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Two-dimensional large strain consolidation prediction and incrementally deposited tailings

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ABSTRACT: Because of the expected high cost of embankment raising under the current tailings disposal strategy at a mine in NSW, Australia, FLAC analyses have been undertaken to study the strength gain due to consolidation in the Stage 1 dam. The problem is summed up as a two-dimensional consolidation procedure with incremental construction of the consolidating medium. The numerical modeling allowed porosity and permeability to be a function of accumulated volumetric strain, the drained modulus to be a function of depth of tailings and the undrained shear strength to be a function of the vertical effective stress. These procedures are implemented by means of a FISH function. Different modeling approaches have been carried out and compared. The results from the analyses indicate that the high rate of filling of the reservoir will preclude sufficient strength gain of the tailings to allow upstream construction as presently planned.

1 INTRODUCTION

The behaviour of all geomaterials, and in particular of soils, is governed largely by the interaction of their solid skeleton with the fluid, generally water, present in the pore structure.

The incremental formulation of coupled deformation-diffusion processes in FLAC provides the numerical representations for the Biot theory. It provides useful insight into the general ways in which fluid can affect flow and the stability of soil systems. The consolidation is a typical type of fluid / solid interaction, in which the slow dissipation of pore pressure causes displacements to occur in the soil. This type of behavior involves two mechanical effects. First, changes in pore pressure cause changes in effective stress, which affect the response of the solid - for example, a reduction in effective stress may induce plastic yield. Second, the fluid in a zone reacts to mechanical volume changes by a change in pore pressure. In this paper, the potential use of FLAC has been explored to predict the tailings consolidation procedure at a mine in NSW, Australia.

The mine has a planned production of 17Mtpa of tailings. This was planned to be discharged at around 63% solids via a 650mm pipeline to the tailings dam. Thus discharge has been in the range of 53 to 57% solids. The dam with planned raising of embankments has a capacity of around 200Mt.

Because of the expect high cost of embankment raising under the current tailings disposal strategy at the mine, FLAC analysis has been undertaken to study the strength gain due to consolidation in the Stage 1 tailings dam. The problem is summed up as a two-dimensional consolidation procedure. However, it is a difficult problem because the parameters controlling consolidation (permeability and stiffness) are a function of effective stress, which is a function of the degree of consolidation. Also the consolidation medium is increasing in depth with time.

2 MODELING SEQUENCE

The modeling sequence for the 2D FLAC analyses is shown in Figures 1. It divided reservoir filling into five stages, namely:

STAGE 1. Tailings at RL 670m drainage from surface only; allowed to consolidate for 1 month.
STAGE 2. Tailings raised to RL 680m, drainage from surface and from face of starter embankment; allowed to consolidate for 1 month.
STAGE 3. Tailings raised to RL 685m, drainage from surface and face of starter embankment; allowed to consolidate for 3 months (60 days)
STAGE 4. Tailings raised to RL 692m, drainage as before; allowed to consolidate for 6 months (total period to end of this stage = 300 days).
STAGE 5. Tailings raised to RL 698m, drainage as before; allow to consolidate for 6 months (total period to end of Stage 5 is 480 days).

It must be noted that this modeling involves a stepwise simulation of what in reality is a smooth increase in tailings level with time. This stepwise simulation is an approximation, which introduces some error to the answers.

The analyses assume 100% efficiency for drainage through the upstream face of the starter embankment and the top face of tailings. Impermeable conditions have been applied to the right vertical and bottom boundaries.

The analyses were terminated at 480 days.

3 MODELING PARAMETERS

Figure 2 shows the grading curves from the laboratory tests.

The tailings porosity, density, permeability, stiffness and shear strength parameters have been based on an interpretation of available laboratory test data as summarised in Figure 3. For the numerical computations the relationships have been approximated as set out below.

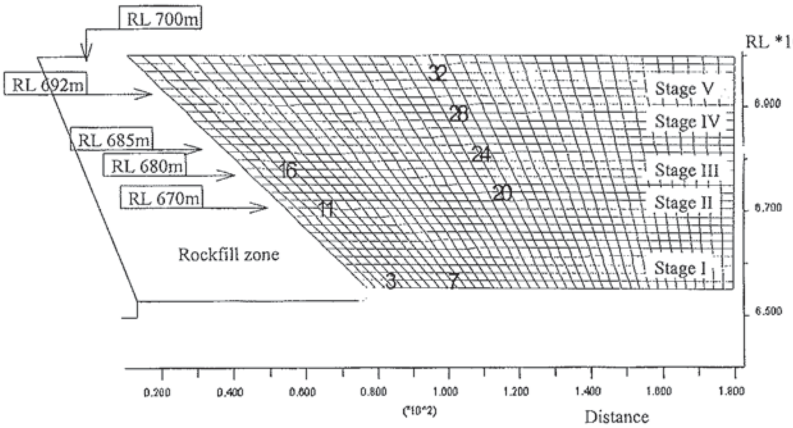

Figure 1. Tailings deposit stages, analysis mesh and selected point position for calculation.

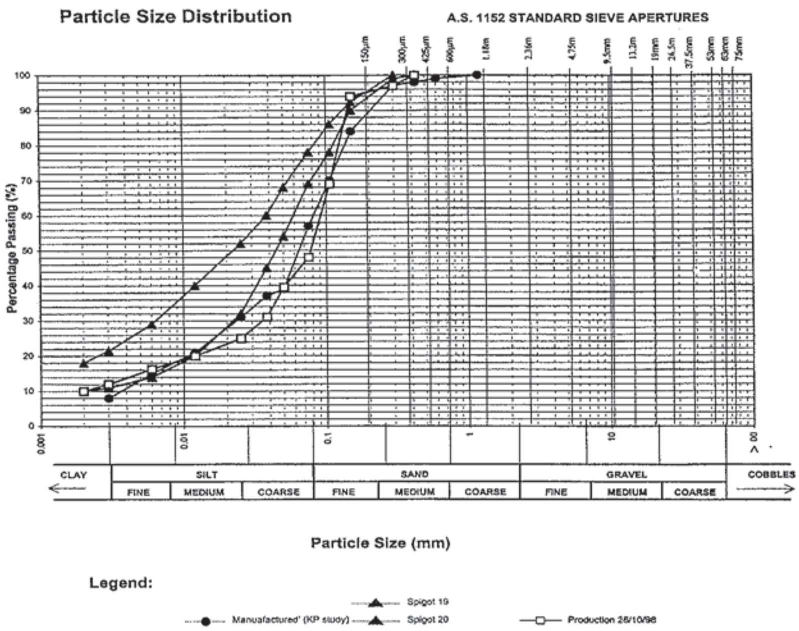

Figure 2. Particle size distribution

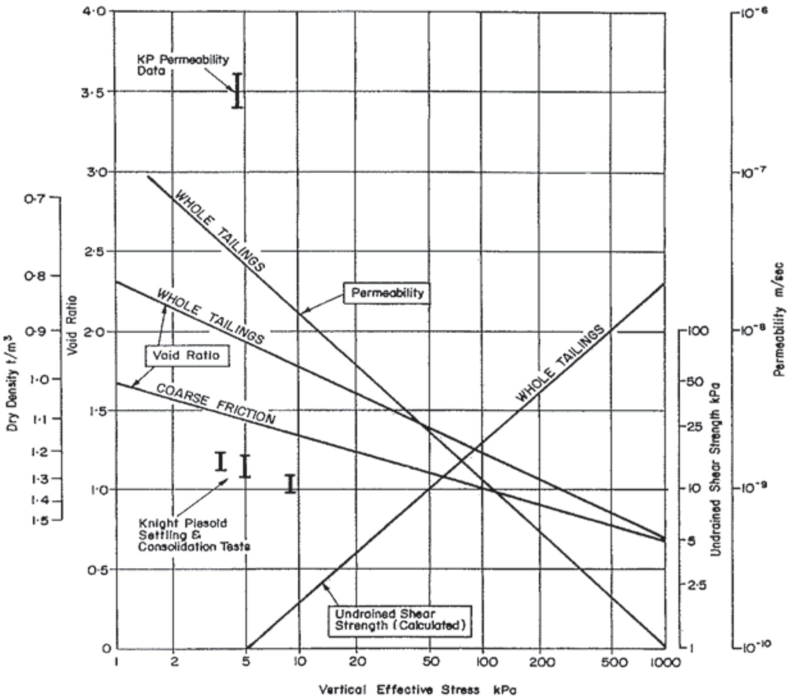

Figure 3. Preliminary assessment of tailings parameters

3.1 *Strain-Dependent Porosity*

For the FLAC analysis, the porosity and permeability are functions of accumulated volume strain, because both porosity and permeability changes affect the settlement and consolidation results.
For large strain mode, the volume strain is approximated by

$$e_v = 2 * (V-V_0) / (V + V_0) \quad (1)$$

which leads to an alternative expression for porosity:

$$n = 1 - (1-n_0) * (2-e_v) / (2+e_v) \quad (2)$$

3.2 *Strain-Dependent Permeability*

Based upon available data (see Figure 3) the porosity vs permeability relationship was assumed to be:

$$n = b_0 + C_k * \log k \quad (3)$$

where $b_0 = 1.349$ and $C_k = 0.097$, therefore,
$n = 1.349 + 0.097 * \log k$ or:
$k = 10^{-8 * (1.29 n - 1.74)}$

$$= k_0^{-(1.29 * n - 1.74)} \quad (4)$$

where $k_0 = 10^{-8}$ in m/s or $= 10^{-12}$ in m^2/(Pa-sec) for FLAC.

3.3 *Dependence of Young's Modulus on Tailing Depth*

The drained modulus is defined by the relation

$$E = E_0 \cdot (1 + \sqrt{z}) \quad (4)$$

where z is the depth of tailing deposition, and $E_0 = 10^6$Pa.

In future studies it may be appropriate to set the drained modulus as a function of the strain.

3.4 *Undrained Shear Strength*

An estimate of the probable relationship between undrained shear strength and confining stress has been made using the equation:

$$S_u = \frac{\sigma_1' \sin\phi'(1-(1-K_0)A}{1+\sin\phi'(2A-1)} \quad (5)$$

where S_u= undrained shear strength; ϕ'= effective stress friction angle of the tailings (assumed to be 32°; K_0= 1-sinϕ'; A = Skempton's pore pressure parameter; σ_1' = major principal effective stress $(= \sigma_v')$.

In *FLAC*, the compressibility of the solid phase is neglected compared to that of the drained bulk material, and we have

$$A = 1 - \frac{1}{1 + K_w / (nK)} \quad (6)$$

where K_w is the bulk modulus of the fluid, n is the porosity and K is the drained bulk modulus of the material. Because the bulk modulus of the fluid is much larger than the drained bulk modulus of the tailings, Skempton coefficient A is almost equal to one, the equation (5) simplifies to:

$$S_u = 0.2\ \sigma_v' \quad (7)$$

This procedure is implemented in FLAC by means of a FISH function.

3.5 *Density:*

$$\Delta\gamma = \gamma_{sat} - \gamma_{dry} = \rho_w * n * s \quad (8)$$

where n is porosity and s is saturation.

4 INITIAL RESULTS

The real time scale has been applied in the initial analysis. The numerical analysis for this problem provides a solution at each of the five stages. The analysis begins at an initial state. Because the drainage system, which depressurises the upstream rockfill zone, was only opened at stage II, the analyses assumed no drainage into the rockfill until the tailings reached RL 670m.

Presentation of analyses within this paper is in accordance with the following system of units:

- coordinates - metres
- displacements - metres
- time- second
- stress - Pascal

The detailed output is given in subsequent selected figures. These details are:

Figure 4 shows the plot of increment settlement versus time for the selected points (ref. to Figure 1). It can be seen that internal settlements between 200m and 450mm are expected at these points.

Figure 5 is the plots for grid (3,1) (point 3, near toe of starter dam) of total stress, pore pressure and vertical effective stress versus time. It shows the significant increase in effective stress in the upstream toe area of the starter dam once the upstream rock fill zone is allowed to drain.

Figure 6 is a similar plot to Figure 5 and shows the change in average total stress, pore pressure and effective stress versus time for grid (10,1) (point 7, 40m upstream of the face). At grid (3,1) (point 3) pore pressures dissipate rapidly and the effective stresses approach overburden stress by the end of each stage. At grid (10,1) (point 7) there is only minor to medium consolidation and by the end of stage 5 the average total stress is 700 kPa and the pore pressure is 435 kPa. Grid (10,1) (point 7) is 40m below the surface and therefore the hydrostatic pressure would be 400 kPa. Hence the FLAC analysis indicates the tailings to be under consolidated at this point after 480 days.

Figure 7 shows vectors of total flow from the tailings at the end of stage V. It can be seen that the major component of seepage is into the upstream face of the starter dam.

Equipotentials and flow streamlines at the end of stage V are been shown in Figure 8. From Figure 9 it can be seen that there is a substantial zone of depressurised tailings adjacent to the wall of the starter dam.

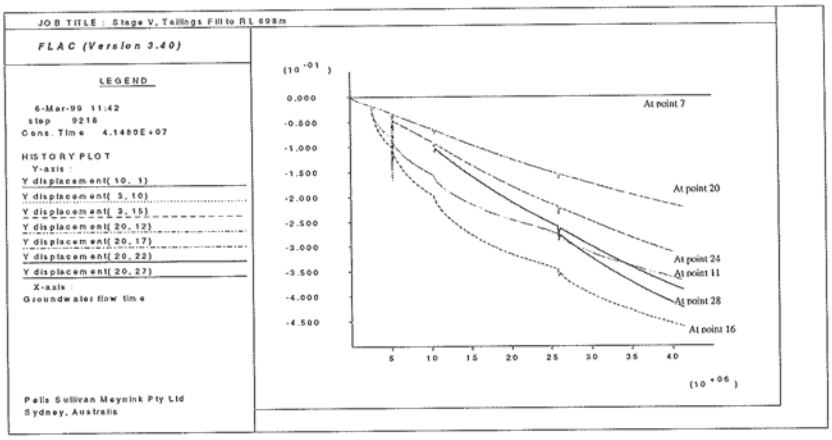

Figure 4. Settlement history at selected points

Figure 10 shows contours of vertical effective stress at the end of stage V. These stresses are a key prediction because they can be used to estimate the undrained shear strength at the end of stage V as shown in Figure 11.

Figure 11 is the critical prediction in relation to potential upstream construction. It gives contours of undrained shear strength based on the estimate of:

$S_u=0.2\sigma_v'$

where S_u = undrained shear strength (kPa); and σ_v'= vertical effective stress (kPa)

It shows that even in the immediate vicinity of the starter embankment the shear strength is < 30 kPa to a depth of at least 10m (ie down to about RL 690m). This would be inadequate to allow upstream construction.

Figure 12 and 13 predicted permeability and porosity distribution after 480 days.

Figure 14 is contours of cumulative settlement at the end of 480 days. Maximum settlements in the center are about 1.3m. It is noted that for each new filled layer, the initial displacement at the top of new filled layer is zero, which means the previous settlement has been filled back.

5 FURTHER ANALYSES

Additional analyses have considered the following items:

- constant permeability of 7e-8 m/s.
- tailings fill increment height reduced to 5m/stage.
- 10m lower permeability foundation layer added in the model (compared with an impermeable boundary for the first analysis).

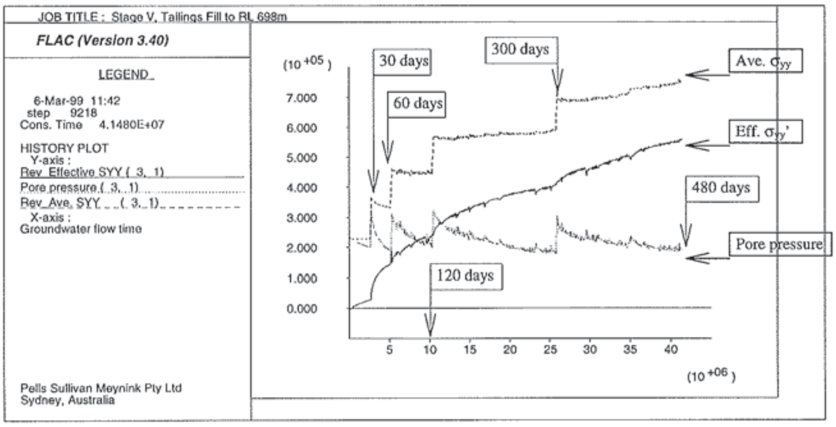

Figure 5. Stress evaluation at grid (3,1) (app. 10m away from bottom of upstream face)

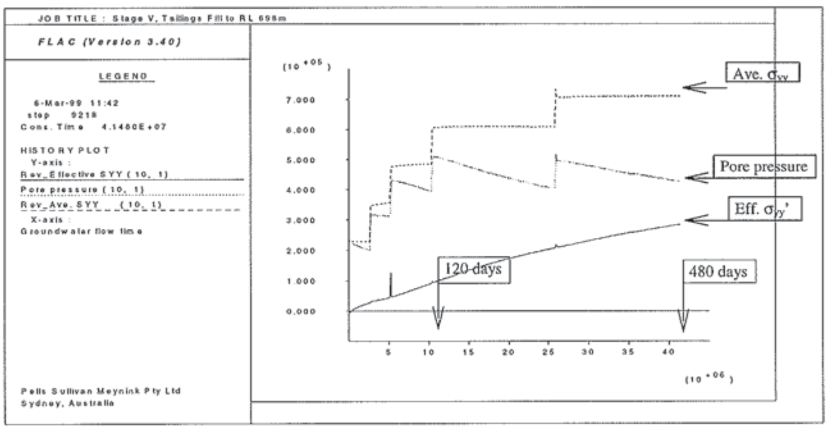

Figure 6. Stress evaluation at grid (10,1) (app. 40m away from bottom of upstream face)

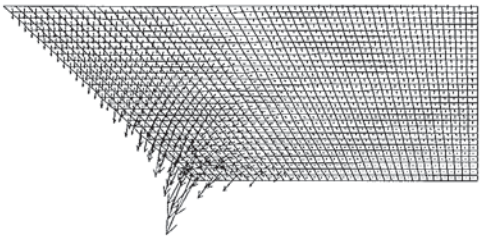

Figure 7. Flow vectors at the end of stage V

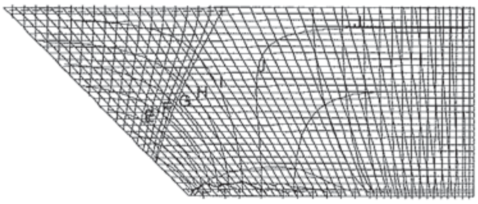

Figure 8. Head and flow streamlines distribution at stage V. Head contour interval = 5. D: 6.7E+02 J: 7.0E+02

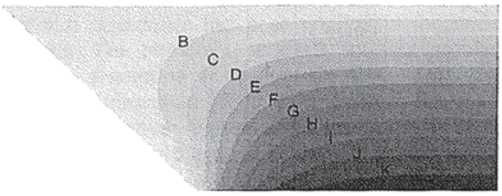

Figure 9. Pore pressure distribution at stage V. Contour interval 5e+4Pa. B: 50kPaK: 500kPa

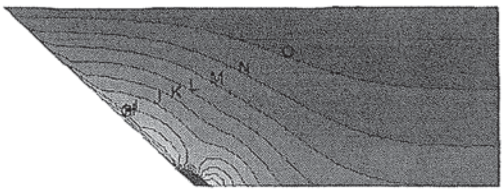

Figure 10. Effective stress distribution at stage V. Contour interval 5e+4Pa. O: 50kPa, G: 400kPa

Analyses were ongoing at the deadline time for this paper but some interesting observations from the results available to date are given below.

5.1 *Timestep determination*

Numerical simulation of the mechanical response of a coupled groundwater-solid analysis becomes a

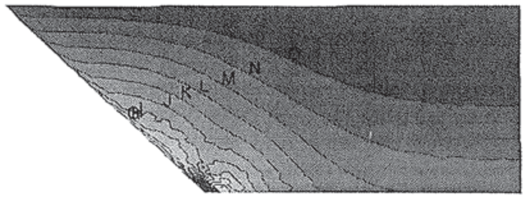

Figure 11. Cu - Undrained shear strength. Contour interval = 1e4Pa. O: 10kPa I: 70kPa.

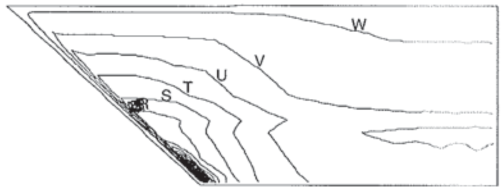

Figure 12. Predicated permeability profile at end of stage V. Contour interval = 5e-12m^2/(Pa-sec). O: 4e-11m^2/(Pa-sec)W: 1.2e-10m^2/(Pa-sec)

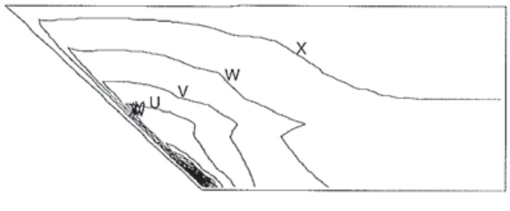

Figure 13. Predicated porosity profile at end of stage V. Contour interval = 4e-3. S: 5.80E-1X: 6.48e-1

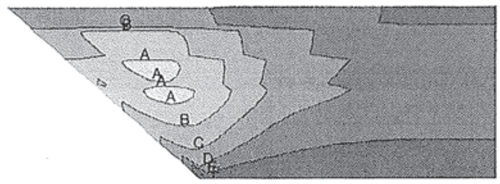

Figure 14. Settlement distribution at end of stage V. Contour interval = 2.5e-1. A: -1.25m F: 0

time-consuming task in FLAC when the Biot modulus, $M = K_w / n$, of the pore fluid is much larger than the (drained) confined modulus, $K + (4/3)G$, of the porous medium, i.e., when the stiffness ratio $R_k = M / (K+(4/3)G) >> 1$ (in our case here $R_k > 300$). In another project, which is about depressurisation by unloading, it had been found that the computing time was equal or even slower than the real time. Therefore it is necessary to adjust the K_w value to make analysis practical specifically for the large R_k value case.

As a rule of thumb, for the above tailings material, if K_w is adjusted to reduce $R_k = 200$, then the time response is close (typically within 5-10%) to the above response of with full K_w. This decreases computing time on a Pentium II 300kHz machine from monthly to weekly.

5.2 *Boundary conditions*

Figure 15 is tailings suction profile from field desiccation experiment on a mine in Australia. With the aid of this data, an approximately linear relationship between suction force and consolidation time had been applied where the "partial saturation" developed in the analysis.

5.3 *Water retention*

The relationship between pore pressure and saturation for a given medium is termed the water retention behavior. After consolidation has proceeded for a period of time, zones of partial saturation may appear. Therefore the relationship between pore water pressure and saturation is required to allow computation of further consolidation.

In FLAC, an approximate relationship has been implemented. Figure 16 summarized and schematically shows the relationship between water pressures and saturation. That is: pore pressure is set identically to zero if the saturation at any point is variable, which may reflect a possible full surface flux (figure 16b). If the saturation remains equal to 1, further expansion of the pore volume will cause negative pore pressures to build up, which may reflect zero or much smaller surface flux compared with the figure 16b case (see figure 16a). The true case may be between these two cases.

5.4 *Some results*

Figure 17 is the same plot as Figure 6 and shows the change in stresses based on the new model run. Compared with Figure 6, it can been seen that the model with constant permeability shows much more rapid consolidation than the model with stress-dependent permeability. Unfortunately the stress-dependent model is more realistic.

Figures 18 and 19 show the saturation variation at different consolidation stages based on the Figure 16b model. 520 days after the top layer is placed, the unsaturated zone will be up to 10-15m deep. However, the consolidation procedure is slow. Figure 20, it can be seen the pore pressure vs. consolidation time almost perform like steady state.

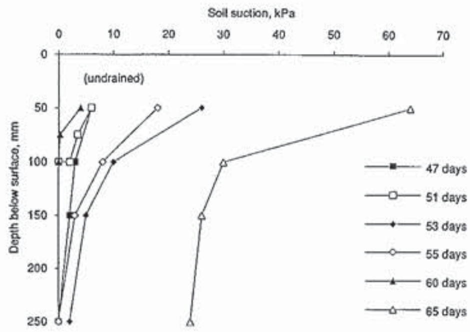

Figure 15. Tailings suction profile from field experiment.

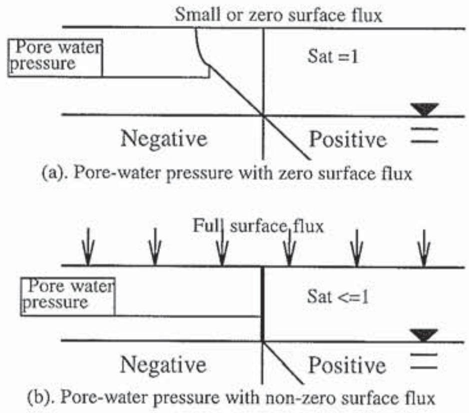

Figure 16. Schematic diagram of water retention relationship in partially saturated medium by FLAC

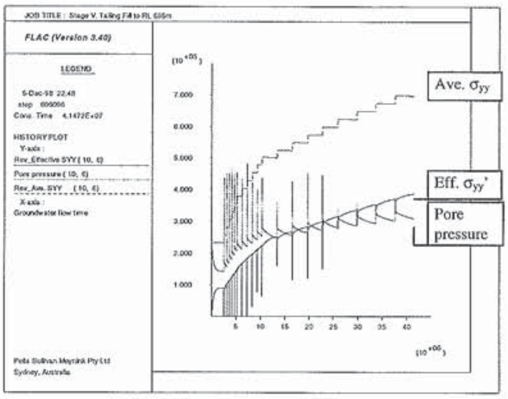

Figure 17. Stress evaluation at grid (10,6) based on the small tailings fill increment height and a constant permeability.

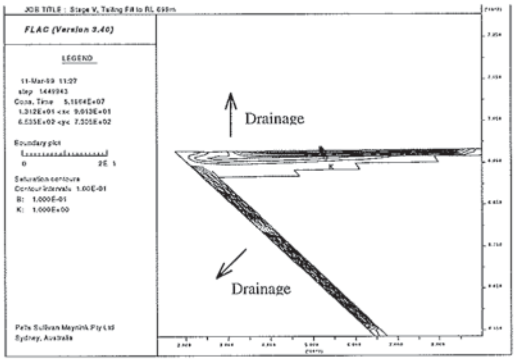

Figure 18. Saturation contours at 120 days after top layer placed

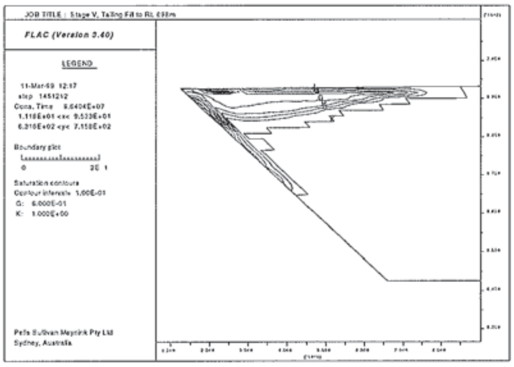

Figure 19. Saturation contours at 520 days after top layer placed

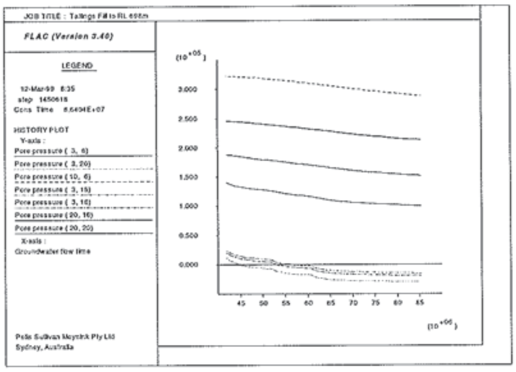

Figure 20. Pore pressure vs. time at selected grids based on the figure 16b condition

Figures 21 and 22 give corresponding results for the model based on the Figure 16a assumption. Negative pore pressure are generated and the consolidation procedure is quicker than for the model based on Figure 16b.

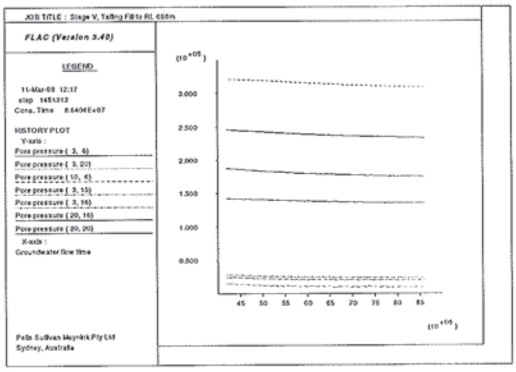

Figure 21. Pore pressure vs. time at selected grids based on the figure 16a condition

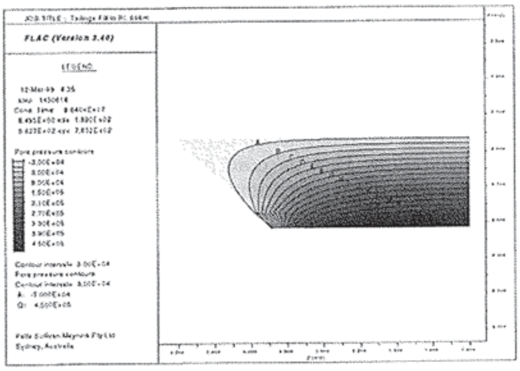

Figure 22. Pore pressure distribution after 520 day (model 16a)

5.5 *Alternative Computation of Transient State*

The final model had been analyzed by FEM program SEEP/W. Figure 23 gives the pore pressure distribution after 17 months using SEEP/W. This may be compared with Figure 22 and represent good agreement in the hydrology aspect. However SEEP/W cannot deal with the mechanical aspects such as settlement, effective stress and shear strength.

6 CONCLUSIONS

- Analysis of consolidation of incrementally placed tailings is a very difficult numerical problem requiring very long computational times on con-

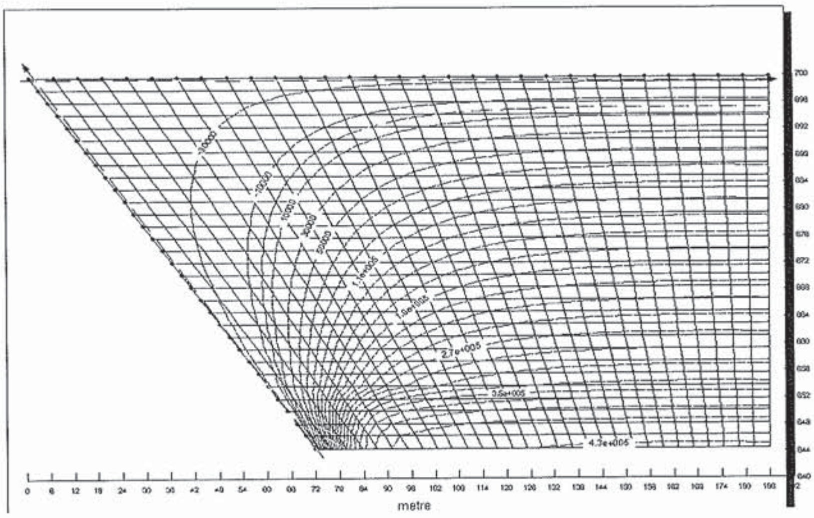

Figure 23. Pore pressure distribution after 17 months

ventional PCs.

- FLAC is a very useful tool in understanding strength development in tailings.
- A constant permeability assumption gives quick consolidation and relatively short computation times but is unfortunately not realistic for assessing the effectiveness of underdrains and strength gain with time.
- In FLAC flow logic, a realistic negative pore pressure in zones of partial saturation medium results in a more reasonable consolidation estimates than a zero pore pressure.
- Hybrid models specifically with high R_k values) in FLAC are a very complex and require a good understanding of hydrogeology, soil mechanics, FLAC and its internal language FISH.

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