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**DEVELOPMENT OF TWO AND THREE-DIMENSIONAL METHOD OF FRAGMENTS TO  
ANALYSE DRAINAGE BEHAVIOR IN HYDRAULIC FILL STOPES**

**Thesis submitted by**

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**in September 2007**

**for the degree of Doctor of Philosophy  
in the School of Engineering  
James Cook University**

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**This work is dedicated to my wonderful family – Dad,  
Mum, Tegan, Rudd, Shauna, Briony, Kirralee and  
Lachlan**

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# Abstract

The extraction and processing of most mineral ores, result in the generation of large volumes of finer residue or tailings. The safe disposal of such material is of prime environmental, safety and economical concern to the management of mining operations. In underground metaliferous mining operations, where backfilling of mining voids is necessary, one option is to fill these voids with a tailings-based engineered product. In cases where the fill is placed as a slurry and the fill contains free water, permeable barricades are generally constructed to contain the fill within the mining void whilst providing a suitable means for the drainage water to escape from the fill. Recent barricade failures, resulting from poor drainage, have led to an immediate need for an increased understanding of the pore pressure developments and flow rates throughout the filling operation. This thesis presents simple analytical solutions, based on the ‘method of fragments,’ for estimating discharge and maximum pore pressure for two and three-dimensional hydraulically filled stopes. Shape factors were developed to account for the inherent individuality associated with stope and drain geometry. The influence of scaling on discharge and pore pressure measurements is also investigated. The proposed solutions are verified against solutions derived from a finite difference program and physical modelling of a scaled mine stope and results showed excellent agreement. Using these analytical solutions developed for flow through three-dimensional hydraulic fill stopes, a user-friendly EXCEL model was developed to accurately and efficiently model the drainage behaviour in three-dimensional stopes. The model simulates the complete filling and draining of the stopes and was verified using the finite difference software FLAC<sup>3D</sup>. The variation and sensitivity in drainage behaviour and pore water pressure measurements with, the variation in geometry, fill properties and filling-cycles of a three-dimensional hydraulic fill stope was also investigated.

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# List of Publications

## ***Journals***

Rankine, K.S. and Sivakugan N. (2007) "Application of Method of Fragments in Three-Dimensional Hydraulic Fill Stopes." *Journal of the Geotechnical Division ASCE, Under Review 3<sup>rd</sup> draft*

Sivakugan, N. and Rankine, K.S. (2006). "A simple solution for drainage through 2-dimensional hydraulic fill stope," *Geotechnical and Geological Engineering*, Springer, 24, 1229-1241.

Sivakugan, N., Rankine, K.J., and Rankine, K.S. (2006). "Study of drainage through hydraulic fill stopes using method of fragments," *Journal of Geotechnical and Geological Engineering*, Springer, 24, 79-89.

Sivakugan, N., Rankine, R.M., Rankine, K.J., and Rankine, K.S. (2006). "Geotechnical considerations in mine backfilling in Australia," *Journal of Cleaner Production*, Elsevier, 14(12-13), 1168-1175.

## ***Refereed Conference Proceedings***

Rankine K.S., Sivakugan N., Rankine K.J. (2007). *Drainage behaviour of three-dimensional hydraulic fill stopes: A sensitivity analysis*, 10th Australian and New Zealand Conference on Geomechanics – Common Ground, *Paper accepted*

Rankine, K.S. and Sivakugan, N. (2005). "A 2-D numerical study of the effects of anisotropy, ancillary drains and geometry on flow through hydraulic fill mine stopes," *Proceedings of the 16th ISSMGE*, Osaka, Vol.2, 955-958

Rankine, K.J., Sivakugan, N. and Rankine, K.S. (2004). Laboratory tests for mine fills and barricade bricks, *Proceedings of 9th ANZ Conference on Geomechanics*, Auckland, 1, pp. 218–224

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Rankine, K.J., Rankine, K.S., and Sivakugan, N. (2003). "Three-dimensional drainage modelling of hydraulic fill mines," *Proc. 12th Asian Regional Conf. on Soil Mech. and Geotech. Engineering*, Eds. CF Leung, KK Phoon, YK Chow, CI Teh and KY Yong, 937-940.

Rankine, K.J., Rankine, K.S. and Sivakugan, N. (2003). "Quantitative Validation of Scaled Modelling of Hydraulic Mine Drainage Using Numerical Modelling," *Proc. of the International Congress on Modelling and Simulation, MODSIM 2003*,

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## List of Symbols

$A$  = cross-sectional area

$a$  = air content

$B$  = stope width

$C$  = Hazen's constant

$C_{\text{slurry}}$  = percent solids of slurry

$C_u$  = coefficient of uniformity

$C_v$  = viscosity coefficient

$C_0$  = Terzaghi (1925) shape factor

$C_2$  = Kozeny-Carman (1938) shape factor

$C_3$  = Taylor (1948) shape factor

$C_4$  = Samarasinghe (1982) constant

$C_5$  = Amer and Awad (via Das, 2002) constant

$c'$  = effective cohesion stress

$D$  = drain height

$D_r$  = relative density

$D_s$  = effective particle diameter

$D_5$  = the grain size for which 5% of the particles are finer

$D_{10}$  = the grain size for which 10% of the particles are finer; effective grain size

$D_{30}$  = the grain size for which 30% of the particles are finer

$D_{50}$  = the grain size for which 50% of the particles are finer

$D_{60}$  = the grain size for which 60% of the particles are finer

$E_1, E_2$  = material property constants, Carrier et al. (1983)

$e$  = void ratio

$e_{\text{max}}$  = maximum void ratio

$e_{\text{min}}$  = minimum void ratio

$F$  = drain width

$Fr$  = Froude number

$f$  = soil fabric

$G$  = equivalent drain height

$G_s$  = Specific gravity

$g$  = acceleration due to gravity

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H = height  
 $H_w$  = height of water  
 $h_i$  = head loss in  $i^{\text{th}}$  fragment  
 $h_L$  = head loss  
 $\Delta h$  = change in head between two points  
 $i$  = hydraulic gradient  
 $i_{\text{entry}}$  = entry hydraulic gradient  
 $i_{\text{exit}}$  = exit hydraulic gradient  
 $J$  = fill height increase per hour  
 $K_0$  = horizontal pressure coefficient (assumed to be 0.5)  
 $k$  = permeability  
 $k_{0.85}$  = permeability at void ratio of 0.85  
 $k_e$  = effective permeability  
 $k_{\text{equiv}}$  = equivalent permeability for a layered system  
 $k_h$  = permeability in the horizontal direction  
 $k_v$  = permeability in the vertical direction  
 $L$  = length  
 $L_a$  = length of ancillary drain  
 $m$  = soil compressibility  
 $m_s$  = mass of solids  
 $m_w$  = mass of water  
 $N_d$  = number of equipotential drops  
 $N_f$  = number of flow channels  
 $n$  = porosity  
 $n_{\text{eff}}$  = effective porosity  
 $P_b$  = pressure exerted by the bulkhead on the fill  
 $Q$  = discharge  
 $q$  = discharge per unit length  
 $Re$  = Reynold's number  
 $R_s$  = solids filling rate  
 $S$  = saturation  
 $S_s$  = specific surface area of grains

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$S_v$  = grain surface per unit volume

$s$  = shape factor

$T$  = temperature

$t$  = time

$u$  = pore water pressure

$u_{\max}$  = maximum pore water pressure

$v$  = discharge velocity

$V_{\text{drained}}$  = volume of water that has drained

$V_f$  = volume of fill

$V_{\text{free}}$  = total free water that is drainable

$V_{\text{in}}$  = volume of water entering stope

$V_{\text{out}}$  = volume of water draining from the stope

$V_{\text{residual}}$  = volume of residual water

$V_s$  = volume of solids

$V_{\text{to-drain}}$  = volume of water that is yet to drain

$V_v$  = volume of voids

$V_w$  = volume of water

$W$  = stope thickness

$w$  = water content

$w_{\text{res}}$  = residual water content

$w_{\text{sat}}$  = saturated water content

$w_{\text{slurry}}$  = water content of hydraulic fill slurry

$X$  = drain length

$\alpha_{2D}$  = fraction of the head loss within fragment 2 for a two-dimensional stope that takes place in the horizontal segment of the largest stream line

$\alpha_{3D}$  = fraction of the head loss within fragment 2 for a three-dimensional stope that takes place in the horizontal segment of the largest stream line

$\Delta h$  = change in head between two points

$\Phi$  = two-dimensional form factor for  $i^{\text{th}}$  fragment

$\Gamma_i$  = three-dimensional form factor for  $i^{\text{th}}$  fragment

$\gamma_t$  = total bulk unit weight of fill

$\gamma_w$  = unit weight of water

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$\eta$  = dynamic viscosity  
 $\varphi$  = effective frictional stress  
 $\kappa$  = intrinsic permeability  
 $\mu$  = water viscosity  
 $\mu_T$  = water viscosity at T degrees Celsius  
 $\mu_{10}$  = water viscosity at 10 degrees Celsius  
 $\rho_d$  = dry density  
 $\rho_s$  = soil grain density  
 $\rho_w$  = density of water  
 $\sigma_h$  = horizontal/ barricade pressure  
 $\sigma_h'$  = effective horizontal pressure  
 $\sigma_v'$  = effective vertical pressure  
 $\tau_w$  = shear strength of rock-fill interface  
 $\omega$  = fluid surface tension