

GRAUND WATER ASSESSMENTS FOR MINE DEVELOPMENT AND PRODUCTION

MADENLERDE HAZIRLIK VE ÜRETİM İÇİN YERALTI SUYUNUN ETÜDÜ

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ABSTRACT

There is a growing awareness of the need to carry out hydrogeological investigations during the initial planning for mine developments. This requirement varies from a basic risk assessment to a detailed analysis of likely water inflows during initial development and also production mining phases.

This paper describes the methods currently used to obtain hydrological data required for the assessment of water inflows to excavations and includes references to problems encountered in some recent mine developments.

ÖZET

Madenlerde hazırlık işlerinin planlanması sırasında hidrojeolojik araştırmaların gerekliliği yolundaki görüşler giderek yaygınlaşmaktadır. Bu araştırmaların kapsamı hazırlık ve Üretim aşamasında olası su baskını için ön risk hesabından detay risk analizine kadar değişmektedir.

Bu bildiri ocak su gelirinin etüdü için gerekli hidrolojik verilerin eldesine ilişkin günümüzde kullanılan yöntemler tanıtılmakta ve son yıllarda hazırlık işlerinde karşılaşılan sorunlara örnekler verilmektedir.

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1. INTRODUCTION

Water has always posed one of the major problems in the development and operation of underground mines. Unforecasted occurrences of inrushes have often led to costly recovery operations and, at worst, major disasters involving loss of life and even the abandonment of mines.

Mine water inflows have a variety of origins. Access shafts or surface drifts will often encounter substantially horizontal-lying aquifers before reaching the coal horizons. These aquifers may be relatively shallow water-table aquifers or deeper *confined* aquifers, and their nature may range from high intrinsic permeability alluvial deposits or sandstones, to intensely fractured and vuggy limestones. Underground tunnels, drivages and galleries may encounter major faults which can transmit groundwater through relatively impermeable zones from such aquifers into mine workings. Similarly the presence of faults and other discontinuities in the rock mass may present water problems for developments under bodies of water such as lakes, reservoirs, large rivers, and the sea, or to developments in close proximity to abandoned mines, unsealed or poorly sealed shafts and boreholes which are likely to be flooded.

In most respects the situations mentioned so far, all represent water inflow problems related to naturally occurring primary and secondary permeability in the ground. To these must be added the range of problems relating to 'artificially' induced permeability changes due to *mine* development and mineral extraction, particularly coal. Channels may be created through basically impermeable roof strata to connect with groundwater sources of the forms described previously.

As well as the cause, the form of water inflow is also of great significance. This may range from a steady percolation to a sudden inrush. Depending on the local characteristics of the ground and the nature and location of the source of flow, the inflow may decline rapidly or over a period of time, or may steadily increase. A fairly minor inflow may be an early indication of major groundwater problems ahead.

From the foregoing it is fairly obvious that the ability to predict likely water inflow rates is a very important aid to mine planning. Knowledge of potential water problems can have an important influence on investment decisions for new mines, as these problems affect not only capital and operating costs, but also the cash flow, and the level of risk associated with the investment. This knowledge must come through hydrogeological investigations of the groundwater regime over a wide area, and these should be included, ideally, within the exploratory drilling programme. In this way a complete hydrological "picture" can be built up and applied, along with geological and geotechnical information, at all stages of a mining project from the initial construction of a means of access to the mineral through to full mine production. Prior knowledge at this early stage gives the best oppor-

tunity of cost effective planning in the design and location of mine access, the incorporation of ground treatment methods to reduce or eliminate inflows during construction, the design of mining methods which minimise inflows during production, and the design of mine water handling systems. It is worth noting that current National Coal Board policy in the U.K. is one of exclusion of groundwater rather than pumping (Dunn, 1982).

The main objectives of this paper are to describe the form of hydrological testing that is found to be most appropriate for new mine developments, to discuss how the data is utilised, and how test methods are being developed and extended to cover the wider aspects of mine development and production. It should be mentioned that although the emphasis here will be on hydrological testing, it is the correlation of this data, together with that from other sources, such as core drilling, logging and testing, and geophysical logging, that is necessary for a full hydrogeological assessment of the groundwater problem.

2. REVIEW OF HYDROLOGICAL TEST METHODS

The most detailed hydrological investigations for a new underground mine development are usually conducted in connection with the design for the shaft or drift required to provide access to the mineral reserves. Previous exploratory drilling aimed primarily at proving the reserves, in most cases, only gives an indication of the likely geological setting for the more important aquifer zones. Assessments of future groundwater problems are at this stage often extrapolated from such qualitative data as drilling fluid losses, and from experiences, when available, of earlier mine, shaft or well developments in the vicinity.

For this reason the more sophisticated hydrological test methods currently employed at any stage of mining development and production, are those related to shaft sinking assessments. The background to this type of testing and the development of suitable test methods has been described in previous publications by one of the authors, e.g. Daw (1984). In most instances for cost and practical reasons testing is limited to a single borehole. In such circumstances the most satisfactory technique to determine the hydrological parameters for a deep aquifer is one in which the measurement is of the recovery of pressure following a period of controlled flow from the isolated aquifer zone. This is the basis of the drill stem test, developed within the oil industry, but used in recent years in many shaft sinking assessments.

The essence of the drill stem test is that all the equipment for the starting and stopping of a flow from the formation, and for recording the recovery of pressure is built into attachments to the drill string itself. This includes packers, pressure recorders, remotely operated valves, and auxiliary components for safety and convenience. A double, or straddle packer system will most commonly be used with a series of tests carried out at different horizons once the test borehole has been drilled to full depth.

With the packers expanded to seal off the test section, the test valve is opened to connect the test zone to the central empty drill pipe, and in a permeable formation groundwater will flow into and rise up the drill pipe. After a specific time the flow is stopped and the pressure is recorded as it "recovers" towards the undisturbed aquifer pressure. Test times are dictated by the rate at which the drill pipe fills up, which is determined by the permeability of the formation and the depth of the test zone.

The transmissivity, average permeability and undisturbed groundwater pressure of the aquifer are derived from the average flow rate and the recovery period pressure data. The method of analysis originates in the theory of pumping tests developed for the assessment of water resources, and subsequently adapted for the analysis of drill stem test data. These various procedures, their use and limitations, are discussed in some detail by Daw (1984), and the paper also includes further references for background information.

The basic drill stem test has a number of disadvantages, and to overcome these the Cementation Company has developed modified hydrological test arrangements for specific projects, which retain the basic pressure recovery principle of the drill stem test. The major difference is the incorporation of a submersible borehole pump to enable control of flow during the production periods and to eliminate the problems experienced in drill stem testing when very high flows are encountered. In addition, pneumatically inflatable packers are employed, together with electrical pressure transmitters and wireline connection to the surface recording equipment, which enables assessment of the downhole measurements in real time. The current version of the equipment is illustrated in Figure 1.

The downhole system comprises a pair of inflatable packers joined by a perforated straddle pipe and suspended below the submersible pump on a section of drill rods. The packers are inflated with air applied from a compressor at the surface via high pressure braided hose. The borehole pump itself is contained within a special pump chamber which is connected via a subsidiary non-return valve and length of drill rods to the surface. From the top of the rods an extension pipe containing an electromagnetic flowmeter directs the water flow to a graduated collecting tank. The main "shut-off" valve is located just above the top packer assembly. The electrical pressure transmitters for monitoring the downhole pressure are located in the pump chamber, immediately above the top packer and within the test zone between the packers. They are connected via armoured cable to the associated surface electronics, comprising data logger and computer, for displaying, storing, and processing the downhole data. In addition to the downhole pressures the systems also records packer pressure, flow rate, and downhole temperature. Progress of the test can be followed throughout, and preliminary analysis of the results carried out rapidly at the borehole site.

Recent development of the commercial drill stem test equipment, operated by oil industry service companies, also includes the use of inflatable packers and down-

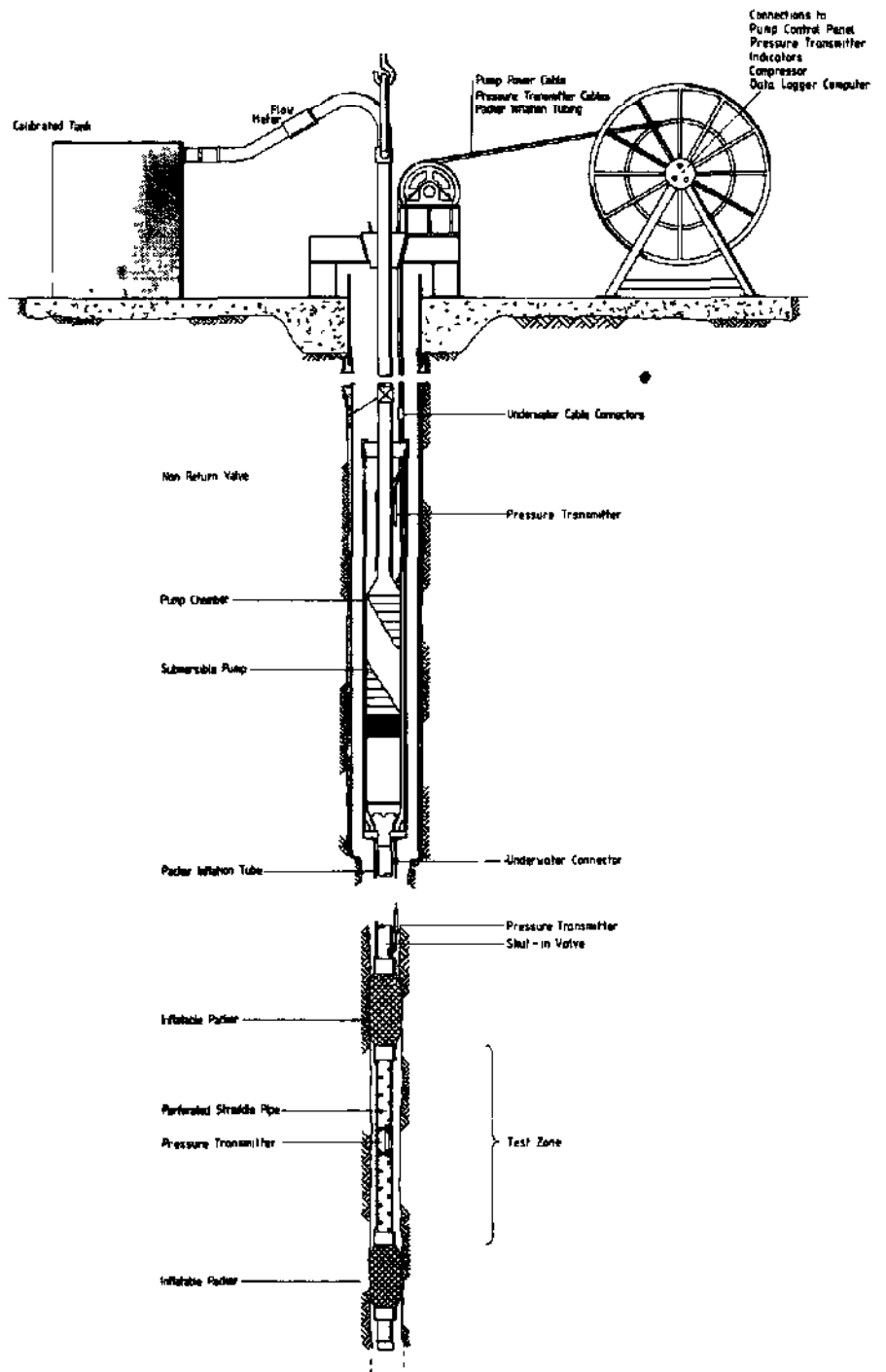


Figure 1. Borehole hydrological test equipment

hole electric pressure recording with surface based computer-processing. However, due to the very high costs this system has not, as yet, gained widespread use in the mining industry. In the United Kingdom the drill stem test was gradually introduced in the National Coal Board's shaft investigation programme during the various phases of the Selby project in the late 1970's. At that stage the conventional oil-industry test procedure was used but, subsequently, the various advances mentioned previously were introduced in co-operative development programmes between the N.C.B. and the drill stem test service companies. Such techniques were employed during detailed hydrological investigations for the most recent N.C.B. projects in the South Midlands area, and a viewpoint on current N.C.B. practice is given by Jeffery(1983).

3. ANALYSIS OF DATA FOR INFLOW ESTIMATES

The main purpose of the hydrological tests, described in the previous section, is to locate major aquifer zones which will have an influence on mine construction, and to obtain a quantitative measurement of their transmissivity, average permeability, and groundwater pressure. When correlated with the drilling and geophysical borehole logs, and the core examination, logging and laboratory test results, it is possible to deduce the nature and distribution of the water conducting fissures, faults, or pore channels within the aquifers. This information allows one to design the most appropriate method of water exclusion for the proposed excavation.

The specific hydrological data enables estimates to be made of the potential inflows to the excavation, prior to any lining or ground treatment, under the known groundwater pressure and within the required time-scale. For such estimates a mathematical model of the aquifer is required, and it is the definition of the chosen model that determines the reliability of the subsequently estimated inflows. The major factors, along with the measured aquifer properties are the nature, extent and boundary conditions of the aquifer, and the geometry of the proposed excavation.

The two equations usually adopted to govern groundwater flow are Darcy's Law and a mass conservation equation. Details of the mathematics are to be found in most text books on hydrology or flow in porous media. Various methods of analysis, representing different solutions of the basic equations, have been developed to cover the many aquifer conditions. For example, aquifers may be unconfined, confined or semi-confined; flow may be regarded as steady-state or non-steady state; aquifers may be isotropic, layered, horizontal, wedge-shaped or sloping.

In most respects the case of a vertical shaft is relatively straightforward, as the geometry is symmetrical. The shaft can be regarded as a large well and standard well flow models adapted in order to estimate inflows. Probably the most commonly applied solution is that of radial flow to a shaft fully penetrating an extensive, confined, horizontal, and isotropic, aquifer, as indicated in Figure 2.

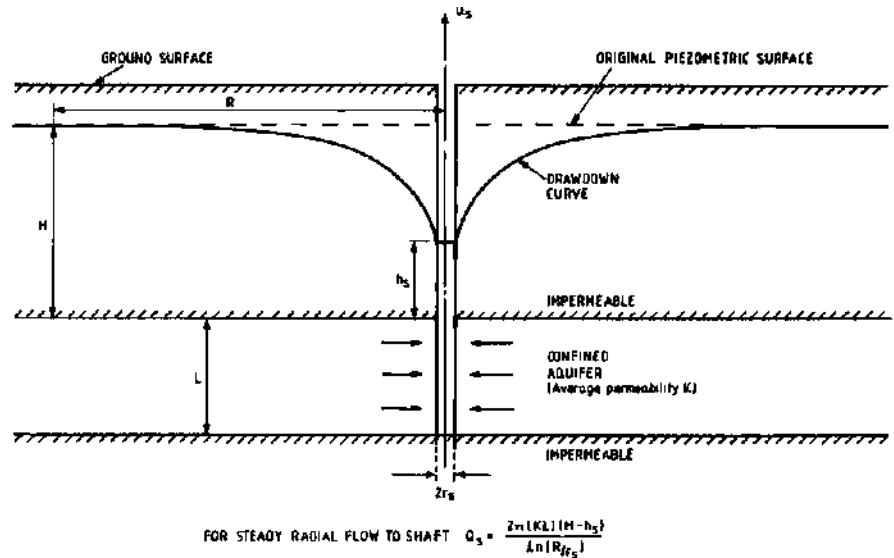


Figure 2. Model for steady flow to shaft from confined aquifer.

The values for transmissivity T , ($= KL$) and aquifer pressure H are obtained from the hydrological testing. A value for R is usually estimated from an approximation of the form $R = (Kt)^{1/2}$, where t is time. Since R appears in the equation in logarithmic form its value is not too critical on the accuracy of Q_s .

Whilst this relatively simple calculation is adequate in many instances, more sophisticated approaches are available using numerical and analogue techniques which allow more complex situations to be modelled. For example, a thick confined aquifer may be segregated into "layers" of different permeability, (as deduced from "short-span" hydrological tests), which allows more refined and localised estimates for shaft inflow. Such an example is described by Lloyd, Rushton, and Jones (1983), who employed an electrical resistance network analogue.

In the case of tunnels or drifts the geometry is more complex than for a shaft. Under certain circumstances a simple approach can be employed to model small sections of the tunnel by approximation to the cylindrical well geometry, and then by using the same calculations as for the shaft.

An extension of the two dimensional and radial model approach to estimate inflows to a drift through multi-layered permeability ground is described by Edwards (1985). Probably a more satisfactory approach again comes from the use of three dimensional electrical analogue models, and Wills has produced general solutions for the case of both horizontal tunnel, (1977) and inclined tunnel (1981). The paper by Lloyd et al (1983) contains an illustration of the application of their resistance network analogue to a particular surface drift in the U.K.

Inflow to a shaft, or to a short section of tunnel or drift represents a fairly localised situation, whereas a larger scale approach is required when considering the overall inflow to the underground mine. However, as a first order approximation to the problem resort may be made, once again, to an analytical solution based on well theory. The simplest approach is to find the smallest circle which can completely enclose the proposed mine area and to imagine a well drilled in the centre. The well is assumed to fully penetrate a thick aquifer which contains the mining horizon. The rate of water inflow to the mine is calculated approximately as the rate at which the well has to be pumped to lower the piezometric surface of the aquifer below the circle enclosing the mine. This "first attempt" approach to the problem is obviously subject to a number of limitations and these, together with several more advanced analytical solutions, are discussed by Singh and Atkins (1985).

The use of numerical techniques in conjunction with high speed digital computers, permits the incorporation of more realistic geometries, boundary conditions and ground and flow properties into the groundwater model. Three such numerical models, which were developed for specific applications, are described by Fawcett, Hibberd and Singh (1984) in a paper which gives an overall view of the field of mathematical modelling as applied to water inflows to underground mines. In practice the main limitation with the numerical models is the large input of data required and the lack of real data that is generally available.

Whilst the various models and solutions described can be employed for order of magnitude estimates at the pre-development phase of investigation, it is obvious that in practice the resolution of mine inflow predictions is complex in that the vertical conductivity of a multi-layered strata sequence over a large areal extent has to be assessed along with predicted changes in permeability due to subsidence or caving as a result of future mineral extraction. This topic and, in particular, the specific application to British longwall coal mining techniques is the subject of an extensive study at Nottingham University, various aspects of which are described by Whittaker, and Fitzpatrick (1985) and Singh, Hibberd and Fawcett (1985). The implications of such inflow studies are discussed more fully in section 4 of this paper.

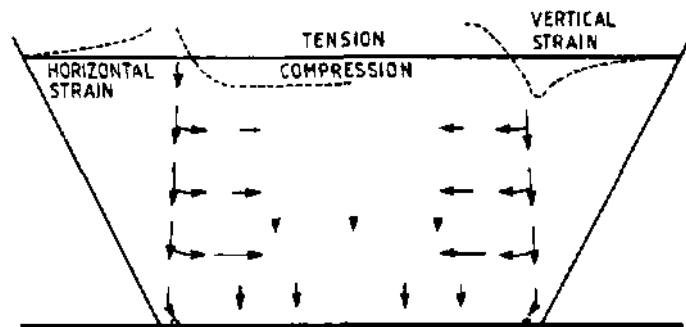


Figure 3. Water migration above a longwall panel (after Garrity, 1980).

The main point to bear in mind when making water inflow estimates for any underground excavation is that, whatever the limitations in the mathematical model that is used, the solution can be no more accurate than justified by the quality of the data defining the aquifer properties. Often this is insufficient to warrant the use of highly sophisticated modelling techniques. What is required is a greater appreciation of the importance of high quality hydrological testing introduced at the initial stages of a mine development project. Such testing needs to span a much wider field than just the immediate vicinity of a proposed shaft, and further consideration of these points is given in the subsequent sections.

4. WATER INFLOW PROBLEMS DURING PRODUCTION

During the production phase of underground mine development, a strata zone of artificially modified permeability is created around the excavation. The dimensions of this zone are dependent on several factors including the seam thickness, the length of the working face, its location relative to previous workings and rate of advance. The overlying beds in the modified permeability zone exhibit broken, fractured rock behaviour, and sometimes react as separated beams. If this zone intersects or connects to an aquifer, or any surface water body, water will flow into the working areas. Figure 3 illustrates the expected pattern of water migration above a longwall face with respect to ground strain at the surface.

The method for working under water bodies and aquifers is regulated by codes of practice, in order to minimise the risk of inundation and water inflow into the workings. The various codes of practice adopted by several countries were reviewed by Allonby, Biçer, and Tomlin (1985). These guidelines have evolved generally from local practical experience and strata movement investigations. However, despite their application production in mines continues to be interrupted by un predicted water inrushes, and it is obvious that the codes of practice lack the necessary consideration of detailed hydrogeological information.

Even the most modern mine developments have suffered such experiences. Massey (1984) reports that "on Saturday, July 23rd, the young pit (Wistow in the new Selby complex) was the subject of a disaster when water from the Permian strata broke through at the coalface and very severe-weight - affected the middle third of the coalface and damaged many of the chock legs". Observations have shown that the water inflow in this instance was associated with weighting of the roof measures, due to groundwater transmitted through the Permian strata from the Lower Magnesian Limestone aquifer some 80 m above the Barnsley coal seam.

In New South Wales, Australia many mine workings are located under or adjacent to large dams and reservoirs. The New South Wales Dams Committee was established in 1979 as a statutory authority responsible for ensuring the safety of all significant dams and making recommendations on proposals for coal mining operations in the vicinity of such dams and reservoirs. However, despite the van<ms criteria specified

and subsequently adhered to, pillar extraction adjacent to the sill at the Wongawilli mine resulted in a water inflow to the workings of unprecedented quantity and duration. Whilst the most recent reports of investigations into the source of the water (Wilson 1985), indicate that it was probably not from the nearby Avon reservoir, the incident again serves to demonstrate the unpredictability of such inflows.

These are recent, severe and well documented examples of many similar incidents of unexpected inflows of water into mines. They illustrate that hydrogeological investigations on a wide scale are crucial, in order to assess the risks associated with mineral extraction under aquifers or surface bodies of water. Before deciding on the type of hydrogeological investigation, it is essential to study the geological and structural features of the location, and anticipated strata movements resulting from the preferred method of mineral extraction. The results of the investigation may show that the preferred method of extraction may require modification in the interests of safety. It is worth remembering that even relatively minor inflows of water may have considerable affect on the stability of the excavations, or the efficiency of equipment operating within the excavations.

In the United Kingdom, permeability changes induced by mining were investigated in the late 1960's, notably by Soul and Orchard, following water problems in several collieries, mainly in the South East Durham coalfield. Saul (1970) reported examples of "hydraulic pressure zones" at Horden and Blackwall collieries. He proposed a series of borehole drilling programmes to tap the water from the overlying beds and, hence reduce the pressure. Investigations by Orchard in the South Derbyshire and Leicestershire coalfield, concluded that a zone of increased permeability could extend to a height of 60m above a longwall face. His work was limited to subsidence investigations only, and did not consider the hydrological aspects.

The first reported hydrological tests to gain information about increased permeability were carried out in Australia. In 1976, a public inquiry was held in Sydney to investigate whether mining of coal should be permitted under the stored waters in the Southern Coalfield. Williamson (1978) reported that several vertical boreholes were drilled over the worked areas, and pumping and Lugeon tests were carried out. Although test results gave information about the increased permeability, they did not allow comparison with conditions over unworked areas. Subsequently, a second hydrological test programme was undertaken and the results confirmed that permeabilities of the worked area were consistently higher than those of the unworked area.

A research group at Nottingham University conducted a series of field tests in order to monitor the in situ permeability changes of British coal measures strata. Neate, and Aston, developed novel designs for multipoint test apparatus which succeeded in obtaining data on permeability changes around longwall faces.

Respite these instances of field studies to measure increased permeability in recent years, the results obtained are of limited general application.

S. AREAS FOR DEVELOPMENT

It is evident from the previous discussions that hydrological conditions at the mining horizons have not, in general, been investigated comprehensively in the past, and that there is a real need for more integrated exploratory borehole programmes involving hydrological assessments for new mine developments. The additional costs involved at this stage are negligible compared to the large losses that can occur if the presence of groundwater problems is not identified. Hydrological testing in exploratory boreholes needs to be backed up by further testing and continuous monitoring from underground, and in some instances from surface, once mine development has commenced.

Borehole tests of the type described in Section 2, for shaft assessments, are equally applicable to these widescale hydrological studies, although more conventional long-term pumping tests with observation wells will also be required. It is desirable to observe the changing hydrological conditions over long periods in order to assess seasonal effects, therefore a multihole programme of piezometer installations should be considered.

There is some evidence that the need for these wider hydrological studies has been recognised. In the U.K., the National Coal Board, probably in the light of the Wistow incident, have implemented a detailed hydrological borehole programme over the area of the new Asfordby mine, prior to the sinking of the access shafts.

Hydrological tests relating to the altered permeability conditions over mining developments are not widely reported. In the study for mining under major storage reservoirs in New South Wales, Australia, (see Section 4) both pumping tests and pressure injection tests (Lugeon) were used in both vertical and inclined boreholes, to measure permeability. The research group at Nottingham University, U.K., has reported detailed investigations of permeability changes within British Coal Measures strata, using in situ measurement techniques, (Aston & Singh (1983)). Such reports are few and far between, and most observations are purely of changes in level of inflow.

Several test techniques employed for somewhat different purposes may find useful applications here. Black, Pollard, and Daw (1982) described a pressure recovery test method for use from exploratory boreholes drilled ahead of an advancing shaft sump (Figure 4). This test was employed successfully during shaft sinking at the Sclby mine to check the hydrological conditions directly ahead of the sump, and to allow modifications to the primary grouting design as necessary. Such a test may offer wider scope to underground hydrological investigations during mining operations.

Similarly it is envisaged that the integral "packer-flowmeter" test arrangement described by Lushnikova (1985) for high resolution studies of fissure sizes and spacings, etc. may have wider potential applications.

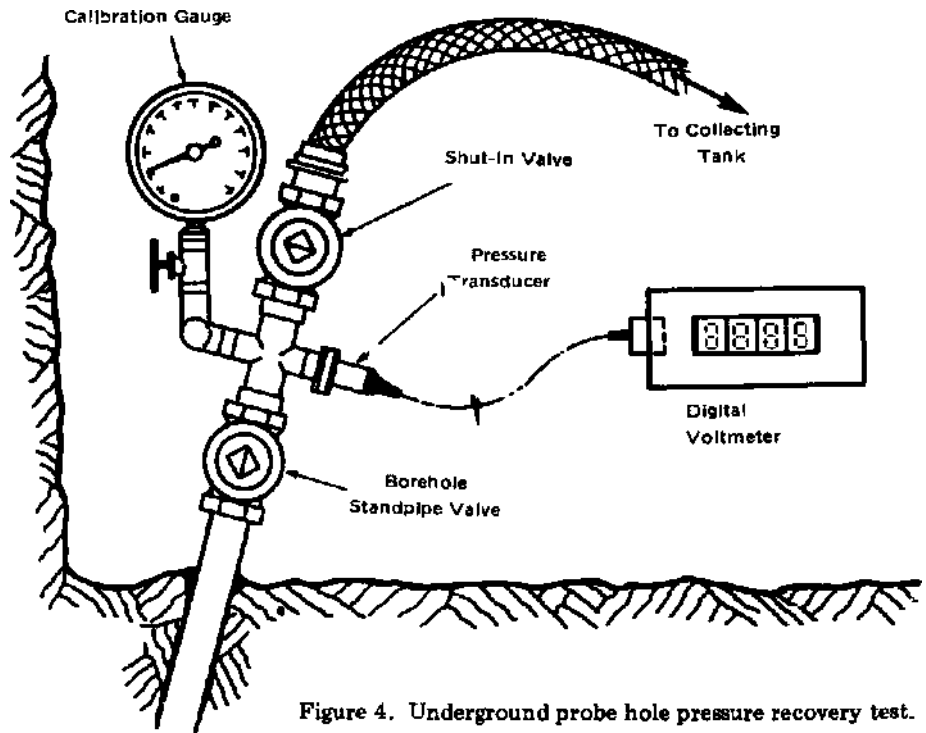


Figure 4. Underground probe hole pressure recovery test.

A more indirect approach might come from geophysical tests such as the seismic probe transmission techniques described by Spathis, Blair and Grant (1985). Whilst these presently can assess changes in the rock mass condition induced by mining it may prove possible to link this with alteration or creation of fracturing, and, hence, with permeability.

The purpose of this paper is to highlight the role that hydrology plays in the assessment of mine developments and the general need for more extensive hydrological studies. There should be three main aims for such studies:

- To obtain a greater knowledge of the hydrology of the entire area for a new mine by hydro logical testing during the early exploration and planning stages.
- To carry out more in-situ hydrological testing to gain a better understanding of the effects of underground mining on the hydrological environment.
- To continue laboratory modelling and theoretical model studies, incorporating more realistic data from such extended field testing.

The integration of these studies will assist a more cost effective and safer planning of new mine developments.

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