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AN ASSESSMENT OF GROUNDWATER INFLOW INTO A PROPOSED SHAFT AND DRIFT IN THE WARWICKSHIRE COALFIELD USING PACKER TEST DATA IN AN ELECTRICAL ANALOGUE MODEL

J.W. Lloyd[1], K.R. Rushton[2], and P.A. Jones[3].

[1]Department of Geological Sciences,[2]Department of Civil Engineering University of Birmingham, P.O. Box 363, Birmingham B15 2TT.

[3]Geological Branch, South Midlands Area, National Coal Board, Cole Orton, Leicester.

ABSTRACT

The assessment was carried out in multilayered permeability ground using packer testing techniques to ascertain permeability. Borehole instability occurred through using water as a drilling fluid in the variable lithologies. This resulted in some difficulty in obtaining good packer seatings with foundation engineering equipment. Oil industry drill stem test strings proved more effective. Reliable permeabilities were, however, eventually obtained and a permeability assessment was carried out using various weighting techniques to provide a complete vertical distribution on which analogue models of potential inflows were based. The analogue models allowed a detailed investigation of the flow patterns around both the proposed shaft and drift. Very high inflows were predicted at certain depths and therefore neither the shaft nor the drift were constructed.

INTRODUCTION

During shaft and drift construction one of the major constructional and cost problems can be the inflow of groundwater into workings. In shallow ground where uniform permeability conditions can be approximated, the assessments of inflow may not prove too difficult, however, in deep multilayered permeability ground both testing techniques and analysis pose severe difficulties. As depth increases the classical groundwater industry testing techniques become non-applicable so that dependence has to be placed upon the adaption of foundation engineering or oil field techniques to determine permeability.

Once the permeabilities have been estimated it is possible to use mathematical modelling techniques to establish the probable inflows. Because of the multilayered conditions digital models are not easily applicable so that for the work discussed below a resistance network analogue com-

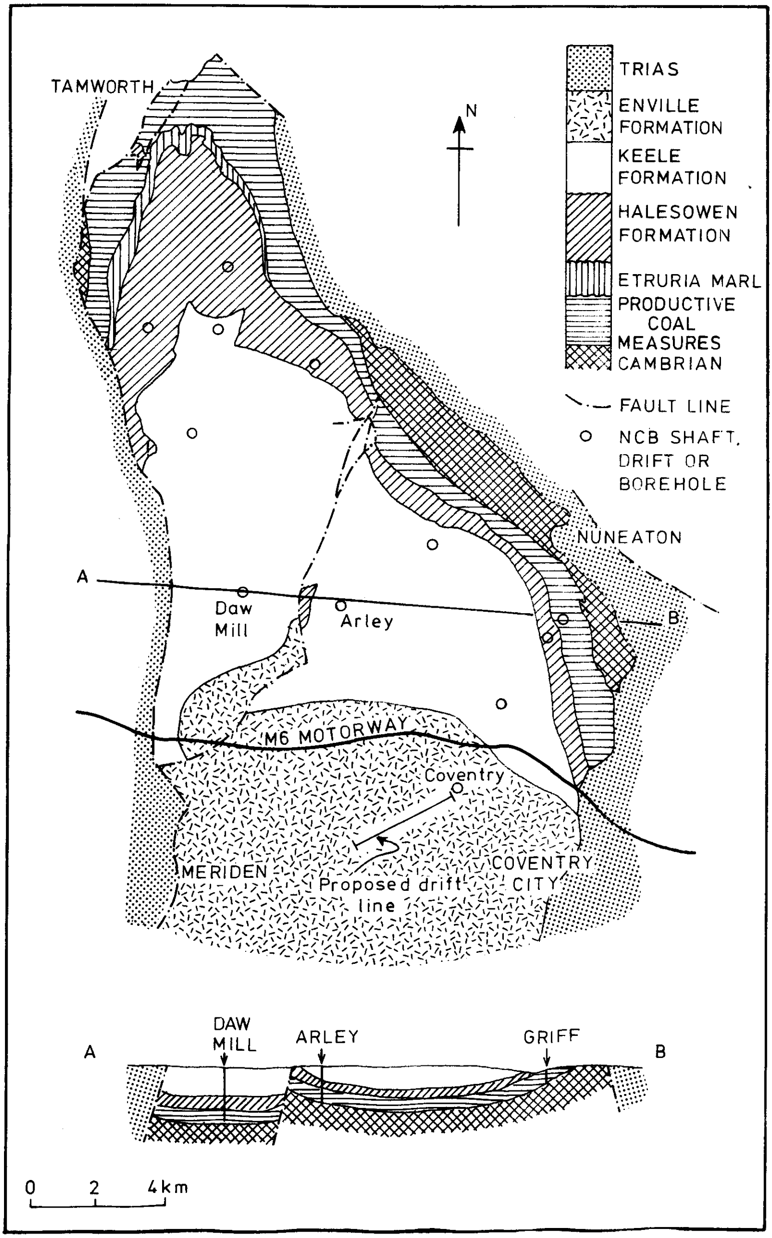


Figure 1. Geological map of the Warwickshire Coalfield

puter technique was selected to simulate flows in the ground. From such models it was found that it is possible to estimate the detailed inflow pattern into the open section of a shaft or drift.

In the following discussion the difficulties of obtaining inflow assessments are illustrated by using the specific study carried out for a proposed new access to the Warwickshire Coalfield north of Coventry. The study exemplifies multilayered ground permeability and is a good representation of the hydrogeological conditions encountered in National Coal Board (NCB) shaft and drift construction investigations.

GENERAL GEOLOGY AND HYDROGEOLOGY

The regional geology of the Warwickshire Coalfield is shown on Figure 1 with the general succession given on Table 1.

Table 1. Geological succession at Coventry Colliery

Geological Units	Lithology		Thickness (m)
CARBONIFEROUS	Enville Formation	Sandstones and siltstones with thick conglomerates	140
	Keele Formation	Siltstones and mudstones occasional sandstones	260
Upper Coal Measures	Halesowen Sandstone Formation	Mudstones and siltstones, thick sandstones towards base	120
	Etruria Marl	Mudstones and siltstones	15
Middle and Lower Coal Measures	"Productive Coal Measures"	Mudstones and siltstones with coal seams	160
CAMBRIAN	Monks Park Shales	Mudstones	-

In the Productive Coal Measures of the Coventry area the Warwickshire Thick Coal seam is worked in two sections which are between 550 and 650m below ground surface.

Faulting of a comparatively minor nature is present in the coalfield although data show substantial areas of fault-free ground.

Groundwater is abstracted from the Enville Formation and to a minor extent from the Keele and Halesowen Formations for local water supply purposes. High yielding aquifers are not present. In the main

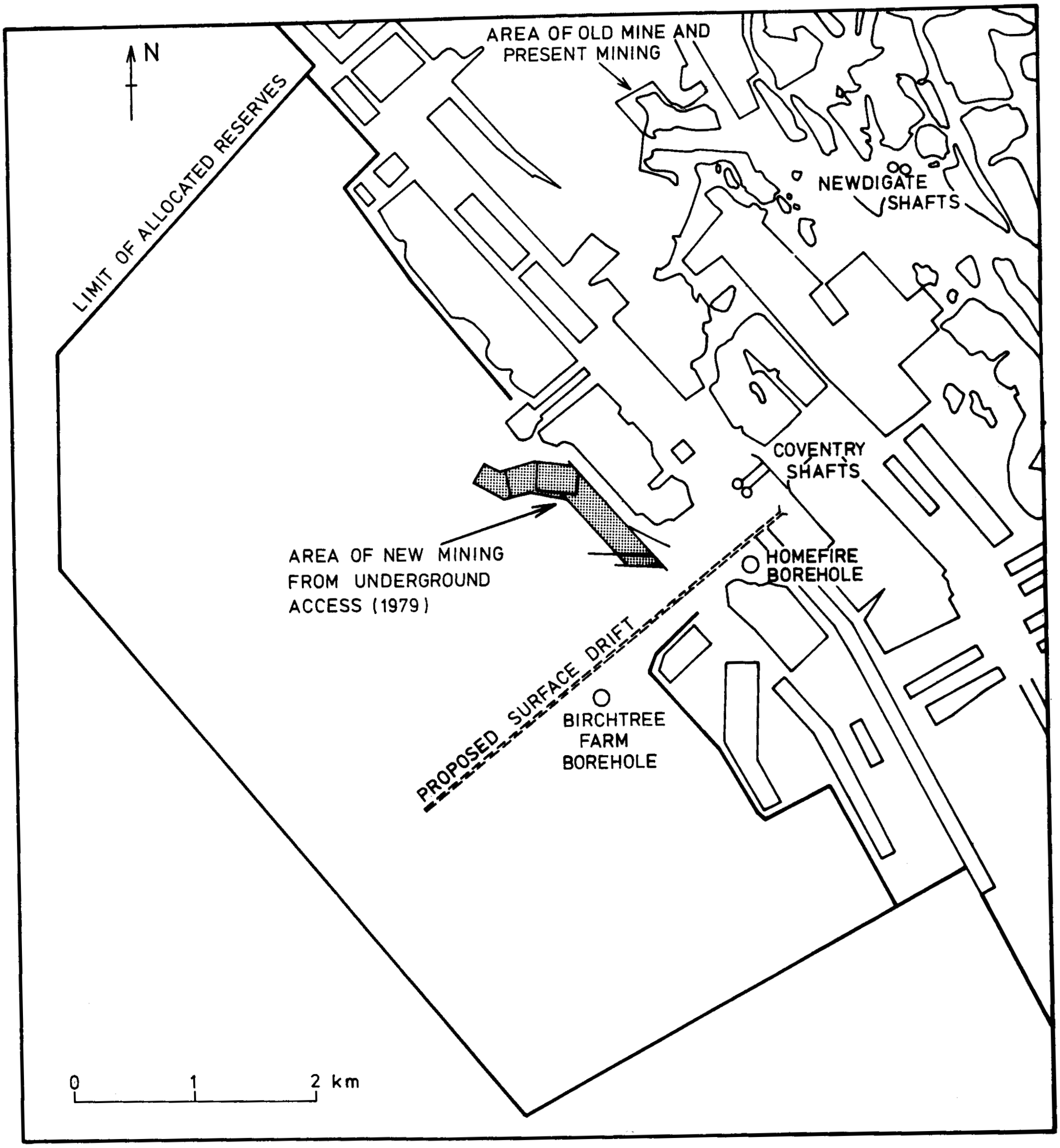


Figure 2. Location map of the proposed drift line

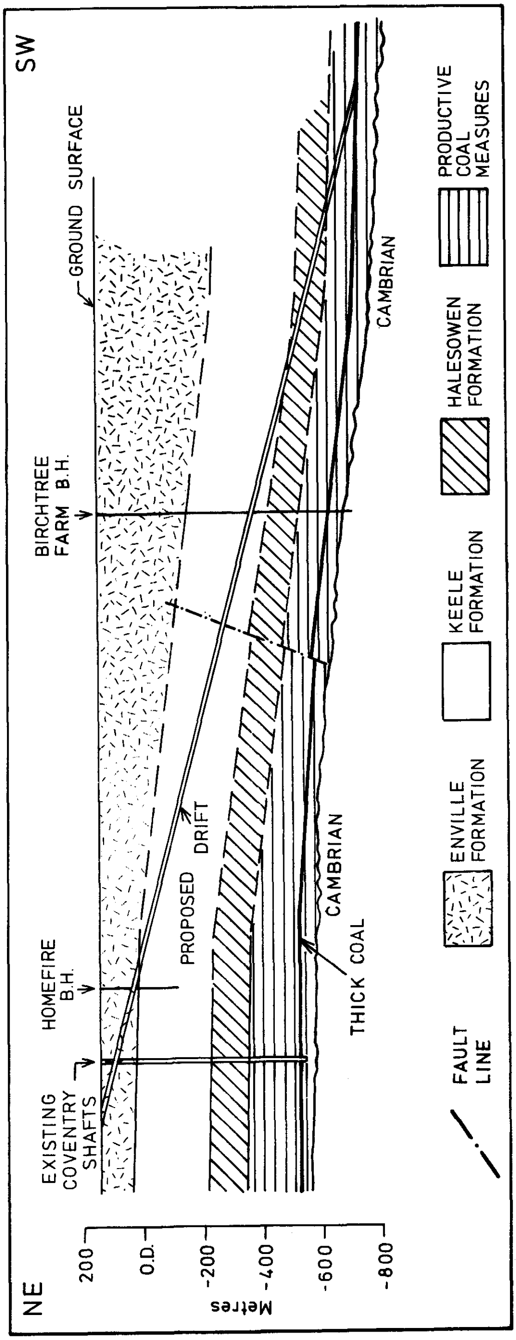


Figure 3. Geological section along line of proposed drift

Coventry Shafts, adjacent to the proposed access, significant groundwater inflows were recorded during construction down to 200m below surface. These inflows are given in Table 2. Below this depth grouting ahead of excavation was carried out so that inflow characteristics were not known.

Table 2. Inflow records from the Coventry Shafts taken during construction* (m^3/d)

Depth (m)	Shaft No. 1	Shaft No. 2
33.5	980	229
46.0	2290	-
49.0	3270	1050
58.0	-	2420
91.0	-	3270
97.0	6220	-
104.0	7860	3600
110.0	9490	-
116.0	-	5240
122.0	11130	-
125.0	11910	9160
134.0	-	1050
149.0	4910	-
152.0	7860	13750
158.0	301	-
167.0	-	17480
189.0	-	3600
219.0	-	183

*Construction - progressive excavation and lining, grouting ahead of excavation carried out below 152m in No. 1 Shaft and 190m in No. 2 shaft.

SITE INVESTIGATION

The location of the proposed drift line is shown on Figure 2. The geological cross section for the drift is given on Figure 3 with the proposed shaft being in similar ground.

The proposed drift is from the surface, a little to the south of the existing Coventry shafts, dipping 1 in 4 to reach the main coals approximately 3.5 km to the west. To assess the hydrogeological conditions two boreholes, Birchtree Farm and Homefire, were drilled at the locations shown on Figure 2.

Birchtree Farm borehole was drilled to a total depth of 862.67m with the section below 300m continuously cored at a diameter of 175mn. Homefire borehole was continuously cored at the same diameter from 10m to its total depth of 255.55m. The stratigraphic overlap between the two boreholes is approximately 100m. During drilling detailed lithological and fracture logs were prepared and samples selected for laboratory permeability determinations. Comprehensive geophysical logging was also carried out. All logs demonstrated a multilayered geological character.

For testing purposes the Homefire borehole was drilled with water to avoid mud invasion of the formations, but because of its depth Birchtree Farm was drilled with conventional bentonite muds. Testing at Homefire was carried out using foundation engineering compressional packers, while at Birchtree Farm oil industry compressional drill stem test strings were used.

In carrying out the testing at Homefire two major problems were encountered, firstly the layered lithological succession did not remain very stable with water used as the drilling fluid and secondly, the foundation engineering packer equipment proved too light and delicate for the rigs normally employed for National Coal Board cored holes.

Hole instability was related chiefly to the washing out of soft formations during tool operations, as a result of which reliable packer seatings were difficult to obtain. The degree of borehole erosion was assessed using Schlumberger X-Y calipers as shown in the example on Figure 4. Excessive and eccentric erosion is shown in the upper section on Figure 4 decreasing with depth because of less tool operation.

As drilling progressed debris from top hole sections caused packers to be stuck lower down the hole and on occasions lost. To alleviate this problem casing was eventually inserted to 105m and then 183m before drilling and testing continued.

The packer tool weight problem caused uncertainty in knowing when packer seating has been obtained and in knowing when packers were free of obstructions. As a result certain tests proved abortive and packers were on occasions damaged.

Irrespective of the testing difficulties Homefire borehole was tested throughout with the exception of a 15m section between 69 and 84m (see Figure 4). Injection tests were carried out using a double packer assembly with pressure measurements monitored by a transducer placed in the flow system immediately above the top packer. Pressures were recorded by a chart output at the surface. Flows into a test section were measured at surface from readings on a Kent flowmeter. Sections tested were about 5 to 10m and sometimes overlapping.

For testing a maximum net increase in pressure above hydrostatic was given by 2 psi for each metre of depth from the surface to the middle of a test section for depths to 75m, beneath this depth a pressure of 150 psi was used. Five injection stages were carried out, each until steady flow and pressure conditions were obtained.

At Birchtree Farm borehole little difficulty was encountered during drilling and a reasonable gauge hole was obtained. Drill stem testing was carried out below 256m with a standard procedure of two phases of inflow and shut-in. The testing proves very lengthy due to the

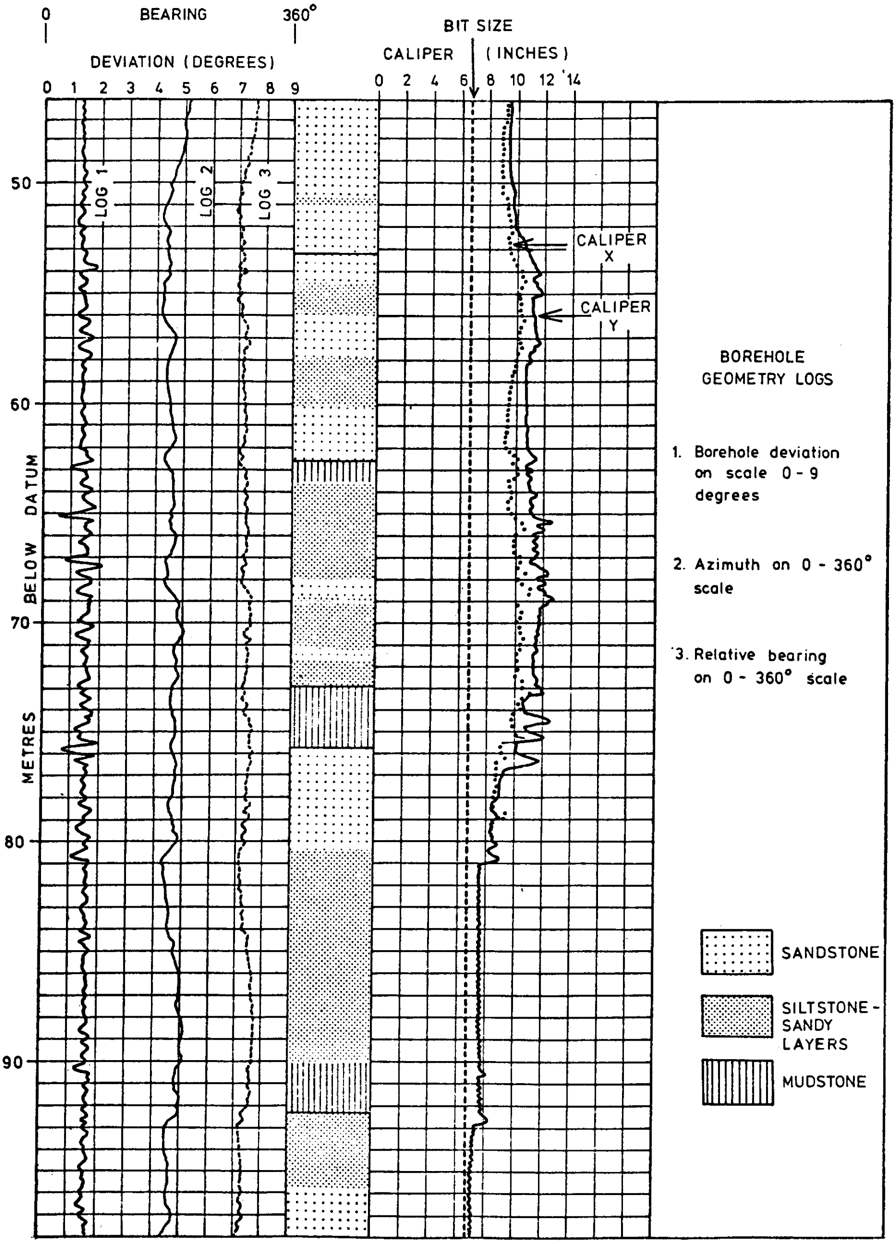


Figure 4. Borehole caliper log

inherent inflexibility of the conventional compressional drill stem strings and the limited control of testing, however, consistent results were obtained which are considered reliable.

While the permeability testing at the two boreholes proved effective, and indeed provided valuable guidance as to the applicability of techniques, the overall approach was not sufficiently efficient for the type of strata encountered. Subsequently fully automated oil industry inflatable packer systems have been very successfully used under similar cirumstances by the National Coal Board in boreholes drilled with bentonite muds (1).

INTERPRETATION

The injection test data were interpreted using classical steady state flow equations for each injection stage. As in all testing of this type some permeability variation was found for different stages of a test section. In order to select a representative permeability value, a subjective set of criteria was adopted based upon a variation of the criteria as outlined in Table 3. The final permeability values determined are given in Table 4 which illustrates a very

Table 3 Criteria for selecting permeability from staged injection tests.

Flow Condition	Houlsby Permeability (2)	Inflow Permeability
Laminar	Average pressure	Average pressure
Turbulent	Highest pressure	Initial pressure
Dilation	Highest pressure	Initial pressure
Wash Out	Highest pressure	Highest pressure
Void Filling	Final pressure	Initial pressure

The differences in criteria were considered as follows:

Turbulent Flow: Under natural groundwater head conditions it is not thought that turbulent flow will occur in the type of fracture opening present in the sequence. In any case from the results turbulent flow even during injection is limited. The initial permeability value was selected.

Dilation Flow: Dilation of the ground under natural groundwater heads in the drift or shaft is thought unlikely. The initial permeability value before the ground is dilated was selected.

Void Filling: As flow will be outward from the cavity wall void filling should not probably occur. The initial permeability value before filling occurred in testing was selected.

variable and random distribution consistent with the lithology and presence of the fractures. The testing indicated that the highest permeabilities are present in sandstone units possessing both intergranular and fracture permeability. Both fractured siltstones and mudstones were found to possess some permeability in certain sections, while in other sections sandstones, siltstones and mudstones were found to have no real permeability in the context of the study.

Table 4. Permeabilities from injection tests

Test No.	Test Interval m	Static Water Level m below surface	Permeability ($m/d \times 10^{-3}$ at 10^oC)
1	11.5- 20.5	4.6	167
2	20.5- 36.5	6.1	125
3	36.5- 55.2	22.9	217
4	63.8- 69.0	18.0	0
6	94.3-101.8	29.3	134
8	84.3- 94.3	26.3	75
10	56.0- 59.0	18.1	59
12	102.0-111.0	13.7	0
13	111.0-122.1	9.7	0
14	122.0-129.0	13.9	92
17	129.0-142.3	10.2	17
18	145.0-148.0	18.9	42
21	148.0-159.8	20.6	8
22	163.0-173.5	42.9	551
23	160.0-163.7	19.3	25
25	173.5-185.3	3.9	1950
26	186.0-192.1	38.4	551
27	188.0-198.1	53.7	376
28	187.9-204.1	46.3	175
29	201.0-210.1	46.5	0
31	211.0-217.2	46.5	1190
32	217.8-223.0	50.0	2880
33	233.6-228.8	48.7	626
34	227.1-233.7	52.8	0
35	233.4-239.4	39.9	50
36	238.5-245.0	46.2	100
37	245.7-250.7	46.3	0

Below 228m in the Homefire borehole permeability values were found to decrease quite significantly. This decrease in permeability in depth is consistent with the drill stem test results from Birchtree Farm borehole.

Twelve tests were carried out at Birchtree Farm with interpretation methods based upon classical oil field techniques [3]. In the sections 256 to 450m permeabilities of upto 3 x 10^{-2} m/day were recorded below this depth to 650m values up to 8 x 10^{-4} m/day were recorded and between 650m and total depth no drill stem test responses were obtained.

Although both intergranular and fracture permeabilities were found to exist, no distinction was made in the method of analysis adopted. Injection test analyses are based upon steady-state theory which draws no distinction between modes of permeability. Further, the final inflow calculations are for 20m sections which make such distinctions unnecessary.

As the permeabilities determined in the testing relate to the average permeability per interval length, weighting was carried out with respect to lithology and fracture in order to obtain a full permeability assessment of the total depth to 650m. This proved particularly difficult because of the interbedded nature of the sequence. Three subjective criteria were adopted for input to the analogue model used in inflow analyses:

(i) In sections where lithologies are very interbedded and mudstones are not prevalent the average permeability determined directly by testing was adopted.

(ii) In sections where fractured sandstones dominate and mudstones are important the calculated test permeabilities were distributed with respect to the sandstone thicknesses assuming that all of the permeability related to the sandstones.

(iii) Where 'zero' permeabilities were determined by testing an arbitrary minimal permeability of 4×10^{-3} m/day was adopted down to 650m.

The weighted permeabilities determined for input into the analogue model together with the groundwater heads are given in Table 5. In the overlap section preference was given to the injection test data.

MATHEMATICAL MODELS

Inflows into underground excavations can be assessed using mathematical models. Before a mathematical model can be devised, however, care must be taken in the formulation of the problem. This involves a statement of the equation of flow within the aquifer as well as the conditions on the internal and external boundaries in terms of groundwater heads or flows.

There are differences between the formulations for a shaft and for a drift. It is reasonable to assume that the flow towards a shaft is approximately the same on any radius and therefore radial symmetry can be used. However, no such approximation can be made with a drift. Due to these differences, reference will be made initially to the proposed shaft.

Radial Flow to the Shaft

For the study only a single set of permeability data was prepared. In the absence of more detailed information it was assumed that the zones of different permeability extend laterally throughout the region which makes a significant contribution to the flow into the shaft. For this example, this is a reasonable approximation provided that there are no significant discontinuities within 100m of the shaft.

From Darcy's Law and the conditions of continuity of flow an equation can be derived which describes the flow. The appropriate equation is:

$$\frac{\partial}{\partial r}\left(k(z) \cdot \frac{\partial h}{\partial r}\right) + \frac{k(z)}{r} \cdot \frac{\partial h}{\partial r} + \frac{\partial}{\partial z}\left(k(z) \cdot \frac{\partial h}{\partial z}\right) = 0$$

Certain important features can be noted about this equation:

(i) Flow is important in horizontal (radial) and vertical directions

(ii) The permeability is written k(z). This means that it takes different values for different depths (z) but that at a particular depth it is the same in the radial and vertical directions. Information about the ratio of horizontal to vertical permeability is not available for the study. The assumption that the horizontal to vertical ratio is the same is not likely to lead to significant errors since the important feature is that contrasting permeability layers are represented.

(iii) Since the right hand side is zero, only steady state conditions are represented.

It is also necessary to state the conditions on the sides of the shaft. The shaft is pumped until there is water only at the base of the shaft. Consequently the conditions on the base and the sides of the open section of the shaft are that the pressure is known. Therefore the groundwater head equals the height above datum. Where lining is present, no flow can enter the shaft and $\partial h/\partial r = 0$.

The actual radius of influence cannot be determined, but it is reasonable to assume that it is no more than 500m. Therefore the condition applied at 500m radially from the axis of the shaft is that the groundwater head takes an average of the values of column of Table 4.

Resistance Network Analogue

Solutions to this problem can be obtained using a resistance network electrical analogue. The resistance to the flow of water through the aquifer can be represented by electrical resistances with the resistance inversely proportional to the permeability. Electrical voltage equals groundwater head and electrical current represents the flow of water. The region was divided into discrete space steps, with a logarithmic increase in the radial direction and vertical spacing of 5m. Rather than using the lumping derivation described above, it is possible to write the governing equation in finite difference form and select a resistance network which has analogous equations. Further information can be found in [4].

The resistance network, which represents this particular aquifer has horizontal bands of higher resistances in regions where the permeability is low and bands of lower resistance where the permeability is high (Table 5). The open section of the shaft is represented by applying voltages which correspond to the base and face of the shaft.

Table 5. Permeabilities determined for model analysis

Depth m	Permeability (m/dx10^{-3} at 10^{o}C)	Groundwater Head m below surface	Comment
0 - 20.5	170	4.6	Interbedded Section
20.5- 41.0	125	6.1	Interbedded Section
41.0- 53.0	340	22.9	Sandstone weighted
53.0- 62.5	20	22.9	Interbedded Section
62.5- 69.0	10	18.0	No take
69.0- 80.0	60	18.0	Interbedded Section
80.0- 95.0	75	26.3	Interbedded Section
95.0- 97.0	620	29.3	Sandstone weighted
97.0-124.0	10	13.7	No take
124.0-129.5	130	13.7	Sandstone weighted
129.5-144.0	20	10.2	Interbedded section
144.0-163.5	25	18.9	Interbedded section
163.5-172.5	550	42.9	Highly fractured
172.5-187.5	1950	3.9	Highly fractured
187.5-192.0	550	38.4	Evenly fractured
192.0-201.0	375	53.7	Evenly fractured
201.0-215.5	10	46.5	No take
215.5-223.0	4010	46.5	Highly fractured
223.0-226.5	1540	48.7	Highly fractured
226.5-233.5	10	52.8	No take
233.5-245.0	160	43.0	Sandstone weighted
245.0-250.0	10	46.3	No take
250.0-650.0	5	46.3	DST low permeability
650.0-750.0	0	46.3	DST no response

Where lining is present, no electrical connection is made thereby modelling the condition of zero flow. A series of experiments are performed with the open section of the shaft at different depths.

Results for the Shaft

Once the conditions have been applied to the shaft it is possible to measure voltages corresponding to the groundwater head. In addition it is possible to measure the flows on entering the wall and the base of the open section of the shaft. These are the direct measurements that can be made. However, from the groundwater head distribution it is possible to determine the magnitude and direction of flows within the aquifer.

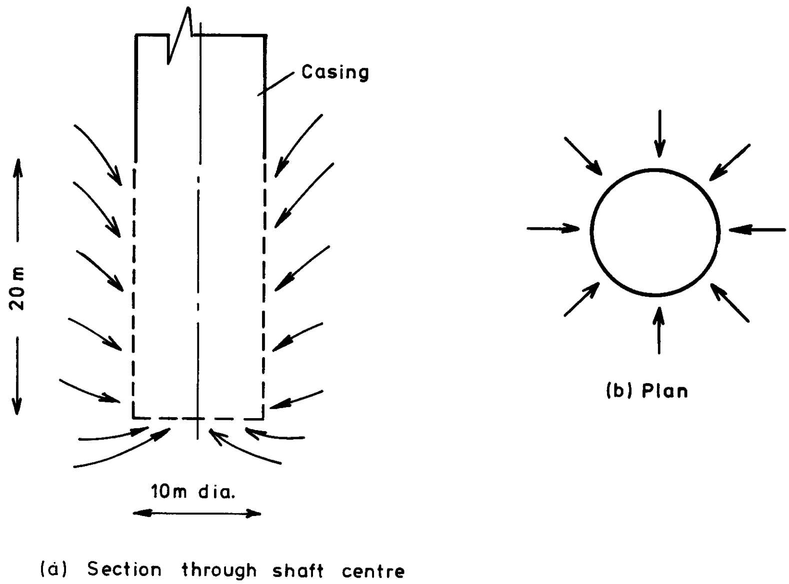


Figure 5. Section and plan of flow to a shaft

Figure 5 shows the general pattern of flows within the aquifer illustrating the manner in which water is drawn upwards into the base of the shaft and downwards towards the top of the shaft. Figure 6 indicates the estimated inflows into the face and base of the shaft.

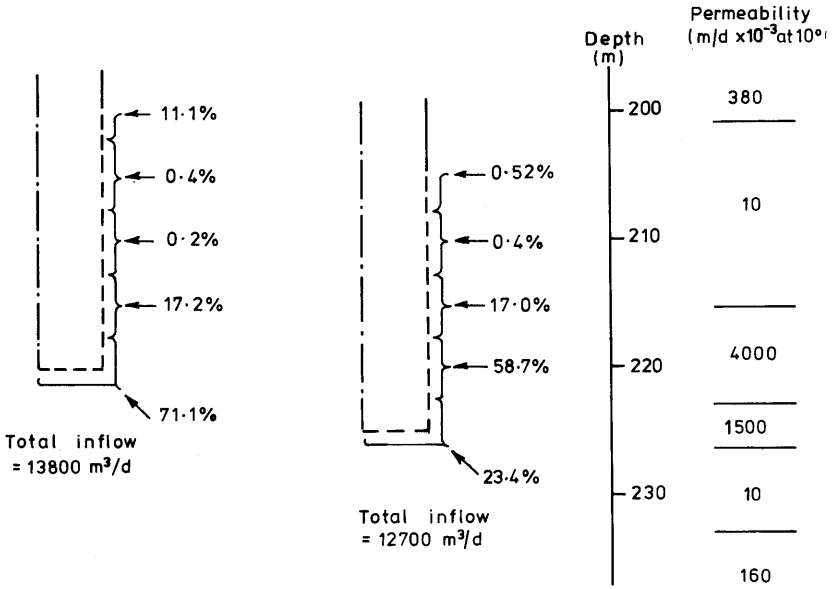


Figure 6. Inflow distribution, base of shaft is 220m or 225m. The percentage inflow over different portions of the open section are shown.

The two diagrams show that as the shaft is sunk a further 5m, the total inflow remains approximately the same but the distribution over the sides of the shaft alters considerably. This occurs because of the bands of higher permeability between 216 and 226m below ground level.

Detailed results can be obtained for each position of the open section of the shaft. A summary of the results is to be found in Table 6 which lists the inflows over a wide range of depths. As would be expected, the greater inflows occur when the open section of the shaft coincides with a band of higher permeability.

Table 6. Inflows to shafts

Base of Excavation	Inflow (m^3/d)
20m	130
40	390
60	650
80	390
100	650
120	200
140	430
160	590
180	10800
185	11260
200	10210
220	13750
225	12770
240	124380
260	1510
280	130
300	130
400	160
500	160
600	260

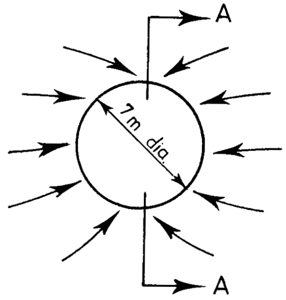
Table 7. Inflows to drift*

Axis below ground level	Inflow (m^3/d)
12.5m	290
22.5	520
32.5	790
42.5	1440
52.5	1700
62.5	590
72.5	650
82.5	1080
92.5	1700
97.5	1570
102.5	920
112.5	260
122.5	920
132.5	980
142.5	650
152.5	920
162.5	9620
172.5	23570
182.5	13750
192.5	19640
202.5	7860
212.5	29460
217.5	36000
222.5	36330
232.5	5560
242.5	4910
252.5	430
262.5	260
302.5	230

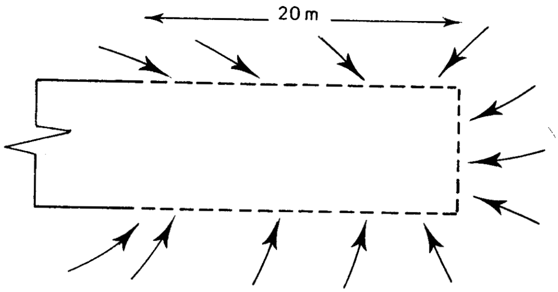
*7m diameter with 20m longitudinal section open

Flow to Drift

Flow to a drift is three-dimensional. This is illustrated in Figure 7 which shows inflows on lateral- and cross-sections. The construction of a three-dimensional network to represent this complex aquifer is very difficult and therefore the preliminary approach adopted was to take a representative section, Figure 7, which would simulate the inflow on a section towards the centre of the open portion of the drift. At the end of the drift adjacent to the lining a slightly larger inflow will occur than for the typical section. At the open end of the drift the inflow will be significantly higher than at the typical section. Corrections for these conditions can be made by increasing the flows. This is a similar procedure to the correction for the inflow into the bottom of a well.



(a) Section through drift



(b) Section on A - A

Figure 7. Sections showing flow to a drift.

Estimated inflows to the adit of 7m diameter are recorded in Table 7. These have been determined from a resistance network similar to that of the shaft. Once more the higher inflows occur when the adit passes through zones of higher permeability.

Since the flows for the drift appear to be higher than those for the shaft work is proceeding on the three-dimensional analysis of a drift in a layered aquifer.

In this type of study it is difficult to determine the accuracy of the calculated results. Some indication maybe forthcoming during excavation about small and intermediate inflows; where high inflows are anticipated ground freezing, will probably be adopted and no inflow information obtained.

In the Coventry example it is re-assuring to note that the calculated inflows are of the same order of magnitude as the existing shaft values. The flows calculated for the drift are higher than the shaft and maybe significantly higher under non-steady state flow conditions.

The study illustrates that although techniques can be applied to provide an estimate of permeability surrounding a shaft or drift it may be difficult to understand the real distribution and select the subjective criteria that have to be adopted.

In interpreting the permeability data with respect to inflows into a shaft the analogue resistor model used is believed to be reliable in terms of steady state flows. More work, however, is required to study the non-steady inflows. The drift solution and while providing a reasonable answer it is clear that more attention needs to be paid to drift inflow analysis.

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