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NUMERICAL CALCULATION OF GROUNDWATER INFLOW TO LONGWALL COAL FACES

R N Singh*, S Hibberd ** and R J Fawcett*

*Department of Mining Engineering,
**Department of Theoretical Mechanics,
University of Nottingham, University Park,
Nottingham, NG7 2RD, United Kingdom.

ABSTRACT

The paper describes numerical calculations of groundwater inflow to longwall coal faces through heterogeneous anisotropic rock strata using the boundary element method. The influence of mining induced changes in conductivity is investigated. The effect of a protective layer of intact rock between damaged strata and water bearing strata is examined. Results are supported by diagrams of Darcy seepage velocities.

INTRODUCTION

Many analytic and numerical calculations of groundwater inflow to surface and underground mine workings have been reported within the mining and water engineering literature. Such calculations predict the likely quantity of water flowing into a mine, elucidate the pattern of water movement and identify regions where flow rates are particularly large. This knowledge is an important aid to the planning of mining operations as it contributes to assessments of safety and economic viability. Necessary pumping capacity can be forecast which in turn reduces the frequency of costly delays caused by unexpected flooding. Flow calculations are quick and cheap to perform and it is possible to analyse the water problems associated with several proposed approaches to a mining problem in order to find the optimum. This can result in smaller costs, improved safety and operating efficiency and a reduction in environmental damage.

ROCK PROPERTIES NEAR LONGWALL EXTRACTIONS

The behaviour of rock strata near a region of total extraction mining has been discussed extensively elsewhere, for example by Singh and Kendorski (1981) and Singh and Atkins (1982), and is generally accepted to possess the typical characteristics illustrated in figure 1. The figure represents vertical cross sections from the coal seam to the ground surface passing either through the two gates or through the face and start line. The strata immediately above the mined region cave into the mining void while those at greater heights collapse by bending to cause the familiary subsidence trough at ground level. Of particular importance in deep longwall mining are the wedge shaped zones of fracturing induced by intense stresses above the gates and face. Various formulae have been suggested to calculate the extent of the fractured zone but typical results give its height between 30 and 58 times the extraction thickness. Experiments reported by Whittaker, Singh and Neate (1979) demonstrated that the hydraulic conductivities of strata above longwall faces increased to between 40 and 80 times the intact values. Behind the face the conductivity decreased gradually towards its original value but results were not available to determine the location of the steady state or the residual conductivity.

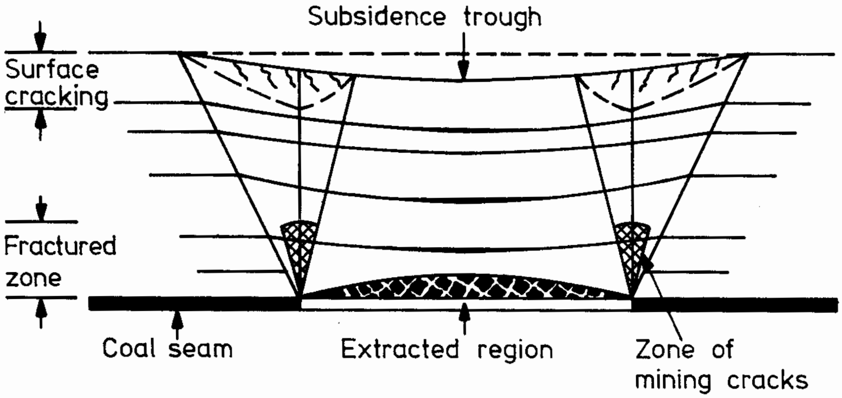

Figure 1. Strata behaviour above a longwall extraction.

CALCULATION OF MINE WATER INFLOW

The majority of groundwater flow calculations are based upon the assumption that such flow is governed by Darcy's Law. The most general anisotropic version of this law has been given by Scheidegger (1957) in the form

$$u_i = - \sum_j K_{ij} \frac{\partial h}{\partial x_j} \tag{1}$$

in which u_i is the seepage velocity in the direction of the ith Cartesian co-ordinate, K_{ij} represents the terms of the conductivity tensor, h is the hydraulic head and x_j is the jth Cartesian co-ordinate. The use of a tensor to describe conductivity distinguishes equation (1) from the simpler isotropic formula and means that seepage velocity and hydraulic gradient are not generally in the same direction. Dullien (1979) noted that the three principal axes along which velocities and gradients are parallel are usually assumed to be mutually orthogonal.

Anisotropy is an important feature of rocks surrounding longwall extractions because bedding planes, natural fracture lines and cracks caused by mining subsidence give rise to directional variation in material properties. Heterogeneity is another characteristic as the extent of mining damage varies with position and there are differences between strata; this property is included in the mathematical formulation by allowing the conductivity in equation (1) to vary with position. Darcy's Law applies strictly to flow through porous rather than fractured media but it is generally assumed to be a reasonable approximation to flow in rock strata providing cracks are widespread and seepage velocities low.

A time independent continuity condition combined with equation (1) generates a governing equation for h of the form

$$\sum_i \sum_j \frac{\partial}{\partial x_i} K_{ij} \frac{\partial h}{\partial x_j} = 0 \qquad (2)$$

in which t is the time. A time dependent version of equation (2) is required when storage coefficients are large and transient phenomena are important but it can be shown to be unnecessary in most investigations of water inflow to longwall coal faces.

Equation (2) must be solved within a domain defined by the physical features of the problem under investigation. For longwall workings the domain boundary includes the extracted seam and major water sources such as saturated aquifers. Boundary conditions for any groundwater flow calculation are usually specified as hydraulic heads or flow rates or a linear combination of the two.

EXISTING CALCULATIONS

Under major simplifications the governing equation can be solved by analytic methods. This type of groundwater calculation is related to work on wells in horizontal aquifers begun by Theis (1935), Jacob and Lohman (1952) and Hantush and Jacob (1955) and subsequently extended in several individual papers by Hantush. Analytic calculations can often be performed with only a hand calculator and a table of well functions but they are limited to simple geometries and uniform material properties. Much detail is lost when applying such calculations to mine water flow as entire mines are represented by simple wells. Furthermore it is not possible to include the heterogeneity which is vital to describe rock strata around longwall extractions.

The advent of fast digital computers has enabled more flexible approaches beyond the scope of hand calculation to be adopted. The most important of these in solving equations of the forms given above are the finite difference and finite element methods and the more recently developed boundary element method. Existing calculations of groundwater inflow to underground coal workings using the first two numerical methods have been assessed by Fawcett, Hibberd and Singh (1984). Most were based on the well models of the analytic solutions and although additional features such as awkward geometries, multiple wells and heterogeneous material properties were included much of the vertical detail essential to describe longwall mining was omitted because the models remained horizontal. Only two of the calculations reviewed included the vertical dimension but neither was used to investigate in any detail the effects of the essential features of longwall mining mentioned above. New calculations have consequently been developed by the authors.

MATHEMATICAL REPRESENTATION OF A LONGWALL EXTRACTION

Numerical calculations of water inflow to a longwall extraction can be performed most reliably if the mathematical representation of the workings is made as simple as the requirements of physical validity allow. In this respect a calculation based upon a vertical two dimensional cross section is preferable to a full three dimensional calculation and is expected to be adequate for most longwall faces. The approximation gives incorrect solutions close to gates but the resultant errors have negligible effects on overall flow rates. A straightforward but useful representation of the region around a solitary face used by the authors is illustrated in figure 2. A water source aquifer formed the top of the external boundary, a stratum below the workings provided the bottom while two remote vertical lines completed the perimeter. The lower stratum was assumed to possess such aquiclude properties that little water crossed it. The vertical lines were placed where water flow was almost non-existant so that small changes in position had negligible effects on the calculated results. An internal boundary represented the open and uncompressed part of the extracted coal seam acting as a water sink. The top and bottom surfaces of the seam were taken to be coincident because the seam height is usually small relative to other vertical distances. The unworked and closed parts of the coal seam did not form boundaries but were part of the domain of water flow. This domain consisted of all the strata contained within the external boundary.

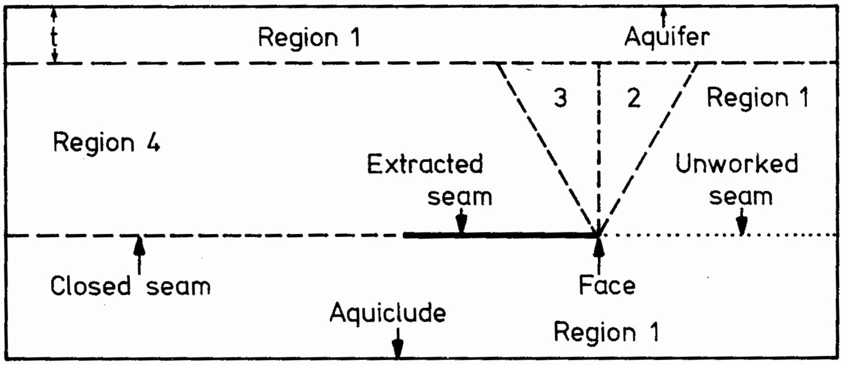

Figure 2. Simplified representation of a longwall face.

Boundary conditions applied to this representation of a longwall region were a constant hydraulic head at the aquifer, a lower constant head at the extraction and no flow across all other boundaries. These simple conditions are good first approximations to the actual boundary conditions which in any case are not known exactly. True boundary hydraulic heads must depend upon flow rates as the passage of water from aquifer to extraction causes a loss in head at the former and a gain at the latter. Specified constant heads are the appropriate conditions for calculating initial flow rates and are sufficient to elucidate flow characteristics.

Numerical calculations can be given more general use if the quantities involved in them are expressed as non-dimensional parameters which must be scaled appropriately to give true physical values. In the calculations described here the non-dimensional unit length was taken to be the vertical distance between seam and aquifer, the non-dimensional hydraulic heads at the aquifer and extracted seam became unity and zero respectively and heterogeneous anisotropic hydraulic conductivities were represented as variable tensor multiples of a fixed scalar base conductivity.

SOLUTION METHOD

Fawcett, Singh and Hibberd (1984a and 1984b) tested three major numerical techniques to determine the most suitable for calculating the flow associated with longwall representations of the type described above. Their extensive investigations of a homogeneous isotropic longwall representation using the finite difference, finite element and boundary element methods revealed that the last was to be preferred under most circumstances. It gave the most accurate results and, because its elements were defined only around the boundary, dealt easily with refinements and changes of geometry. Its major disadvantage was its inability to deal directly with a heterogeneous hydraulic conductivity which would have to be represented as a set of individually homogeneous conductivities in a corresponding set of sub-domains. Such a representation would require the introduction of internal boundaries.

In practice the field data required to define a longwall representation are usually so sparse that the restriction on heterogeneity is unimportant. If full heterogeneity were required then the finite element method would be the appropriate choice although this would involve more intricate mesh manipulations. The finite difference scheme possessed no obvious advantages and several major disadvantages compared with the other two methods.

On the basis of these conclusions the authors have developed a boundary element computer program for performing heterogeneous anisotropic longwall water flow calculations. The details of the program have been described by Fawcett, Singh and Hibberd (1985) and are not repeated here. The remainder of this paper describes some results obtained using the program.

AN INITIAL INVESTIGATION

The major purpose of the current research has been to develop a numerical procedure capable of accurately describing groundwater inflow to longwall coal faces and to use it to examine the effects of the heterogeneous and anisotropic conductivity changes resulting from mining subsidence. These changes are incorporated into numerical calculations by allowing the magnitudes and directions of the principal conductivities, and consequently the terms of the conductivity tensor in equations (1) and (2), to vary between sub-domains of the flow.

In order to gain an understanding of the importance of mining induced heterogeneity and anisotropy the authors performed various calculations based upon the sub-domains illustrated in figure 2. The angles subtended by the two wedge shaped zones of fracturing and increased conductivity were both taken to be 35^o and the mine sink was assumed to extend to five times the distance between it and the aquifer. A protective layer of undamaged rock between the fractured region and the aquifer was assigned a thickness t which varied between calculations. Natural heterogeneity between strata was ignored so that the undisturbed conductivity was represented as homogeneous. The base conductivity was defined to be the undisturbed horizontal value. Seven models of this type, with conductivities and other details listed in table 1, were investigated by the authors.

Isotropic Heterogeneous Calculation

The first calculation investigated isotropic heterogeneity in a model with a protective thickness equal to one fifth of the vertical distance between mine and aquifer. Relative conductivities, listed in the first entry of table 1, were assigned on the basis of the typical increases measured by Whittaker, Singh and Neate (1979) and on the assumption that the direction of major conductivity lay along horizontal bedding planes in the undisturbed and settled regions labelled 1 and 4 and along vertical fracture lines in the wedge regions 2 and 3. The measured results gave conductivities in the front and back wedges and the settled region as 5, 40 and 25 relative to the base conductivity respectively. The ratio of horizontal to vertical conductivity in the undisturbed and settled regions was taken as 100:1 which was within the range of typical results quoted by Adyalkar and Srinivasan (1978) and Williamson (1978).

	t	Region 1		Region 2		Region 3		Region 4		Total Flow	Range
		K_H	K_V	K_H	K_V	K_H	K_V	K_H	K_V		
1	0.2	0.01	0.01	5.0	5.0	40.0	40.0	0.25	0.25	0.33	10
2	0.2	1.0	0.01	1.0	5.0	1.0	40.0	25.0	0.25	1.17	65
3	0.4	1.0	0.01	1.0	5.0	1.0	40.0	25.0	0.25	0.80	85
4	0.6	1.0	0.01	1.0	5.0	1.0	40.0	25.0	0.25	0.59	90
5	0.8	1.0	0.01	1.0	5.0	1.0	40.0	25.0	0.25	0.42	85
6	1.0	1.0	0.01	N/A	N/A	N/A	N/A	N/A	N/A	0.21	60
7	0.0	1.0	0.01	1.0	5.0	1.0	40.0	25.0	0.25	5.91	1

Table 1 Conductivities and results of initial investigation

Table 1 gives the total non-dimensional flow for the isotropic heterogeneous calculation as well as the range of flow. The latter was defined as the horizontal distance between two points on the aquifer where the perpendicular component of seepage velocity had reduced to one tenth of its maximum value. In the isotropic investigation it was equal to ten times the distance between mine and aquifer. Flow rates at discrete points within the domain are illustrated in figure 3 by means of vectors with lengths proportional and parallel to seepage velocities. Velocity calculation points lie at the centre of the vectors. Figure 3 demonstrates that most flow occurs in the wedge regions.

Anisotropic Heterogeneous Calculation

The second calculation investigated anisotropic heterogeneity for a model with identical geometry to that of the first but using the relative conductivities listed in the second entry of table 1. The assumptions made in defining these values were the same as for the isotropic calculation with the additional condition that vertical fracturing within the wedge regions 2 and 3 did not effect horizontal conductivity. Table 1 shows that the total anisotropic flow was substantially larger than the isotropic quantity even though vertical conductivities were unchanged. The main reason for this was the larger horizontal conductivity in the undisturbed region 1 which enabled

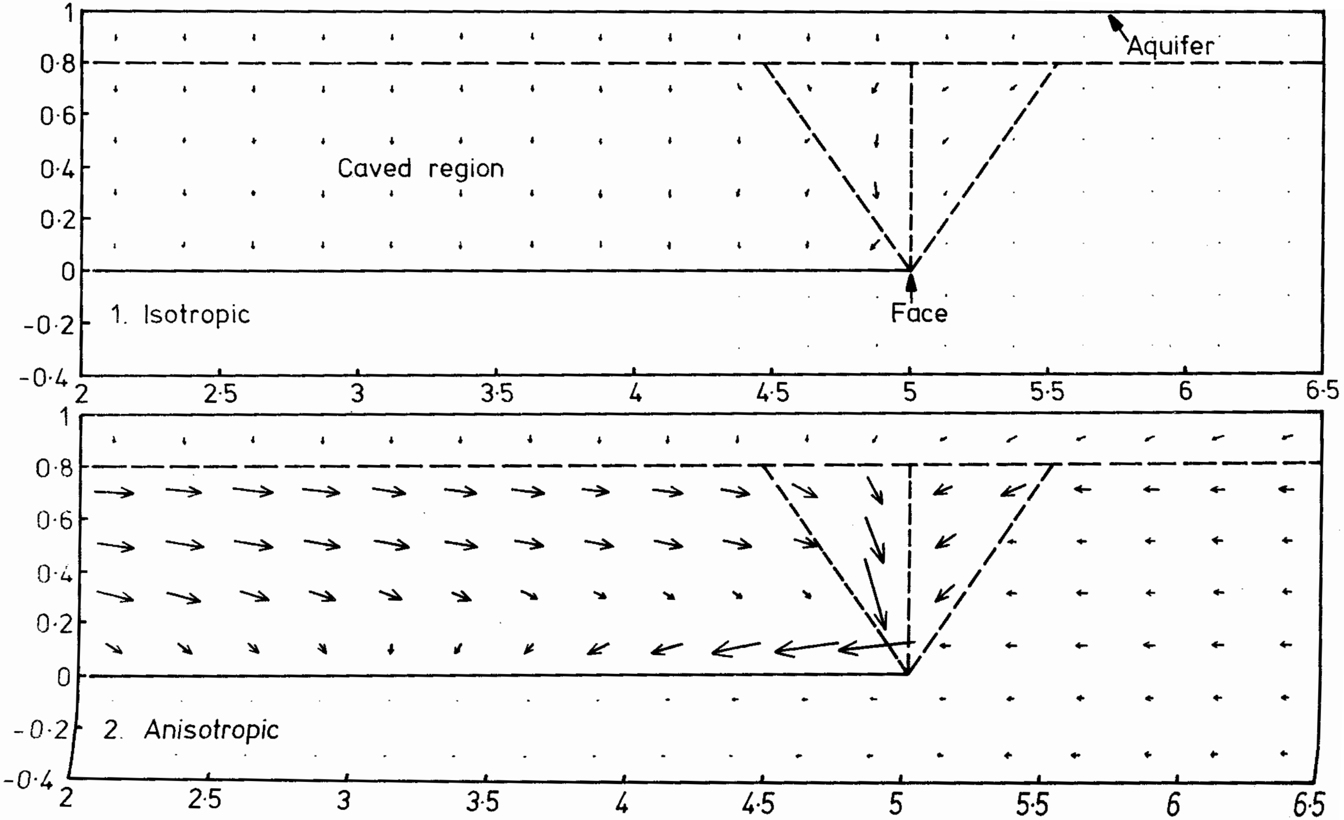

Figure 3. Flow diagrams for isotropic and anisotropic calculations (length of each vector indicates magnitude and direction of seepage velocity).

water to be collected from a greater extent of the aquifer. This is clearly demonstrated by the increase in the range of flow from 10 to 65. Furthermore the high horizontal conductivities in the settled region 4 enabled water to make better use of the high vertical conductivity in the wedge region 3 by flowing horizontally into its top and out of its base. The two anisotropic phenomena are illustrated by the second flow diagram of figure 3 in which the vectors are drawn to the same scale as in the isotropic diagram. Large differences between the two flows are apparent.

Effect of the Protective Layer

The five remaining calculations maintained the same anisotropic conductivities but the thickness of the protective layer was allowed to alter. The entries in table 1 show that the total flow decreased as the thickness t increased and that the effects of variations were largest at small thicknesses. This is more clearly illustrated in the graph of figure 4. The range of flow increased initially with protective thickness as the higher vertical resistance of the protective layer made it necessary to supply the wedge regions from a greater length of aquifer. With further increases in the thickness of the protective layer the settled region became thin and its ability to supply the wedges with water was reduced. Consequently horizontal flow in the settled region became critical in the later calculations and reductions in the thickness of the region led to corresponding reductions in the horizontal range of flow. Detailed results also revealed movements in the centre of the range such that there was a marked shift to the right in calculations 5 and 6.

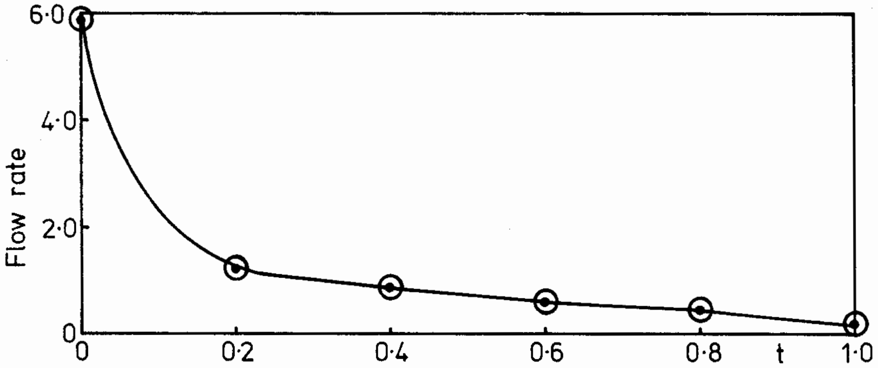

Figure 4. Flow rate v protective thickness

The final calculation shows the result of removing the protective layer altogther. In this case the total flow was five times as high as it was with the smallest protective layer and the range was so reduced that most of the flow came from a length of aquifer equal to the vertical distance between mine and aquifer.

The flow patterns for all six anisotropic tests are provided in figure 5. The vectors in the first five diagrams are drawn to the same scale but those in the last are necessarily reduced by a factor of 30. The six diagrams clearly illustrate the points made in the preceding paragraphs.

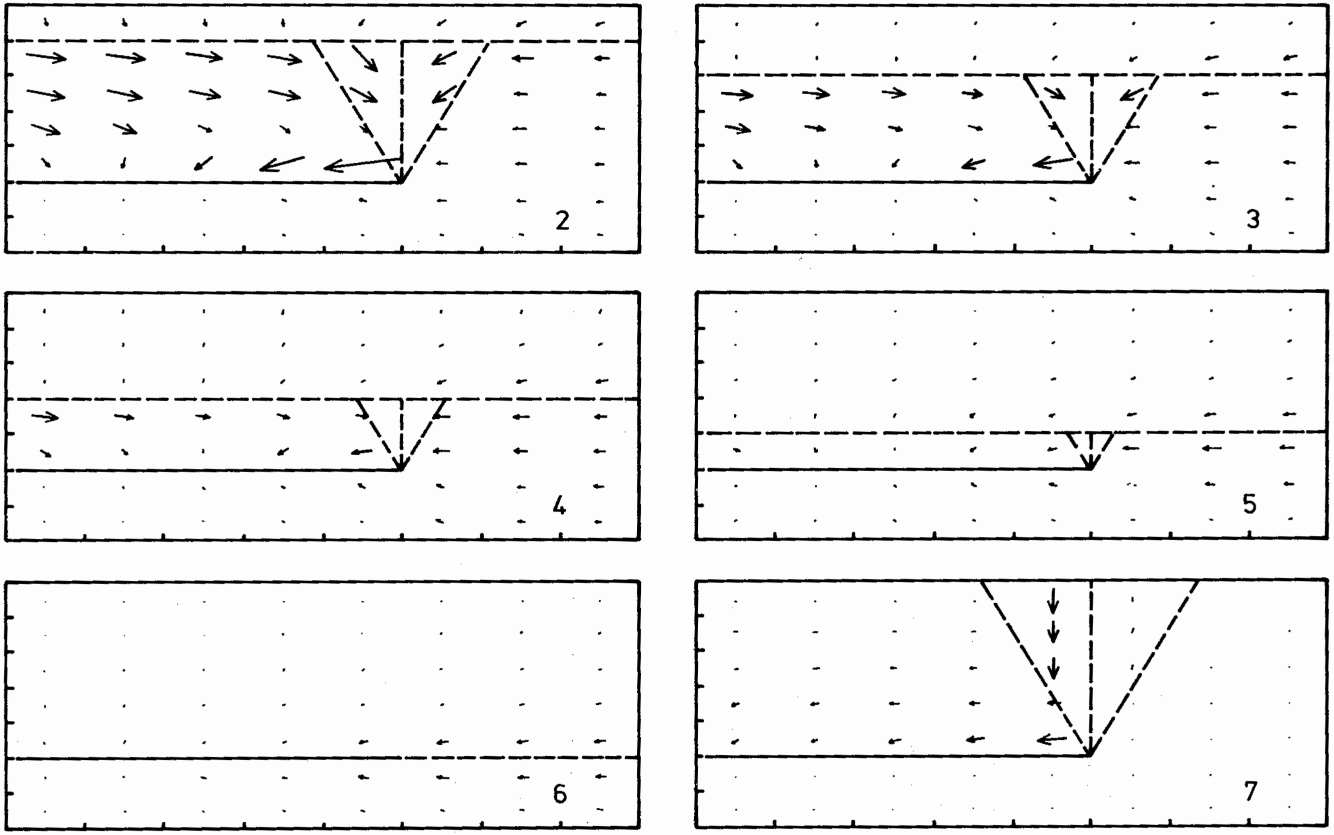

Figure 5. Anisotropic flow with varying protective thickness.

A MORE COMPLICATED CALCULATION

The boundary element program developed by the authors is able to solve mine water inflow models with an arbitrary number of sub-domains although the computer time required for solution increases rapidly with increasing model complexity. A more sophisticated model based on the initial calculations which has been solved by the authors is illustrated in figure 6. Table 2 lists the conductivities assigned to the eight different regions and shows that the first three were the same as in the initial investigations. The remaining conductivities were chosen according to the argument that the collapsed regions would be sufficiently evenly broken to be isotropic but that there would be a gradual reduction in conductivity behind the face as the broken rock became consolidated. This effect would also increase with depth so that a shallow wedge at 5° to the horizontal was given an isotropic conductivity of only double the base value.

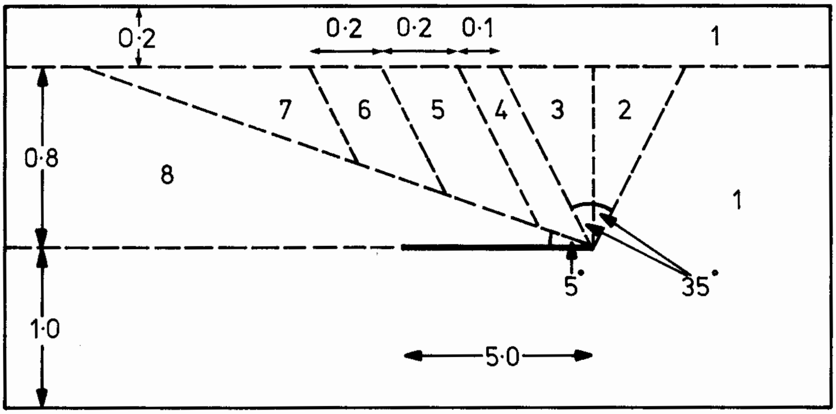

Figure 6. More complex representation of a longwall face.

The total flow in the new calculation was 0.79 with a range of 35. Both values were smaller than the corresponding results for the earlier anisotropic calculation with the same protective thickness because the settled region of high horizontal conductivity no longer extended indefinitely. The differences provide a further demonstration of the importance of anisotropic effects.

Region	K_H	K_V	Region	K_H	K_V
1	1.0	0.01	5	20.0	20.0
2	1.0	5.0	6	10.0	10.0
3	1.0	40.0	7	5.0	5.0
4	30.0	30.0	8	2.0	2.0

Table 2 Conductivities for the more complex calculation

The flow pattern associated with the new calculation is illustrated in figure 7 where the region from x = −5.0 to x = +7.0 has been split into two adjacent parts for convenience of presentation. Small instabilities in the top diagram, particularly above the line y = 0.0, were the result of numerical errors in the calculation of seepage velocities and were not reflected in the total flow rates. The latter were highly stable to the extent that detailed refinements altered the total flow rates by less than one tenth of one per cent. The same refinements had little effect on the overall flow pattern which may be taken as a reliable indication of the nature of the flow.

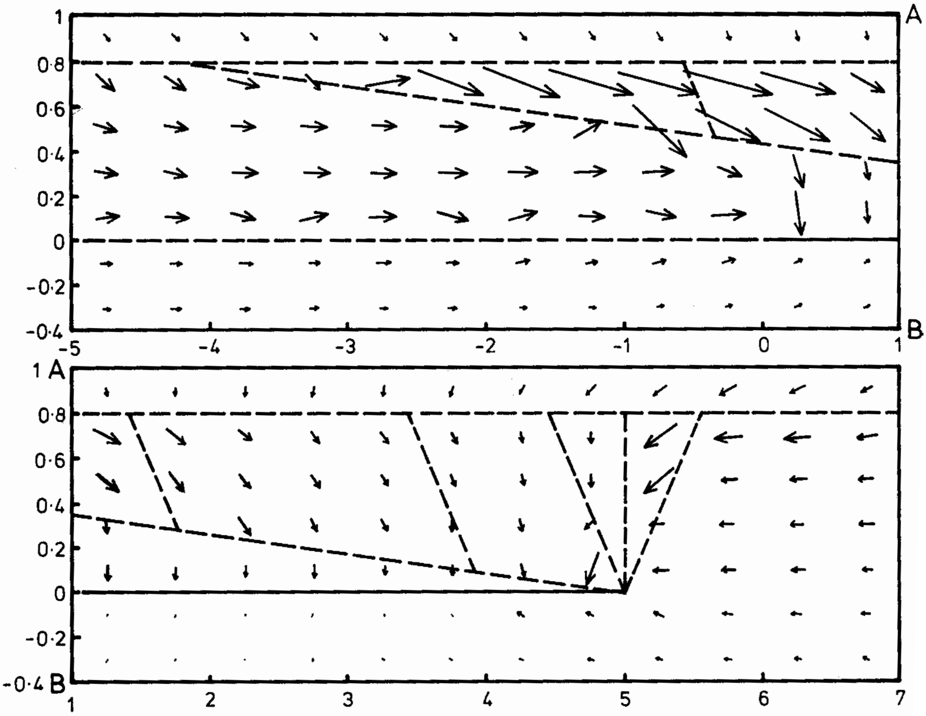

Figure 7. Flow for the more complex calculation in two adjacent regions joined by line A B

It can be seen from the two parts of figure 7 that regions 2 to 7 behaved like the two wedge regions of the earlier calculations and provided an easy water path to the mine. The phenomenon whereby water flowed horizontally into the top of the wedge and out of the bottom was absent because of the removal of anisotropy in the settled regions. The suspiciously high flow rates at the left hand end of the mine sink were the result of inadequate boundary conditions along the mine and will be the subject of future investigation.

CONCLUSIONS

The authors have successfully developed a boundary element program to calculate groundwater inflow to longwall coal faces through heterogeneous anisotropic rock strata and to produce corresponding seepage velocity diagrams. Initial investigations have, as expected, demonstrated that mining induced heterogeneity has a major influence on mine water inflow while anisotropy is less important but nevertheless significant.

Further investigation of the two phenomena of heterogeneity and anisotropy in the context of mine water inflow is clearly needed and the authors have this in hand. A major aim of the work is to identify more precisely those material properties which are most influential in determining inflow rates. Increased knowledge in this area would indicate where experimental efforts in the field measurement of physical data should be concentrated. Such data are currently rather sparse and it would be of particular value to know how they could most effectively be improved.

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