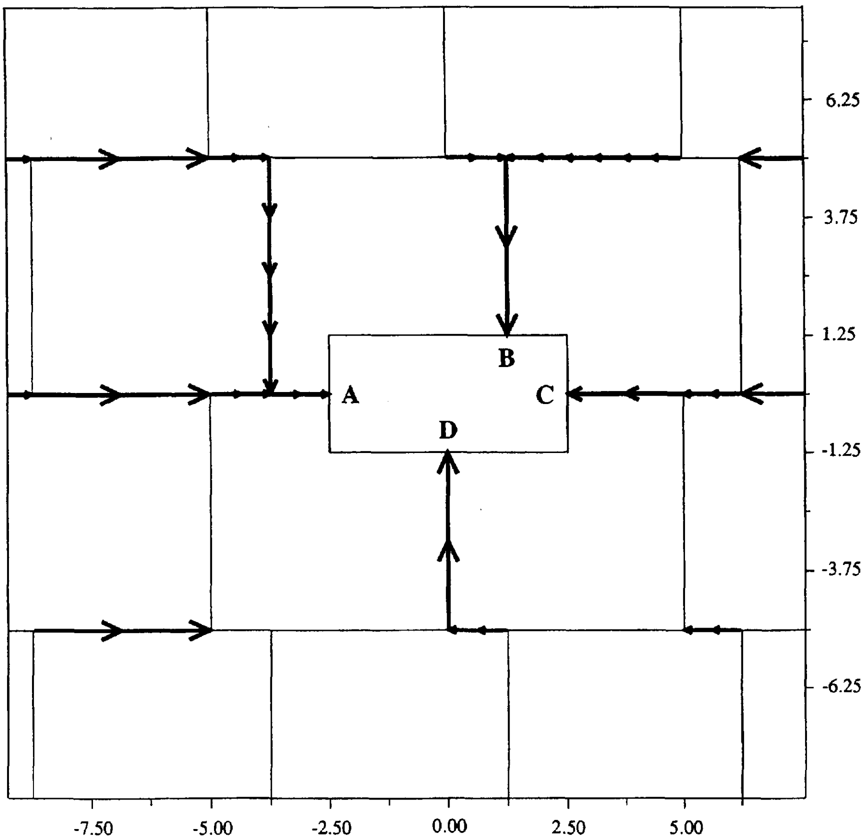


Figure 3 Ingress of Groundwater towards Ecxcavation

value of 0.5mm. The total flow into the excavation is determined by adding the individual flow rates from the four joints intersecting the excavation boundary, ie. 9.87 litres/sec in the above case. For an excavation of size 5m x 2.5m, a total flow of 9.87 litres/sec (36m^3/hour) corresponds to definite inundation unless the dewatering measures are provided. The capacity of dewatering equipment utilised in underground mines is influenced by the location of the excavation in relation to the outcrop. The standard equipment used by mines discharging to the Illawarra area has pumping capacities varying from 8 to 30 litres/sec for motor capacities between 70 and 150 kW (Jones, 1993).

Table 2 Joint Parameters Characterising Various Block Models

Model ID	S_h (m)	S_v (m)	S_t (m)	a_h (mm)	a_v (mm)	$k_{jn} \times 10^3$ (MPa/m)	$k_{js} \times 10^3$ (MPa/m)
SIAO+	5	-	-	1.2	-	10	10
SIAI	5	5	1.3	1	1	10	10
SIAIK	5	5	1.3	1	1	20	10
SIA2	5	5	1.3	0.8	0.8	10	5
SIA3	5	5	1.3	1.2	1.2	10	5
S2AI	5	5	0	1	1	10	10
S3AI	5	5	2.5	1	1	10	10
S4A1	2.5	2.5	1.3	1	1	10	10
highw*	5	2.5	1.3	0.8	0.8	10	5

+ No vertical flow; * Water level 0.3m above ground surface

S_h, S_v = spacing of horizontal and vertical joint sets;
S_t = stagger of vertical joint sets
a_n, a_v = aperture of horizontal and vertical joints;
k_{jn}, k_{js} = normal and shear joint stiffness.

Figure 4 illustrates the predicted inflow for nine different joint models (Table2), where the analysis is carried out for an insitu stress ratio ($I = \sigma_h/\sigma_v$) of 0.5 and 2.0. It is demonstrated that the total flow decreases at high horizontal stress levels (I=2), because the apertures of vertical joints are significantly decreased in relation to a_o. The lowest inflow is evident for the model s1a0 where flow through vertical joints does not take place. The influence of increasing the joint stiffness is reflected by an increased flow (s1a1k), the implications of which are considerable at an insitu stress ratio of 2. Increasing the joint apertures from 1.0mm to 1.2mm (s1a13), and reducing the joint spacing from 5m to 2.5m (s4a1) cause an increase in the flow volumes. A rise in the groundwater level (highwt) further enhances the risk of inundation. It is also interesting to note that the stagger of joints does not significantly affect the rate of inflow, as long as the number of vertical joints intersecting the excavation boundary remains the same.

A normalised block size defined by the ratio of block area to the excavation area was introduced, in order to investigate the effect of joint spacing around the excavation. The block area between the adjacent joint sets is defined by the product of vertical joint spacing and horizontal joint spacing ($s_v.s_h$). When the normalised block size increases or less number of joints intersect a given excavation area, the total inflow decreases as shown in Figure 5. It is also evident from Figure 5 that the risk of inundation increases substantially if the normalised block size becomes smaller than 2. By performing a statistical regression analysis, it was possible to obtain linear relationships between the flow rate and the normalised joint geometry factor, α, which can be expressed by the following expression:

$$\alpha = (s_v.s_h / A)^{-1/3} \qquad \text{(eqn. 4)}$$

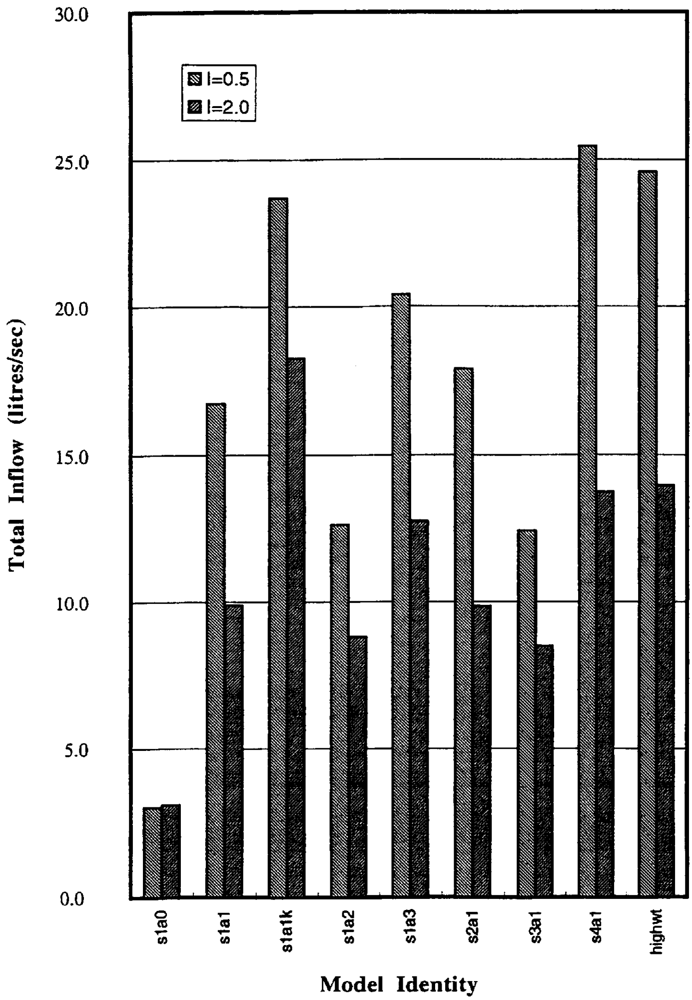


Figure 4 Predicted Water Inflow to Excavation Based on Various Joint Models

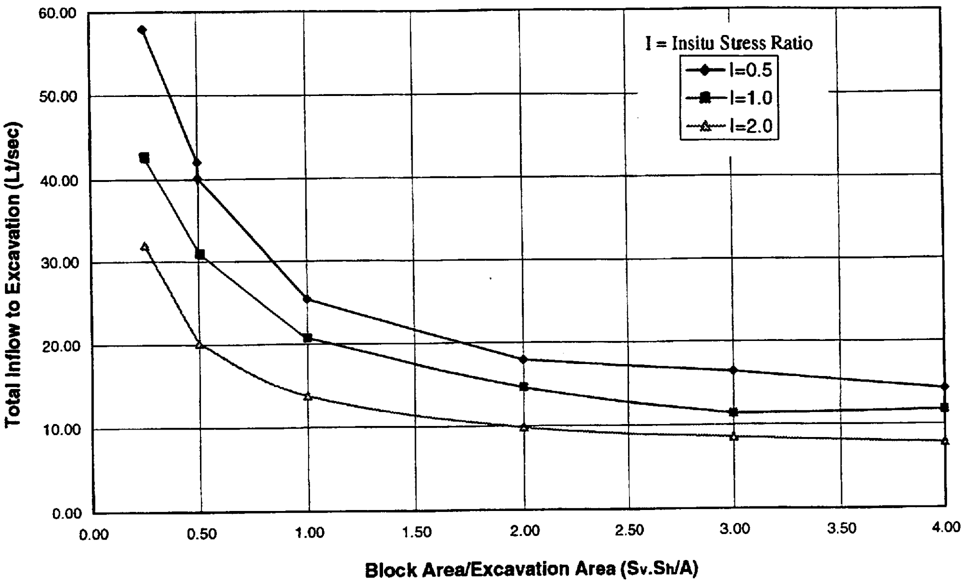


Figure 5 Effect of Normalised Block Area on Total Inflow to Excavation

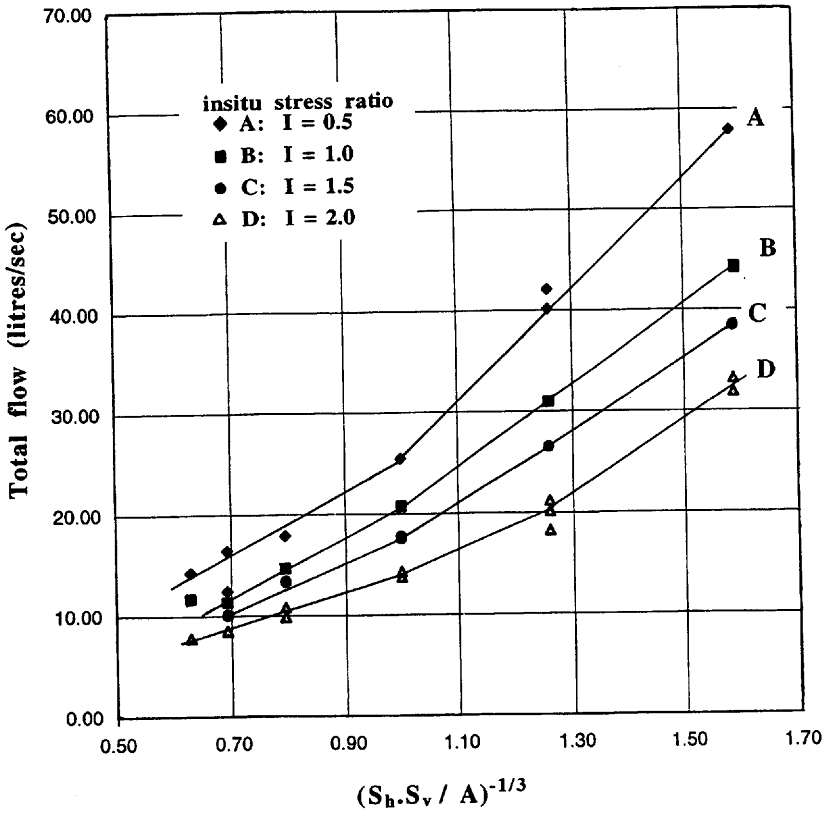


Figure 6 Effect of Dimensionless Joint Parameter and Insitu Stress Ratio on Total Inlow

Figure 6 plots the above relationship for a large number of flow models, where bi-linearity is demonstrated for the two regions, (a) $0.6 < \alpha < 1.0$, and (b) $1.0 < \alpha < 1.6$. As α exceeds unity, the flow rates increase significantly, especially at lower levels of insitu stress ratio. This implies that in addition to dewatering, at enhanced values of α (flow > 20 litres/sec), sufficient bolting of joints may be necessary to increase the normal stress at the joints, such that the joint apertures can be controlled at acceptable or minium possible values.

PROBLEMS ASSOCIATED WITH INFLOW MODELLING

The effects of shear stiffness and shear displacement on the flow volumes have not been modelled in this analysis. The lack of understanding in this area is partly due to the experimental difficulties associated with flow measurements under shearing conditions. For instance, the influence of wearing of asperities and gouge formation on the actual apertures is difficult to model numerically without having adequate experimental knowledge.

The selection of appropriate model parameters is most important in obtaining realistic results based on numerical modelling. Inevitable uncertainties are introduced when extrapolating laboratory results to represent actual field conditions. Defining the initial anisotropic permeability tensors and prescribing the apertures at zero normal stress for the distinct element method are such examples.

Formation of saturation zones and bed separation zones in the actual rock mass has a significant influence on the groundwater behaviour. Although the flow regime in jointed rock was considered linear in this analysis, non-linear conditions generally prevail at the excavation boundaries. Transient flow can also occur for a significant period of time due to the progressive nature of the excavation process. The effect of post-failure behaviour and the formation of new cracks on one hand, and the simulation of associated conductivity changes on the other hand are also of concern.

CONCLUSIONS

The risk of inundation or water ingress to mine excavations can be analysed using the distinct element method. By using simplified joint geometries characterised by horizontally stratified and vertically jointed rock media, this study has shown that greater the insitu horizontal stress to the vertical stress ratio, the lower the water inflow towards underground excavations. An insitu stress ratio of about 2 is particularly relevant for coal mines in New South Wales. The findings of this study also indicate that ncreasing the joint normal stiffness has the same effect as increasing the initial aperture of the joints. An important result of this analysis was the suitability of the normalised block size ($s_v.s_h/A$) in predicting water inflows. The smaller the normalised block size, the greater the number of joints intersecting the excavation boundary, hence the larger the total inflow. Moreover, it was illustrated that the volume of inflow significantly increases when the dimensionless parameter (α) expressed by $(s_v.s_h/A)^{-1/3}$ becomes greater than unity.

The current analysis was based on the parallel plate flow model adopting an equivalent aperture which is determined as a function of the normal stress. The equivalent aperture by itself cannot represent accurately the effect of joint geometry on the flow behaviour of tight joints. Indraratna et al. (1994) have pointed out that although the effects of tortuosity and asperity contacts are difficult to quantify, with the developments in profilometer techniques, it may be possible to characterise the surface topography of joint specimens more accurately in order to modify the existing joint-flow models. The numerical accuracy is also dependent on the ability to quantify the influence of shear stiffness (shear deformation) of asperities on water flow through joints under changing stress distributions.

The limitations due to small strain assumption render the quasi-continuum methods unsuitable for situations where finite displacements and rotations can occur. Although the distinct element method is more suitable for such problems, the assumption of impermeable blocks limits its application in certain sedimentary rocks where the permeability of the rock matrix cannot be ignored. Accurate prediction of flow under complex longwall mining situations should also consider large deformations near the excavation, mechanical and hydraulic anisotropy, transient and non-linear flow, periodic roof collapse, post-failure behaviour of the goaf and three-dimensional geometries. Currently, most numerical codes require simplification of several of these conditions. Therefore, increased accuracy in predictive models requires further development of versatile numerical models for fully coupled hydro-mechanical analysis.

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