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# ESTIMATION OF GROUNDWATER INFLOW TO AN UNDERGROUND MINING OPERATION

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## ABSTRACT

The methodology of investigations for the determination of the hydraulic parameters necessary for initial inflow estimations are discussed. These include the methods of testing at depth for permeability, and data interpretation.

The techniques of inflow estimation are described for shafts and drifts which are based upon advanced mathematical modelling of flow in multi-layered permeability sequences. For shafts, flow is approximated as being axisymetric about the shaft axis allowing the use of radial flow models. The reliability of steady-state analysis is discussed.

As the geometric relationship between drift and the geological controls cannot be so simply approximated as in a shaft, the problem is essentially one involving three-dimensional flow. Due to the complexities involved in the three-dimensional modelling, the drift inflows are investigated using two-dimensional and radial models.

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The development of the three dimensional model is discussed together with the application of modelling techniques to estimate inflows into longwall faces.

## INTRODUCTION

Groundwater inflows to underground shafts, drifts, and mines can cause severe problems, both in practical and economical terms. Unexpected inflows lead to poor working conditions, reductions in safety standards, and costly delays in excavation and operations. The ability to form reliable mine inflow estimates is therefore highly important. Planning decisions concerning ground-water control measures such as grouting freezing and dewatering may then be undertaken in advance, thus contributing to a more efficient assessment of the economic feasibility of new mine development.

An inflow assessment for an underground mining operation consist of two phases, data acquisition and inflow estimation. Both are discussed in this paper., with the emphasis on the conditions in sedimentary sequences. The types of methodology that are employed in site investigation are a mixture of geotechnical hydrogeological and oil field techniques. The range of methodology is determined by the depth to which assessments are necessary in that drifts, shafts and mines frequently exceed the effective operating depths of geotechnical and hydrogeological equipment and modified oil field methods have to be used.

Inflows to underground mining operations may be estimated using either analytical or mathematical modelling methods, While analytical are easier to apply , they are only suitable for very simple inflow problems. Mathematical modelling methods are based on numerical solution and thus provide a more flexible approach in which the typically complex ground conditions in the mine environment may be presented. Several digital computer models, and their application in inflow assessments, are described in this paper.

## SITE INVESTIGATION

As with any civil engineering works the site investigation for drifts, shafts or mines can be relatively site specific. Whereas a geological and hydrogeological appreciation is of value particularly in respect to controlling hydrogeological boundaries in the model input, as discussed below, flow adjacent to an underground opening is controlled essentially by the local permeability unless very major throughgoing discontinuities are present.

Drilling investigations are conducted in the classical manner along drift lines, at shaft centres and along roadways etc. The drilling schedules are designed so that continuous core recovery and permeability testing can be carried out over the hydrogeologically important sections. Experience shows that wire-line methods are to be preferred over conventional rotary coring. However, because a borehole side is relatively protected throughout the wire-line drilling operation instability can occur during testing as a result of the movement of the tools in the hole. From the point of permeability testing hole stability and completion at or close to the design gauge diameter essential.

Conventional bentonite muds are normally used for drilling in the sedimentary sequences. There is evidence that such muds can be detrimental affect borehole conditions so that there is room for experimentation in the use of bio-degradable polymers, as used extensively in the water industry, for test hole drilling particularly in the deeper holes.

The permeability data are established from the core plug testing and from packer or drill stem testing (DST). Work is currently underway to examine porosity and permeability from an integration of neutron, sonic focused resistivity and gamma logs. Although such an approach may prove of some value for recognising primary permeability it may not help particularly with secondary or fracture permeability which is important in many of the sedimentary sequences that have been examined.

While core permeability and possibly geophysical log analysis can provide important data the main reliance for permeability determination is placed upon packer or drill stem testing. Both techniques have reached a high level of sophistication with computerised output and methods of remote control of the equipment.

The techniques allow a significant sample size examination of the permeability and also a bulk determination. There are, however serious drawbacks. Packer settings can be problematical if hole enlargement or eccentricity occur. In conventional packer testing used at the shallow depths, it is difficult to know if the steady state interpretations used in injection tests are reliable. Where pump- out techniques are used difficulties can occur in the lack of compatibility between pump and aquifer yields.

In drill stem testing considerable difficulties have been experienced with valve sizes and effective opening which needs to be instantaneous. The technique now adopted is a maximum valve opening approaching the drill pipe internal diameter to minimise frictional losses. For interpretational the standard oil field Horner (1951) method is used for the shut-in data although it frequently appears to be very approximate, while for the inflow data radial flow modelling methods are used (Lloyd and Jeffery, 1983). In the latter analysis good simulations are obtained for low to moderately high permeabilities but turbulence when very high permeabilities occur does pose interpretational problems (Figure 1).

The permeability values derived from the various methods are typically of variable reliability for the sections tested. One of the major difficulties is that these data have to be allocated to non-tested sections before the permeability sequence used in the inflow modelling can be determined. The allocation is currently very subjective but may be improved if the geophysical; log interpretation of permeability proves worthwhile.

## INFLOW ESTIMATION BY MATHEMATICAL MODEL

### Mathematical Approaches to Inflow Estimation

Following a reliable interpretation of site investigation data the hydrogeological conditions in a mine area is approximated. This information may then be used for the estimation of groundwater inflows to a mining operation. The emphasis in this paper is on the estimation of inflows to shafts sand drifts under construction, although this is followed by a brief discussion of inflows to operating longwall faces. In all three cases, inflow estimations essentially involve the mathematical formulation and solution of a groundwater flow problem.

There are broadly two mathematical approaches to shaft and drift inflow estimation. Firstly it is possible to estimate inflows using analytical methods. These are based on simple groundwater flow formulae, commonly derived for the analysis of flow to a well. While analytical methods are relatively cheap and easy to use, they are generally only suitable for simple flow problems involving homogeneous permeability conditions and geometrically

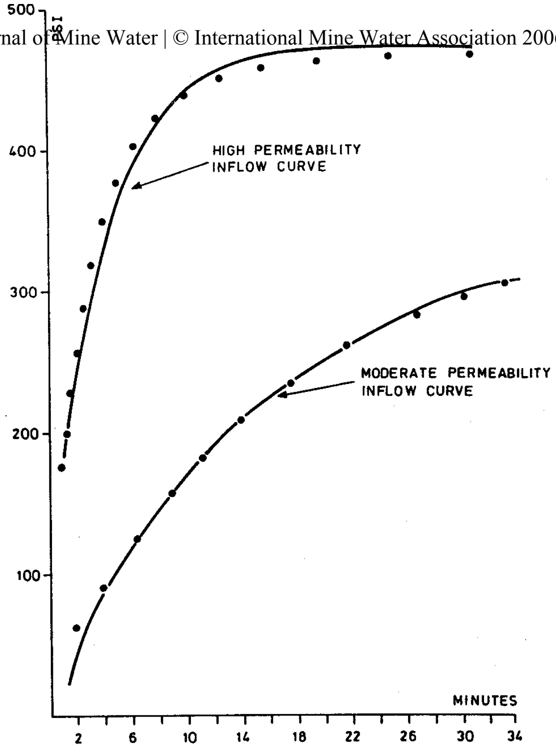


Figure 1 Simulation of DST inflow data

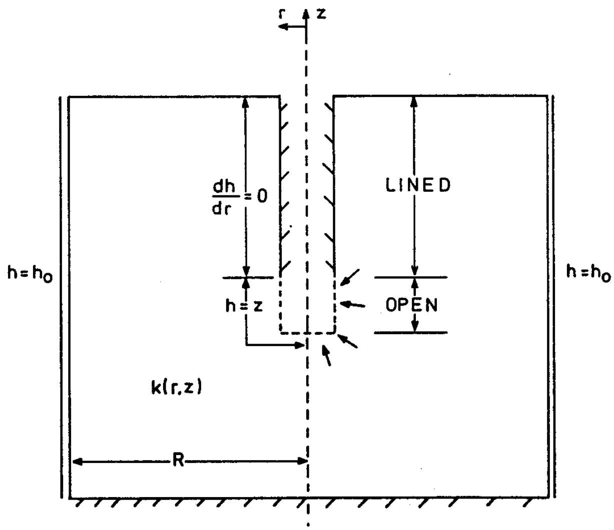


Figure 2 Definition sketch of vertical section through flow domain of a shaft inflow problem.

regular boundaries. The typically complex conditions that characterise many practical mine inflow problems cannot be described and inflow estimates are likely to be only of an order of magnitude accuracy. The application and limitations of the analytical methods of minewater inflow estimation are described by Singh and Atkins (1985).

A second approach to mine inflow estimation is provided by mathematical modelling methods. These involve the numerical solution of flow problems, usually by digital computer, and form the approach described in this paper. The advantage of mathematical modelling methods over analytical methods lies in the greater range of ground and boundary conditions that may be represented in an inflow problem. Providing sufficient data are available, this allows a more detailed representation of the groundwater system in the mine environment and leads to more accurate inflow estimates.

Several mathematical modelling methods have been developed for the numerical solution of groundwater flow problems. These include finite-difference methods (Remson et al. 1971, Rushton and Redshaw 1979), finite-element methods (Huyakorn and Pinder, 1983) and the boundary integral equation method (Liggett, 1977). Fawcett et al. (1984) review the application of these methods in mine inflow investigations. The techniques of inflow estimation described in this paper are based on finite-difference methods. These are mathematically and conceptually simple yet allow solution to complicated inflow problems involving heterogeneous (or multi-layered) and anisotropic permeability conditions, and confined or unconfined flow. Only techniques based on a steady-state flow analysis are considered in this paper; whether or not this approach provides a realistic estimation of groundwater inflows to shafts and drifts under construction is discussed below.

## MODELLING INFLOWS TO SHAFTS UNDER CONSTRUCTION

### Mathematical Formulation

Three-dimensional flows towards a vertical shaft may be approximated as being radical and axisymmetric about the shaft axis. This is reasonable assumption providing that the overall geometry of a given shaft inflow problem, which includes ground permeability and boundary conditions, shows a similar symmetry.

Using a radical (r-z) model, flow is analysed both in the radial (r) and vertical (z) directions. Assuming steady state conditions, governing equation of flow is:

$$\delta/\delta r(Kr(\delta h/\delta r)) + (Kr/r)(\delta h/\delta r) + \delta/\delta z(Kz(\delta h/\delta z)) = 0$$

Where

| | |
|---|---|
| h(r,z) | is the groundwater head distribution |
| $k_r$ and $k_z$ | are permeabilities in the radial and vertical directions. |

Having stated the approximate flow equation the next step in the formulation of a shaft inflow problem involves the specification of ground permeability conditions and boundary conditions. The latter consist of the hydraulic conditions that exist on the boundaries of the domain in which flow is considered.

A vertical section through the flow domain of a shaft inflow problem is shown in Figure 2. The permeability distribution within this domain, which must be estimated from site investigation data, is defined by k(r, z). Boundary conditions must be firstly specified on the shaft itself. Assuming by construction is by successive excavation and lining, the shaft consists of a lined section and an open section at any one time during sinking. In water bearing strata shaft linings are designed to be virtually impermeable (Dunn, 1982). Consequently, the lined section forms an inpermeable boundary ($\delta h/\delta z$) and flows are only considered to the open section.

The boundary condition on the open section is based on the assumption that any inflows are quickly removed so that the pressure condition within the shaft remains approximately atmospheric (i.e. zero pressure). The groundwater head condition on the open section follows from the definition of groundwater head as the sum of a pressure head and an elevation head, and consists of a field head condition where the head is equal to the elevation (h=z).

The conditions on the other boundaries of the flow domain depend on the hydrogeological conditions existing in the mine area. In the absence of any information on natural boundary conditions a radius of influence is commonly fixed at a relatively large distance R from the shaft (Figure 2). A fixed head condition is set on this boundary where the head value is equivalent to the level of the water table prior to shaft construction ($h=h_o$). this represents a hydrostatic pressure condition and is equivalent to zero drawdown. The effect of this boundary on the shaft inflow rate may be established by repeated solution for different values of R. The base of the modeled ground is usually represented by a no-flow horizontal boundary. ($\delta h/\delta z = 0$). This is situated at a level where the ground permeability conditions indicate that no significant flow likely to occur. Finally, the uppermost boundary may consist of the water table, or an impermeable or leaky geological horizon.

Based on the formulation above, the digital finite difference model may be developed to solve the steady-state shaft inflow problems. the flow domain is represented by a two dimensional finite difference grid (in r and z) on which numerical solutions are formed. The final solution consists of as discretised groundwater head distribution h(r, z) defined only at the nodes of the grid. Using Darcy's law it is then possible to evaluate the flow distribution around the shaft and thus the inflow rate. Finite difference modelling of steady- state shaft inflows, using a specially constructed electrical resistance analogue computer, has previously being carried out by Lloyd et al. (1983).

## Example of Shaft Inflow Estimation

As an example of the application of a radial (r-z) shaft inflow model, steady state shaft inflows were evaluated to a shaft at various levels in the multilayered sequence shown in Figure 3. the ground consists of Coal Measures strata overlain by a sandstone , a thin marl, and a thick limestone.

Permeability values were obtained through the interpretation of data from from hydraulic testing in a single borehole, assumed to have been drilled on the centre line of the proposed shaft. The distribution of permeability and the anisotropic character of some of the hydraulic units (e.g. units M and CM1, Figure 3) were estimated on the basis of geological borehole data. The permeability layering within unit CM1 is representative of the sandstone-mudstone alternations typical of Coal Measures strata. The same section is used to demonstrate drift inflow modelling later in this paper.

The site investigation showed that the undisturbed water table lay at a depth of 28 m bgl. Any inflow to the shaft, particularly during construction in the uppermost hydrogeological units, may result in the drawdown of the water table. The steady state position of the water table during inflow can be determined by the finite difference model employed. This forms part of the

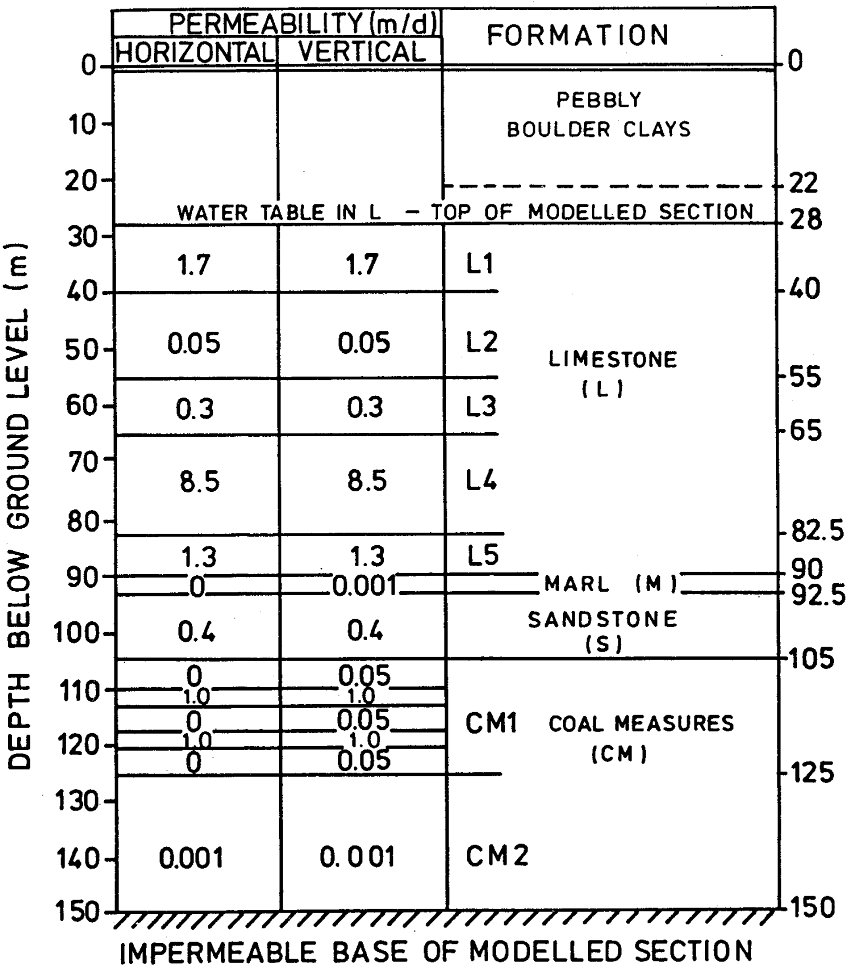


Figure 3 Permeability depth-profile for shaft and drift inflow estimation

solution to each shaft inflow problem since the geometry of the flow domain cannot be defined until the position of the water table is known.

The outer radial boundary, or radius of influence, of the model was set at 500 m from the shaft. The permeability layering indicated in Figure 3 was assumed to extend horizontally to this distance. While geological data indicated that there was a shallow regional dip, this is a reasonable approximation. A fixed head condition of $h = -28$ m was set on this boundary. This is the elevation of the water table prior to shaft construction and represents a hydrostatic pressure condition. Inflows were evaluated at 5 m depth intervals to a shaft of diameter 10 m and an open section of length 10 m.

The inflow results obtained are shown graphically in Figure 4 and indicate the variability of the expected inflow rate during construction. as anticipated, the inflow rate is largely dependent on the permeability of the ground surrounding the open section. The highest inflow rates to the shafts therefore occur from the limestone unit L4. It is also noticeable that inflows decrease markedly beneath the thin marl (unit M). since this has the effect of reducing vertical flow from the limestone above. Sensitivity tests showed that i the marl was not present, inflows to the shaft in the Coal Measures would be roughly four times the levels shown in Figure 4.

The expected distribution of inflow over the sides of the shaft open section may also be examined from the model results. (Figure 5). At a depth of 65 m ninety five percent of the inflow originates from unit L4 and is directed towards the base of the shaft. At a depth of 95 m most of the inflow is experienced by the upper part of the open section. At 120 m flow to the shaft is due to the relatively high permeability Coal Measure sandstones and inflows therefore only occur at discrete horizons. It is clear that the percentage distribution of inflow over the sides of the shaft open section is strongly controlled by the relative permeability values of the hydrogeological units surrounding the shaft.

## Reliability of Steady State Inflow Prediction

In the example of shaft inflow assessment described above the results obtained are based on a steady-state flow analysis. It is clear that shaft construction is a dynamic process and it is

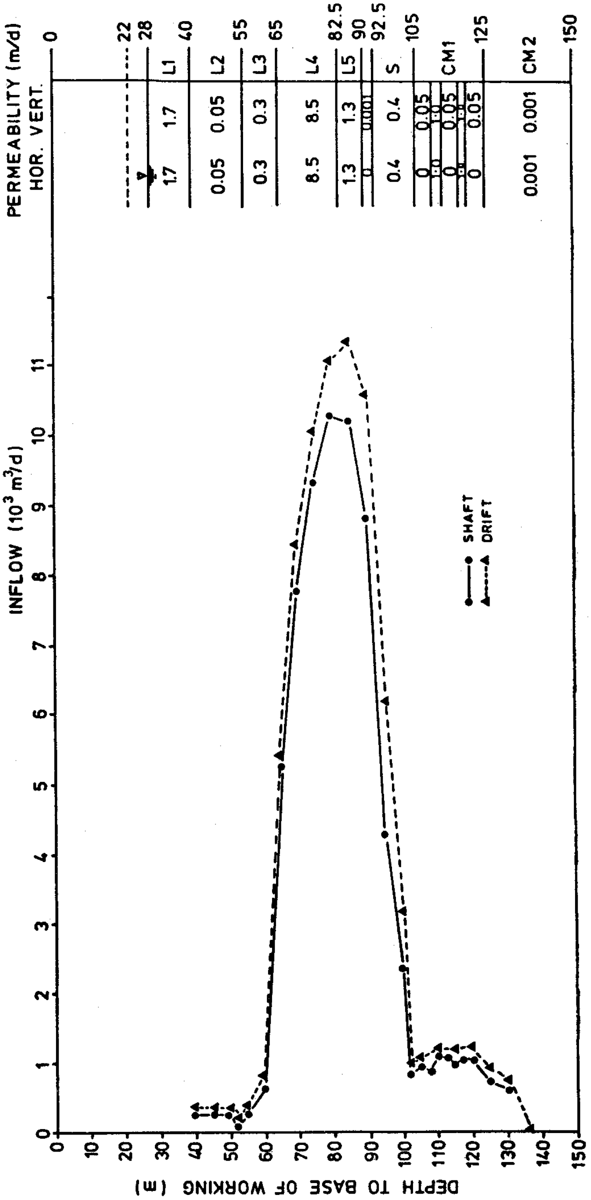


Figure 4 Variation of steady-state shaft and drift inflows with depth

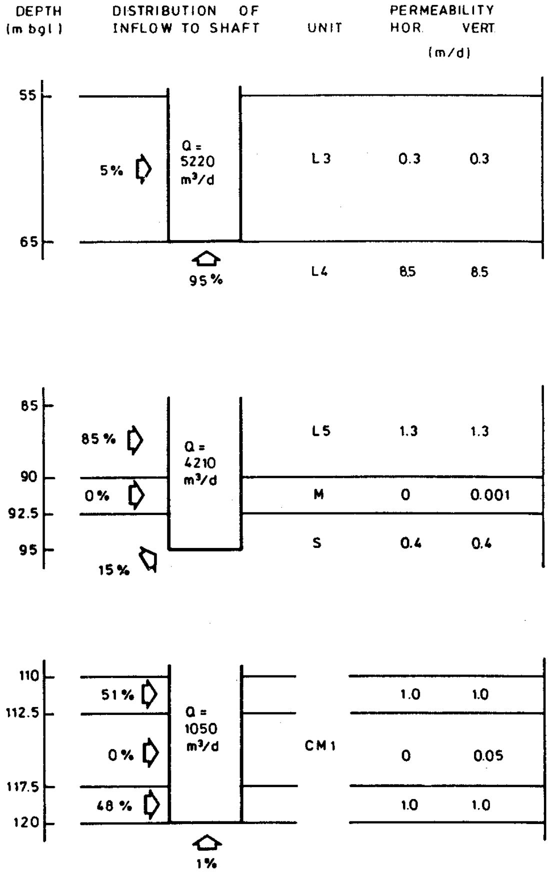


Figure 5 Distribution of inflow over sides of shaft open section at depths of 65 , 95 m and 120 m

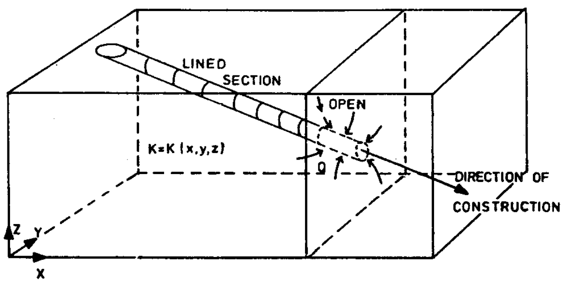


Figure 6 Three-dimensional inflows of a drift

therefore likely that flow conditions will be essentially nonsteady-state in character. In this context, the reliability of a steady-state inflow analysis should be examined. The following discussion applies equally in principle to the case of a drift.

As a shaft is sunk in virgin ground, inflows are initially derived from the release of storage from ground in the vicinity of the shaft. The effect of the shaft spreads radially in time and storage is released at greater distances from the shaft.

The associated inflow rate therefore decreases in time, tending towards a steady-state value governed by the natural boundary conditions in the mine area. In general, the faster the spread of the shaft effect, the faster the inflows approach near steady-state value.

The effect of shaft would be expected to spread fastest where the permeability of the ground is relatively high and the storage low. The inflow rate would then quickly approach virtual steady- state levels. If the permeability is low then the decline in inflow rate occurs more slowly. However, the inflow rate, either steady or non-steady, in this cases is likely to be low and not generally of concern. A steady-state inflow analysis may therefore provide reasonably accurate inflow estimates for much of the construction period, particularly under critical permeability conditions. In addition steady state estimates may be taken as a lower bound to the inflow range expected.

The simple qualitative analysis above does not take into account the depth of the shaft. Each phase of excavation increases the depth of the shaft and may include a new period non steady state adjustment by the local groundwater system. The slower the overall construction rate greater the likelihood that near steady conditions will approach. A faster construction rate does not allow the groundwater system to stabilise so easily and inflows may remain at levels significantly above the potential steady-state values.

This analysis recently been supported by initial results from an investigation based on the development of a non steady-state shaft inflow model (Edwards, 1987). Such a model is extremely complex in that the shaft forms a downward moving boundary condition in time. In other words, the construction process of the shaft must be presented in the model.

# MODELLING INFLOWS TO DRIFTS UNDER CONSTRUCTION

## Characteristics of Drift Inflows

The estimation of drift inflows poses more difficulties than shaft inflows. This is because there is no simple geometrical relationship between the drift itself and and associated hydrogeological controls such as permeability layering. This suggests that the only totally adequate model through which drift inflows can be estimated involves solution for three-dimensional flow.

The three dimensional nature of the drift inflows is indicated in Figure 6. As in the shaft, it is assumed that the drift is constructed by progressive excavation and lining. Hence at any one time during construction the drift consisted f a lined impermeable section and a short (i.e. 5-20 m). section open to flow. Flows towards the open section are likely to be convergent in three dimensions, particularly so to either end of the open section.

Three dimensional modelling is extremely complicated and initial efforts to model drift inflows have been carried out using steady state inflow two dimensional and radial (r-z) flow models to approximate inflow process. (Edwards 1985) These approximations are described below. As in a shaft (see above), it is consider that under certain conditions a steady state inflow assessment will provide reasonable inflow predictions for much of the construction period.

## Two Dimensional Approximation

This involves the analysis of flows in two dimensions (y-z) in a vertical section of unit width across the drift open section (Figure 7). The governing flow equation in this case is:

$$\delta/\delta y(Ky(\delta h/\delta y)) + \delta/\delta z(Kz(\delta h/\delta z)) = 0$$

Where

$h(y,z)$ is the groundwater head distribution

$k_y$ and $k_z$ are permeabilities in the horizontal and vertical directions.

Total inflow values are obtained by summing the inflows

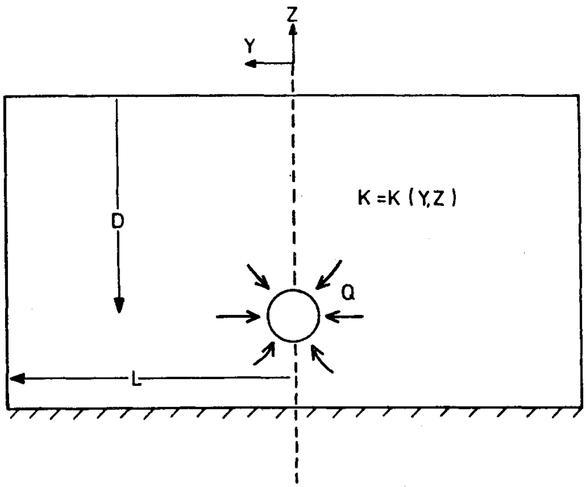


Figure 7 two dimensional approximation for drift inflows

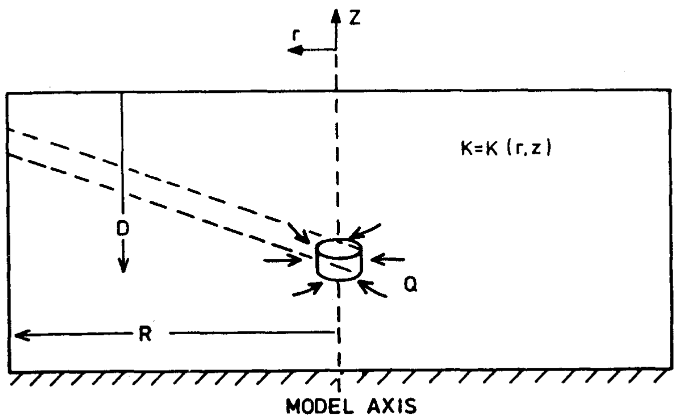


Figure 8 Radial (r-z) approximation for drift inflows

calculated to each unit length along the open section. While this form of approximation may be good for a very long structure such as unlined tunnel, it may be inaccurate when applied to the open section of a drift, the length of which is unlikely to be greater than 20 m. The convergent nature of the flow in the x-y plane, particularly to either end of the open section. (Figure 6) is not presented.

## Radial r-z Approximation

In this approach the open section of the drift is approximated as a suitably dimensioned ellipsoid or cylinder and the lined section is ignored (Figure 8). Flow towards this opening can then be analysed using radial (r-z) flow models, for which the governing equation is equation (1). This form of approximation has the advantage that flow is represented in three dimensions, if only in an axisymmetric manner. However, the geometry of the open section, and therefore the inflow pattern near to the drift, is poorly presented. Details of formulation of drift inflow problems based on both approximation are given in Edwards (1985).

## Validity of Two Dimensional and Radial (r-z) Approximations

The two approximations described above have been applied to several drift inflow problems by Edwards (1985). Results indicated that the two dimensional approximation was unlikely to provide realistic drift inflow values and that the radial (r-z) approximation presented the better approach. However, the difficulties caused by the inaccurate presentation of the drift open section in the radial (r-z) approximation remained.

It was difficult to state inflow estimated with precision since the relationships in terms of inflow between a certain length of actual open section and a given size of cylindrical opening in a radial (r-z) model was not clear.

Recently, however, a full three dimensional drift inflow model has been developed (Edwards, 1987). The computational effort required two solve three dimensional problems is prohibitive and for drift inflow assessments involving large numbers of individual problems it would be preferable to use a model based on the radial (r-z) approximation. However, the development of the three dimensional model has allowed several interesting characteristics of the two approximations to be established.

Firstly, a comparison between drift inflow results using two dimensional, radial (r-z) and three dimensional models has indicated quantitatively that the two dimensional approximation gives rise to under estimated inflow predictions. Secondly, it has confirmed that the radial (r-z) approximation, while not allowing an accurate simulation of the inflow pattern near to the drift, does provide realistic inflow values. Finally, a comparison of radial (r-z) results for different size cylindrical openings, and three dimensional results for different lengths of open section, has provided a guide to the size of cylindrical opening required to achieve an inflow equivalent to that expected to a given length of drift open section.

In the following section an example of drift inflow estimation is described. A steady-state model based on the radial (r-z) approximation is used.

## Example of Drift Inflow Estimation

Drift inflows were evaluated to a drift under construction through the ground section shown in Figure 3. It was assumed that the permeability layering extended horizontally throughout the region of drift construction. The validity of this assumption is considered later in this paper.

The outer radial boundary of the modelled region, or radius of influence, was situated at a distance of 500 m from the drift open section (Figure 9). The drift open section was represented by a modified cylinder of largest radius 7.34 m and a vertical height of 10 m. According to recent results (Edwards, 1987), this size of opening experiences an inflow equivalent to an actual horizontal drift of diameter 10 m and open section of length 15 m to 20 m. This model was used to evaluate the inflows to the drift open section at 5 m, or in some cases, 2.5 depth intervals. The procedure is equivalent to shifting the entire model along the line of drift, adjusting the depth of the modeled open section accordingly.
The inflow results are shown in Figures 4 and 10. There is a strong relationship between the permeability of the ground enclosing the drift open section and the expected drift inflow. The lowest horizons of the limestone give rise to the highest inflow rates. The inflows are slightly larger than those estimated to the shaft; this is to expected when the increased size of open section is taken into account.
The inflows indicated in Figure 10 are shown in relation to

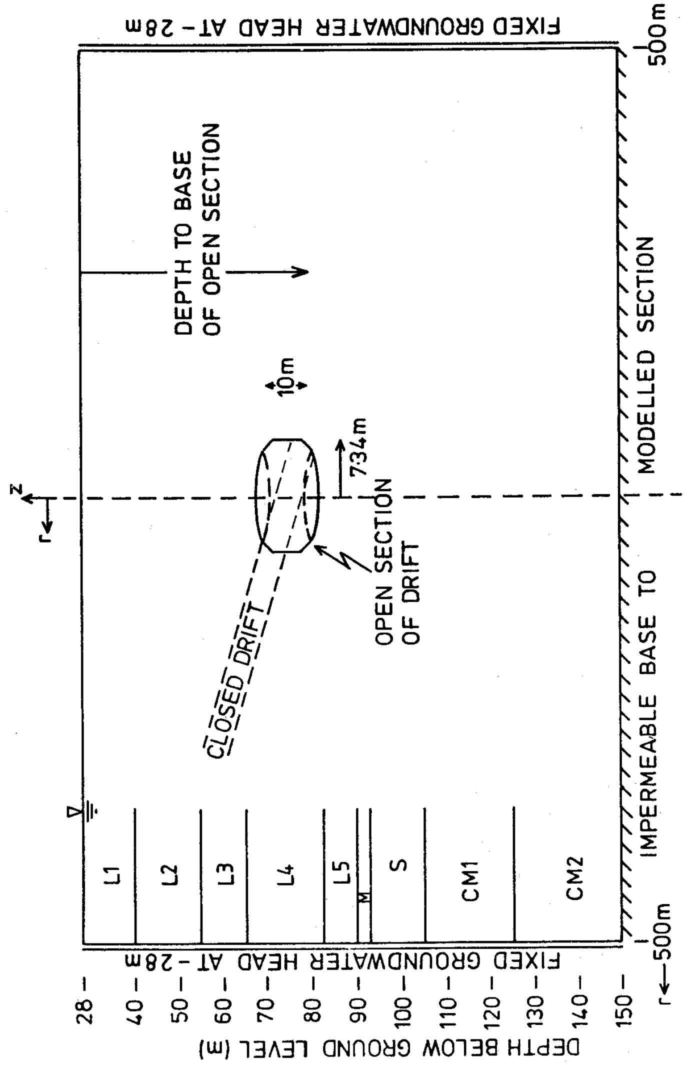


Figure 9 Vertical section through flow domain showing representation of drift open section

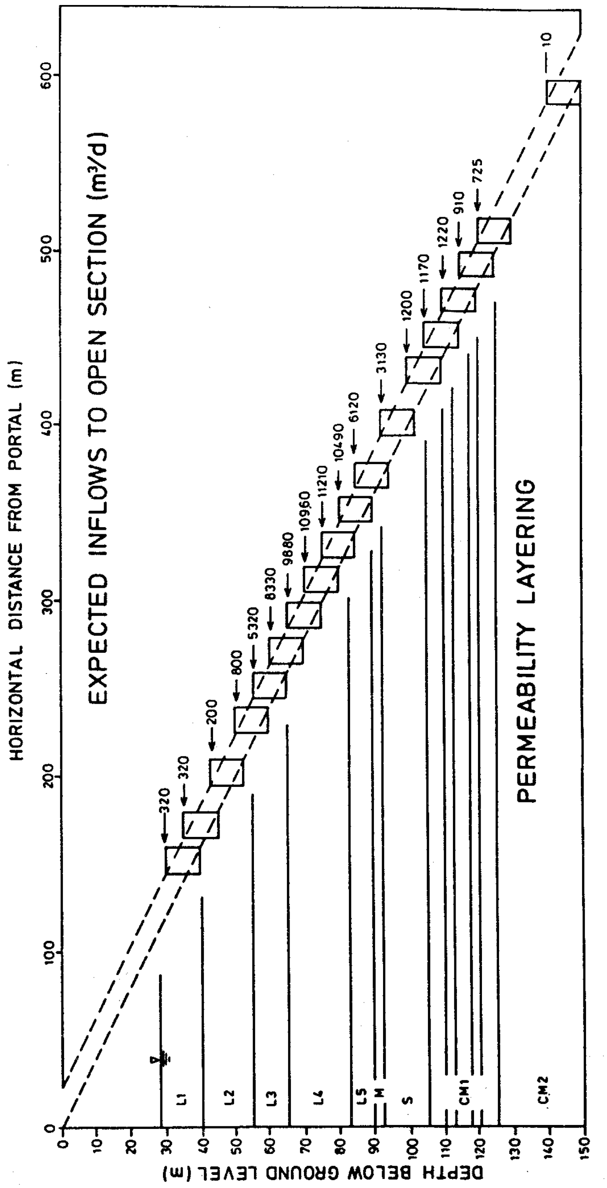


Figure 10 Steady-state inflows to the drift at successive stages of construction

permeability layering which is assumed to be horizontally continuous over the region of drift construction. This is because subsurface data were only obtained from a single borehole in this project. The validity of assuming constant permeability layering over large horizontal distances is certainly questionable. Under this conditions, inflow estimates are therefore more likely to be accurate in the area where the exploratory borehole intersects the proposed line of construction. It is clear that adequate data collection poses greater difficulties in drift inflow estimation than in shaft inflow estimation. This is basically due to the inclined nature of a drift.

## MODELLING INFLOWS TO OPERATING LONGWALL FACES

The estimation of groundwater inflows to operating longwall faces poses additional difficulties to those of shaft and drift inflow estimation. This is due to fracturing and caving above and behind the longwall face as it advances. This results in a significant increase in permeability in the vicinity of the face. Since the original permeability of the ground is typically low, the inflow rate is dominantly controlled by the extent of fracturing, and the presence of any water bearing strata that the fractures may intersect. The accurate estimation of groundwater inflows to a longwall face is therefore clearly dependent on a good understanding of the associated aspects of rock mechanics.

Valuable first attempts at mathematical modelling of inflows to longwall faces have been presented by Singh et al. (1985, 1986). These studies used the boundary integral equation method to investigate steady state inflows in a two dimensional vertical section at the centre of a face. The fracture pattern above the face, and the associated increased permeability conditions, were estimated on the basis of a finite element stress analysis and experimental evidence. Recent work at the University of Birmingham has employed finite difference methods to evaluate similar problems. An example of the modelled flow distribution in the vicinity of a longwall face is shown in Figure 11. This work has indicated that flows towards longwall faces are considerably affected by the formation of unsaturated zones above the face. Further work on both steady state and non steady state inflows estimation is in progress.

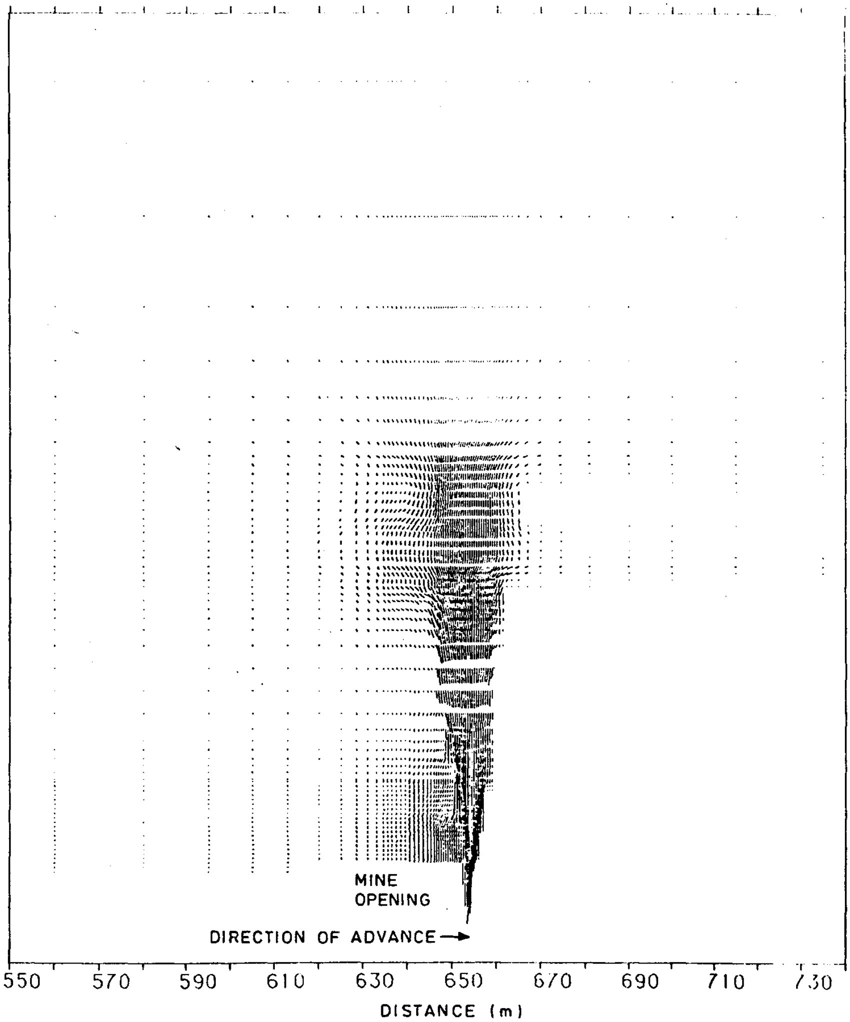


Figure 11 Flow distribution to a longwall face

## CONCLUSIONS

Several aspects of inflow assessment to underground mining operations have been considered. While difficulties in application and interpretation still exist, techniques for the acquisition of subsurface hydrogeological data now allow a fairly detailed approximation of ground conditions. The development of new techniques based on geophysical log interpretation may provide a further advance in this direction.

Improvements in techniques of data acquisition justify the application of more advanced methods of inflow estimation for proposed new shafts, drifts and mines. Mathematical modelling methods provide not only inflow predictions, but also much information on the behaviour of flow in the vicinity of a mining operation. The dominant hydrogeological controls on inflow rates may be established, leading to further optimization of data acquisition in future site investigations.

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