THREE-DIMENSIONAL WATER PRESSURE TESTING OF FRACTURED ROCK

P.I. Boodt, T. Maini and E.T. Brown

Department of Mineral Resources Engineering,
Imperial College of Science And Technology,
London SW7 2BP, UK.

ABSTRACT

The theory upon which conventional water pressure tests are based is critically examined and the differences between the theory and practical applications are identified. A series of three-dimensional water pressure tests are initiated using equipment design to minimise the errors in interpretation of field data. The tests are being carried out at a site in the U.K. to determine the principal permeabilities of a discontinuous rock mass. A successful interpretation of the tests relies on an accurate knowledge of the continuity, orientation, spacing and aperture of the discontinuities in addition to the initial hydrologic conditions. The Borehole Impression Packer Probe developed at Imperial College is used to characterise the fractures. A hydraulic probe is being developed to carry out pumping tests and the paper shows how the combined use of the two probes will lead to better estimates of permeability.

INTRODUCTION

The prediction of groundwater flows in a fractured rock mass and the assessment of their subsequent effect on mining operations depends on adequate geohydrologic characterisation of the rock mass.

The characteristics of a site in terms of its potential for the transport of fluids requires an understanding of the total geologic system as well as the determination of initial piezometric conditions and the permeability, effective porosity and storage coefficient of the rock mass. For these purposes, qualitative and quantitative descriptions are required of the rock mass through which flow may occur. It is important to define and delineate the major dimensions of the geologic units and to describe the fracture systems in terms of their spacings, orientations, apertures and continuities. Such studies lead to a qualitative understanding of whether or not the system behaves as a porous continuum or as a fractured discontinuum: it also helps to guide the detailed determination of the insitu hydraulic parameters. In general, flow is said to occur in a porous medium if the fluid transport occurs predominantly in the rock matrix or if, at the scale of the problem considered, the fractures are sufficiently numerous and uniformly distributed as to lead to the same effect.

The geometrical ability of the medium to conduct fluids is termed its permeability. Hydraulic conductivity refers specifically to water under certain conditions and relates the water velocity to the existing pressure gradients. The permeability depends on the degree of heterogeneity and anisotropy of the geologic medium and on the fluid properties. It is therefore imperative that fracture frequency, orientation, continuity and aperture be measured and correctly used in the interpretation of permeability tests in rock. This Paper describes the concepts and equipment being used by the authors in the current development of a national approach to the three-dimensional water pressure testing in fractured rock.

ROCK MASS PERMEABILITY

Fluid flow in geologic media is generated by hydraulic gradients. These are generally assumed to obey the simple relationship given by Darcy's law:

$$v_i = k_{ij} I_j \qquad \ldots(1)$$

where v_i is the flow velocity vector,

k_{ij} is the permeability tensor,

and I_j is the hydraulic gradient.

Several attempts have been made to provide a theoretical basis for this linear relationship (see for example, Bear, [1] but its justification is mainly empirical. The law certainly assumes laminar flow and, in order to be applicable, it must be used for volumes of rock which include a sufficiently large number of fractures and/or interconnected voids. A simple way of illustrating this effect is to consider the flow from a section of a borehole between packers into an ideal fracture system (Fig. 1). As the length of the test section is increased, the flow per unit length fluctuates and eventually stabilises beyond a certain length [2]. The implication is that, if the control volume is smaller than a critical value, a continuum approach will not hold and due account must be taken of the individual fractures. Two different concepts of groundwater flow then arise: the continuum and the discrete models.

In the discrete approach, the flow is considered to occur in a series of interconnected channels between parallel plates. Under certain conditions, the flow between two parallel plates has been shown to approximate reasonably well that occurring in individual fractures in rock (Louis [3]). However, in many cases flow will occur only partially in fractures and will follow a tortuous route [2, 4].

The permeability of an equivalent porous medium can be related to the aperture and spacing of a parallel set of regularly spaced fractures by the equation [3].

$$k = \frac{g e^3}{12 \nu \Delta} \qquad \ldots(2)$$

where k is the permeability of porous medium in any direction parallel to the fractures,
g is the acceleration due to gravity,
e is the fracture aperture,
ν is the kinematic viscosity of water at ambient temperature and pressure,
and Δ is the fracture spacing.

In many problems in crystalline rock, groundwater flow is controlled primarily by a few fractures. For example, Maini and Hocking [5] showed that the flow in 100m of porous medium with a permeability 10^{-7}m/sec could be carried in a single fracture with an average aperture of 0.0002m. The difference in the velocity of a fluid particle in a fracture compared to that in an equivalent porous medium is also important. Particle velocities in porous and fractured media for the same flow are related by the equation:

$$V_f = \frac{V_p n \Delta}{e} \qquad \ldots(3)$$

where V_f is the velocity in the fracture,
V_p is the velocity in the equivalent porous medium,
and n is the effective porosity with respect to flow through the porous medium.

For example, for a porous medium of permeability 10^{-8}m/sec and an effective flow porosity of 0.15, the aperture of an equivalent single fissure is found as 2×10^{-5}m using the above equations. Hence, the flow velocity in the fissured medium is 9400 times greater than that in the equivalent porous medium if the effective fracture porosity is computed on 50% of the fissure aperture.

The discrete flow approach is theoretically very attractive for fracture-dominated flows because it most resembles the actual situation in the field. However, enormous practical difficulties are encountered in its application since it requires site-specific data on fracture spacing, orientation, aperture, continuity and filling material. At present such information is very difficult to obtain, particularly as regards the connectivity, persistence and apertures of fractures.

Theoretical and field studies are currently addressing this problem. The obvious approach is to identify representative volumes of the rock mass and perform numerous groundwater tests thus obtaining measured site-specific data on groundwater response. This approach is simple in that it avoids the measurement of fracture spacing, orientation, aperture, continuity and connectivity but it is time consuming and expensive. Another approach is to apply statistics/probability theory to structural geological data measured at rock exposures within the rock mass under consideration and to use the results to predict values for the unknown parameters. [6, 7, 8]. These values can then be used to calculate the theoretical values of the hydraulic characteristics of the rock mass. It is necessary to decide on the relative merits of the results obtained using the synthesised observation of geological structure as compared with the direct measurement approach.

Mathematical equivalences of porous and discrete flows are also being studied [9 - 11]. All of these studies are important for prediction calculations and for establishing the correct framework for field testing.

Borehole or shaft tests for hydraulic parameters measure the response of the groundwater system to a pressure perturbation caused by the injection or withdrawal of water. Apart from the knowledge of the geometry of the rock, the test must include measurements of the initial and induced pressures, as well as the flow rates. By use of suitable scaling laws and equations it is then possible to determine directional values of permeability. Effective porosity, being a geometrical property, is very difficult to measure; its measurement can be attempted by tracer tests but, in practice, calculations try to avoid its explicit appearance by using formulations which involve a response 'constant' (permeability) rather than the geometrical property.

WATER PRESSURE TESTING

The three-dimensional water pressure test considered by the authors to be most appropriate for jointed rock is similar to the widely used Lugeon test except that important factors relating to the structure of the medium are taken into account when planning the test. As shown in Fig. 2, the Lugeon test relies on an inflatable packer system. A horizon can be isolated by lowering a tube to the desired level and inflating the packer. Fluid is injected under pressure and the flow rate is noted after a steady state is reached. The pressure measured in an adjacent hole is then related to the continuum permeability by the formula [4].

$$Q = \frac{2\pi\, l\, K_s}{\log_e(r_1/r_2)} (P_o - P_1) \qquad \ldots(4)$$

Where Q is the flow rate
l is the test section length,
K_s is the continuum permeability,
r_o is the radius of the borehole,
r_1 is the distance between the two holes,
P_1 is the pressure at a distance r_1,
and P_o is the pressure at borehole.

If the borehole is perpendicular to a fracture system with a mean aperture of e and N fractures are included in the test section then [2]

$$Q = \frac{2\pi\, eN\, K_j}{\log_e(r_1/r_o)} (P_o - P_1) \qquad \ldots(5)$$

where K_j is the joint permeability or conductivity.

Louis and Maini [21] gave the details of testing and permeability evaluation for non-orthogonal joint sets. By carrying out a series of tests for different pressures, it is possible to obtain a P-Q curve: the mean K_s and K_j can then be calculated for a zone of influence represented by r_1.

The Lugeon test has been used extensively for determining rock mass permeabilities for the last fifty years. Its success depends very largely on the care with which the test is planned and executed. In carrying out the test, the following points should be carefully noted [2, 3]:

(i) The test section should be sufficiently long to account correctly for scale effects.

(ii) Excess fluid pressure should be as low as possible (certainly less than the overburden pressure) to avoid propping open the fractures.

(iii) If possible, all pressure and flow measurements should be taken downhole: this minimises errors in calculating pressure losses and leakage past packers.

(iv) The boreholes should ideally be orthogonal to the main fracture system. Should this be difficult, then a parallel test (source and sink in a single borehole) becomes essential.

The main limitation of this test is that, as the permeability decreases, the problems of measuring flow and the duration of test increase. This limits the applicability of the test to permeabilities greater than about 10^{-8} cm/sec.

It is equally possible to implement the philosophy of constant-pressure tests in openings other than boreholes, such as shafts, galleries or tunnels. The advantages arise from the larger diameter and test length of the cavity. The most common gallery-type of test is carried out by sealing several hundred metres of gallery and observing the leakage rates and piezometric conditions [14, 15]. Such large scale tests can lead to values of global permeability [15] and can provide indications of the important, confining effects of faults [4].

Often when Lugeon-type pressure tests are carried out, some of the above mentioned guidelines are ignored or simply cannot be adhered to (e.g. downhole pressure and flow measurement). This, together with the fact that piezometric monitoring is usually only performed during large scale aquifer pumping tests, often give very misleading values for the insitu hydraulic parameters.

The series of tests being carried out by the authors have attempted to overcome these problems. The essential feature of the approach being used is the concept of multiple packer testing [2 - 4] which can overcome many of the difficulties associated with the Lugeon test. The equipment developed for this purpose is based on an original idea proposed by Louis [3] for achieving radial flow from a section of borehole undergoing a pumping test.

In simplified form, the test equipment consists of three sections isolated by pneumatic packers (Fig. 3) through which water is pumped. In this case, the hemispherical flow that occurs at the ends of a normal single test sectioin (Fig. 2) will occur solely from the two sub-cavities on either side of the test section. Thus the flow from the test section, is measured separately and will be purely radial satisfying one of the assumptions made in the theory. [2, 4]. This concept was analysed by Sharp [4] and tested in a limited way in the field by Maini [2]. Sharp found that the minimum length of the sub-cavities for radial flow in the test section should be half the test section length when all sections were pressurised to the same level, but that this length could be reduced by 50% by increasing the pressure in the sub-cavities to 1.5 times the pressure in the test section.

As a consequence of this and the desire to be able to vary the length of the test section to investigate scale effects, the equipment was designed as quick assembly units. This enables the test section to be varied from 0.5m to, in this case, 16m in length. Merely by the manufacturing of extra components virtually any test configuration is possible with any length of isolating pneumatic packer. For most purposes a single pneumatic packer unit 1.5m long will suffice since 80% of the pressure is lost within a radial distance equal to 4 times the radius of the borehole [2].

To complement this equipment a similar system with a single monitoring section instead of the pumping section has been designed to be used in adjacent boreholes to monitor the effects of the pumping tests. If necessary the whole length of a borehole except for the section being monitored can be isolated with pneumatic packers thus preventing the discontinuity under test short circuiting to other discontinuities via the borehole.

Following Maini [2] all pressure measurements are made using electronic pressure transducers in the each of the sections. Flow measurements are made using electrical flow-meters and all data is stored on magnetic tape using a data acquisition system.

A central feature of the approach being used is that tests are carried out in multiple boreholes drilled perpendicular to each of the major discontinuity sets in the area being studied (Fig. 4). This permits the theory based on radial flow to be applied to each borehole and the hydraulic characteristics of each set of discontinuities to be studied independently. Thus, the permeability tensor of the rock mass which can be generally expected to be anisotropic, can be determined with greater accuracy than in the standard Lugeon test.

DISCONTINUITY ORIENTATION SPACING AND APERTURE MEASUREMENT

A wide number of techniques have been developed in the civil engineering site investigation and petroleum industries for the detection of discontinuities intersected by boreholes and their measurement [16, 17]. The borehole impression packer probe (B.I.P.P.) Developed by Hinds [17, 18] at Imperial College, London, and later adapted by others, provides a simple and cheap way of obtaining an accurate and permanent record of discontinuity geometry.

The construction of the B.I.P.P. is shown in Fig. 5. An inflatable rubber packer is mounted on a central support tube via plugs at each end.Two metal side plates are mounted either side of the pneumatic packer and arranged to freely move against the borehole wall upon inflation of the pneumatic packer. A resilient plastic foam is attached to the outer faces of these side plates, on which fresh impression film is mounted for each run into the borehole. At each end of the packer assembly there are skids which centralise the probe in the hole and prevent scuffing of the impression film. The top end mounting serves as a termination point for the wire line for retrieving the B.I.P.P. and the air line to the pneumatic packer. The lower mounting has an attachment for a clockwork self-locking fully gimballed compass.

When the packer is used in a horizontal borehole its orientation must be known and it must be pulled or pushed down the hole. This is achieved by mounting the packer on two tensioned guide wires which are attached to a pneumatic anchor at the bottom of the hole. The packer is then pulled down the borehole by means of another cable which is attached to the bottom mounting on the probe, passes through a pulley on the pneumatic anchored and back up to the 'surface'. By this method the orientation of B.I.P.P. is known from the orientation of the tensioned guide wires and it is simply pulled down to the required 'depth'.

Each pair of impressions record approximately 70% of the section of borehole under examination. 100% coverage may be obtained by rotating the pneumatic anchor and tensioned guide wires through 90^{o} and taking another pair of impressions at the same depth. The orientation is periodically checked by attaching a fully gimballed magnetic compass with a clockwork locking mechanism to the bottom of the probe.

Interpretation of the orientated impressions is facilitated by laying them out in a continuous overlapping sequence. The dip of a discontinuity is obtained from the relationship.

$$\tan \alpha = \frac{a}{d}$$

where α = dip with respect to the borehole,
a = amplitude of sinusoidal impression
and d = borehole diameter

By combining this dip with the dip of the borehole the actual dip of the discontinuity is obtained. The dip direction is found using a strip compass and the know position of north on the orientated impressions.

At present three methods are used to measure the apertures of the discontinuities. For large apertures (greater than 3mm) the film is placed on an overhead projector and the aperture measured with a transparent scale. For smaller apertures either a magnifying glass or a low powered microscope is used with a graticule. Laboratory tests by the authors and by Hinds [17] have shown that the impressed widths of discontinuities are in good agreement with the actual widths.

A more permanent record of the impressions is obtained by tracing the outlines of discontinuity impressions on to draughting paper. The tracings are shaded where the impressions show voids (Fig. 6). As a result of this method of reproduction the accuracy of fracture aperture data obtained on the impression film is largely lost and a certain amount of subjectivity of interpretation is necessarily introduced.

The impressions can also be reproduced photographically by using the impression film as a negative. This may be preferable for important sections within boreholes since it accurately reproduces the impression width but the increased cost is obviously prohibitive.

It is often more convenient to measure the spacings of the discontinuities on the core obtained from diamond drilled boreholes but this may give false values because breaks in the core and discontinuities are often indistinguishable. Since the B.I.P.P. takes impressions of the wall of the borehole it will only detect the pre-existing discontinuities. This also means that the B.I.P.P. can be used in percussion drilled boreholes although some detail will be lost because of the rougher wall surface.

FIELD WORK

A programme of work is currently underway to apply the concepts and equipment described above to the hydraulic characterisation of the granite rock mass at a site in the tin mining district of Cornwall, England. The test site is located near the margin of the Carnmenellis granite batholith [19, 20]. The principal rock type is a coarse grained (5mm) feldspar porphyritic, biotite-muscovite granite. The granite exhibits hydrothermal alteration which has resulted in partial to complete chloritisation of biotite and kaolinisation of feldspars. Granite porphyry dykes varying in thickness between 10mm and several metres are known from surface outcrops and exploratory boreholes.

Structural mapping in an adjacent quarry and in shallow workings has revealed two major sets of steeply dipping fractures striking 103° and 194°. They have spacings of the order of 1 metre. Some are lined with variable thicknesses of secondary minerals such as chalcedony and haematite and are bordered by zones of kaolinised or haematised granite. Sub-horizontal fractures have spacings of less than one metre immediately below the present land surface but the spacing increases with depth. Rare mineralised veins and most of the porphyry dykes strike at approximately 050°, parallel with the regional trend while fractures with moderate dips (45° - 70°) have variable strike directions but are less frequent. Like the steeply dipping fractures they may have closely matching walls or be more or less open, lined with soft secondary minerals and bordered by zones of altered granite.

Three 100mm dia. 30m long boreholes have been drilled orthogonal to the major discontinuity sets and each mapped using the borehole impression packer probe. Fig. 6 shows a section of the tracing of the impressions.

At the time of writing, the test equipment designed by the authors is under construction. The first use of the monitoring system will be to measure the existing piezometric profile along the lengths of each of the test boreholes. Each discontinuity identified using the B.I.P.P.

will then be subjected to a steady-state pressure test followed by a transient pressure test. The hydraulic conductivities calculated from the results of these tests will then be compared with the hydraulic conductivities determined from the discontinuity apertures measured from the impression packer. Once this is completed larger lengths of the borehole will be subjected to the same tests. The length of the test sections will be increased incrementally to include additional discontinuities Fig. 7 (a - d) in an attempt to find the test section length above which there is no increase in equivalent permeability for increased test section length. The results of all these tests will define the minimum volume of this rock mass which can be treated as a continuous medium and the permeabilities which can be applied when calculating groundwater flow volumes.

Further tests will be carried out to assess the effectiveness of the sub-cavities for linearizing the flow in the test section.

CONCLUSIONS

It has been shown how conventional water pressure tests may lead to erroneous results in fractured rock. In order to correctly assess the permeability of a rock mass, measurements have to be made with due care and regard to the rock mass characteristics and insitu hydraulic conditions. Rock mas characteristics, i.e. fracture spacing, continuity and aperture are shown to be adequately estimated by using the borehole impression packer. Hydraulic characteristics will be assessed with due regard to scale, anisotropy and homogeniety in three-dimensions using a probe that is currently being built at Imperial College. With the combined use of these two probes permeability of a discontinuous rock mass can be measured with some confidence.

REFERENCES

1. Bear, J. Dynamics of Fluids in Porous Media American Elsevier New York, /1972/.

2. Maini, Y.N.T. Insitu Hydraulic Parameters in Jointed Rock. Their Measurement and Interpretation. Ph.D. Thesis Imperial College London, /1971/.

3. Louis, C. A Study of Groundwater Flow in Jointed Rock and its Influence on the Stability of Rock Masses. Imperial College Rock Mechanics Research Report No. 10. London, /1969/.

4. Sharp, J.C. Fluid Flow through Fissured Media. Ph.D. Thesis Imperial College London, /1970/.

5. Maini, Y.N.T. and Hocking, G. An Examination of the Feasibility of Hydrologic Isolation of a High Level Repository in Crystalline Rock. Geol. Soc. Am. Abs. Annual Meeting. /1977/.

6. Hudson, J.A. and La Pointe, P. R. Printed Circuits for Studying Rock Mass Permeability Int. Jnl. Rock Mech. Min. Sci. Vol. 17, No. 5 pp 297 - 301/1980/.

7. Priest, S.D. and Hudson, J. A. Estimation of Discontinuity Spacing and Trace Lengths Using Scanline Surveys. Int. J. Rock Mech. Min. Sci., Vol. 18, No.3., pp 183 - 197/1981/.

8. Samaniego, J. A. A Statistical Model for Simulating Discontinuities in Two Dimensions.
MSc Thesis Imperial College London.

9. Witherspoon P.A. Personal Communication. /1981/.

10. Runchal, A.K. and Sagar, B. Permeability of Fractured Rock: Effect of Fracture Size and Data Uncertainties.
To be published. /1981/.

11. Woo, G. Unpublished Research on the Mathematical Represension fFractured Media, Principia Mechanica Ltd. /1981/.

12. Brace, W.F. Permeability of Crystalline and Argillaceous Rocks. Int. Jnl. Rock Mechs. Min. Sci. Vol. 17, No.5. pp 241 - 251 /1980/.

13. Ziegler T. Determination of Rock Mass Permeability U.S. Army Engineer Waterways Experiment Station Vicksburg, Misissippi, Technical Report No. S-76-2 /1976/.

14. Di Biagio, E. and Myrroll, F. Insitu Tests for Predicting the Air and Water Permeability of Rock Masses Adjacent to Underground Openings. Proc. Symp. Percolation

through Fissure Rock.
Stuttgart, Paper No. T1-B/1972/.

15. Pentz, D. Case Examples of Open Pit Mine Drainage. Proc. 1st Int. Mine Drainage Symp. Denver Colorado pp 324 - 341/1979/.

16. Barr, M.V. Downhole instrumentation - A Review for Tunnelling Ground Investigation. Tech. Note 90, Construction Industry Research and Information Association, London/1977/.

17. Hinds, D.V. A method of Taking an Impression of a Borehole Wall. Rock Mechanics Research Report No. 28. Imperial College, London/1974/.

18. Brown, E.T., Harper, T.R. and Hinds, D.V. Discontinuity Measurement using the Borehole Impression Probe. A Case Study Proc. 4th Congr. Int. Soc. Rock Mech., Montreux, Vol. 2., pp 57 - 62.

19. Hill, J.B. and MacAllister, D.A. The Geology of Falmouth and Truro and The Mining District of Camborne and Redruth. Memoirs of Geological Survey of UK /1906/

20. Ghosh, P.K. The Carnmenellis granite: Its Petrology, Metamorphism and Tectonics Quart. Jnl. Geol. Soc. London Vol. 90 pp 240 - 276/1934/.

21. Louis, C and Maini, Y.N.T. Determination of Insitu Hydraulic Parameters in Jointed Rock. Proc. 2nd Int. Cong. on Rock. Mechs. Belgrade Vol. 1. Theme 1 paper 32 /1970/.

LIST OF FIGURES

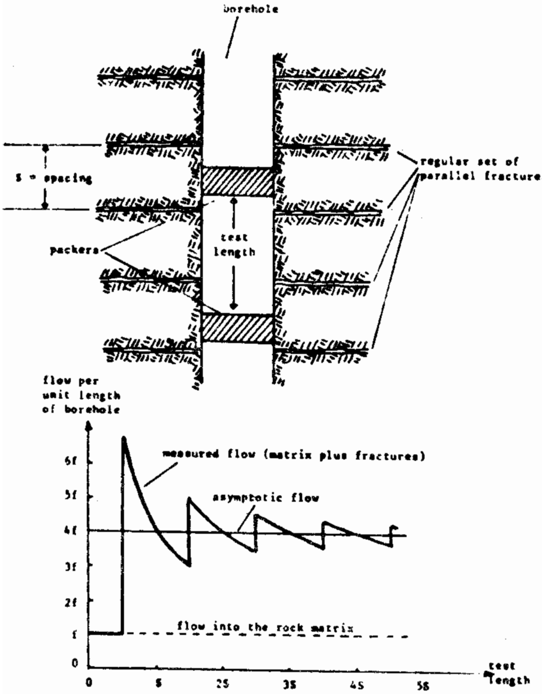

Fig. 1. Significance of Scale Of Measurements in Discrete Flow Systems (after Maini[1])

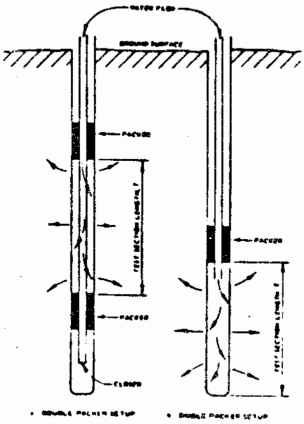

Fig. 2. Typical Water Pressure Test Setups (after Ziegler [12])

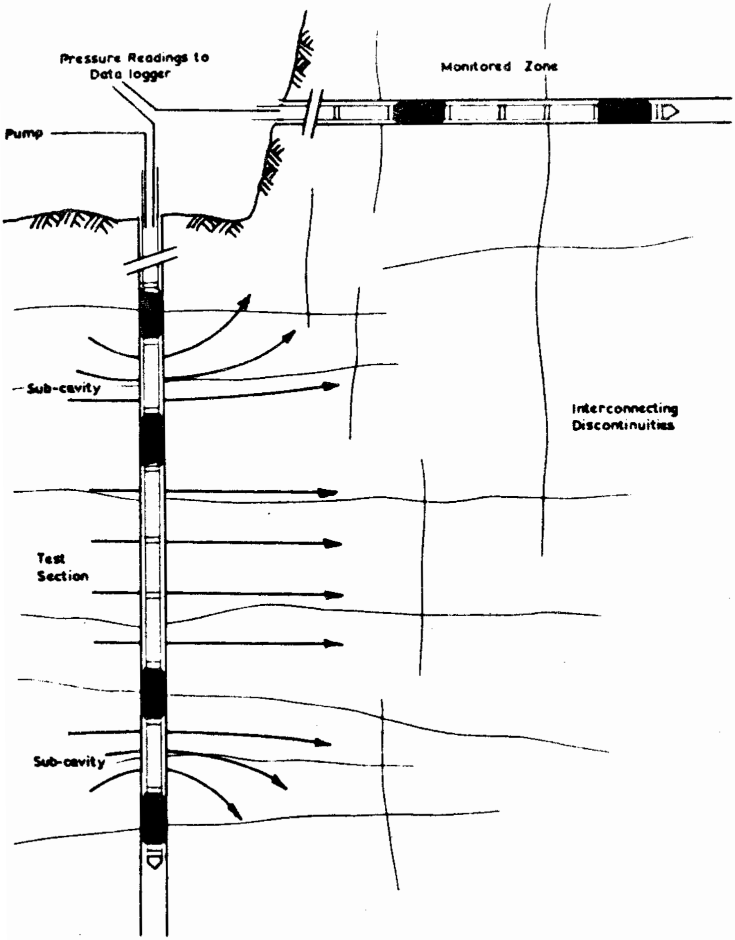

Fig.3 Pumping Test Equipment

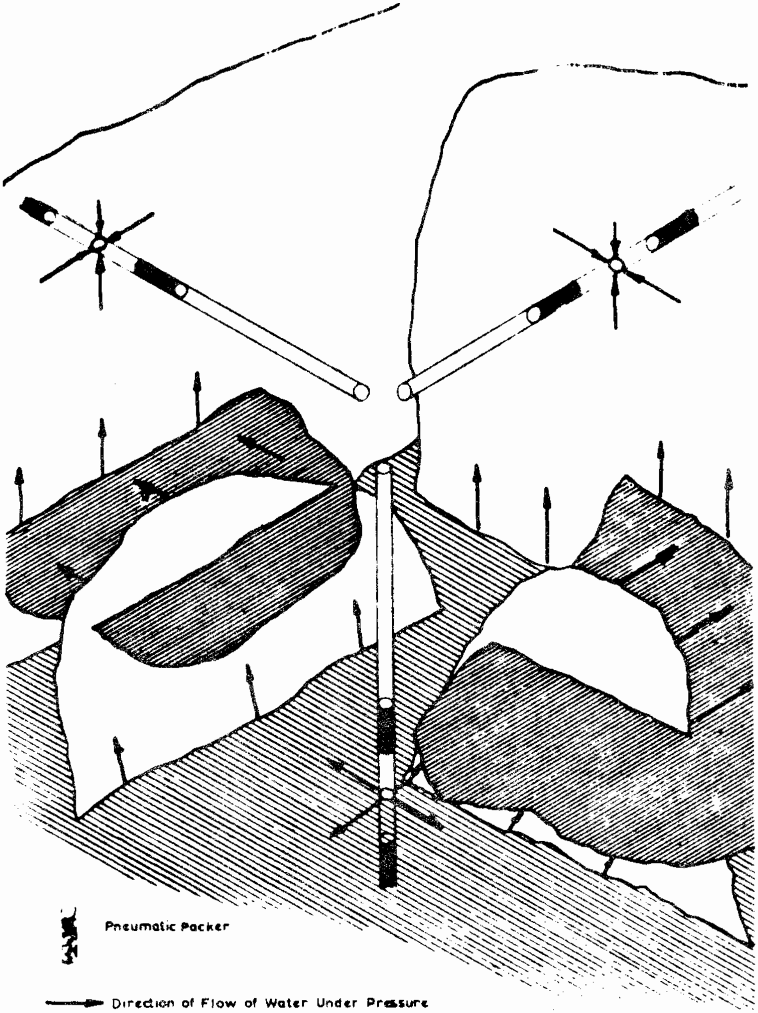

Fig 4 Test in Multiple Boreholes Orthogonal to the Major Discontinuity Sets

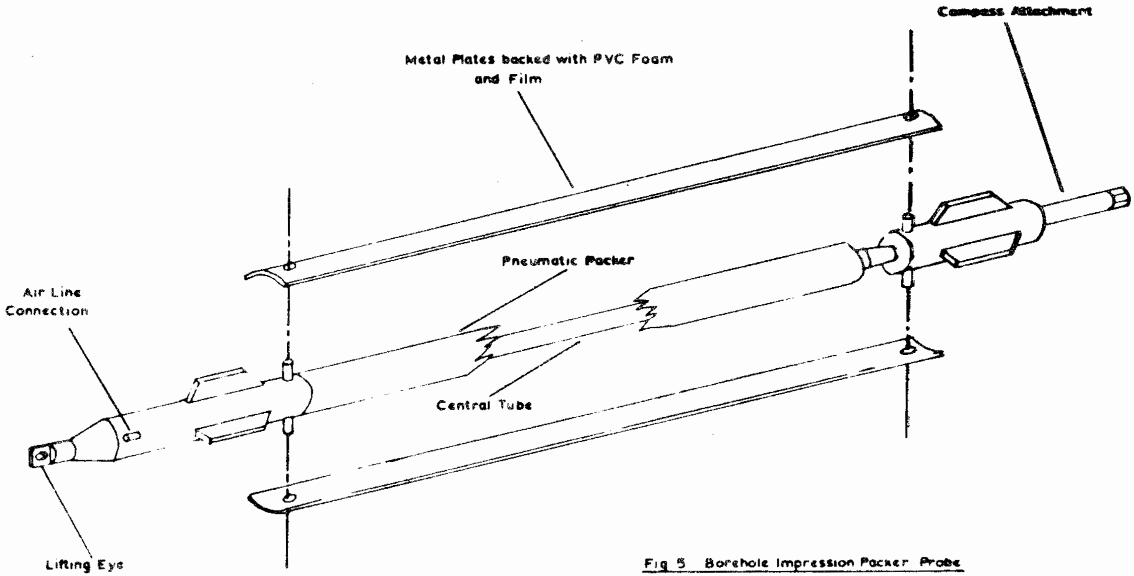

Fig 5 Borehole Impression Packer Probe

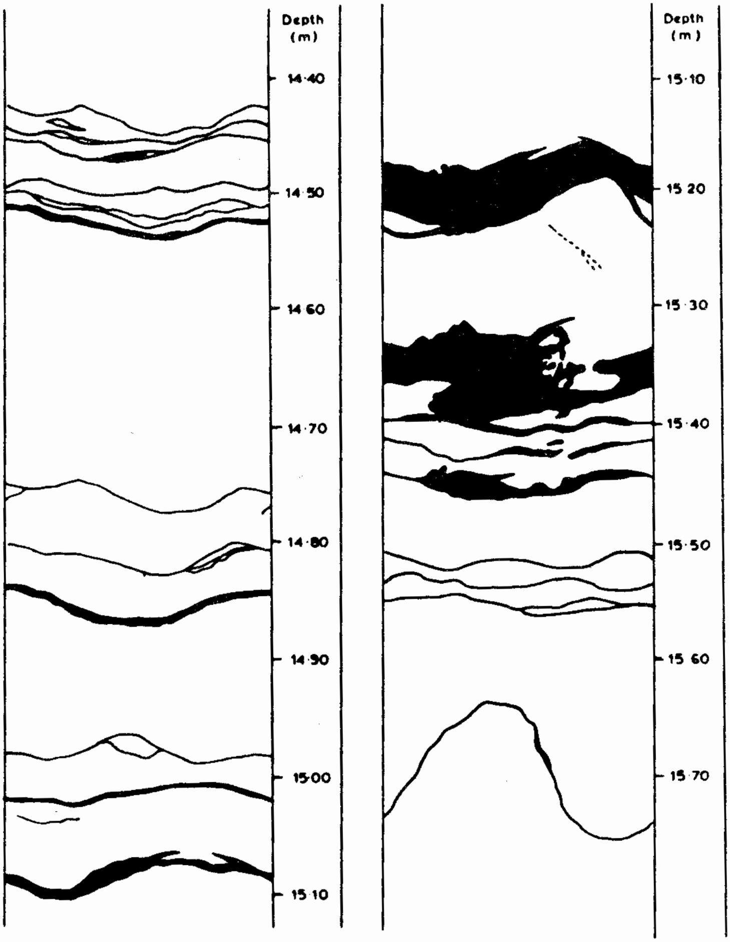

Fig 6 Tracing of impressions from a horizontal borehole

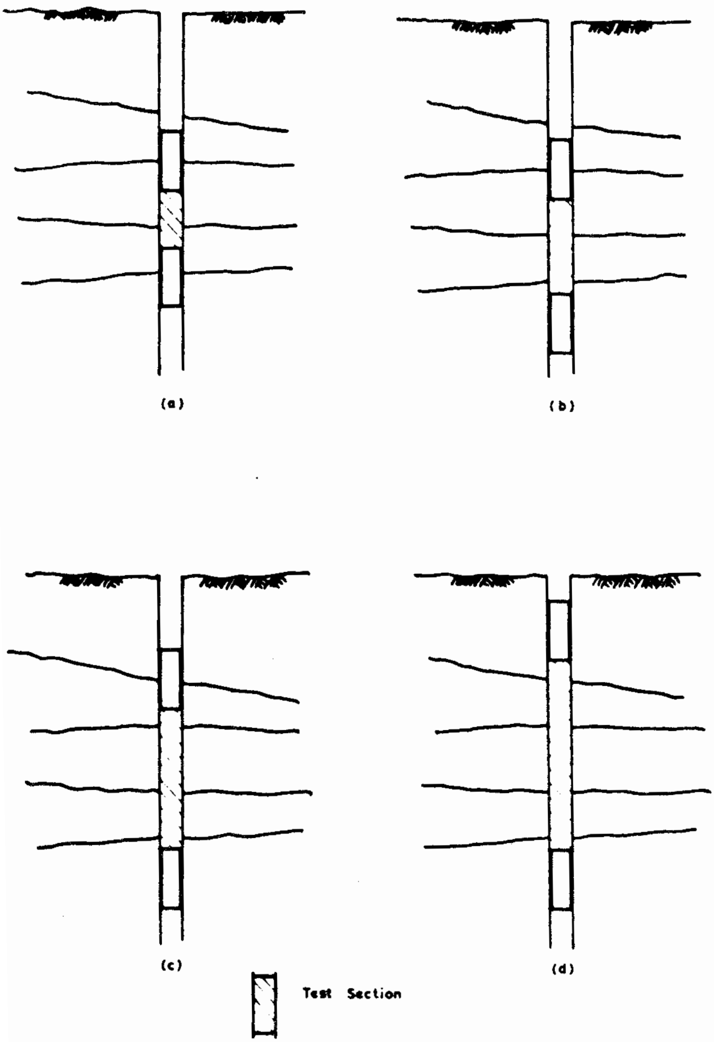

Fig.7 (a-d) Increasing Test Section