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UNCONFINED NON-DARCY FLOW NEAR OPEN-PIT MINES

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ABSTRACT

Non-Darcy flow can cause significant reductions in groundwater flows into open-pit mines in very permeable aquifers. The variables and flow equations which govern non-Darcy flow to open pits are discussed and the computation of a set of dimensionless curves designed to facilitate the prediction of non-Darcy flow effects is described. Examples of the curves are given. Two sets of field data which indicate non-Darcy flow over distances of tens of metres from pit boundaries are presented.

INTRODUCTION

Flow of groundwater into an open-pit mine in a highly permeable aquifer may induce significant non-Darcy head losses at considerable distances from the pit boundary. Field measurements to be discussed later have indicated the presence of non-Darcy flow over distances of some tens of metres from pits. Numerical analysis can be used to demonstrate that for a partially penetrating pit in a very permeable aquifer the flow field which results when non-Darcy flow occurs at high velocities can differ significantly from that for wholly Darcy flow over a region extending up to two aquifer thicknesses from the pit.

Since aquifers of high permeability cause the greatest de-watering problems, it is particularly important to be able to make a correct analysis of the flow in cases where non-Darcy flow occurs. Failure to allow correctly for non-Darcy flow effects will cause errors in predicted values of both inflow and water levels. If wholly Darcy flow is assumed, serious over-estimates of water inflows and under-estimates of water levels near the pit may occur. If flow in the non-linear flow zone is assumed to be fully turbulent when, in fact flow is in some transition state over most of this zone, inflows will be under-estimated and water levels will be over-estimated.

A general assessment of the combined effects of finite pit diameter, partial penetration and non-Darcy flow is most easily made with the aid of a set of pre-computed data covering the ranges of these variables likely to be encountered in practice. Finite element computations to provide this data have been carried out by the author for steady flow to fully de-watered pits. The results have been plotted as a series of dimensionless curves which can be used to estimate the relative effects of the variables governing flow into open pits. If boundary conditions for actual problems match those used to determine the curves, quantitative solutions to these problems can be obtained without further computation. Since the number of dimensionless curves required to cover the practical range of aquifer and pit variables is large, only typical graphs are included in this paper. The full set is being made available in report form.

Computation of the curves and their application in practice are discussed in subsequent sections of this paper. Two examples of de-watered open pits with groundwater inflows substantially reduced by non-Darcy head losses are discussed in the context of the numerical investigation described.

EQUATIONS FOR NON-DARCY FLOW

Numerical analysis of groundwater flow involves the solution of a field equation formed by combining a continuity equation and an energy dissipation equation. If there is a possibility that non-Darcy flow will occur in zones of high velocity in the flow field the dissipation equation used must be able to describe the relationship between macroscopic velocity and hydraulic gradient over both the laminar-linear (Darcy) and post-linear (non-Darcy) flow regimes.

In aquifer materials, such as unconsolidated gravels, in which flow occurs in a large number of irregular channels, the laminar-linear (Darcy) regime is not followed immediately by a partially turbulent transition to full turbulence as is the case for flow in circular pipes and between flat plates. Instead, there is an intervening regime of laminar non-linear flow in which inertial forces associated with frequent acceleration and deceleration of flow on the microscopic scale cause the relationship between macroscopic velocity and hydraulic gradient to become increasingly non-linear as the velocity increases. Eventually, shear rates become sufficiently high to cause spots of turbulence to appear. These spread as the velocity becomes greater until a fully turbulent state of flow exists. From the onset of turbulence the degree of non-linearity of the velocity-gradient relationship increases further. However it is only at very high flow rates that the hydraulic gradient becomes effectively proportional to the square of the macroscopic velocity.

The Forchheimer equation

$$i = aV + bV^2 \tag{1}$$

where i = hydraulic gradient

V = macroscopic flow velocity

a, b = coefficients which depend on aquifer and fluid properties

has been shown theoretically and experimentally to be an appropriate energy dissipation equation for flow through gravels and crushed rock materials. Although the constancy of the coefficients a, b over the various flow regimes described is open to discussion it has been shown by Cox (1977) that a single pair of a and b values gives an acceptably accurate fit to permeameter results for gravels over a range of velocities which covers those to be expected in the field.

The flow regimes which occur in fractured rock aquifers as the macroscopic velocity increases have not been thoroughly investigated. If the flow is viewed at a scale which includes a large number of irregular fracture flow channels, the changes in the nature of the macroscopic flow would be expected to follow the sequence described for gravels. However, if the flow occurred in a regular system of channels of considerable length the transition from laminar to turbulent flow should occur over a smaller range of velocity as is the case for flow between parallel plates and in tubes. Since real aquifers generally display a great deal of irregularity in the flow channels formed by the fracture system it is argued that for them the same type of energy dissipation equation that applies for gravels and crushed rocks should be valid. For fractured rock aquifers of this type, even relatively abrupt transitions to turbulence at the scale of individual channels would be spread over an extensive range of macroscopic flow velocity averaged over a representative volume of the aquifer.

Although a considerable amount of experimental work has been carried out to determine the nature of the flow relationship for single fractures in rock there appears to be no data available from laboratory experiments with fracture systems similar to those which occur naturally in the field. Data from field tests which would provide information on the relationship between flow rate and hydraulic gradient for flow through real fractured rock aquifers at high flow rates is also absent from the published literature.

Interpretation of the results of pumping tests on small diameter boreholes in fractured rocks when non-linear losses are evident is a potential source of information on the relevant non-linear flow relationship. However this presents serious difficulties because of the unrepresentative nature of the flow field developed near a small diameter hole which may intersect only a limited number of fractures in which flow occurs. Unless several holes are tested for periods long enough to extend the drawdown cones over representative samples of the fracture system and piezometric surface measurements are made in a sufficiently large number of holes to define the mean drawdown-distance relationship in a number of directions, non-Darcy flow effects measured will not represent the macroscopic flow situation.

Inflow measurements and piezometric surface observations made in an area surrounding a large pit whose boundary intersects a large number of fractures provides an alternative source of information on non-Darcy flow in fractured rock aquifers. Two examples are quoted later in this paper.

In the absence of more definite information on the velocity-gradient relationship applicable to flow near pits in fractured rocks it is considered by the author that the Forchheimer equation is the best equation of those available because of the degree of irregularity observed in flow in fracture systems intersected by mines. The transition from laminar-linear to turbulent flow is likely to be gradual and cover a wide range of velocity as it does for gravel aquifers for which the Forchheimer equation is known to provide a good fit to observed data.

The major problem inherent in the application of the Forchheimer equation in fractured rocks is the determination of the non-linear coefficient b. The coefficient a of the linear term can be approximated by $\frac{1}{K}$ where K is the hydraulic conductivity in the Darcy equation,

$$V = Ki \tag{2}$$

Cox (1976) has deduced a relationship between the coefficient a and b from results of permeameter tests on gravels. Pérez-Franco (1982) has also reported the derivation of expressions for predicting the coefficients from measurements made on porous media. In the absence of other data these expressions might be used as a first approximation for fractured rock aquifers with a large number of fracture flow paths. More definitive data can only be obtained by interpretation of appropriate field tests backed up by the results of laboratory experiments. Until appropriate research has been carried out it will not be possible to define properly the range of types of fractured rock aquifer for which the Forchheimer equation holds.

PREDICTION OF NON-DARCY FLOW EFFECTS

For those aquifers for which the Forchheimer equation is considered an appropriate relationship, there exists the problem of identifying the cases for which convergence of unconfined flow towards pits is likely to lead to non-Darcy flow. The increased difficulty of analysing flows for which Darcy's law is not valid throughout the entire flow region makes it desirable to be able to assess this possibility before detailed analysis is carried out. Since the occurrence of non-Darcy flow near pits depends on flow concentration, which in turn depends on variables such as pit diameter, degree of penetration of the aquifer and permeability, it is necessary to combine together the effects of all these factors. Two approaches should be considered. The first is to attempt from the outset to set up a numerical model which will correctly account for all boundary conditions and allow for the possible occurrence of non-Darcy flow. This may prove to be very expensive and only justifiable in a limited number of cases. The second alternative is to produce a series of pre-computed dimensionless relationships which will allow the prediction of non-Darcy effects for simpler boundary conditions without direct use of a numerical model and computer. This latter course of action has been found practical if the analysis is restricted to cases of axi-symmetric flow to pits in homogeneous aquifers. For more complex boundary conditions the amount of computation and plotting would be unmanageable. It is considered that the axi-symmetric flow case treated will provide a good general "feel" for the effects on the inflow rate of the important variables.

Solution by the finite element method of a sufficiently large number of flow cases to produce a set of dimensionless curves which allow the estimation of non-Darcy flow effects is described by Dudgeon (1985). Only the results relating to inflow rates to de-watered pits with bottom and side inflow are dealt with in this paper. Typical results which demonstrate the magnitude of the difference between inflow rates when non-Darcy flow is allowed for or ignored are given in the following section.

TYPICAL RESULTS OF FINITE ELEMENT ANALYSIS

Figure 1 defines the variables required to describe axi-symmetric flow to a fully de-watered partially penetrating pit in an unconfined aquifer. The discharge Q required to maintain the water level at the base of the pit is a function of the variables

r_w = radius of pit

r_o = radius of influence of aquifer

h_o = saturated thickness at radius of influence

h_b = height of pit above base of aquifer

a,b = Forchheimer equation coefficients

Dimensional analysis can be used to show that

$$\frac{aQ}{h_o^2} = \phi\left(\frac{r_o}{h_o}, \frac{r_w}{h_o}, \frac{h_b}{h_o}, \frac{b}{a^2}\right)$$

If a is replaced by $\frac{1}{K}$, where K is Darcy's hydraulic conductivity,

$$\frac{Q}{Kh_o^2} = \phi\left(\frac{r_o}{h_o}, \frac{r_w}{h_o}, \frac{h_b}{h_o}, \frac{b}{a^2}\right)$$

Figures 2 and 3 show the effect of the non-Darcy parameter b/a^2 on the inflow rate for large and small values of the penetration parameter h_b/h_o and radius of influence parameter r_o/h_o. The graphs have been selected from the full set which cover the range of values of dimensionless parameters given in Table 1.

It will be observed that for $b/a^2 = 100$ the inflow to a pit may be as little as 25 percent of the corresponding inflow for wholly Darcy flow. Values of b/a^2 even higher than 100 have been measured in very permeable gravels. Whether such high values could apply to fractured rocks is yet uncertain.

FIELD STUDIES

Measurements of inflows to two excavations in carbonate aquifers in Australia have provided data which indicate the presence of non-Darcy flow.

Open Pit in Limestone Aquifer

The first example is that of an open-pit mine in a well-fractured limestone deposit. The limestone dips steeply but the aquifer appears to be practically horizontal as the flow system has been formed by dissolution of carbonate from joints in a zone of relatively horizontal water table fluctuation. Figure 4 shows the water surface profile measured near the pit following long-term pumping at approximately 20 L/s. It can be seen

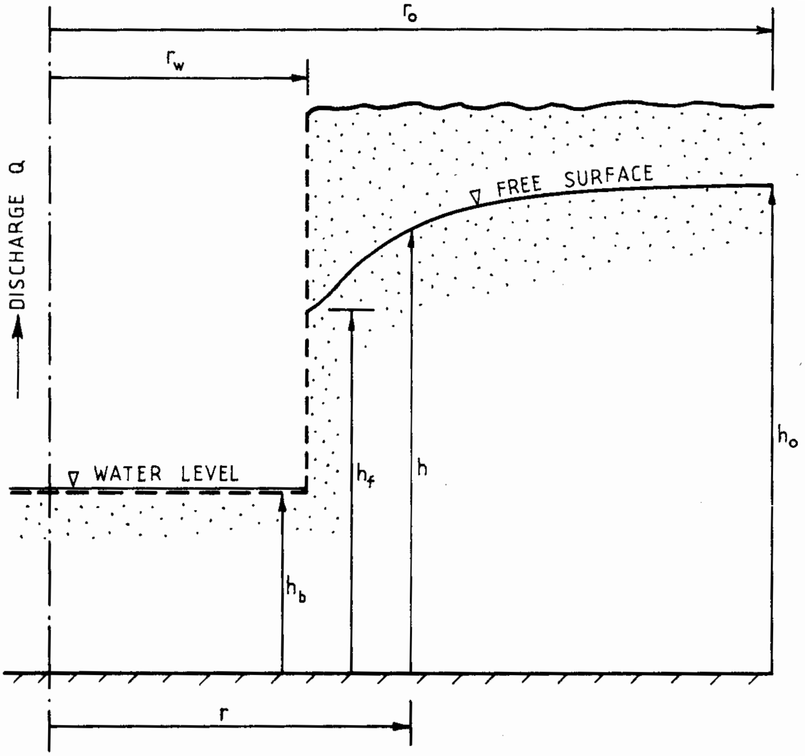

Fig. 1. Variables for flow to de-watered open pit.

TABLE 1

Values of dimensionless parameters for which values of $\frac{Q}{Kh_o^2}$ have been computed

Parameter	Values
$\frac{r_o}{h_o}$	4, 8, 20, 50, 100
$\frac{r_w}{h_o}$	0.1, 0.2, 0.5, 1.0, 1.5
$\frac{h_b}{h_o}$	0.1, 0.2, 0.3, 0.4, 0.6, 1.0
$\frac{b}{a^2}$	0, 0.1, 1, 10, 100

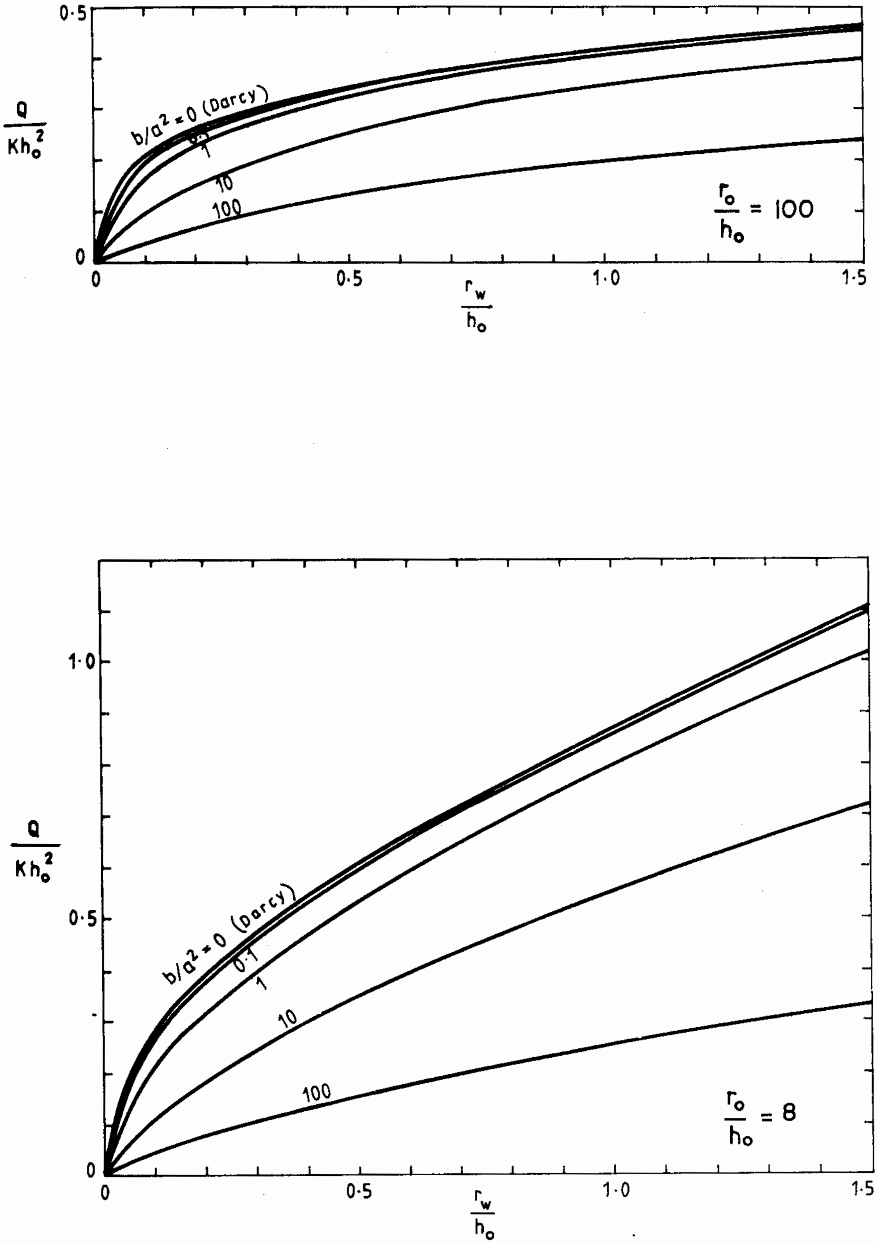

Fig. 2. Inflows to de-watered circular pits in unconfined aquifers for $^{h}{}_{b}/^{h}{}_{o} = 0.6$

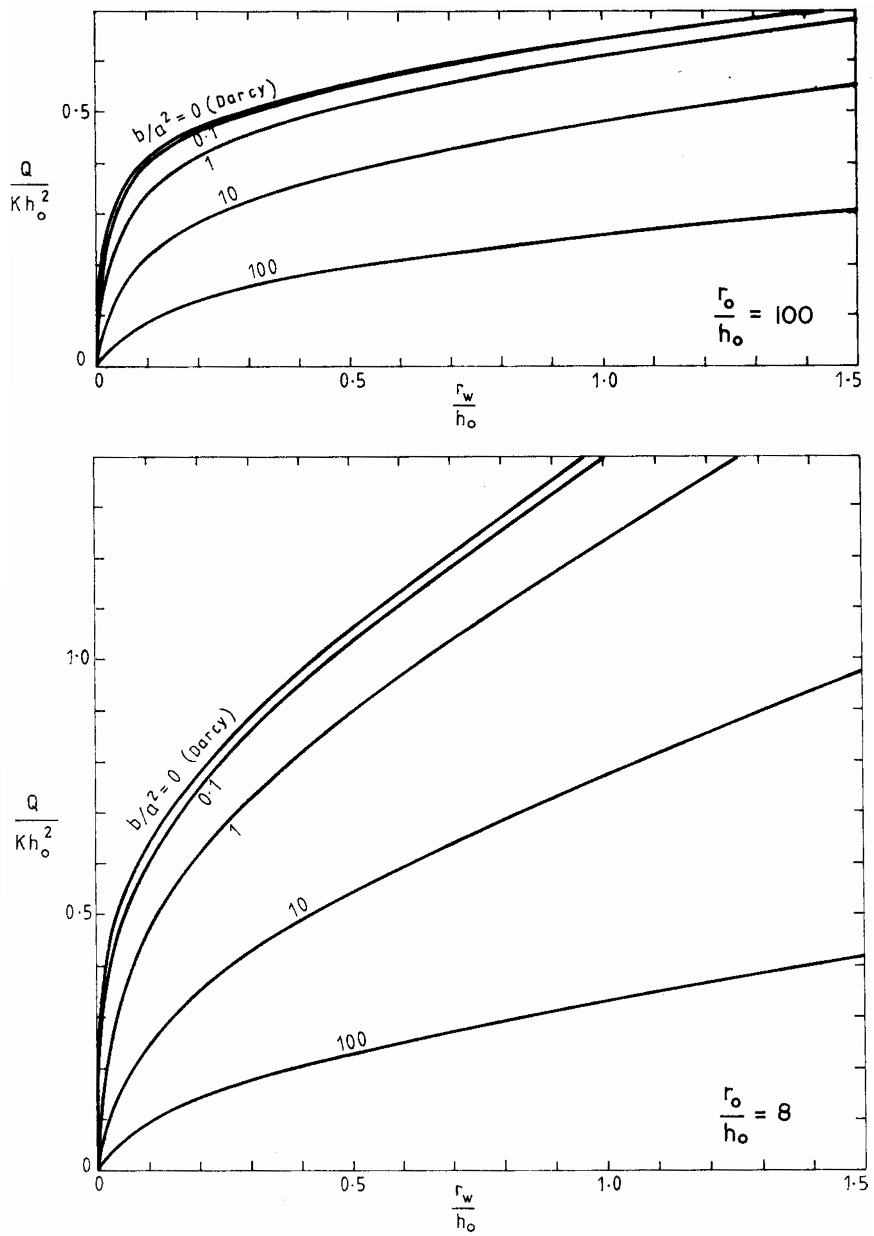

Fig. 3. Inflows to de-watered circular pits in unconfined aquifers for $h_b/h_o = 0.2$

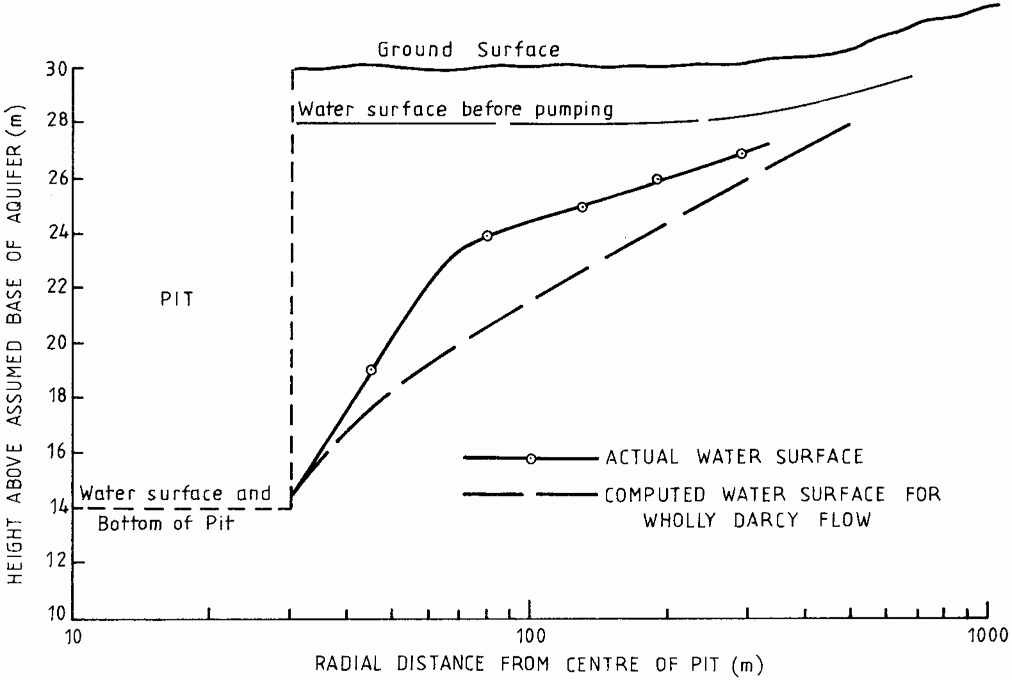

Fig. 4. Unconfined flow to a de-watered pit in a fractured limestone aquifer.

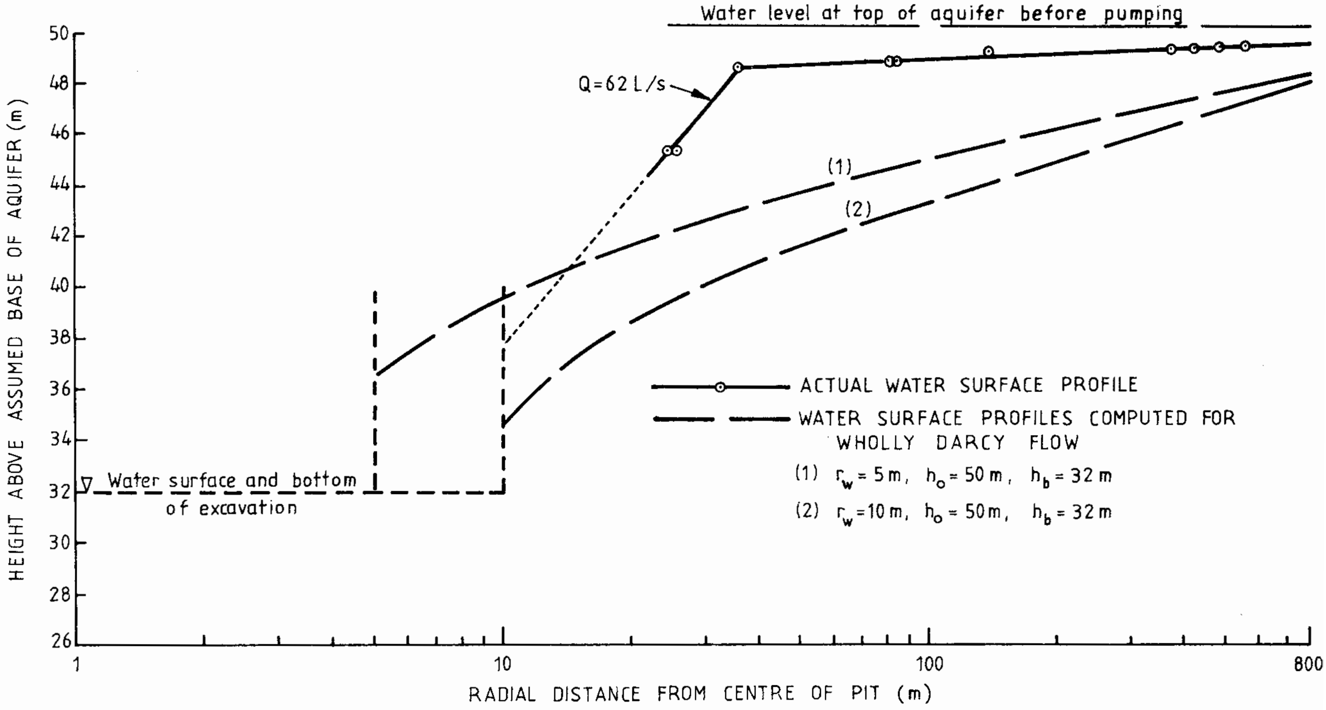

Fig. 5. Unconfined flow to a de-watered pit in a fractured dolomite aquifer.

that the log-linear profile rises steeply for the first 40 m from the boundary while the more distant part of the profile is approximately a straight line. The water surface predicted by finite element analysis for wholly Darcy flow is that shown by the second curve in Figure 4. The distinct difference between the profiles is apparent.

Although no tests were carried out to determine the effective thickness of the aquifer, drilling results suggested a thickness of the order of 30 m. Use of this value together with a radius of influence indicated by the known extent of the drawdown cone, a value of K estimated from the straight line portion of the actual water surface profile and the measured inflow rate allows a value of b/a^2 to be estimated from the dimensionless graphs described previously. Using this method K = 4 m/day and $b/a^2 = 10$ were arrived at. For K = 4 m/day the inflow predicted for wholly Darcy flow was 35 L/s compared with the measured value of 20 L/s.

Excavation in Dolomite Aquifer

Another excavation for which water level measurements have been analysed is a decline driven into a fractured dolomite aquifer. Pumping was carried out at more than 60 L/s for some months before the excavation was abandoned. Knowledge of the geometry of the bottom of the decline led to the assumption of an equivalent circular pit of between 5 m and 10 m radius. For pits of these two radii and the nearly steady measured water surface shown in Figure 5, values of K = 80 m/day and $b/a^2 > 100$ were estimated by the method described in the previous section for $h_o = 50$ m, $r_o = 2000$ m and $h_b = 32$ m.

As in the previous example the water surfaces computed using the finite element method for wholly Darcy flow are markedly different from the actual surface. The predicted inflow rates for wholly Darcy flow and K = 80 m/day were 450 L/s for $r_w = 5$ m and 600 L/s for $r_w = 10$ m compared with a measured inflow of 62 L/s.

DISCUSSION

The preceding description of the analysis of the field data covers only a preliminary assessment of the non-Darcy characteristics of the flow. A more comprehensive investigation would require the matching of predicted non-Darcy flow profiles with the actual profiles. The appropriate dimensionless profile data has not yet been tabulated or plotted although the basic computations have been performed.

Better data on the effective aquifer thickness and hydraulic conductivity for Darcy flow would greatly assist the determination of the non-Darcy parameter b/a^2. At neither field site was there sufficient testing of the aquifer to provide reliable data on these variables. As a result, matching of the water surface profiles would require the use of a range of trial values of h_o, K and b/a^2. Until the relevant dimensionless water surface profiles are available this would require a great deal of specific use of the finite element computer programs.

Another problem which is not yet solved is allowance for anistropy of the aquifer. The finite element analysis can take anisotropy into account but the number of computations and graphs required to give data for a sufficiently wide range of the ratio K_x/K_z has so far prevented its production.

Although the work reported in this paper is incomplete it is hoped that the computations and field studies described will have demonstrated with sufficient force that non-Darcy head losses in very permeable aquifers can have a large effect on inflows to open pits.

When the non-Darcy parameter b/a^2 has been determined from field testing as discussed or estimated by some appropriate correlation from the Darcy flow hydraulic conductivity it can be used in the comparison of inflows for other pit diameters and depths. With the aid of the dimensionless graphs these comparisons can be made with a minimum of effort and cost.

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