RELATIVE CONTRIBUTIONS OF NEAR-MINE & REGIONAL AQUIFER PROPERTIES TO WATER TABLE LOWERING NEAR OPEN-PIT MINES

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ABSTRACT

The lowering of the water table and consequent environmental effects of open pit mines depend mainly on the hydraulic characteristics of the aquifer close to the mine, regional aquifer properties and the amount and distribution of natural recharge and discharge. This paper will examine the relative effects of local and regional hydraulic properties of the aquifer according to the time scale of pit development. Finite element modelling of the situation around a circular pit will be described. Many open pit mines can be treated approximately as circular pits. The actual radial distribution of water table fall over a period of 20 years around a limestone mine which has been the subject of previous IMWA Congress papers will be used as an example. The monitoring of environmental effects around this mine has been exceptional by Australian standards. The initial assumption that the steepness of the drawdown cone would restrict significant water table drawdown effects to a relatively localised area around the mine proved true for about the first 10 years of pit development. However, as time has passed, more distant effects controlled by regional aquifer properties and recharge / discharge have become significant.

INTRODUCTION

The areal extent of the zone significantly affected by dewatering an open pit mine can be the subject of much argument, particularly when the effect of the mine on the water table is masked by naturally occurring fluctuations caused by climatic variation and other natural and artificially imposed drainage of the aquifer.

Visitors to mines who are unfamiliar with hydrogeological principles frequently get an exaggerated impression of the effect of mine dewatering when they view the water table in the pit to be approximately level with the pit floor. Their minds extrapolate the observed low water table level beyond the pit boundary and they go away with the impression that the surrounding water table is affected to a much greater extent than it really is. The problem lies mainly in the lack of awareness by most people of the existence of a seepage face at the pit boundary, and that it is the top of the seepage face, not the water level in the bottom of the pit, which is the starting point from which the level of the water table around the pit should be pictured.

There is also a general lack of awareness of the large variations in water table level which may occur naturally in areas where climatic conditions are very variable. The range of these variations may greatly exceed movements caused by mine dewatering. Fluctuations of surface water levels and flows between flood and drought conditions are visible and common knowledge, whereas changes in water table levels , whether natural or caused by mine dewatering, are generally hidden.

The height of the seepage face at the boundary of a mine pit is governed to a large extent by the hydraulic conductivity of the aquifer close to the pit where flow velocities induced by pit dewatering are relatively large. This is particularly so in the case of fractured rock aquifers in which many mines are situated. The seepage face height also depends considerably on the degree of penetration of the aquifer by the pit.

The volume of the aquifer near the pit which is dewatered by pumping from the pit is a function of the seepage face height and the relatively steep profile of the drawdown cone near the pit. The profile may be particularly steep if flow is restricted to a limited number of fissures in fractured rocks with the result that the relationship between velocity and hydraulic gradient is non-linear (non-Darcy flow). Changes in the water table profile beyond this "near-pit" zone are dependent on aquifer transmissivity, storage coefficient, recharge, natural drainage from the aquifer and pumping for purposes other than mine dewatering.

Although each hydrogeological situation is unique, many can be considered as a first approximation in terms of radial flow to a circular pit. General principles established for this simplified case may be useful in predicting the likely effect of mine dewatering in particular instances. Computer modelling using finite element analysis has been used to produce some non-dimensional curves which can be used to illustrate general effects of the parameters on the water table profile for this case. The model has also been used to calculate the volume of aquifer which will be dewatered in the near-pit zone and in the more distant regional-scale aquifer to supply the water which will flow into the mine under the influence of gravity. It is assumed that the pit is kept dry and that water pumped from the pit is not returned to the aquifer.

COMPUTATIONS

The computer program used to obtain the results from which non-dimensional curves have been plotted is described by Dudgeon (1985). The technique used requires selection of a trial seepage face and water table for each case considered and iteration to produce the water table for which the field equation (which results from the continuity and velocity / hydraulic gradient relationships) is satisfied for the particular boundary conditions specified. Some results from this program have been verified by comparison with results from a program which uses a saturated-unsaturated technique to determine the water table (Kalf, 1988). The program was also checked by comparing results with those obtained from large scale laboratory experiments.

Figure 1 shows a typical case analysed and defines the variables. Since water table changes under the influence of gravity alone are relatively slow, changes over time in the near-pit zone can be approximated by a series of steady flow profiles. More precise analysis requires unsteady flow modelling with recharge from rainfall superimposed. This is particularly so at greater distances from the pit where horizontal travel times following recharge are orders greater than the vertical time of travel of recharge to the water table. Because of short horizontal distances, relatively steep water table slopes and small aquifer storage volumes in the near-pit zone, the effect of local recharge on the water table near the pit dissipates rapidly. The short term increase in inflow due to short duration recharge near the pit is important in terms of maximum pumping requirements but is not important in relation to long term decline in the water table due to mine dewatering in areas which receive only intermittent rainfall such as most parts of Australia. The long term effect of distant recharge on the water table profile in the near-pit zone is a slow variation of the water table level at the outer boundary of the zone. The general effect of this can be studied by varying the value h_0, the saturated aquifer thickness at the radius of influence, in the computer program.

DIMENSIONLESS RELATIONSHIPS

Definition of variables and dimensionless parameters

The basic variables affecting the water table profile around a circular pit dewatered by pumping from within the pit are defined in Figure 1.

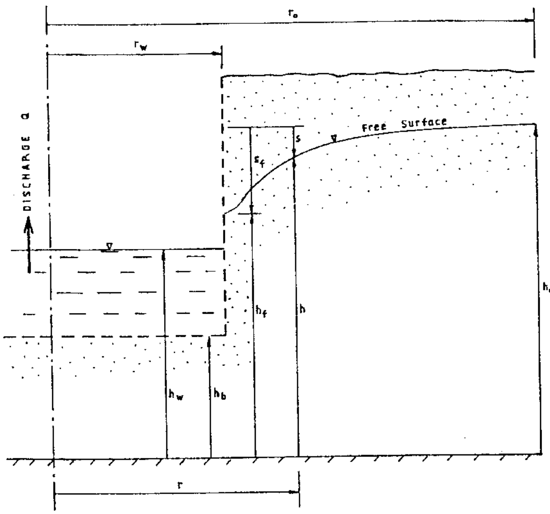

Figure 1: Definition sketch for unconfined flow to a circular pit

h = height of water table above base of aquifer at radius r from centre of pit
h_b = height of bottom of pit above base of aquifer
h_f = height of seepage face (at pit boundary) above base of aquifer
h_o = height of steady (or only slowly varying) water table at outer boundary of influence
h_w = height of water table in pit ($h_w = h_b$ for the case of a dewatered pit)
r_o = radius of influence at which water table height h_o occurs
r_w = radius of pit
s = drawdown of water table below h_o at radius r
s_f = drawdown at pit boundary (i.e to top of seepage face)

These variables can be grouped by dimensional analysis into the dimensionless parameters:

h/h_o, h_b/h_o (= h_w/h_o), h_f/h_o, r/h_o, r_w/h_o, s/h_o, s_f/h_o

If the volume of aquifer dewatered is denoted by $\bar{V}$, a corresponding dimensionless volume parameter $\bar{V}/h_o^3$ is obtained.

If $\bar{V}'$ is defined as the proportion of the aquifer within the radius of influence r_o which has been dewatered, $\bar{V}' = \bar{V} / \pi r_o^2 h_o$ and is dimensionless.

If $\bar{V}''$ is defined as the proportion of aquifer material dewatered in the annular volume $\pi (h_o-h_f)(r_o^2-r_w^2)$, $\bar{V}'' = \bar{V} / (\pi (h_o-h_f)(r_o^2-r_w^2))$ and is also dimensionless.

Note that the volume $\pi (h_o-h_f)(r_o^2-r_w^2)$ represents the volume of aquifer between the pit and the radius of influence r_o and between levels h_f, at the top of the seepage face, and h_o, the water table level without mine dewatering. The parameter $\bar{V}''$ is a more sensitive indicator of the steepness of the drawdown cone near the pit than is $\bar{V}'$ since it is independent of the large volume of aquifer at depth which is not dewatered.

The Forchheimer equation was used as the energy dissipation equation to cover both linear (Darcy) and non-linear (non-Darcy) groundwater flow. This equation, $i = dh/dl = aV + bV^2$, where

i = hydraulic gradient, dh/dl
V = flow velocity
a = linear Forchheimer coefficient ($\cong 1/k$, where k = Darcy's hydraulic conductivity)
b = non-linear Forchheimer coefficient

leads to the dimensionless parameter b/a^2 which is a measure of the degree of non-linearity of the velocity / hydraulic gradient relationship at the higher velocities which occur as flow nears the pit boundary. The value of b/a^2 depends on the number and apertures of channels through which water approaches and enters the pit.

Derivation of dimensionless relationships

Relationships between the dimensionless parameters listed above were obtained by repetitive calculation using the computer program referred to in the Introduction. The values of the dimensionless parameters used in the computations are shown in Table 1. The limiting values were obtained by inserting the lowest and highest values of the basic variables considered likely to be relevant to mine dewatering. (Note that on the basis of subsequent experience, the maximum value of b/a^2 should be increased from 1,000 to 10,000.)

Table 1: Values of dimensionless parameters for which computations were performed

r_w/h_o	0.1, 0.2, 0.5, 1.0, 1.5
r_o/h_o	4, 8, 20, 50, 100
h_b/h_o	0, 0.1, 0.2, 0.3, 0.4, 0.6
b/a^2	0, 0.1, 1.0, 10, 100

Plots of dimensionless relationships

The relationships were plotted as curves, of which some typical examples are given Figures 2 to 4. Because of space limitations, only examples of curves for seepage face height h_f and dimensionless dewatered volume $\bar{V}''$ for circular pits with water able to enter both the bottom and side of the pit are given. A full set of curves for this entry condition is given in Reference 1. A set of curves is also provided for the case where entry of water is restricted to the bottom of the pit (for this condition there is no seepage face, but h_f still represents the height of the water table at the pit boundary).

APPLICATION OF DIMENSIONLESS CURVES

The curves can be used for qualitative comparisons. By holding some variables constant, the effect of variation of others can be seen. Alternatively, particular cases of mine and aquifer geometry and aquifer hydraulic variables can be examined by calculating values of dimensionless parameters to enter the curves and reading the corresponding value of the remaining parameter. The value of an unknown basic variable can then be determined from the parameter by inserting values of the known variables. Because of the non-linear nature of the relationships, extrapolation should be limited where rapid change is evident.

The curves have been found useful in making preliminary estimates of the effect of mine dewatering on the water table. If the hydraulic parameter b/a^2 can be estimated, the seepage face height and the increase in volume of aquifer dewatered as the radius of influence of the pit expands can be determined. The results take into account the effects of finite pit diameter, partial penetration and non-Darcy flow near the pit. A series of dimensionless curves representing water table profiles for the range of variables covered by Table 1 would also have been useful, but it was found that the large number of curves required made the task of providing them impractical. If the water table profile near the pit is required, the computer program referred to in the Introduction must be used for each specific case.

A corresponding set of dimensionless inflow curves is also given in Reference 1. These curves allow preliminary estimates of pumping requirements to be made.

Relative effects of near-mine and more distant aquifer properties on water table

It is evident from Figures 2a & 2b that the seepage face height does not vary much for r_w/h_o values greater than 0.5 over the wide range of r_o/h_o from 8 to 100, regardless of the values of b/a^2 and h_b/h_o. For example, with r_w/h_o =1.5 and h_b/h_o = 0.6 (i.e penetration 40% of saturated thickness), the seepage face height varies only between about 60% and 65% of the saturated thickness. This indicates that control of the seepage face height is exerted mainly in the higher velocity flow zone near the pit. Figures 2a & 2b and 3a & 3b show that the existence of non-Darcy flow, for which the necessary high velocities can exist only in the rapidly converging flow near the pit, can increase seepage face heights significantly. This is further proof that the hydraulic properties of the aquifer near the pit exert the main control on seepage face height and thus the water table profile near the pit.

The dimensionless drawdown cone volumes given in Figures 4a & 4b can be used to illustrate how little change occurs in the water table level due to dewatering as distance from the pit is increased. The marked difference between the percentage dewatered volumes for the range of r_o/h_o from 4 to 100 demonstrates the rapid fall of the water table near the pit and, consequently the heightened effect of the hydraulic properties of the near-pit zone compared with those of the more distant part of the aquifer. For approximate quantitative estimates of the rate of change of the water table with distance from the pit as the drawdown cone expands, the change in volume dewatered as the cone extends from one r_o value to another can be divided by the annular surface area between the radii. It will be seen that the change in water table level necessary to provide the volume falls off rapidly with increase in radius.

Application to water table assessment around dewatered limestone mine

Discussion of the water table changes around an open pit limestone mine in Queensland has been presented in previous conference papers (Dudgeon (1997) and earlier papers). In this case, the effective saturated thickness in which the main groundwater flow has occurred has been estimated to be between 50m and 100m. In the early life of the mine most of the inflow came from the surface zone of solution channelling and the aquifer could be treated as shallower than in later years when the water table had fallen into the deeper fractured limestone (marble) in which solution channelling was less developed.

The dimensionless curves were found useful for the first ten years of pit expansion. For early predictions of both water table level adjacent to the pit and water inflows, a range of assumed values of effective aquifer thickness, pit diameter and bottom level, and b/a^2 gave results which agreed reasonably well with subsequently measured values. They allowed suitable dewatering pumps to be selected and gave a satisfactory picture of the effect of dewatering on the water table and farm water supplies around the mine. The water table lowering was insignificant beyond 1km from the mine and the seepage face remained relatively constant as the pit expanded in diameter at a given depth. This observation is in agreement with predictions of the radial flow seepage face model. The drawdown cone near the mine was steep as a result of non-Darcy flow and thus was controlled mainly by local hydraulic characteristics of the aquifer.

Comparison of the measured water table profile near the mine in 1985 with that predicted by the computer program used to produce the dimensionless curves allowed a value of $b/a^2=1,000$ to be determined for the aquifer at the mine. At that time the water table had fallen below the superficial zone of natural water table fluctuation in which solution channelling was pronounced and flow was mainly in fractured marble with limited dissolution in fissures. This value of b/a^2 has been used for all subsequent estimates.

Unfortunately, an unusually prolonged and severe absence of recharge for the past eight years and the finite boundary of the limestone body has now invalidated the assumption that the radius of influence could stabilise or expand indefinitely. Natural drainage, other pumping by farmers and lack of recharge has caused the regional water table to fall and the seepage face at the mine to fall slowly in response. It is now regional aquifer effects, including storage, which are influencing the water table away from the mine. The drawdown cone at the mine is still controlled by local hydraulics but the saturated thickness is now decreasing because of the lack of recharge. It has become difficult to separate the water table fall into components attributable to the drawdown cone and decrease of saturated thickness.

Another growing problem with using the data derived from the simplified radial flow model is caused by elongation of the pit to follow the elongated nature of the limestone body. The approximation to a circular pit is now not very good. In the distant future, the mine will be a long trench. The inflow and water table profile normal to the trench have again been analysed approximately by the methods given in this paper. If a sufficiently large radius of pit and radius of influence are introduced into the computer program, the model approximates flow into one side of a trench. The future water table profile near the mine and inflow per unit length of trench have been estimated using this approximation. Only future measurements will determine the accuracy of the predictions.

Unfortunately, the curves given in Reference 1 do not cover values of radius of influence and pit radius which are great enough to allow flow to a trench to be examined. However, the curves could be extended to cover such a case or the model could be modified to analyse two dimensional flow.

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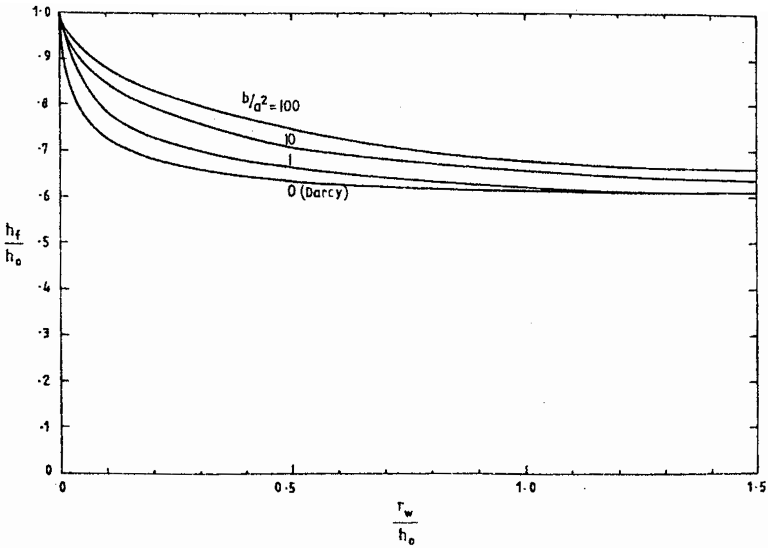

Figure 2a: Water level at dewatered circular pit in unconfined aquifer for r_o/h_o=8, h_b/h_o=0.6

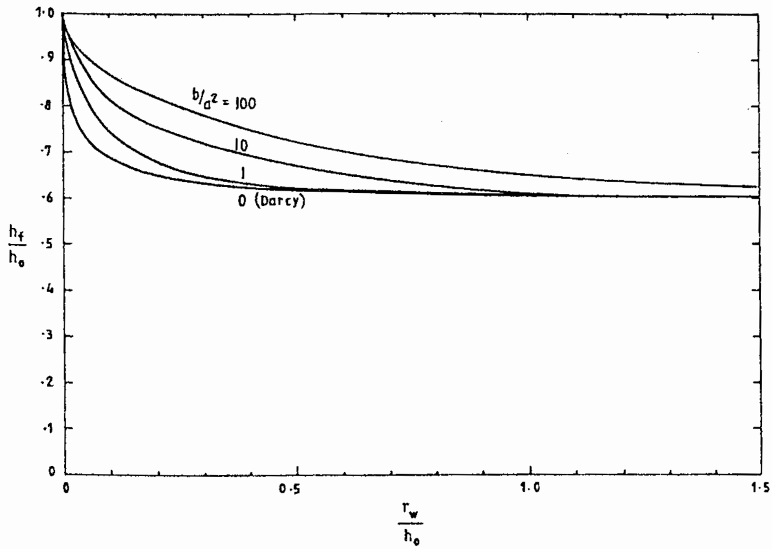

Figure 2b: Water level at dewatered circular pit in unconfined aquifer for r_o/h_o=100, h_b/h_o=0.6

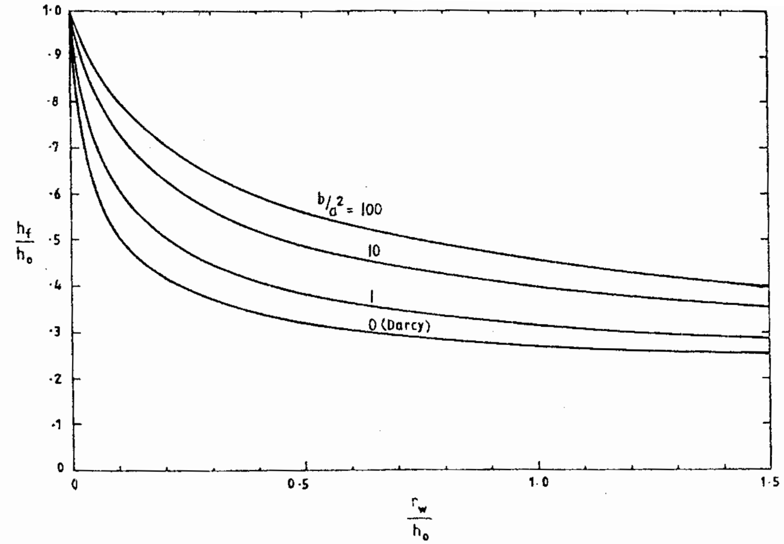

Figure 3a: Water level at dewatered circular pit in unconfined aquifer for $r_o/h_o=8$, $h_b/h_o=0.2$

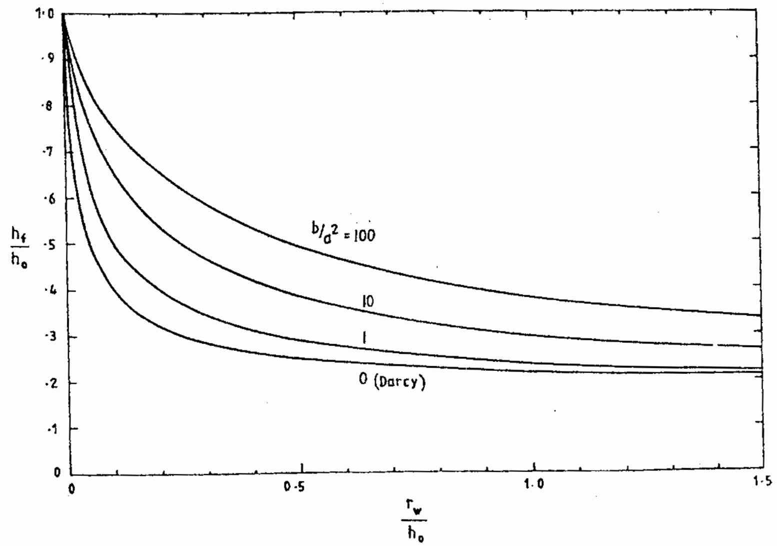

Figure 3b: Water level at dewatered circular pit in unconfined aquifer for $r_o/h_o=100$, $h_b/h_o=0.2$

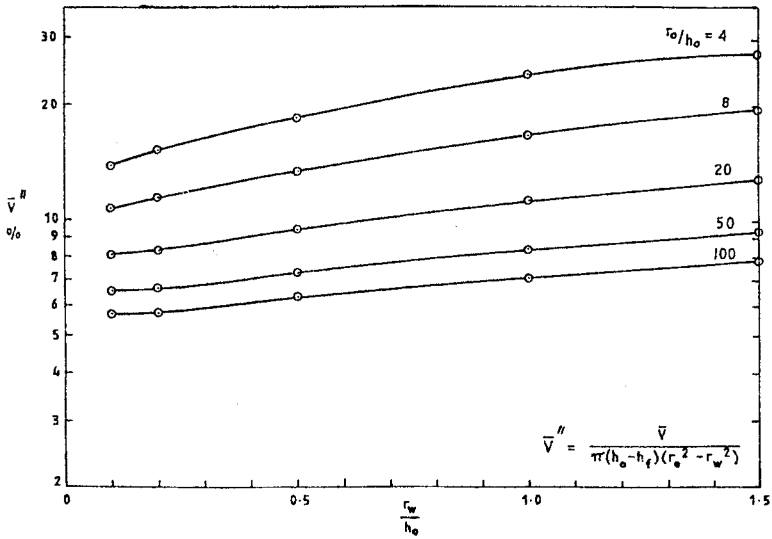

Figure 4a: Dimensionless drawdown cone volume $\bar{V}''$ for $b/a^2=0$, $h_b/h_o=0.2$

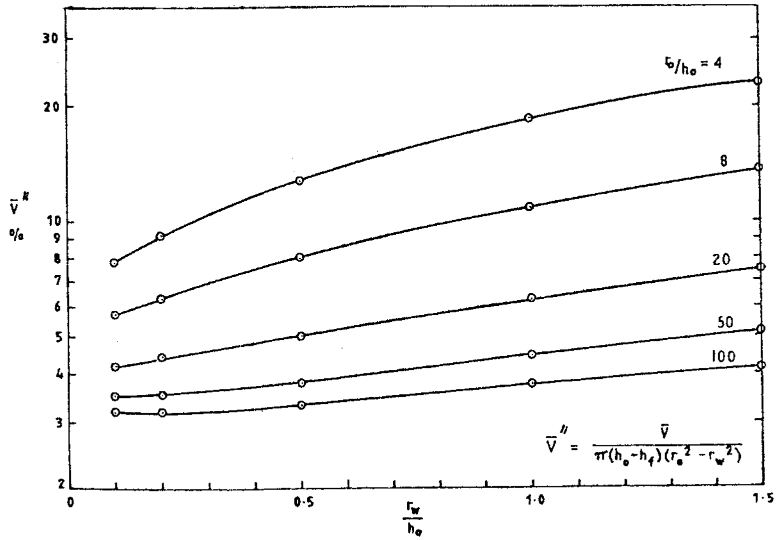

Figure 4b: Dimensionless drawdown cone volume $\bar{V}''$ for $b/a^2=100$, $h_b/h_o=0.2$