Geological Controls on the Flow of Groundwater into Underground Excavations

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ABSTRACT

The accurate prediction both of the water ingress into sub-surface excavations and the nearby groundwater pressures is of fundamental importance to the control of the stability and flooding of tunnels or mines constructed below the water table. Predictions are usually based on laboratory and *in situ* permeability determinations together with observations of groundwater conditions in boreholes.

Although established theoretical methods provide a basis for prediction, the actual ingress depends on many factors. The objective of this paper is to explore the geological controls on groundwater conditions, and the available methods of prediction of both groundwater flow and pressure are outlined.

Salient points are emphasised by reference to a case history involving the construction of a tunnel in a faulted and mixed sequence of sandstones, siltstones, shales and coals. Water ingress quantities have been monitored for a variety geological and geotechnical conditions including heavily faulted and mine disturbed ground. The overall results are discussed with reference to the relevant hydrological and geological conditions in terms of the geological structure, lithology and rockmass condition as well as the construction methods.

INTRODUCTION

Excavation in water-bearing ground is a difficult operation requiring a detailed knowledge of the ground in which the work is to be performed. The problems which arise due to adverse water conditions during open pit mining operations in rocks include the workability and trafficability of the ground but side slope stability is usually the major consideration [1]. An increase in slope angle is economically desirable since this reduces both land-take and the amount of overburden which must be removed. Thus considerable effort to improve stability by dewatering excavations can be justified. Similar arguments also apply in the case of tunnels and other forms of underground excavation where, in addition to the danger of instability, flooding constitutes a considerable hazard.

Groundwater control measures may entail the artificial lowering of groundwater levels in the vicinity of an excavation. Appropriate construction methods and structural designs should be chosen or there may be a need to ensure that pumping capacity can cope with natural water inflows. An accurate prediction of the quantities of water involved is an obvious prerequisite.

The paper includes a brief review of the more important geological factors which are liable to exert significant controls over the flow of groundwater into excavations. Reference is made to the ingress of groundwater during the construction of the Don Valley Intercepting Sewer in Sheffield, England. The ingress is discussed with respect to the geological and hydrological situation of several parts of the excavations.

PREDICTION OF WATER INGRESS

In order to determine the effects of dewatering on the existing groundwater conditions and to predict the influence of mining or engineering operations on these conditions, information of the following types would be required.

(a) The location, disposition and thicknesses of aquifers and aquicludes in the area, including the presence of any hydrological barriers or highly permeable zones.
(b) The levels of water and water pressures, including the presence of perched water tables and the existence of artesian or sub-artesian water pressures.
(c) The permeability and water storage capacity of the ground.
(d) The recharge of water into aquifers by infiltration and from bodies of water.
(e) The fluctuations in water levels or pressures due to variations in abstraction, recharge, tides, barometric pressure and other causes.

Methods of investigation have been reviewed in the literature [2]. Delineation of the hydrological features of the area follows from geological mapping. Attention must be paid to the presence of springs, lakes, rivers and other hydrological features. The significance of faults, fracture zones and other geological structures must also be considered. The objective is to build up a complete picture of groundwater levels and water pressures within the area and from this determine the movement of groundwater.

In addition to the hydrological regime operating in the area, data about the hydraulic conductivity and storage capacity of the ground are also required. Both laboratory and *in situ* determinations of permeability are available. Due to the important role played by discontinuities in fluid movement, *in situ* test methods are much more likely to yield values more representative of the behaviour of the rock or soil mass.

In-situ values of the coefficients of permeability and storage capacity are usually derived by carrying out borehole packer and/or slug tests [3,4]. By recording changes in the head with time both the permeability and storage capacity of the ground may be measured [5]. The relationship between the flow recorded for a series of different pressure heads can provide useful information about the hydrological situation [6].

Field pumping tests [7] may also be used in the determination of hydraulic conductivity or permeability as well as the coefficients of transmissivity and storage. These tests tend to provide data about a greater volume of ground than packer tests. Although in terms of the design of an individual excavation, the more local information obtained from a borehole packer test may be more relevant, it may well be necessary to establish the regional pattern of groundwater movement before assessing the effects of mining or engineering works.

PERMEABILITY AND GROUND CONDITIONS

The quantity of water which may be drained from a given volume of saturated ground is a function of the pore volume present. Not all the water contained within the pore space is likely to be released since some will be retained by molecular and capillary

Rock Type	Specific Yield %	Porosity: Primary (grain)%	Porosity: Secondary (Fracture) (Generally <10%)	Permeability: Range	Permeability: Value (m/s)	Groundwater Flow	Type of Water Bearing Formation
Unconsolidated Sediments							
Gravel	25-30	30-40		Very High-Medium	$10^{0}-10^{-4}$	High	Aquifer
Coarse Sand	30-35	30-40		High -Medium	$10^{-1}-10^{-5}$	High -Medium	Aquifer
Medium to Fine Sand	10-30	25-35		High -Medium	$10^{-2}-10^{-5}$	High -Medium	Aquifer
Silt	5-10	40-50	Occasional Fissures	Low -Very Low	$10^{-6}-10^{-8}$	Medium-Low	Aquiclude
Clay	1- 5	45-55	Often Fissured	Very Low -Impermeable	$10^{-7}-10^{-10}$	Low	Aquiclude
Sedimentary Rocks							
Limestone & Dolostone	0.5-10	1-50	Solution Cavities, Joints, Bedding Planes	Very High-Impermeable	$10^{0}-10^{-10}$	High -Low	Aquifer or Aquifuge
Coarse and Medium Sandstone		<20	Joints and Bedding Planes	High -Medium	$10^{-1}-10^{-5}$	High -Medium	Aquifer or Aquiclude
	5-25						
Fine Sandstone		<10	Joints and Bedding Planes	High -Low	$10^{-2}-10^{-6}$	Medium-Low	Aquifer or Aquiclude
Siltstone and Shale	0.5- 5	< 1	Joints and Bedding Planes	Medium -Very Low	$10^{-5}-10^{-8}$	Low	Aquifer or Aquiclude
Crystalline Rocks							
Volcanic		< 1	Frequent Joints and Permeable Zones	Very High-Impermeable	$10^{0}-10^{-10}$	High -Low	Aquifer or Aquifuge
Plutonic and Metamorphic		< 1	Occasional Joints Decreases with Depth and Weathering	High -Impermeable	$10^{-2}-10^{-10}$	Medium-Low	Aquifuge or Aquifer

Table 1: Permeability of Rocks and Soils

Discontinuity Spacing	Interval (m)	Permeability	
		Range	Value (m/s)
Very close to extremely close	<0.2	High	10^{0}–10^{-2}
Close to moderately wide	0.2–0.6	Medium	10^{-2}–10^{-5}
Wide to very wide	0.6–2.0	Medium-Low	10^{-5}–10^{-9}
Very wide	>2.0	Very Low	$<10^{-9}$

Table 2: Effect of discontinuity spacing on permeability

forces, and some may be held in unconnected pores. The general relationship between specific yield, defined as the ratio of the volume of water that can be drained by gravity to the total volume of a saturated aquifer, and grain size is shown in Table 1. The permeability of a material is a function of pore size and shape and it also depends on the degree of pore interconnectedness so that not all high porosity rocks have high permeability. Typical values of permeability for a number of rocks and soils are given in Table 1.

Geological structures, including stratification, joints, faults, fractured zones and solution channels in carbonate rocks, exert a major control over the flow of water through the ground. Generally speaking these features are more important in low porosity materials which have little intergranular permeability. Many rocks, and some soils, are rendered anisotropic with respect to their fluid carrying capacity by layering, preferred orientation or fracturing. In the Permo-Trias sandstones of north-west England the ratio of horizontal to vertical permeability approximates to 5:1 and values as high as 100:1 occur where marl partings are frequent. Many rocks have extremely low intrinsic permeability, but fluid flow through the discontinuity system gives rise to relatively high bulk permeability. This is illustrated in Table 2. These data should be applied with caution since the permeability of a rock mass depends on the degree of interconnectedness between different discontinuity sets as well as on the openness, surface roughness and presence of infill of fractures [8]. Most fracture zones and faults contain closely spaced and highly interconnected discrete fractures and broken rock [9]. In some the rock fragments are contained in a clayey matrix which considerably reduces the permeability. In shear zones dramatic changes in permeability are liable to occur over short distances depending on the lithology of the rocks affected and whether or not dilation has taken place [10].

The flow through a smooth walled discontinuity can be shown to vary according to the cube of the aperture and since the flow path is greatly increased in narrow rough surfaced discontinuities compared with wider discontinuities of the same roughness small increases in aperture give rise to large increases in fracture permeability [11]. Also the permeability of fracture systems is highly stress dependent [9]. Rockmass relaxation in the vicinity of an excavation and disturbance caused to the rockmass during excavation, particularly where blasting is employed, is liable to induce a large increase in rock mass permeability.

It is possible from measurements of discontinuity orientation, spacings, aperture and roughness to calculate permeability in any particular direction. In practice, it would be difficult to characterise the discontinuity system although this might be done in an analysis of rockmass fluid flow in the immediate vicinity of an excavation. The rockmass remote from the excavation may be modelled as a continuous homogenous medium [9]. This would be acceptable where the average spacing of discontinuities is small in comparison with the dimensions of the rockmass [12]. Such a simplification can be applied only where the persistence to spacing ratio is large so that continuous interconnections between different discontinuity sets occur. Since, measurements of discontinuity apertures tend to give a log-normal distribution of values [9] and flow is governed by a cube law, flow regimes are liable to be dominated by a few highly permeable discontinuities. Also where the spacing of water bearing joints is greater than the width of an excavation, water ingress may exceed estimates made on the basis of the excavation dimensions.

DON VALLEY INTERCEPTING SEWER SCHEME, SHEFFIELD, ENGLAND

The importance of considering fully the geological and hydrological situation of excavations may be illustrated by referring to experience gained during the construction of Phase 1 of the Don Valley Intercepting Sewer in Sheffield, England. The tunnelling conditions have been affected by the ground conditions and hydrological situation in the area. Of particular significance are the presence of hydrological barriers of various types and the effects of mining for coal in several underlying coal seams. Fig. 1 also illustrates the situation and main elements of the scheme. It comprises some 5,726 m of 6.0 or 4.65 m diameter main line tunnel driven at a depth of approximately 20 m below ground level together with 2586 m of branch tunnels ranging in diameter between 1.37 and 2.44 m, 28 shafts with external diameters ranging between 3.0 and 10.0 m and other works. Both boom mounted roadheader tunnelling machines and drill and blast methods of excavation were used. During construction horizontal probe holes were drilled into the face to maintain a bulkhead of at least 10 m of ground. These holes, of average length 50 m and up to 80 m long, served to drain water from the ground ahead of the excavation. The tunnel and shaft excavations were lined with gasketted or ungasketted pre-cast concrete segments.

The scheme is part of a major up-grading of sewerage treatment in the area in which the existing high level brick sewers will be linked to the deep interceptors The work is taking place in an industrial and urbanised area in which there are a number of major steel and other engineering works. In recent years these older industries have suffered a reduction in activity, leading to the release of land for redevelopment. Several major roads, railways and a canal are all located within the valley along which, as indicated on Fig. 1, the River Don also flows.

Geological Conditions

The British Geological Survey Memoir for Sheffield [13] explains that the strata of the Lower Don Valley belong to the Lower and Middle Coal Measures of the Carboniferous System. They are overlain by approximately 7 m of alluvium of Recent and Late Pleistocene age comprising deposits of clayey, silty or sandy loam in the upper part with gravelly material at the base. The alluvium varies in thickness, being thinnest at the margins and upstream parts of the valley. This is overlain in places by variable thicknesses of made ground or fill.

The solid geology comprises sequences of interbedded mudstone, siltstone, sandstone and rock of intermediate grain size, together with coal seams and seatearths deposited in cycles with an average, thickness varying between 10 and 15 m. During tunnel construction it was found that individual members of cycles might be absent and interruptions to the general sequence together with lateral variations in the thickness and composition of individual members were noted. A few transgressive beds of sandstone with erosive basal contacts forming a 'wash out' or channel feature were encountered.

The geological structure of the Lower Don Valley is dominated by the Don Monocline, a strongly asymmetric fold, which trends NE-SW. On the NW flank of this structure the angle of dip ranges between 20^{o} and 30^{o}, although dips in excess of 40^{o} have been recorded. Immediately to the south of this steeply dipping limb the dip lessens to between 5^{o} and 10^{o} and the strike swings from NE-SW to NW-SE. The strata are also affected by numerous faults with major structures trending generally NW-SE and SW-NE accompanied by smaller faults of less consistent trend. A major fault trending NNW-SSE with six individual planes of movement in a zone of disturbed ground approximately 30 m wide, was encountered near shaft A0. The 'Nunnery Fault' was encountered near shaft A10. This fault consisted of one plane of movement which trended NNW-SSE with a throw of about 40 m and a hade of 10^{o}. Elsewhere a number of lesser faults, mostly normal in type with hades of between 10^{o} and 30^{o} as well as occasional small displacement low angle faults were recorded.

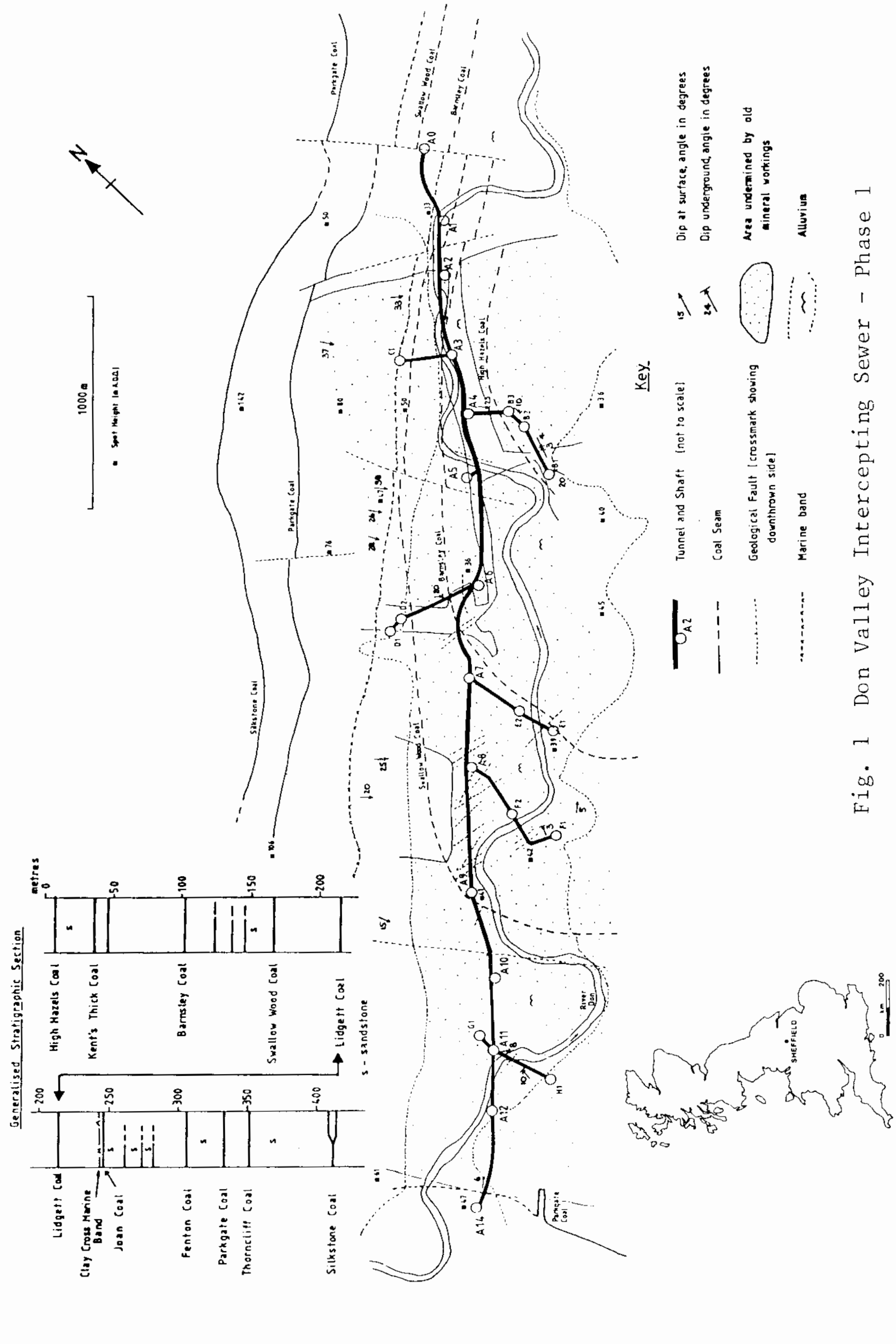


Fig. 1 Don Valley Intercepting Sewer - Phase 1

The Hydrological Conditions

The overall geological structure and the nature of the strata had a significant bearing on the hydrological conditions within the area. In general, due to a relatively high water table, most of the excavations were carried out within the saturated zone such that in most formations groundwater drained into the works by intergranular or fissure flow. Assessments of likely ingress values based on prior *in-situ* permeability determinations indicated that inflows would not exceed values such that extensive ground treatment, artificial groundwater lowering or other control measures would be required.

Observations of groundwater in the Don Valley indicate that in general, two entry levels exist in the area. The upper one stands in the drift deposits and the lower one occurs at a variable level in the underlying rock, beneath the weathered, often clayey zone below rockhead. Locally the standing level of both entries is the same indicating a similar pressure head and probable connection. Occasionally, depressed water levels standing well below the drift deposits were observed indicating downward drainage, possibly through mine drainage systems.

In the valley much of the immediate ground surface comprises deposits of permeable, granular made ground underlain by deposits of unconsolidated alluvial sand and gravel with some horizons of clay and clayey silty. The sand and gravel beds displayed an open, well sorted texture, high porosity and, with permeability coefficients ranging between 1×10^{-5} and 5×10^{-4}m/s, these beds acted as aquifers with a high ground water storage capacity. Recharge occurs generally by infiltration through made ground and from the river. The clayey and silty horizons displayed relatively low permeability and acted as aquicludes and aquitards, occasionally producing confined or semi confined conditions within the drift formations.

In the rockmass, intergranular permeability, which characterised the permeable overburden deposits, was only observed in the coarser grained rock types and was insignificant compared with the fissure flow due to joint and bedding plane discontinuities. The mass permeability and porosity were dependent upon the number, openness, interconnection and degree of infilling of discontinuities and these were closely related to the lithology, bedding characteristics, weathering/alteration state and structural setting. Thus sandstone, siltstone, coal and fractured ground displayed higher mass permeability and water storage capacity than the mudrocks, in which, commonly, open discontinuities were blocked by degradation products. Generally, units of sandstone, siltstone and coal or zones of fractured ground acted as aquifers and the mudrocks or zones of weathered/altered ground formed aquicludes or aquitards. The alternations of aquifer and aquiclude produced only limited zones of unconfined conditions and aquifers were in general confined. The recharge of aquifers occurred directly at outcrop, by infiltration from the drift or by leakage through aquicludes and aquitards.

Although no artesian water pressures were encountered, the cyclical nature of the rock sequence, including both aquifers and aquitards, and the synclinal geological structure gave rise to the possibility that they could occur. Some of the major sandstone formations outcrop on relatively high ground to the NW and SE of the area (see Fig. 1). Direct recharge at this level did produce sub-artesian peizometric water levels in some formations and it also contributed to the variable pressure head present throughout much of the sequence.

Shaft E2: Confined Aquifer

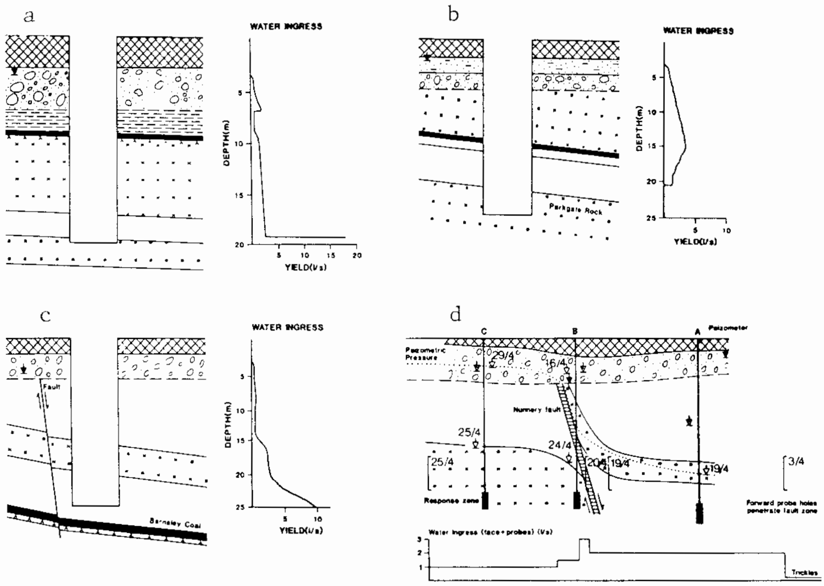
Water yield from a confined aquifer may be illustrated by consideration of the conditions encountered during the construction of Shaft E2. As shown in Fig. 2a, for much of the excavation the sequence consisted of relatively impermeable mudrocks with a mass permeability ranging between 2.7×10^{-6} and 1.5×10^{-5} m/s. Water yields were low during sinking through the penetratively weathered clayey mudstone below rockhead and the underlying unweathered silty mudstone. Towards the bottom of the shaft, an open jointed siltstone unit was penetrated in blast holes drilled into the mudstone forming the base of the shaft and water yield increased suddenly to in excess of 18 l/s.

Due to the presence of the mudstone aquiclude drainage from the siltstone during shaft sinking had had a minimal effect on the peizometric head in that formation. Additionally, although some reduction in flow with time was noted, in contrast to the rapid drawdown which generally occurs in confined aquifers, a steady state flow of 4.5 l/s was maintained probably by recharge of the siltstone at outcrop from the River Don and the water bearing drift deposits.

Shaft A11: Perched Watertable

Fig. 2b illustrates the situation at Shaft A11 in which a perched watertable was encountered. Water ingress occurred in the alluvial deposits and increased gradually to reach a maximum of 3 l/s in permeable, open jointed siltstone at a depth of about 15 m. As sinking progressed the ingress dropped until at a depth of 21 m any water entering the shaft drained away through the shot firing holes so that between 21 m and 25 m the excavation was dry. Although the siltstone at the base of the excavation was permeable and had open joints with iron stained surfaces due to water circulation, the rock was in an unsaturated condition due to a mine drainage system operating in the area.

Even though the formation subcrops beneath the River Don, the overlying impermeable bed inhibited recharge. The unsaturated condition of the Parkgate Rock continued through the entire thickness of this formation, giving dry tunnelling conditions from shaft A11 to between A12 and 14.



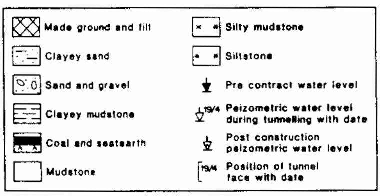


Fig. 2 Geological conditions and water ingress values

Shaft A6: Recharge from Flooded Old Workings

During the construction of Shaft A6, the gradual increase in water ingress for depths between 3.5 and 21 m shown in Fig. 2c conformed well with expectations for the closely jointed mudrock and siltstone formations present. However, below 21 m, water yield unexpectedly increased and high seepage pressures were observed in the mudrock unit. The underlying coal seam had been proved to be intact in the vicinity of the shaft but was known to have been worked elsewhere in the area (Fig. 1). In the course of driving tunnel A6-D2 it was found that the increased water pressure and yield were related to a fault situated about 20 m from A6. This comprised a breccia which formed a zone of enhanced permeability that transmitted groundwater from mine workings about 50 m away.

Due to the presence of a closely spaced cleat, coal seams are relatively permeable strata so that high water pressures were present beneath the mudstone forming the base of the shaft. The increased ingress can be attributed to the effects of stress relief which allowed the opening up of discontinuities in this formation.

Tunnel A9-A10: Hydraulic Barrier

The geological situation, water levels and peizometric pressures for the tunnel in the vicinity of the Nunnery Fault are given in Fig. 2d. As already mentioned, this fault has a throw of about 40 m and an increase in rockmass discontinuities was recorded as it was approached. Drawdown of the pre-contract water pressures occurred in piezometer A as the tunnel approached, although B and C were unaffected until horizontal probe holes drilled from the face had penetrated the faulted zone. During tunnelling the fault was found to include a 1.4 m thick zone of very weak and weak mudstone together with clay and lithorelicts and hence it was acting as a hydraulic barrier.

The water ingress quantities reflect the changes in peizometric pressure. When on 3/4 the probe holes penetrated the fault zone, the ingress increased to 2 l/s. Then until the tunnel face itself penetrated the fault zone on 20/4 and the total flow increased to 3 l/s, the face remained substantially dry with a 2 l/s flow from the probe holes. Once the fault zone had been tunnelled through the water levels in peizometers B and C fell and the total ingress value dropped to about 1 l/s. Water levels measured one year after construction show recovery, although at A this was still incomplete, perhaps because unlike the formation in which B and C were installed, due to the effects of the fault, the relevant rocks subcrop at a considerable distance from this location.

CONCLUSIONS

Reference to experience gained during the site investigation and construction of the Don Valley Intercepting Sewer illustrates the importance of considering the overall hydrological environment in which excavation takes place. However, of equal importance is the consideration of the local geological features which influence water ingress in particular parts of a job. In addition such features need to be taken into account when interpreting measurements of peizometric pressure and the results of laboratory or *in-situ* tests to determine the hydrological properties of the ground.

The overall hydrology is controlled by the interlayered nature of the strata, the structure and the topography of the area It would appear that tectonic movements and mining subsidence have provided sufficient inter-formational connections for full artesian conditions not to occur. In fact, groundwater pumping has given rise to perched water tables where downward water percolation is inhibited by less permeable rocks.

The sequence of Coal Measures rocks is overlain in the valley by open textured, permeable and water bearing drift deposits. Thus recharge to the permeable members within the bedrock may occur where these subcrop in the valley although, probably due to the clogging of discontinuities, not all aquifers are as closely linked to water sources as this would imply. Flooded old coal workings have been shown to be an additional source of water which needs to be considered in determining the hydrology of the area.

Faults have been shown to act as either barriers against or conduits for the movement of groundwater. At the investigation stage it is difficult to determine their effect on the hydrology due to the low level of core recovery which usually occurs in fault affected ground. The enhanced permeability noted at the base of Shaft A6 and elsewhere can probably be attributed to the increased frequency of rockmass discontinuities.

Generally speaking water ingress values conformed with expected values. Penetration of the aquifer at the base of shaft E2 gave rise to flows which were consistent with the presence of open discontinuities with a pressure head equivalent to a standing water level in the drift deposits. It illustrates the point that in relatively impermeable rocks a single very permeable fracture can dominate the local hydrogeology.

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