PROBLEMS OF THE DETERMINATION OF IN-SITU PERMEABILITY IN FISSURED ROCK

Dr. Ing. Dipl. Geol. Hans Joachim Schneider

Federal Institute for Geosciences and Natural Resources
D - 3000 Hannover 51 P.O. Box 51 01 53

ABSTRACT

The permeability of rock is often determined more by the joint fabric than by the porous material. The physical models for percolation through porous media can therefore in many cases not be transferred to fissured rock because the joints as main waterways do not permit a uniform and steady percolation through a specific rock body due to the irregular geometry of the joint fabric. This means that there are several problems left unsolved by the determination of rock permeability. When the model of fissure percolation is taken as a basis for determining of rock permeability, the difficulty is in the exact determination of the geometry of the joint fabric. The applicability of the fissure percolation model for determining the permeability of fissured rock is examined and discussed on the basis of multiple borehole tests using the LUGEON test procedure.

INTRODUCTION

The Lugeon pumping-in test has been in use in civil engineering for over 50 years and can already be counted amongst the classical tests in engineering geology. It is still widely used to assess the need for injection and also to measure its success. Recently, since the introduction of the computer for hydrological calculations, this method has been increasingly used for the determination of permeability parameters (1). The Lugeon value, since it has no definite physical meaning, cannot be utilized directly as a starting point for these calculations. The concept of this classical test, therefore, has to be somewhat modified before it can be utilized to determine the permeabity coefficient (a value with a definite physical meaning). In spite of the extensive research which has been carried out in the last two decades, the state of our knowledge in the field of in-situ permeability tests is hardly satisfactory when compared with the vast capabilities of the electronic computer. The reason lies chiefly in the complex nature of the percolation processes in rocks which are determined by the water pathway preferentially following the joints. An exact geometric analysis of the joint pattern of any site is associated with so many uncertainties that reproduceable mathematical solutions for any particular volume of rock are not always attainable. It is essential, therefore, to find out more about the factors controlling the permeability of rock by carrying out in-situ tests involving extensive series of measurements. The present paper describes the results of our investigations on rock permeability and discusses the problems of accurate determination of the permeability of jointed rock.

EXPERIMENTAL METHODS

The test set-up was based on the same principle as the Lugeon pumping-in test (2) (Fig. 1). A central borehole was drilled in which a 5 m-long injection section was isolated with a combination of two packers at the top and two at the bottom, each packer consisting of 1.5 m of rubber pipe. The injection fluid used was water or a tracer solution containing a few parts per thousand of salt. The flow rate of the injected water, as well as its temperature and the specific electrical resistivity of the tracer were all measured at the pump. The pressure in the injection section was monitored directly by a measuring gauge situated about 1 m from the end of the injection pipe. The pressure was also measured in the injection pipe above the packers, at the pipe bend and at the pump. In order to be able to determine the amount of water by-massing the packers, the water pressure was monitored in the two observation sections of the same borehole, i.e. between the first and second packers and between the third and fourth packers (Fig. 2). Any direct by-pass between the packers and the wall of the borehole can in all probability be ignored, since the packers consist of rubber tubing which is inflated to a pressure of 20 -40 bars. Thus, any by-pass is probably primarily determined by geological factors and takes place by way of the joints in the rock. The measuring element above the four packers was used not only for measuring the pressure in the injection pipe, but also for monitoring the free head of water in the borehole.

Observation boreholes were drilled around the injection hole. These were also divided up by means of packers into separate sections for the monitoring of pressure, temperature and extent of dispersion of the tracer. The injection pump consisted of an infinitely variable triple piston pump with a pumping capacity of 1.5 - 300 l/min at a pressure of 1.5 - 50 bars.

THE TEST FIELD

The tests were carried out in a sparsely-jointed, compact granite at Falkenberg in the Upper Palatinate, Bavaria (Fig. 3). The central operational injection borehole has a diameter of 146 mm and was cored throughout its whole length. Observation boreholes nos. 5 and 6 were sunk at a distance of 16 m from the central borehole diametrically opposite each other. Three other observation holes (nos. 2,3 and 4) were sited 50-60 m from the central borehole, approximately at the corners of an equilateral triangle. The arrangement of the injection section and observation sections in the various boreholes are shown diagrammatically in Fig. 4. The injection section was situated at a depth of 43 - 48 m. Two 2 m observation sections were arranged, one immediately above the injection section and one below it. Monitoring of the free head of water was carried out at a depth of 25 m. Borehole no. 2 contained 5 observation sections each 8 m long and equipped with a measuring element. Boreholes 3 and 4 contained three measuring elements each and boreholes 5 and 6 one each. In Fig. 4 the jointing, as recorded with a borehole camera, is represented diagrammatically on the right hand side of the borehole. It can be seen from the figure that the horizontal joints predominate over the vertical ones; however, only one horizontal joint occurs in the injection section.

RESULTS

Following conventional practice in pumping-in tests, a multistep test was carried out in which the pressure was increased stepwise at intervals of 10 minutes, and then decreased in the same manner. Other tests were carried out over periods of one or several hours at constant pressure. A certain period was left between the various tests so that the pressure decay in the rock could be monitored.

The tests were carried out as in the Lugeon test, either at constant pressure or at constant flow rate. In the multistep test, the pressure at the pump was increased at intervals of 10 minutes and then decreased in the same way. The flow rate was measured between the pump outlet and the pipe bend and showed a similar stepped linear variation as the pumping pressure through which the experiment was controlled (Fig. 5).

If this is compared with the behaviour of the pressure in the injection pipe at a depth of 25 m, it can be seen that for increasing pressure the curve is no longer linear, and only approximately linear for decreasing pressure. The pulses caused by the piston can still, however, be recognized. The same pulses can only just be made out in the injection section, at a distance of 1 m from the outlet, although the initial pulse is clear. A linear relationship, as is given by the classical Lugeon test, cannot be said to be present here. The behaviour of the pressure in the upper observation section above the injection section shows that a hydraulic connection did exist between these two borehole sections, although the rise and fall of pressure are not so pronounced here as in the injection section itself. In the lower observation section, beneath the injection section, only a gradual rise and fall of the groundwater level can be made out. Thus, by-passing clearly did not take place. This confirms our previous conclusion that the contact between the packers and the wall of the borehole was watertight. The free head of water in the injection borehole above the 4 packers rose above the top of the borehole in a few seconds. The effects of injection on the general surroundings of the central borehole can be assessed by means of measurements taken in the observation boreholes. The initial moment of injection was detected almost simultaneously in observation borehole no. 5, although it is 16 m away from the central hole.

In the same way the pressure then rose to a maximum concurrently with that in the injection section. The maximum pressure was 13.7 bars (allowing for the difference in hydrostatic head) which is 1.7 bars less than in the injection section. The drop in pressure is thus remarkably small. In observation borehole no. 6, also 16 m from the injection hole, a rise in water level was observed but no direct hydraulic connection with the injection section. Observation borehole no. 2 is 52 m away from the central hole; the uppermost two of its five observation sections (nos. 1 and 2) showed no change, but nos. 3, 4, and 5 (at depths of 35, 43, and 51 m, respectively) at first showed a fall in pressure which only turned into a rise as the highest injection pressure was reached. While the pressure was being increased in the first phase of the test, the individual pressure steps were not detectable in these three observation sections; however, with falling pressure, the steps could be observed to be almost synchronous with those of the injection section. No variation in water pressure was seen to take place in observation boreholes nos. 3 and 4.

For the 1-hour pumping-in test, the flow rate was held constant at 93 l/min. The pressure at the pump rose continuously from 12 to 14.6 bars (Fig. 6). The pressure in the injection section showed the same linear increase at approximately analogous values, although a hydraulic pressure difference of over 5 bars existed between the two gauges. This gives an idea of the enormous pressure losses inherent in this system. As for the multi-stage test, the upper observation section (above the injection section) recorded an increase of pressure from 5 to 8.4 bars; these values are 4 bars lower than those measured in the injection section. Observation borehole no. 5, 16 m from the injection hole, showed a simultaneous rise in pressure from 1.7 to 8.1 bars, a rather gentle rise in comparison with that in the injection section. The relative pressure difference was 7.1 bars compared with 8.4 bars in the injection section. The pressure loss here is therefore also very small. In the observation borehole 50 m from the injection hole, there was an initial pressure drop. In observation section 3, this pressure decay continued throughout the duration of the test, whereas in sections 4 and 5, a rise began after about 20 minutes and the initial pressure was reached towards the end of the test. No real departure from the initial value was detected in observation boreholes 3,4, and 6, as was the case in the previous tests.

The process of percolation through rock can be demonstrated by means of the results of long duration tests which were run over periods of several hours. The following example is a 13-hour tracer test (Fig. 7): The pumping-in test consisted of injection at a constant pumping pressure of 5.5 bars. During the first 4 hours, the flow rate fell continuously and then, for the remainder of the test, stayed constant, thus approximating a stationary flow regime. The pressures at the pump and in the injection section remained constant.

A steady rise in water pressure from 1.8 to 2.3 bars took place in observation borehole no. 6, 16 m from the injection hole. At a distance of 50 m from the central hole, in observation borehole no. 2, the pressure fell initially in observation sections 3, 4, and 5 and then, after between 30 and 60 minutes, returned to its original level. As the test was continued, the pressure showed a further steady rise in these three sections, while in the two upper sections there was no pressure change. It is most likely that artesian water was present at the level of observation sections 3, 4, and 5. A dilute salt solution was employed as an injection fluid for this test, although the last fifth of the total amount pumped in consisted of fresh water. This can be clearly seen from the specific electrical resistances measured at the pump supply. The tracer began to appear at observation borehole no. 6, 16 m away, after 10 minutes, as recorded by a distinct fall in the specific electrical resistance. This represents an apparent horizontal flow velocity of 0.029 m/sec. The individual measuring elements in observation borehole no. 4 registered very varied arrival times. The tracer took 28 minutes to reach observation section 3, corresponding to a velocity of 0.03 m/sec, section 4 took 1.5 hours, a velocity of 0.009 m/sec, and for section 5, four hours were required, a velocity of 0.003 m/sec. The apparent flow velocity varies, therefore, by a factor of 10, even for one borehole. It is most probable that, in these long-duration tests, we are dealing with the conditions of a stationary flow regime, at least in the immediate vicinity of the injection section. The large "mountain" of water which built up around the injection site gradually spread out laterally. This process can be clearly recognized from measurements taken during the intervals between injection phases. A slide valve was installed to close the pipe connecting the injection section and the pump; this ensured that any pressure release could only take place by way of the rock. The pressure, in fact, decayed rapidly during the first 2 1/2 hours, then decreased into a slow escape of fluid which, even after 11 hours, had not completetly stopped.

DETERMINATION OF PERMEABILITY

The pressure-flow diagram (Fig. 8) served as the basis for determination of the permeability. The experimental results were subjected to statistical processing and the mean values and standard deviations were calculated. In the multi-phase test, the mean injection flow rate and the mean injection pressure were determined for each stage from about 100 individual readings; in the long duration test, between 2000 and 6000 readings per measuring element were utilized for the determination. It is clear that these experimental results are statistically more reliable than those obtained by conventional methods.

In the diagram for the short duration test, the individual pressure steps, designated by capital letters, are plotted by means of the relevant injection pressure and mean flow rate. The injection pressure shows a linear increase in steps A, B, and C. At higher pressures, the flow rate increased more rapidly since the hydrostatic overburden pressure was overcome at 11 - 12 bars and expansion of the joint aperture began. In addition, turbulance became noticeable in the system at this stage. Under conditions of stepwise reduction of pressure, the same pressure was recorded for step F as for step E, although the former has a distinctly lower flow rate. This is due to the raising of the water table in the vicinity of the injection site. The same phenomenon can be recognized in step G, H, and I.

The Lugeon values or permeability coefficients can now be derived from the pressure / flow-rate diagrams. Application of the formula normally used by the US Bureau of Reclamation (3) -- which is only valid for a permeable continuum of infinite extent under homogeneous and isotropic conditions with a constant flow rate and a linear pressure / flow-rate relationship -- yields permeability coefficients around $1 - 3 \times 10^{-6}$ m/sec (Fig. 9). The permeability is more or less dependent on the injection pressure. These permeabilities are clearly not realistic, simply because the continuum conditions mentioned above are not fulfilled in this case. In addition, this particular formula is intended for use with a single borehole test and thus is only valid in the immediate vicinity of the injection section. If the pressure in the adjacent borehole no. 5 is taken into account and continuum conditions are assumed, then the permeability shows a marked increase with the injection pressure from 6 to 20×10^{-6} m/sec, namely from 6 to 20 times larger than the permeability coefficient determined in a single-borehole test.

At this particular site, the injection section was surrounded by rock with a highly compact fabric in which only one joint was present -- without doubt, a discontinuum. It was therefore decided to use the formula devised by MAINI (4) for calculation of the permeability coefficient of a discontinuum. The calculation is valid in the case of joints of infinite radial extent around the borehole, for laminar and radial flow regime, but the effects of inertia during acceleration of the fluid are neglected. This gives permeability coefficients of $1 - 5 \times 10^{-3}$ m/sec (Fig. 9 II).

SUMMARY

The permeability calculated utilizing the discontinuum model is larger than that for the continuum by a power of 3. It is therefore essential to use discontinuum-based data for any numerical analysis where the flow rate, as well as time-dependent flow processes are to be investigated. However, even these permeability coefficients are associated with some degree of unvertainty since the spatial extent of the joint is not fully known. As can be seen from our results, the joint does not possess rotational symmetry. Moreover, the width of the joint could only be measured in the borehole, but it is not known how close this value is to its average width. A further source of uncertainty is that, in this model, possible joint intersections have not been allowed for.

The fact that the water pathway makes use of joints means that consideration of the permeability and percolation is a very complicated matter. A detailed analysis of the joint fabric should therefore be made before any permeability test is carried out. Single borehole tests yield insufficient data. More information about the actual flow pattern, especially its anisotropy, can be obtained from tests involving several boreholes and comprehensive series of measurements.

For this purpose, the distance between the observation boreholes and the central injection borehole should not be too great, ideally between 5 and 20 m. Permeability coefficients can be determined just as readily from short-period tests as from long-period tests. However, in the short-period, multi-step tests, the changes in the hydraulic condition which takes place between the individual steps should be allowed for. One of the tasks of future research in engineering geology will be to discover a means of accurately determining the joint fabric, which is the strongest influencing factor on the behaviour of water in rock, as well as on the permeability and the water pathway.

References

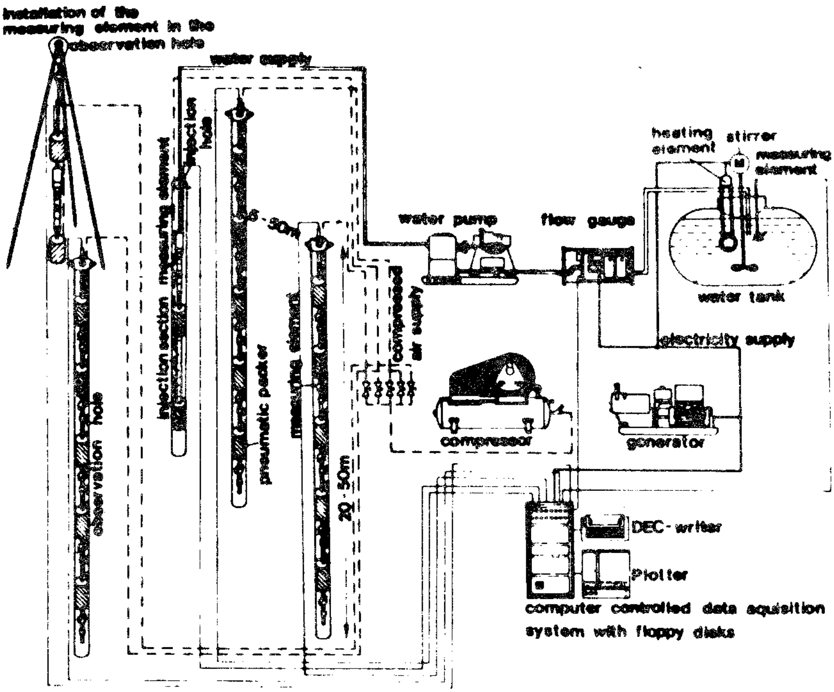
(1) Wittke, W.: Zusammenfassender Bericht und Schlußfolgerungen. - Proc. Int. Symp. Durchströmung von klüftigem Fels, 21, Stuttgart 1972

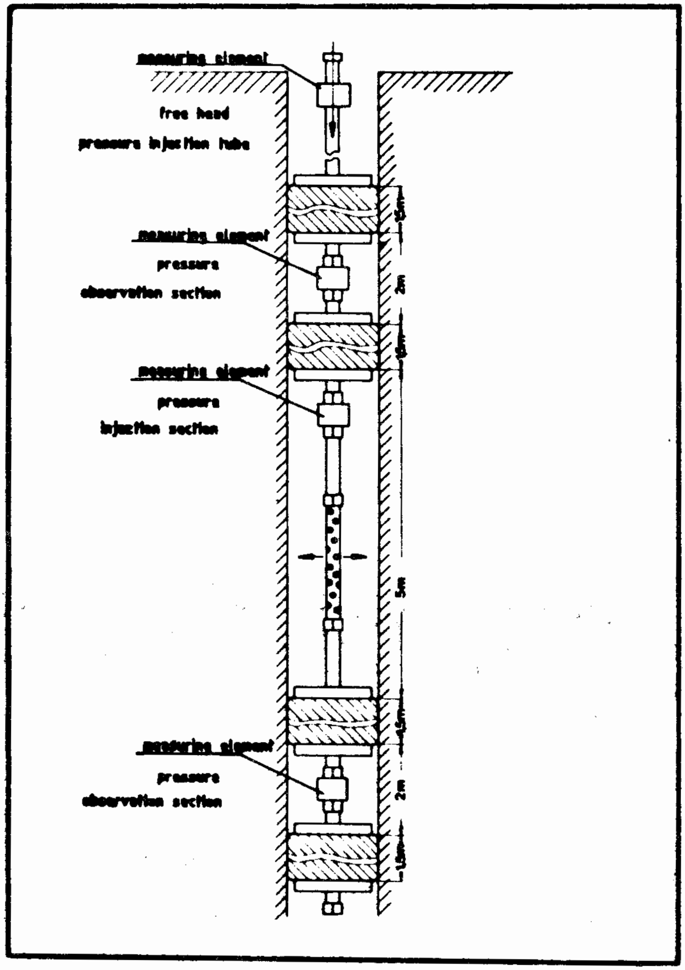
(2) Schneider, H.J.: Neue Versuchsapparatur zur Bestimmung der Durchströmungseigenschaften von Fels. - Ber. 2. Nat. Tagung Ing.-Geol. 75-83, Fellbach 1979

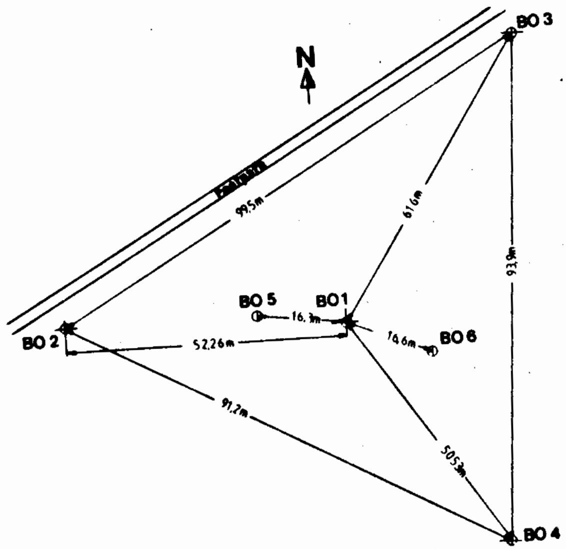
(3) U.S. Bureau of Reclamation: Earth manual - Denver 1963

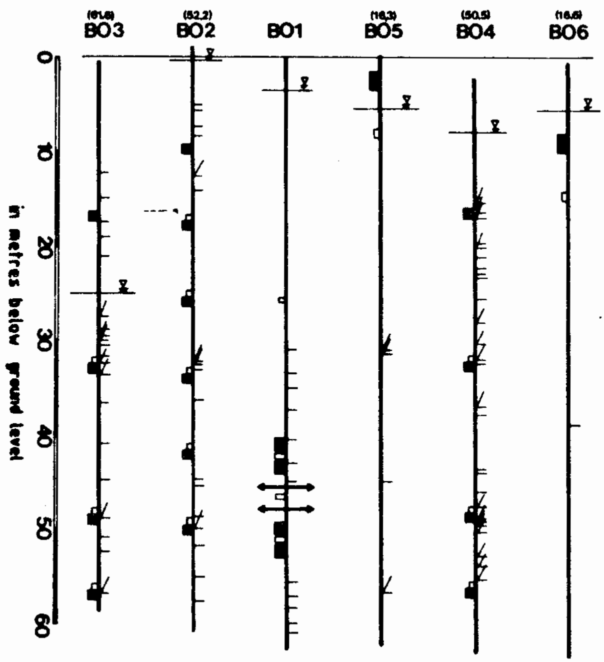
(4) Maini, Y.N.T.: In situ hydraulic parameters in jointed rock - Their measurement and interpretation, London 1971

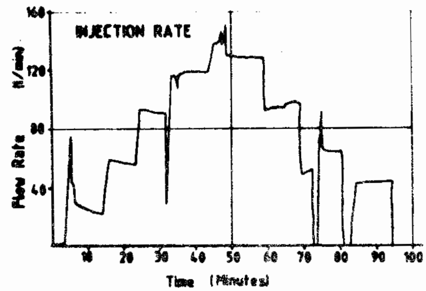
List of Figures

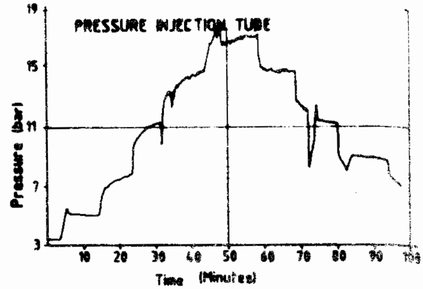

installation of the measuring element in the observation hole
water supply
injection section measuring element
injection hole
5-30m
pneumatic packer
measuring element
20-50m
observation hole
compressed air supply
water pump
flow gauge
heating element
stirrer
measuring element
water tank
electricity supply
compressor
generator
DEC-writer
Plotter
computer controlled data aquisition system with floppy disks

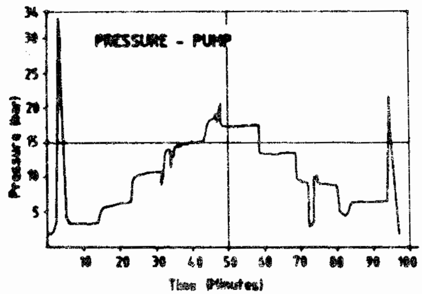

measuring element
free head
pressure injection tube
measuring element
pressure
observation section
2m
measuring element
pressure
injection section
5m
measuring element
pressure
observation section
2m

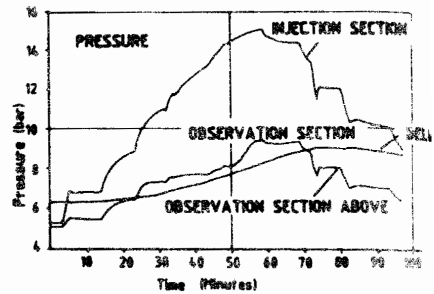

N
BO 3
99,5m
61,6m
93,9m
BO 5
BO 1
16,3m
14,6m
BO 6
BO 2
52,26m
91,2m
50,53m
BO 4

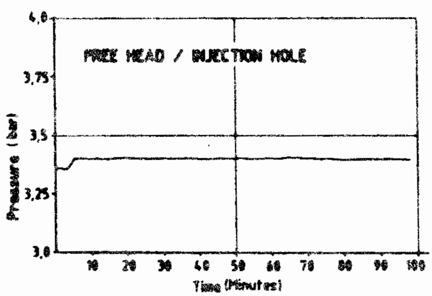

(52,2)
(50,5)
BO3
BO2
BO1
BO5
BO4
BO6
0
10
20
30
40
50
60
in metres below ground level

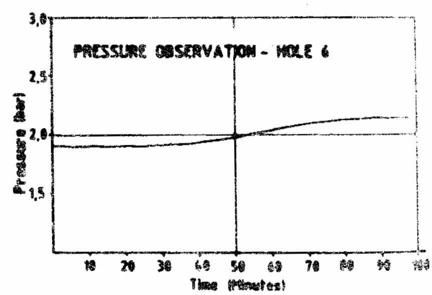

INJECTION RATE
Flow Rate (l/min)
Time (Minutes)

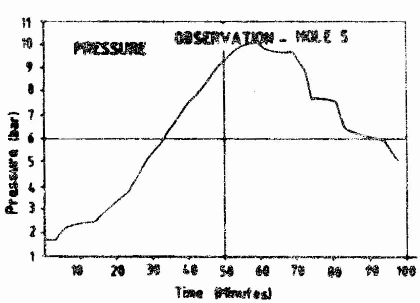

PRESSURE INJECTION TUBE
Pressure (bar)
Time (Minutes)

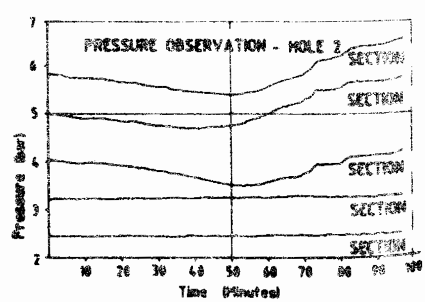

PRESSURE - PUMP
Pressure (bar)
Time (Minutes)

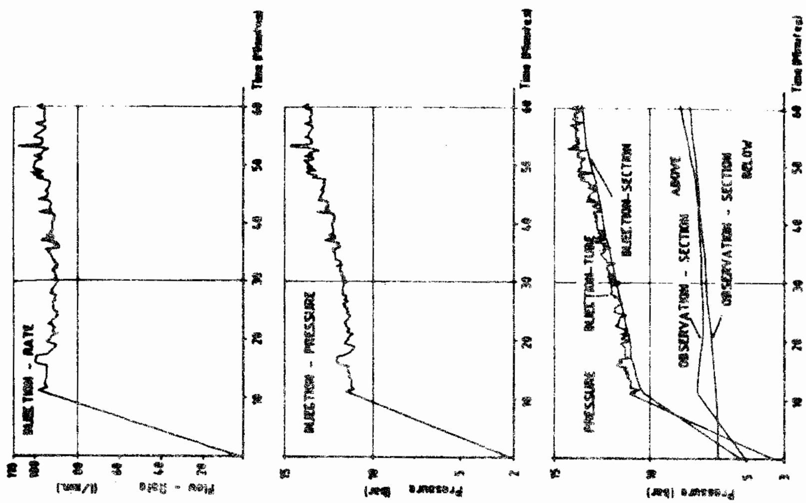

PRESSURE
INJECTION SECTION
OBSERVATION SECTION
OBSERVATION SECTION ABOVE
Pressure (bar)
Time (Minutes)

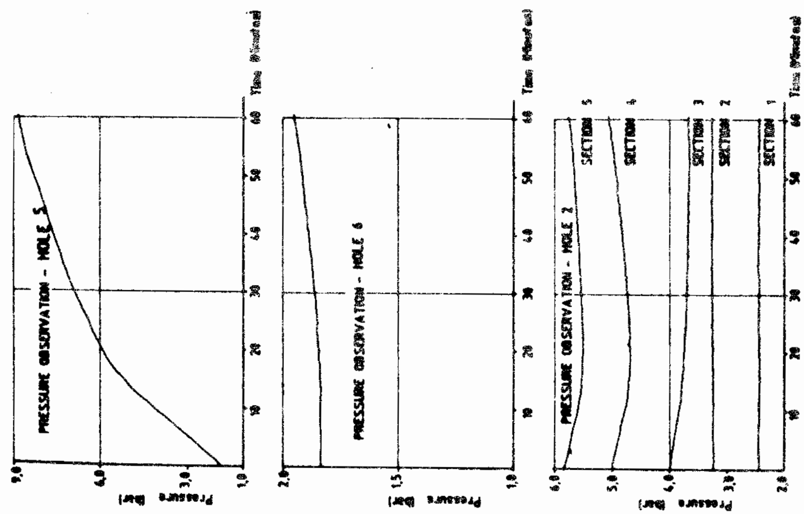

FREE HEAD / INJECTION HOLE
Pressure (bar)
Time (Minutes)

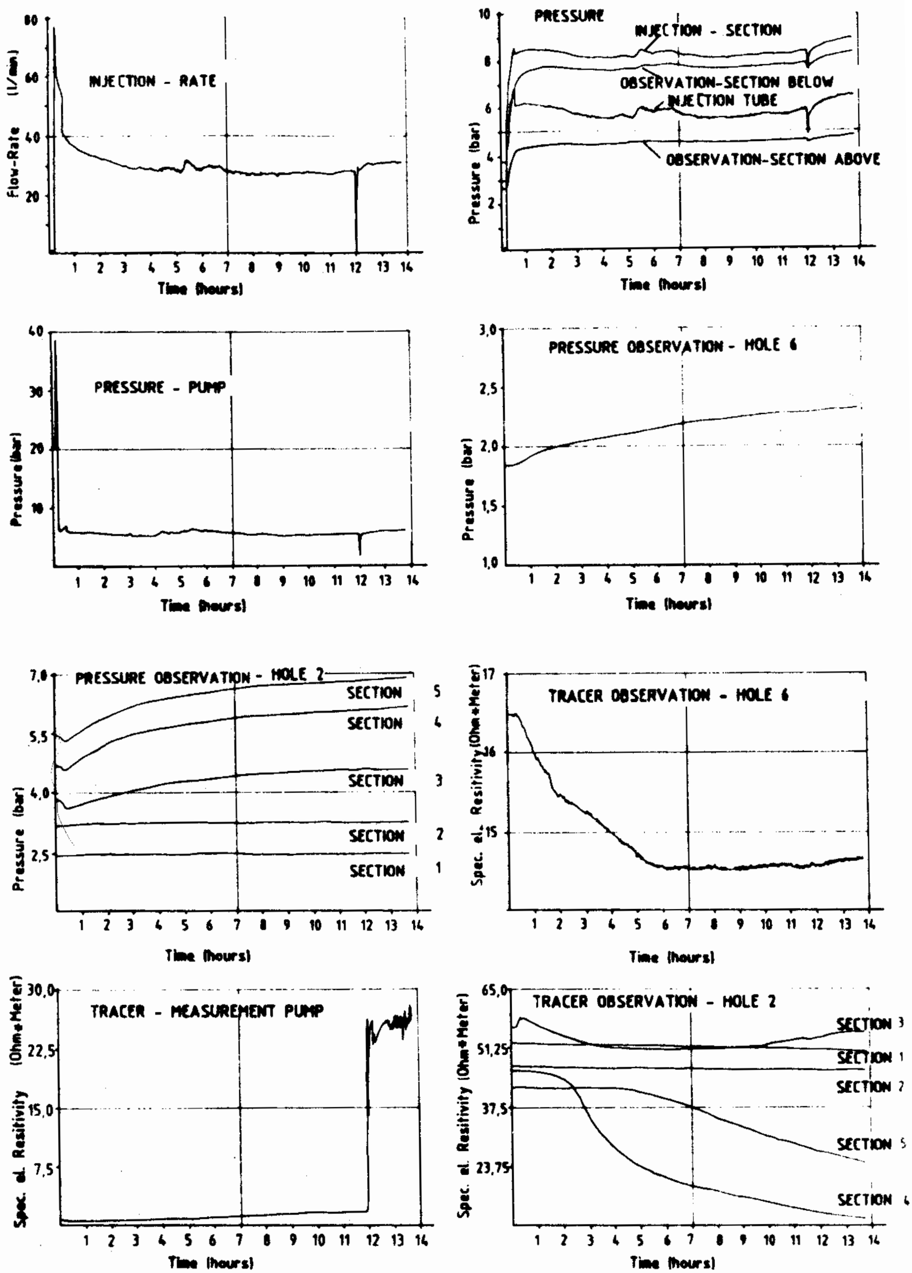

PRESSURE OBSERVATION - HOLE 6
Pressure (bar)
Time (Minutes)

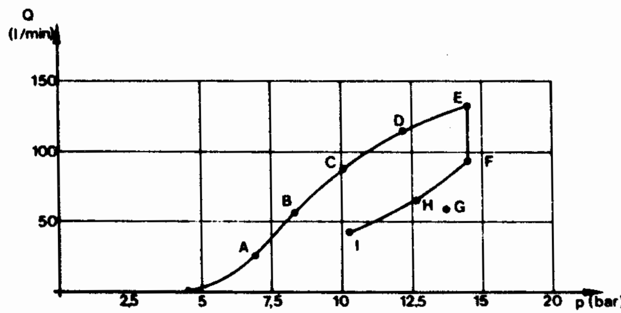

PRESSURE OBSERVATION - HOLE 5
Pressure (bar)
Time (Minutes)

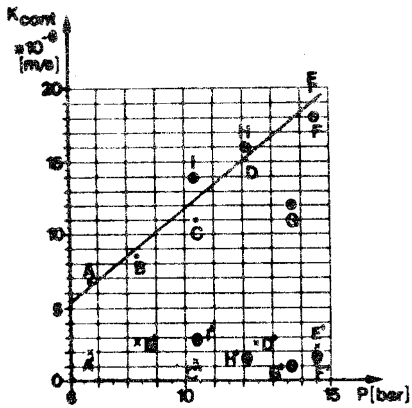

PRESSURE OBSERVATION - HOLE 2
SECTION 5
SECTION 4
SECTION 3
SECTION 2
SECTION 1
Pressure (bar)
Time (Minutes)

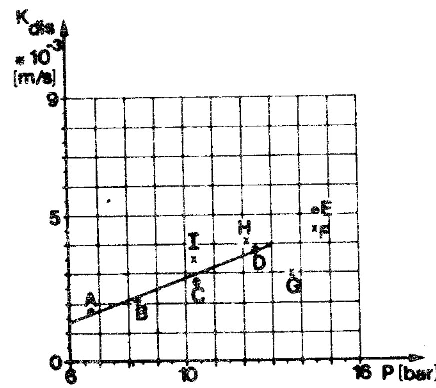

INJECTION - RATE
INJECTION - PRESSURE
PRESSURE
INJECTION-TUBE
INJECTION-SECTION
OBSERVATION - SECTION ABOVE
OBSERVATION - SECTION BELOW
Flow - Rate (l/min)
Pressure (bar)
Time (Minutes)


PRESSURE OBSERVATION - HOLE 5
PRESSURE OBSERVATION - HOLE 6
PRESSURE OBSERVATION - HOLE 2
SECTION 5
SECTION 4
SECTION 3
SECTION 2
SECTION 1
Pressure (bar)
Time (Minutes)


INJECTION - RATE
Flow-Rate (l/min)
Time (hours)
PRESSURE
INJECTION - SECTION
OBSERVATION-SECTION BELOW
INJECTION TUBE
OBSERVATION-SECTION ABOVE
Pressure (bar)
Time (hours)
PRESSURE - PUMP
Pressure (bar)
Time (hours)
PRESSURE OBSERVATION - HOLE 6
Pressure (bar)
Time (hours)
PRESSURE OBSERVATION - HOLE 2
SECTION 5
SECTION 4
SECTION 3
SECTION 2
SECTION 1
Pressure (bar)
Time (hours)
TRACER OBSERVATION - HOLE 6
Spec. el. Resitivity (Ohm*Meter)
Time (hours)
TRACER - MEASUREMENT PUMP
Spec. el. Resitivity (Ohm*Meter)
Time (hours)
TRACER OBSERVATION - HOLE 2
SECTION 3
SECTION 1
SECTION 2
SECTION 5
SECTION 4
Spec. el. Resitivity (Ohm*Meter)
Time (hours)


Q
(l/min)
150
100
50
A
B
C
D
E
F
H
G
I
2,5
5
7,5
10
12,5
15
20
p (bar)


Kcont
*10⁻⁶
[m/s]
20
15
10
5
0
6
10
15
P [bar]
A
B
C
D
E
F
G
H
I


Kdis
* 10⁻³
[m/s]
9
5
0
6
10
16
P [bar]
A
B
C
D
E
F
G
H
I