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A Theoretical Study of Pore Water Pressures Developed in Hydraulic Fill in Mine Stopes

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A
THEORETICAL STUDY OF PORE WATER PRESSURES DEVELOPED IN HYDRAULIC FILL IN MINE STOPES

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Synopsis

A numerical model for the hydraulic back-filling of two-dimensional mine stopes is presented. The use of the model is demonstrated by some analyses in which fill levels, water levels and the pore water pressures developed in the voids of the fill material are predicted. The effects on these features of various parameters, such as rate of pouring of the fill, the fill permeability and of drain location and performance, have been investigated. The model may be useful in the design and interpretation of experiments aimed at observing and measuring these phenomena. Although it would be premature to regard the two-dimensional model presented here as a proven design tool, it might be of some assistance in determining the general requirements for bulkheads and bulkhead drains and in the planning of filling operations.

CONTENTS

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1. INTRODUCTION

One method of winning ore from underground metalliferous mines is by open stoping. These stopes are frequently backfilled with fine solids placed hydraulically and the presence of water in the voids of the fill gives rise to pore water pressures. A knowledge of the magnitude and distribution of the pore pressures developed during the placement of this hydraulic fill is useful for the design of bulkheads and for the planning of fill operations. The best and most reliable information will only be obtained from experimental studies. Until experimental data are available, numerical studies are of value for the understanding they give of the processes involved and for identifying the important parameters for future work. This paper describes a numerical model prepared for Mount Isa Mines Limited to serve these functions. For this initial study attention has been restricted to two-dimensional stopes and results for this simplified case have been obtained to demonstrate the effects of various parameters on the pore water pressures occurring in the fill.

2. PROBLEM DEFINITION

When hydraulic fill is poured into a stope, the bulkheads used to contain the fill at the entrance to drives are subjected to both earth pressure and pore pressure. The work described in this paper was concerned with the prediction of pore pressures throughout the stope in general and at bulkheads in particular.

The first objective was the development of a numerical model to simulate the placement of hydraulic fill, the drainage of water from the fill and the development of pore pressures during the process. The model was subsequently used to investigate the effects of pour rates, fill permeability and drain performance on the pore pressures.

For this study, the problem was simplified to the two-dimensional analysis of a stope with vertical sides (see Figure 1).

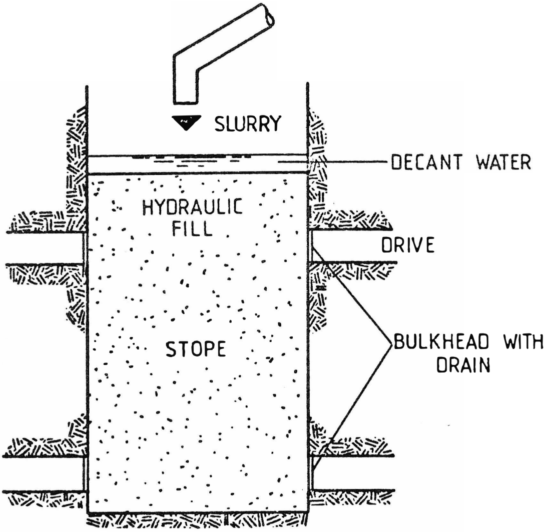

FIGURE 1 : Definition of the 2-D problem

The unsteady problem was dealt with by the use of a series of steady state seepage analyses with adjustments to the conditions in the stope to take account of changes with time. The adjustments were based on the slurry pour rate, slurry composition and on the results from the seepage analyses.

The general procedure used in the solution was:

(1) Specify the stope geometry, drain locations, pour rate, slurry composition and properties and initial conditions at time, $t = 0$.

(2) Perform a steady state seepage analysis and calculate the seepage heads, pore pressures and the seepage discharge, q, for conditions at time t.

(3) For time interval, Δt,
   (a) the seepage discharge equals $q.\Delta t$
   (b) calculate the net water inflow or outflow
   (c) calculate the change in fill level in the stope
   (d) calculate the change in water level in the stope

(4) Update the region of analysis and the boundary conditions for the seepage analysis

(5) Update time, $t = t + \Delta t$.

Repeat steps 2 to 5 until the simulation is completed.

3. SEEPAGE ANALYSIS

The assumptions made for the analysis of water movement through the saturated fill were:-

(1) The porous medium is homogeneous, isotropic and incompressible.

(2) Darcy's law is applicable.

(3) Pore pressure is zero adjacent to functioning drains.

(4) The top surface of the fill is horizontal and
    (a) when decanted water lies above the fill, the upper boundary for the region used in the seepage analysis is the fill level with the seepage head at this boundary determined by the water level

    (b) when the fill is not saturated over the full height, the upper boundary for the region used in the seepage analysis is the phreatic surface and this surface is horizontal.

The seepage analysis was done using a numerical method based on a finite difference formulation. Functioning drains were modelled as nodes with specified head (corresponding to zero pore pressure) in the finite difference grid. The accelerated Gauss-Seidel method was used to solve the equations for the values of seepage head at the finite difference nodes. Subsequently, the computed values of seepage head were used to calculate the seepage discharge through the drains.

Changes During a Time Interval, Δt

The assumptions made for the adjustments during a time interval, Δt, were:-

(1) The seepage discharge rate during the interval Δt between times t and $t + \Delta t$ equals the rate calculated for conditions at time t.

(2) The hydraulic fill is placed uniformly so that the fill surface is horizontal.

(3) If the water level is above the fill level, it will not rise above the level at which the next highest drain is located i.e. decant water will be drawn off at any drains above the fill level.

(4) When the phreatic surface is below the fill level, the volume of water reaching the phreatic surface during the time interval Δt equals the volume of water introduced with the hydraulic fill.

The results obtained for the cases presented in this paper indicate that the maximum pore pressures, at the bottom of the stope, were not influenced by the details of the modelling at the top of the stope nor by the time lag due to unsaturated seepage for those cases when the upper portion of the fill was not fully saturated and it was concluded that these assumptions were reasonable for the purposes of this study.

4. DRAIN PERFORMANCE

This study was restricted to the two limiting cases for drain performance:-

(1) a well designed, functioning drain at which the pore pressure is zero, and

(2) a clogged drain which passes no discharge and which, therefore, is part of the impermeable boundary to the region of seepage analysis.

Actual drain performance would lie between these two limiting cases. Intermediate conditions have not been studied because of lack of experimental data and because the purpose of the investigation has been satisfied by consideration of the two limiting conditions.

5. SOME TYPICAL RESULTS

There is a large number of parameters to be investigated in the hydraulic fill problem. They include: the geometric properties of the stope, its shape and size as well as the location of drain points; the composition of the slurry material, i.e. the relative proportions of solids to water; factors influencing the hydraulic properties of the fill once it has settled from suspension, i.e. its porosity and its permeability coefficient; and the history of the filling operation, including the rate at which the fill is continuously poured and the number and distribution of any rest periods. It is not the aim of this present work to provide an exhaustive coverage of the effects of all of these parameters, as space would not permit such a treatment. Instead, by presenting a selection of results, it is hoped that some of the more important features may be highlighted.

Only two-dimensional, vertical stopes have been considered and each had a width of 40 m and a maximum height of 250 m. In each case the slurry was 69% by weight of solids, the remainder was water. When the solids settled, it was assumed that the resultant fill had a voids ratio of 0.8 (i.e. porosity = 0.444). In all cases the solids had a relative density (specific gravity) of 2.7. Each analysis required the specification of an initial condition at time t = 0. This was arbitrarily selected as saturated fill to a height of 10 m above the bottom of the stope.

Results from a number of analyses are presented below in order to illustrate the significance of:

(a) the permeability of the fill material,

(b) the pour rate and the use of periods of filling followed by periods of no filling (rest periods),

(c) the location of drains and the consequences of drain blockage.

Details for each analysis are set out in Table 1. Case 1 has been selected, somewhat arbitrarily, as a "standard" which may be used as a basis for comparison with the others. A value for the permeability coefficient k of 10^{-5} m/sec is considered to be representative of a fill material like very fine sand. This value was held constant throughout the fill, although the incorporation into the analysis of any specified variation in permeability would be straightforward. The pour rate of 250 tonnes of solids per hour (into a stope of plan dimension 40 m x 40 m) has been arbitrarily selected, but it seems reasonable that this may be a likely maximum for many operations.

In analysing the results from each case, attention has been confined to the following features:

(i) the levels of fill and water obtained in the stope.

(ii) the pore pressures developed in the water which remains in the voids of the fill material.

5.1 The "Standard" Analysis - Case 1

Results for Case 1 are given in Figs. 2 to 5. Fig. 2 shows a plot of the fill and water levels versus time which has been measured from zero at the beginning of the analysis. Both the fill level (the surface of the solids) and the water level (the phreatic surface in this case as it is below the fill) show a steady increase with time. Initially, there was little difference between the fill and water levels, but as both levels rose, more drains along the sides of the stope came into operation and these were able to cope with an increase in overall discharge. After about 400 hours excess water continued to be stored in the voids but this was not sufficient to cause the phreatic surface to rise at the same rate as fill.

The maximum pore pressure predicted in the fill occurred at the middle of the base, i.e. at x = 20 m and y = 0 m. The history of pore pressure development at this point is shown in Fig. 3. Initially, the pore pressure increased rapidly but as the fill level rose more upper drains came into action; the rate thus decreased until about 600 hours at which time the pore pressure reached a maximum value of about 200 kPa. It remained constant during the remainder of the pouring operation. Indeed, the pore pressures in the lower portions of the stope reached an equilibrium distribution at about this time, i.e. they remained effectively constant at times greater than 600 hours, until the filling was completed at 2300 hours. The pore pressure contours in the lower portion of the stope at a time of 2000 hours are shown in Fig. 4.

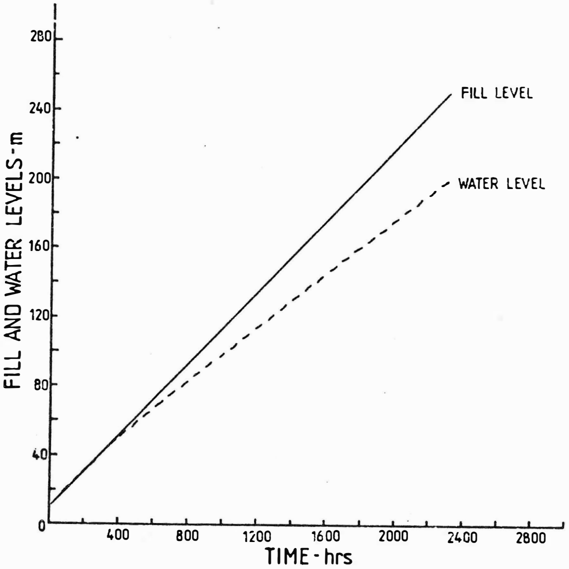

FIGURE 2 : Fill and water levels for Case 1

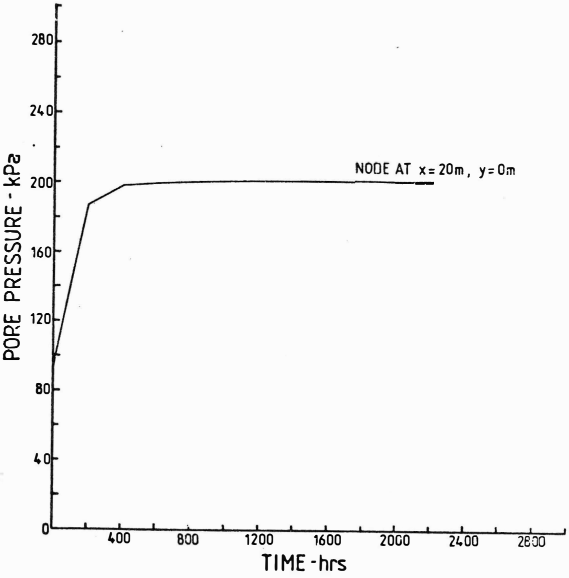

FIGURE 3 : Pore water pressure at bottom centre of the stope for Case 1

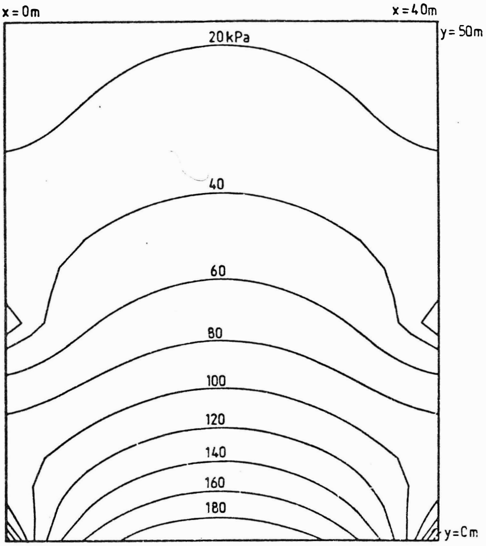

FIGURE 4 : Contours of pore pressure in lower region of the fill at time 2000 hours - Case 1

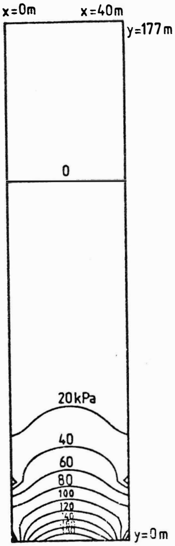

FIGURE 5 : Contours of pore pressure throughout the saturated fill at time 2000 hours - Case 1

Pore pressures in the upper part of the stope were very low. Fig. 5 shows pore pressure contours for the entire region of fill which is saturated at a time of 2000 hours when the fill level is 218 m and the phreatic surface is at 177 m. These results indicate that the hydraulic gradient through the upper part of the stope was very close to unity and that the discharge from the upper drains was very small. Therefore, if a drain in the upper part of the stope became blocked it would probably have little effect on the pore pressures (provided all other assumptions of the model are valid). On the other hand, if a drain near or at the bottom of the stope became blocked, significant changes will occur. This point is discussed at greater length below.

5.2 The Effect of Permeability - Case 2

The rate of drainage of water from the stope will be governed to some extent by the hydraulic properties of the fill material. It is obvious that materials with a higher permeability will drain quicker than those with a lower permeability. Indeed, if the permeability is low enough excess water may decant above the fill level.

In order to investigate such a possibility an analysis has been performed in which the permeability (considered to be constant throughout the fill) was 10^{-6} m/sec, i.e. a reduction of one order of magnitude below that for Case 1. The results of the analysis for this case are summarised in Fig. 6. There are marked differences between this and Case 1 for the water level in the stope. Numerical results showed that the overall seepage discharge was reduced by a factor of a little less than 10, consistent with the reduction in permeability. As a result, the model indicates that water decanted from the slurry and ponded above the fill - see Fig. 6. When this happened the numerical analysis automatically ensured that the water could not pond above the next highest drain from the current fill level.

The change in permeability did not, however, give rise to significant changes in the pore pressures. There was very little difference between the histories of pore pressure development at any location in the fill and consequently the pore pressure contours at a time of 2000 hours are almost identical to those produced for Case 1 (Fig. 3). The amount of saturated fill in the stope was increased but the pore pressure throughout this extended region was close to zero and the hydraulic gradient throughout the upper portion was close to unity.

5.3 The Effect of the Pour-Rate and Pour History - Cases 3, 4 and 5

Two more analyses were performed in an attempt to investigate the significance of the rate at which the slurry is poured into the stope. Case 3 differed from the "standard" Case 1 in that the pour rate was reduced by a factor of 2, while in Case 4 it was reduced by a factor of 10. In Case 3 the phreatic surface rose at a rate much less than half of the rate for Case 1 and the rate of change of this level tended toward zero with increasing time - see Fig. 7. The phreatic surface has approached a constant level as the overall discharge of water from the stope has tended to balance the inflow of water in the slurry, thus leaving little or no extra water to be stored in the voids of the fill material.

Pore pressures in the lower portion of the stope increased more slowly than in Case 1 but still reached the same final values. The results obtained for Cases 1, 2 and 3 showed that the final values for pore pressures at the bottom of the stope were attained when the phreatic surface reached a level of approximately 40 m. Further increases in the phreatic surface level did not significantly alter these values of pore pressure.

For Case 4, in which the pour rate was reduced below that for Case 1 by a factor of 10, the phreatic surface dropped below its initial value of 10 m at time zero, to a value of 7.3 m at 2500 hours and remained at that level until the completion of the pour. The maximum pore pressure in the stope (at x = 20 m, y = 0 m) did not exceed about 70 kPa. The reduction, by an order of magnitude, in the pour rate has had a significant effect on the conditions in the stope.

In all of the analyses considered so far, it has been

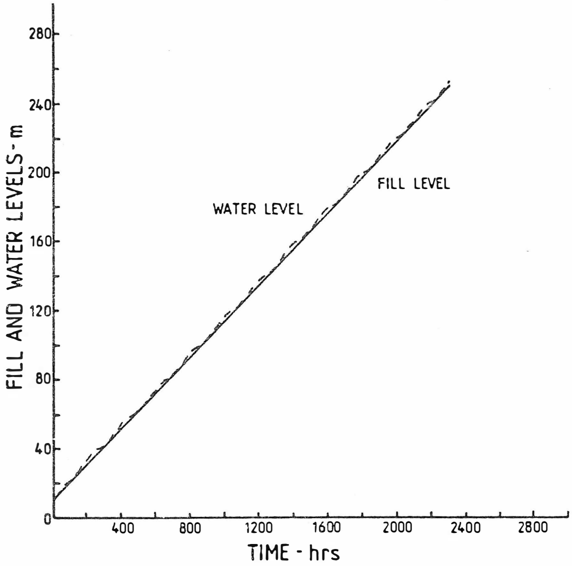

FIGURE 6 : Fill and water levels for Case 2

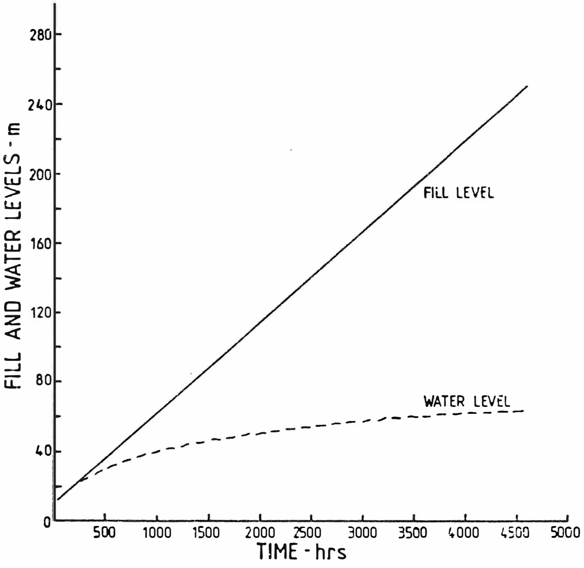

FIGURE 7 : Fill and water levels for Case 3

assumed that the slurry has been poured continuously at some specified constant rate. The analysis of Case 5 was performed in order to determine the effect of a regular sequence of periods of pouring followed by rest periods. Each pour lasted 100 hours and each rest 50 hours - further details are given in Table 1. The results of this analysis are summarised in Figs. 8 and 9. Small ripples in the curves for fill and water levels indicate the cycles of pour and rest periods. During periods of pouring the slurry both levels rise, while during the rest periods the phreatic level falls slightly as the stope drains and the fill level, of course, remains constant. Overall, both levels continue to rise with time, but at rates lower than those predicted in Case 1. The history of pore pressure development at the bottom centre of the stope is shown in Fig. 9. Again an equilibrium condition is reached soon after the phreatic level rises to about 40 m. The maximum pore pressure is about 200 kPa, the same as for Cases 1, 2 and 3. These results indicate that for rests to be significant in the control of pore pressure the rest periods would have to be much greater than the 50 hour duration used here.

5.4 The Effects of Drain Location - Cases 6, 7 and 8

Three more analyses were carried out to determine the effects of drain location and the consequences of a drain(s) becoming blocked.

Firstly, in Case 6, it was assumed that the drain at the bottom right hand corner of the stope (x = 40 m, y = 0 m) did not operate right from the start of the analysis. The history of pore pressure development at the bottom centre of the stope and at the blocked drain are shown in Fig. 10, and the pore pressure contours at 2000 hours, for the lower portion of the stope, are shown in Fig. 11. Calculated pore pressures in the upper part of the stope were again very low. As in Case 1 the maximum pore pressure was reached at about 600 hours and remained constant thereafter. The pore pressure at the centre was about 20% higher than for Case 1 while the maximum pore pressure occurred at the bottom corner and was about 260 kPa. This represents the water pressure that would be exerted on the bulkhead if the drain through it became blocked.

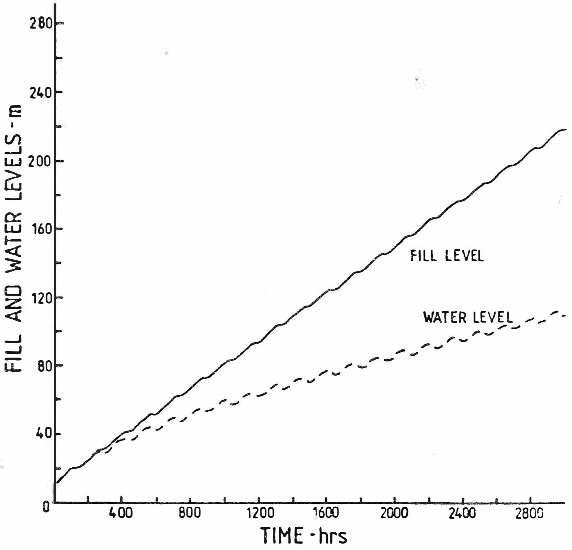

FIGURE 8 : Fill and water levels for Case 5

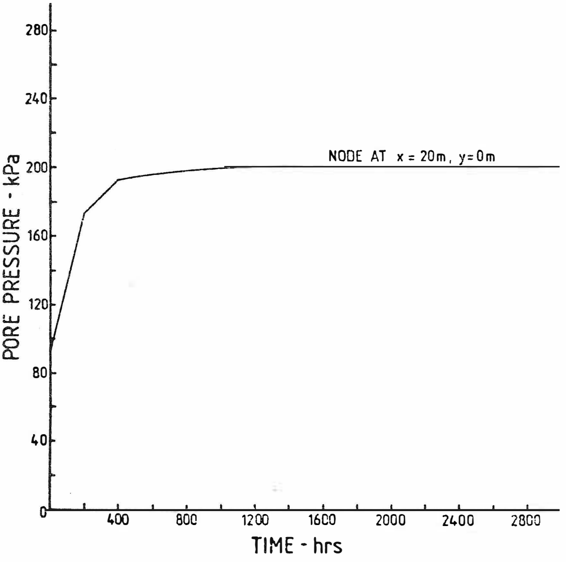

FIGURE 9 : Pore water pressure at bottom centre of the stope for Case 5

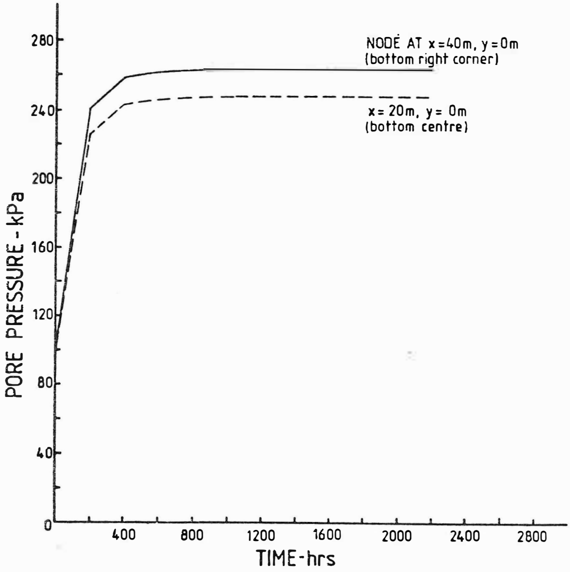

FIGURE 10 : Pore water pressures at selected locations in the stope for Case 6

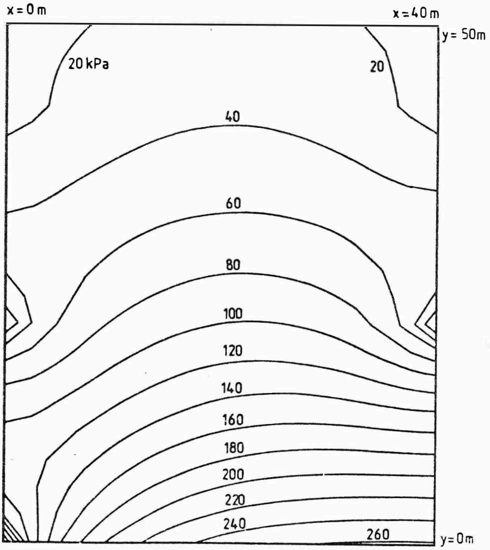

FIGURE 11; Contours of pore pressure in lower region of the fill at time 2000 hours - Case 6

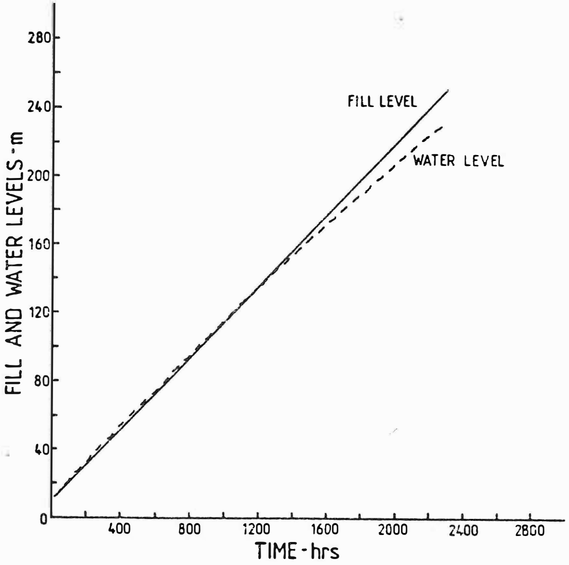

FIGURE 12 : Fill and water levels for Case 7

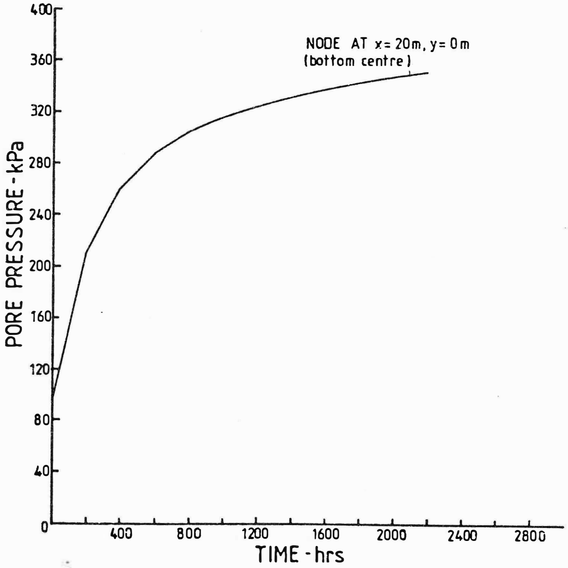

FIGURE 13 : Pore water pressure at bottom centre of the stope for Case 7

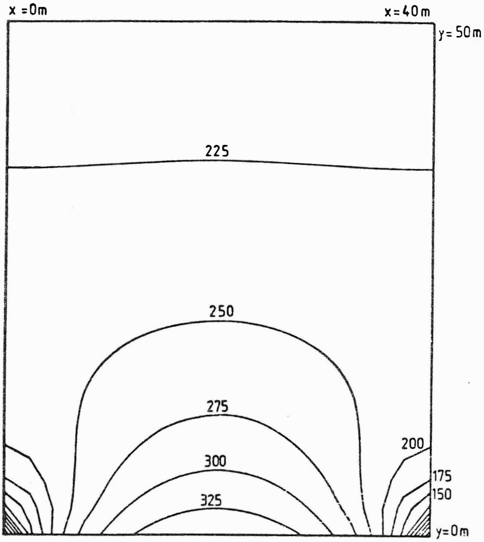

FIGURE 14 : Contours of pore pressure in lower region of the fill at time 2000 hours - Case 7

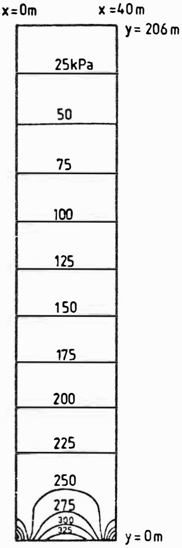

FIGURE 15 : Contours of pore pressure throughout the saturated fill at time 2000 hours - Case 7

For Case 7 the fill material was drained from only two locations; one drain at each of the bottom corners of the stope. Results of this analysis are given in Figs. 12 to 15. Because the pour rate is the same as in Case 1, Fig. 12 shows no difference in the curve for fill level versus time. However, as less drains are now available to remove slurry water from the stope, the water level at any time is correspondingly higher than at the same time in Case 1. At times less than about 1200 hours some decanting occurs; after this time the rate of rise in the phreatic surface is less than the rate of rise of fill level and so decanting no longer occurs. Fig. 13 shows the pore pressure development at the bottom centre of the stope. The pore pressure rises and even after 2300 hours (end of the analysis) an equilibrium or "steady state" condition has not been reached. The maximum pore pressure at 2300 hours is about 350 kPa, which represents an increase of about 75% over the corresponding value in Case 1. Contours of pore pressure at 2000 hours are shown in Fig. 14 for the lower portion and in Fig. 15 for the entire region of fill which is saturated. Fig. 15 indicates that significant pore pressures exist throughout most of the fill material and this situation can be contrasted with the picture given in Fig. 5 for Case 1.

Quite obviously, the number and location of drains are crucial in determining the pattern of seepage which develops within the deposited fill and thus are particularly important in determining the magnitude and distribution of pressures developed in pore water. In Case 8 the water has been allowed to drain from the stope at four locations near the bottom of the fill - the exact details are specified in Table 1. Results for this analysis can be found in Figs. 16, 17 and 18 and they indicate that four drains are almost sufficient to produce a drainage condition and pore pressure regime similar to Case 1. This indicates that the higher drains in Case 1 do not remove much of the water from the fill material, most of it will leave the stope via the bottom four drains. However, the upper drains will assume greater importance if conditions in the stope are such that slurry water is allowed to decant and pond above the fill material. The upper drains would then be important in helping to remove this decanted water from the stope.

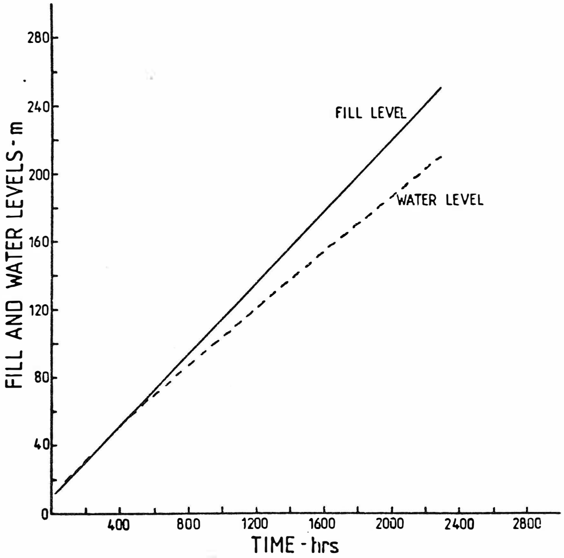

FIGURE 16 : Fill and water levels for Case 8

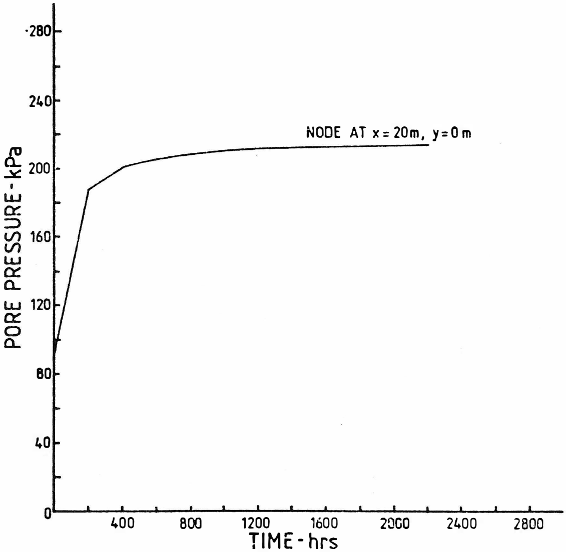

FIGURE 17 : Pore water pressure at bottom centre of the stope - Case 8

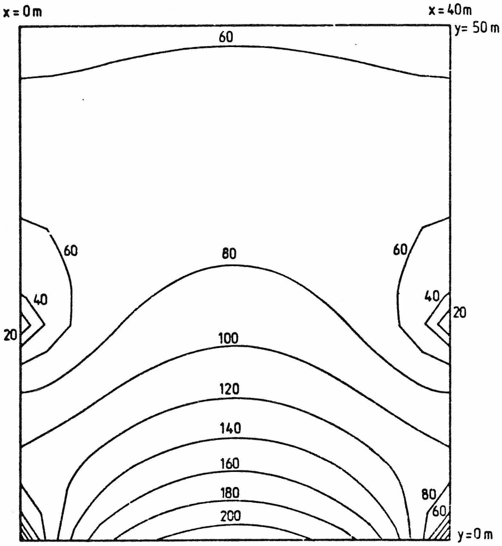

FIGURE 18 : Contours of pore pressure in lower region of the stope at time 2000 hours - Case 8

5.5 Drainage After Stope Filling

Some idea of the pore pressures developed during the filling operation has been given in the preceding sections. Another feature of interest may be the time required for the dissipation of these pore pressures as slurry water drains from the stope after the filling operation has been completed. In order to illustrate this point, consider again Case 1. Figs. 19 and 20 show results for the extended analysis. From time zero to about 2300 the stope has been filling, resulting in a maximum fill level of 250 m and a phreatic surface at almost 200 m - see Fig. 19. At time 2300 hours the slurry pouring has ceased and thereafter the fill level remains constant while the stope continues to drain. A further 3500 hours were required (total time about 6000 hours) for the phreatic surface to fall to the level of the bottom of the stope. Fig. 20 shows the development and subsequent dissipation of the pore pressure at the bottom centre of the stope over this 6000 hour period. The pore pressure at this location rises to a maximum of about 200 kPa, remains steady for a time and then eventually drops again as the phreatic

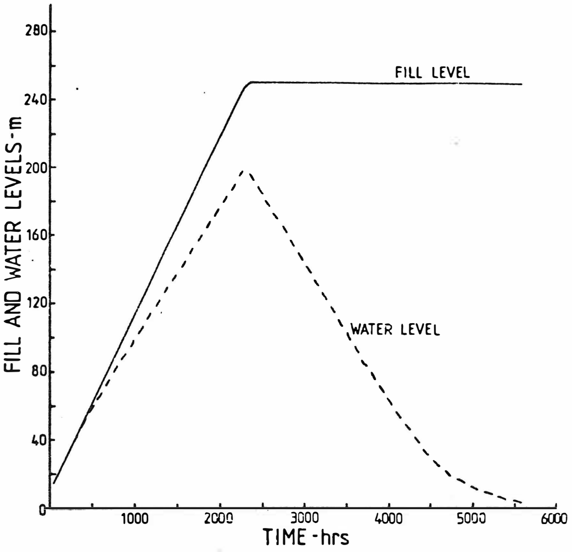

FIGURE 19 : Fill and water levels for Case 9

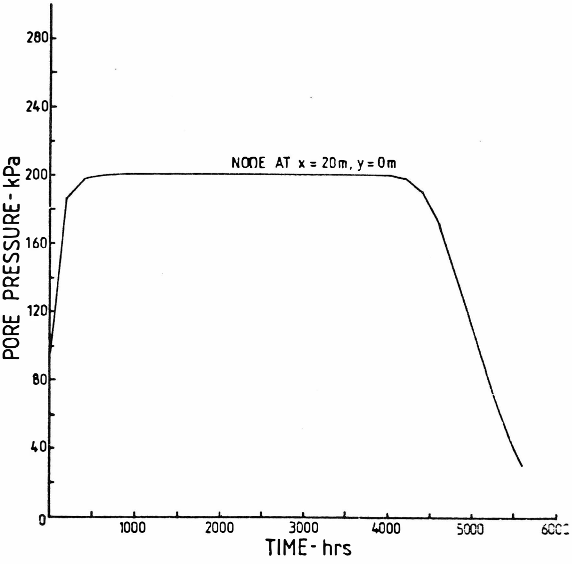

FIGURE 20 : Pore water pressure at bottom centre of the stope for Case 9

surface falls. One feature of special interest on the curve in Fig. 20 is the extended plateau, where the pore pressure is steady at its maximum value. At the bottom of the stope the pore pressure does not begin to fall at the same instant that the filling operation ceases; indeed, there is a considerable time lag as shown by the extent of the plateau. The pore pressure only begins to drop noticeably at about 4300 hours when the phreatic surface is down to about 40 to 50 m above the base. This mirrors the behaviour observed during the filling, where the pore pressure reached its maximum when the preatic surface had reached about 40 to 50 m.

6. CONCLUSIONS

The results from the example calculations indicate that the high pore pressures in the lower part of a stope are not significantly affected by the permeability or the pour rate, unless the pour rate is very low. However, drain performance is very important for the control of pore pressures, especially adjacent to a bulkhead.

While the model has yielded valuable information regarding trends, it is based on a number of simplifying assumptions. It is desirable that these assumptions should be validated against experimental data and, indeed, the model itself should prove useful in the design and assessment of any experimental programme.

Finally, for the design of bulkheads and the planning of fill operations a more general three-dimensional model, incorporating all the essential features of the real case, will have to be produced.

7. ACKNOWLEDGEMENTS

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The authors are also grateful to R. Nilsson and N. Richter for providing assistance and software for computer graphics.

APPENDIX A - NOTATION

Symbol	Meaning
k	permeability of fill material
q	rate of seepage discharge
t	time
Δt	increment of time
x,y	coordinates of two-dimensional stope (origin at bottom left hand corner)

TABLE 1 : Details of Seepage Analysis

Case	Pour Details	Permeability of Fill	Drain Locations	Comments
1	250 tonnes/hr of solids, continuously	$k = 10^{-5}$ m/sec.	At 20 m vertical interval along both sides of stope. First drains at bottom corners	"Standard" case
2	As for Case 1	$k = 10^{-6}$ m/sec.	As for Case 1	To show the effect of the permeability coefficient
3	125 tonnes/hr of solids, continuously	As for Case 1	As for Case 1	To show the effect of the pour rate
4	25 tonnes/hr of solids, continuously	As for Case 1	As for Case 1	To show the effect of the pour rate
5	Cycles consisting of 250 tonnes/hr of solids for 100 hours, followed by 50 hours rest (no pouring)	As for Case 1	As for Case 1	To show the effect of pour rate and pour history
6	As for Case 1	As for Case 1	As for Case 1 except for one blocked drain at the bottom right hand corner of the stope	To show the effects of a drain blockage
7	As for Case 1	As for Case 1	Only 2 drains, 1 at each bottom corner of the stope	To show the effects of drain location
8	As for Case 1	As for Case 1	Only 4 drains, 1 at each bottom corner of stope and 1 on each side of the stope, 20 m above the corner drains	To show the effects of drain location
9	As for Case 1 but sufficient time then allowed for complete stope drainage	As for Case 1	As for Case 1	To investigate seepage behaviour after stope filling has been completed

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