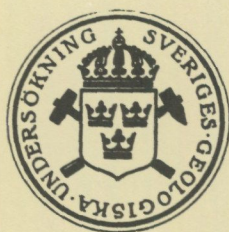


SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 783 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 75 NR 4

ANDERS CARLSSON AND TOMMY OLSSON

HYDRAULIC PROPERTIES
OF A FRACTURED GRANITIC
ROCK MASS AT FORSMARK, SWEDEN



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Addresses:

Tommy Olsson
Geological Survey of Sweden
Box 670
S-751 28 UPPSALA

Anders Carlsson
Swedish State Power Board
Civil Engineering Development
S-162 87 VÄLLINGBY

ORD & FORM AB
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INTRODUCTION

The hydraulic properties of a crystalline rock mass depend mainly on the properties of the existing discontinuities. Hydraulic tests – test pumping and injection tests – carried out in drill-holes make it possible to determine some significant hydraulic properties. However, using this kind of test it is hard to distinguish differences between elements, as the results obtained are mean values representing the whole of the penetrated rock mass, including both rock matrix and discontinuities. As the water-bearing ability of any crystalline rock type is almost exclusively dependent on the presence of open fractures it is of interest to study the individual fractures and their properties.

A great number of conductivity determinations from different areas were presented in an earlier work (A. Carlsson and T. Olsson 1977a). The purpose of that study was to hydraulically compare the areas and rock types with each other and examine the relation between conductivity and depth. The study, however, only considered the conductivity when no other parameters of importance for the hydraulic conditions were investigated.

The aim of the present work is to investigate in what sense different parameters, such as gross hydraulic conductivity, fracture conductivity, porosity, fracture openings and so forth, are interrelated. In consequence of the former work (A. Carlsson and T. Olsson 1977a) on the determination of the conductivity-depth relation, it is of interest to investigate this relation in the case of other parameters too.

In order to fulfil these aims, a specific area was studied, viz. the construction area of the Forsmark Power Plant in northern Uppland, east central Sweden. This area is adjudged suitable as extensive site exploration took place before the construction of the plant. The exploration produced results which form the basis of the present investigation. Another advantage of the Forsmark area is that the main geological and hydrogeological features are well known because of this exploration and the many engineering geological studies made during the construction of the plant.



Fig. 1. The location of Forsmark Power station.



Fig. 2. Aerial photograph of the Forsmark area. The investigation area of the present study, Unit 3, is the construction area in the foreground. Units 1 and 2 are shown in the background. Photograph by G. Hansson/N.

GROUNDWATER FLOW IN FRACTURED MEDIA

From a hydraulic point of view the crystalline rock mass consists of a great number of blocks of rock material (rock matrix) separated by individual fractures. The nature of the fractures varies greatly as regards interconnection, degree of opening and continuity, and the groundwater flow in such formations is almost exclusively confined to the existing fractures. The amount of the groundwater flow depends on the hydraulic conductivity of the formation and the prevailing hydraulic gradient. Normally the flow takes place under laminar conditions and then mainly as a parallel flow within the individual fractures. Turbulent flow may also occur when the conductivity is high and/or the gradient steep.

The rock matrix in a crystalline rock type usually has very low conductivity and the seepage of water follows joints between crystals and micro cracks. The conductivity of the matrix seems to be in the range 10^{-15} – 10^{-10} m/s, with a variation which depends on the existence and character of the micro structures (Pratt *et al.* 1977, Rehbinder 1978).

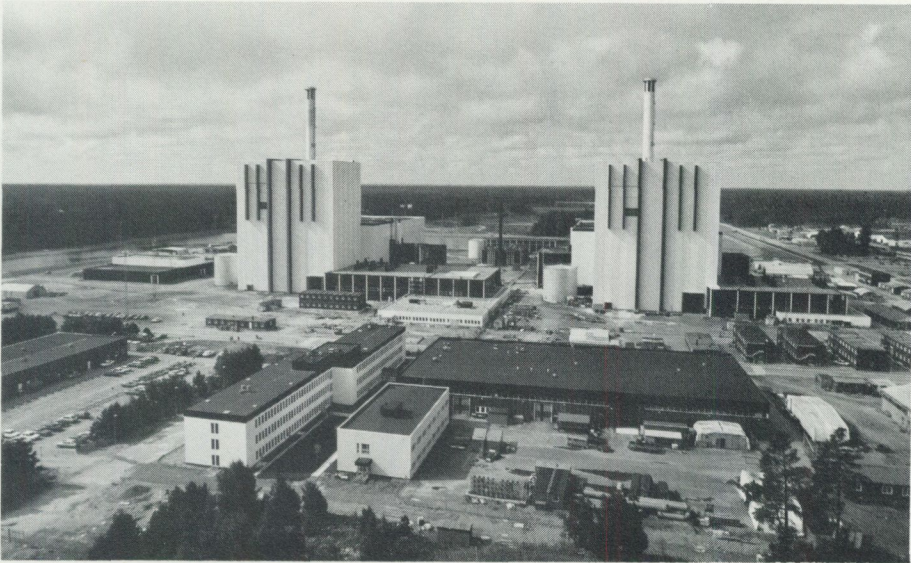


Fig. 3. A view of the area around Forsmark showing the extremely flat character of the landscape. Photograph by G. Hansson/N.

According to Hagen-Poiseulle's law the conductivity of a formation is in proportion to the fourth power of the diameter of the pores, which in a fractured formation corresponds to the third power of the fracture opening. Thus, it is obvious that the characteristic features of the existing fractures are vital for the water-bearing ability of the rock mass.

The rock type is crucial for the development of fractures and fracture systems. Due to their mechanical properties, different rock types give rise to fracture systems with different hydraulic properties. Among the eruptive types the acid granites are more brittle than the basic greenstones, and normally the granites show a better developed and hydraulically interconnected fracture system. The fracture system in a granite is often made up of a number of crossing sets which create the interconnection (cf. T. Olsson 1979).

As for the conductivity, the same condition holds for the porosity of a fractured aquifer, namely that the existing fractures are of cardinal importance. The kinematic (or flow-) porosity is made up of the interconnected fractures, and the non-connected fractures and the micro structures carry additional weight for the total porosity.

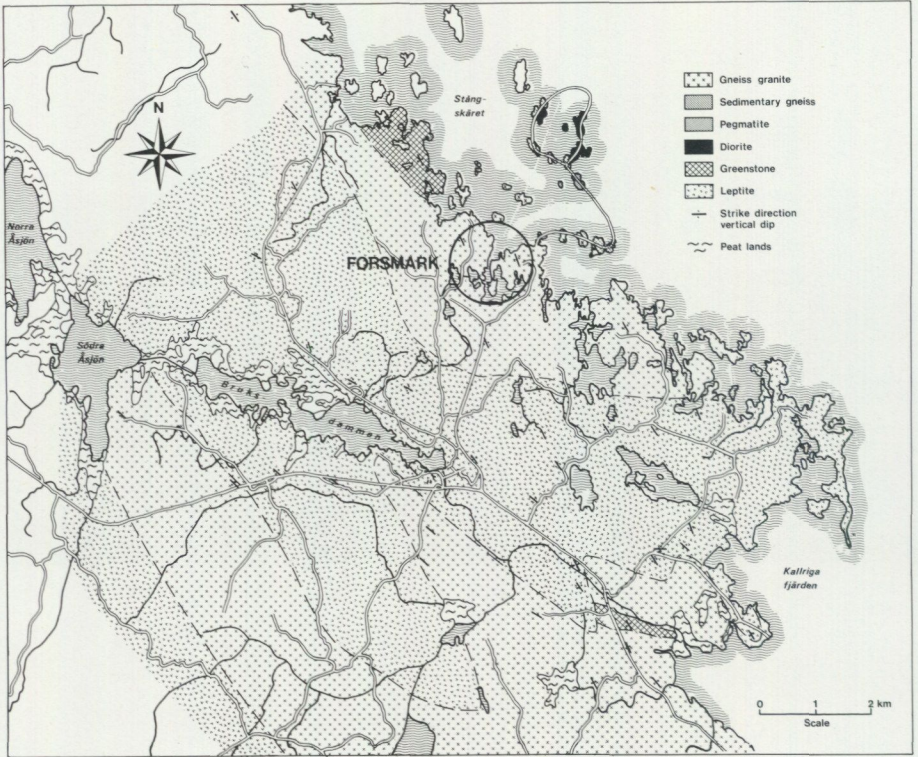


Fig. 4. Sketch map of the geology in the Forsmark area.

INVESTIGATION AREA THE POWER PLANT

The Forsmark Power Plant is situated in Östhammar municipality, in northern Uppland, about 130 km north of Stockholm and 80 km northeast of Uppsala. The plant is close to the coast of the Bothnian Gulf (Figure 1). It is a nuclear power station with three units, two of which are complete and in test operation while a third unit is under construction (1981). The present study concentrates on the rock mass at the site of this third unit. Figure 2 shows the construction area with the site of Unit 3 in the foreground and Units 1 and 2 behind it.

All three units are founded on rock with a depth of foundation of 5–20 m. Due to the excavation for the foundation it was possible to investigate the rock mass in the shafts. The excavation for foundation, tunnels, channels and so forth, amounts to more than one million m^3 rock and another million m^3 of Quaternary loose deposits.

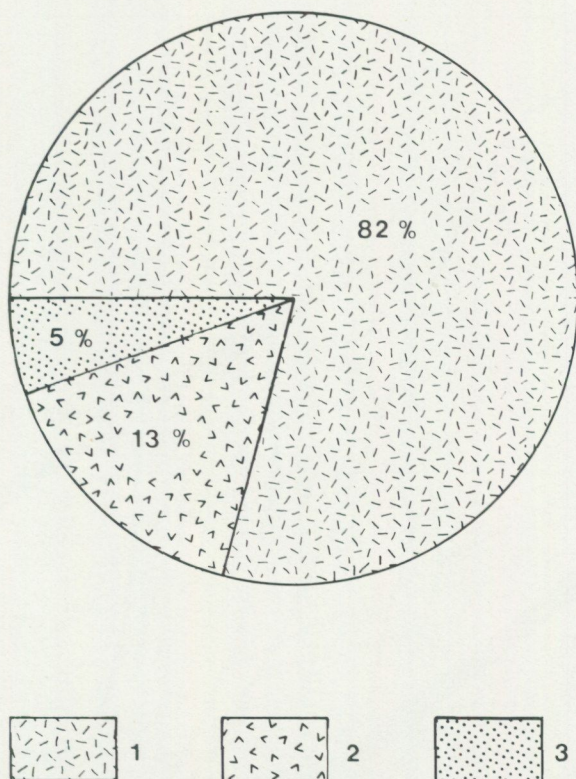


Fig. 5. A quantitative description of the rock distribution within the area of Unit 3. 1 means gneiss-granite, 2 pegmatites, 3 greenstones.

GEOLOGY

From a morphologic point of view, the Forsmark area is remarkably flat with only minor topographic variations. The ground level at the area investigated lies 1 to 5 m above sea level. The altitude increases slightly and about 2.5 km west of the plant, altitudes of about 25 m above sea level are occasionally found. However, it is necessary to go about 15 km westward to find more continuous altitudes of 20–30 m above sea level. This extremely flat character of the landscape in the vicinity of Forsmark is illustrated in Figure 3.

The bedrock in the Forsmark area is mainly made up of old Svecokarelian intrusive, schistose rocks, so-called gneiss-granites. In addition, mica gneiss and mica schist occur on the islands off the mainland. The gneiss-granite includes greenstones of amphibolitic composition and pegmatites.

The gneiss-granite has a fairly well defined schistosity and anisotropy, with a general direction of the foliation of NW–SE with a steep dip to NE. The

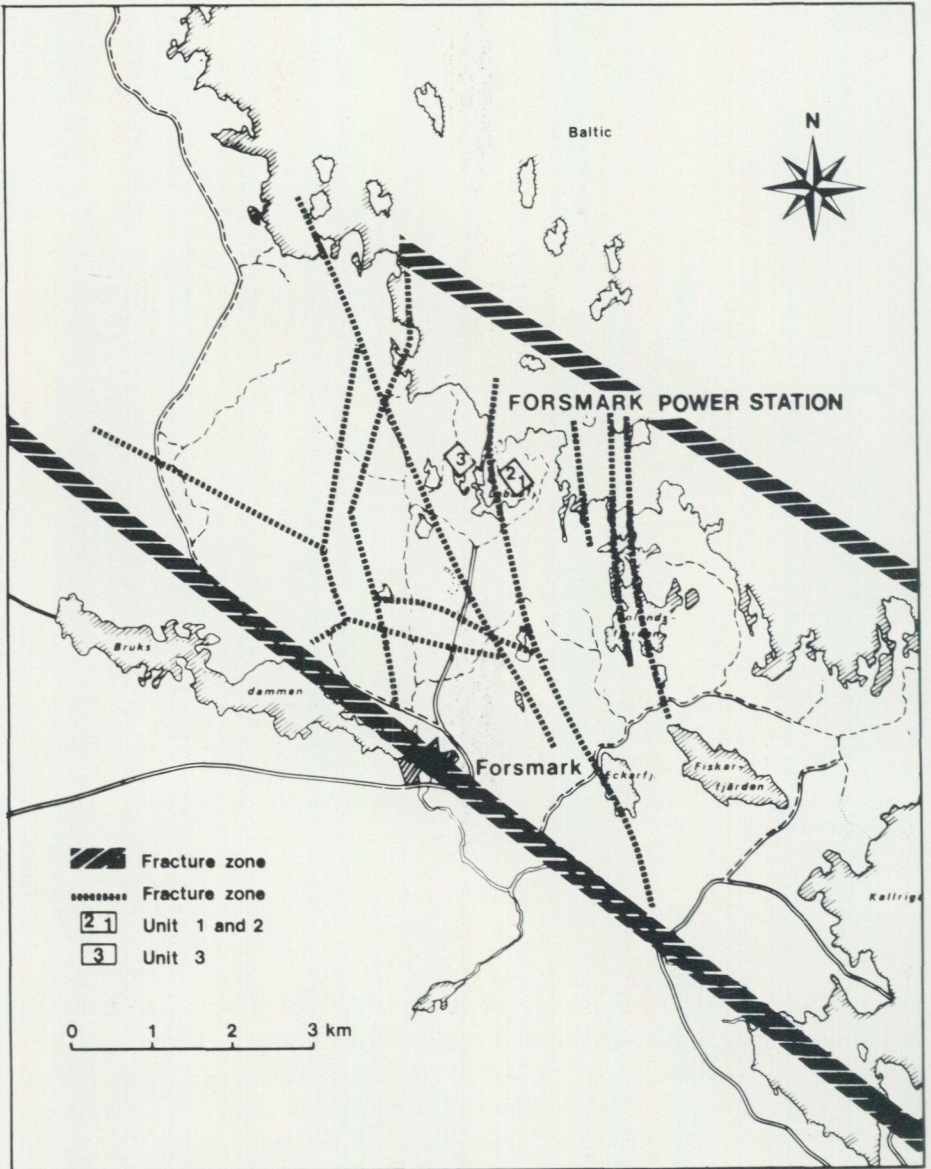


Fig. 6. Main tectonic structures in the Forsmark area (P.O. Karlsson and T. Olsson 1977).

pegmatites and greenstones occur both as layers parallel to the foliation and as massifs and dikes independent of the foliation. Within the investigation area, the gneiss-granite is the main rock type and no mica gneiss is presented. Figure 4 shows a sketch map of the geology in northeastern Uppland while Figure 5 illustrates a quantitative description of the rock distribution within the area of Unit 3. This distribution is based on the core logging obtained during the site investigation for the plant (Larsson and Moberg 1975).

The bedrock is covered by Quaternary deposits, mainly till and peat bogs. These deposits cover almost all the bedrock and natural rock outcrops are consequently rare. Normally the thickness of the Quaternary amounts to about 4–5 m, but thicker layers may occasionally be found with a recorded maximum of 14 m.

TECTONIC FEATURES

The Forsmark Power Station is situated between two major fracture zones with a strike direction of NW–SE and steeply dipping. The intervening rock mass demarcated to the NE and SW shows evidence of a secondary tectonization which probably occurred in connection with movements along these zones. This tectonization has resulted in a number of secondary fracture zones which have a general strike direction of N–S. The fracture tectonization is illustrated in Figure 6, in which the two major zones and the secondary zones are shown.

During the excavation of the discharge tunnel of Units 1 and 2, the northernmost one of the major zones was studied (A. Carlsson and T. Olsson 1977b). The width of the zone is about 200 m. According to Larsson (1973) the post-orogenic tectonization of the rock took place during at least six separate phases, with intermediate calcite and quartz dissemination of the crushed rock. Figure 7 shows the brecciated gneiss-granite with its numerous veins of quartz and calcite. The frequency of open fractures within the zone gradually increased along a 50 m section and clay-filled fractures were also found. Beside these 50 m with high frequency of open fractures, the remainder of the zone had closed and sealed fractures. The southernmost one of the two major zones is of similar width. No detailed studies were made of this zone but a seismic profile which crossed it indicates low seismic velocity (3 000–4 000 m/s). Water wells sited in this zone indicate a comparatively high frequency of open fractures. It seems reasonable to assume that this southern zone has an interior structure similar to the northern one. The reason is that only 5 km of rock separate the zones and this intervening rock mass has the same mechanical properties throughout.

As mentioned above the tectonization of the intervening rock mass is

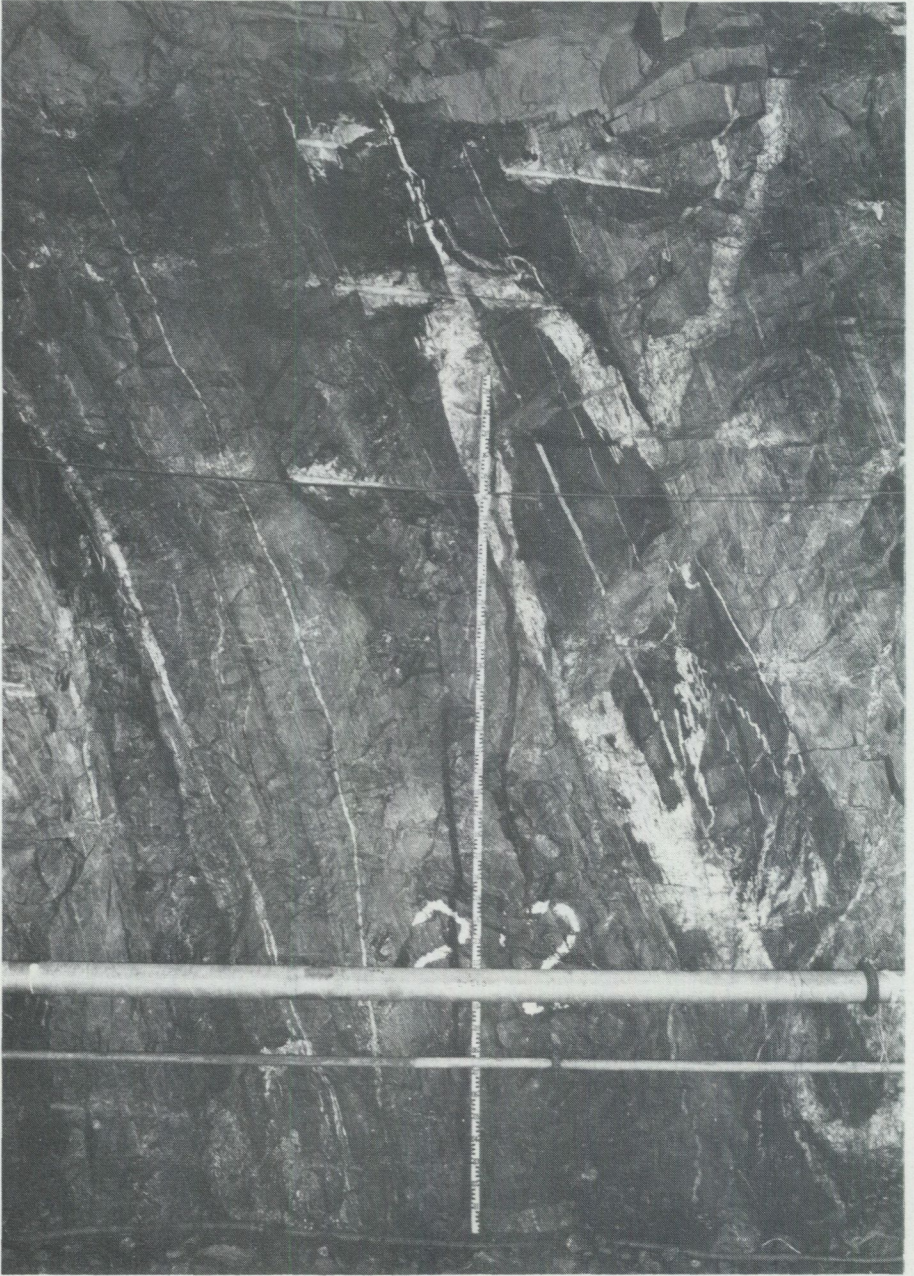


Fig. 7. Brecciated gneiss-granite with numerous veins of quartz and calcite representing a 4 m section of the eastern wall of the discharge tunnel in Units 1 and 2. Photograph by G. Hansson/N.

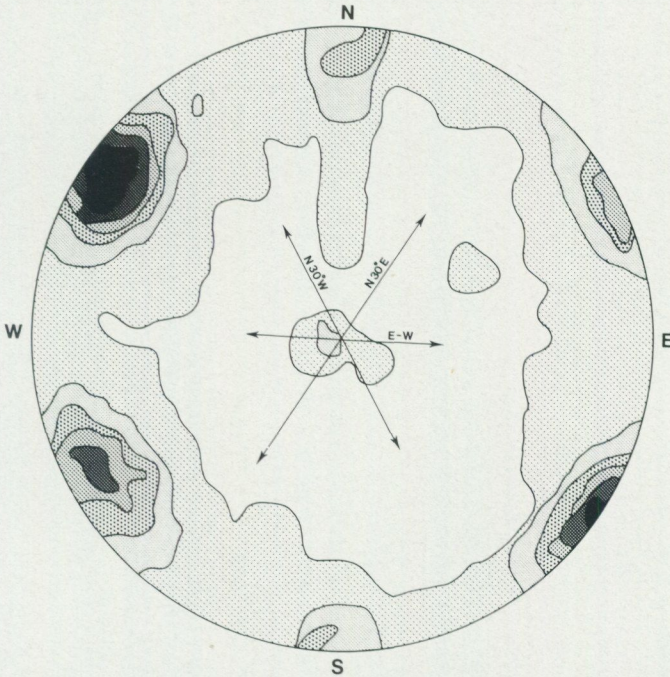


Fig. 8. Fractures in the rock mass of Unit 3, Stereographic projection of the normals of the fracture planes (500 fractures). Lower hemisphere, Schmidt's projection. Contour density 3–6–9–12–15 %. Arrows indicate main directions of joint sets (A. Carlsson 1979).

probably related to the movements along the major zones. The strike directions of the steeply dipping secondary zones indicate their possible development as shear zones in connection with compression of the rock mass, although the initial development may have other causes.

One of the secondary zones intersects the tunnel, and therefore this zone was also examined. Its strike direction is about N 80°W which excludes it from the general system running N–S. In the tunnel the width of the zone is approximately 50 m with a high frequency of open fractures and some clay mineralizations. In contrast to the complicated tectonization of the northernmost major zone with several phases of tectonization, only one phase could be observed in this zone. Like the other steeply dipping fracture zones, it probably developed in connection with deformation of the rock mass during various phases of tectonization. The two major fracture zones were also discovered by interpretation of aerial photographs taken from the Landsat satellites (Ehrenborg and Stephansson 1976). Marine geological studies in the Åland Sea have shown a south-eastern continuation of these two zones, the total length amounting to about 60 km (Flodén 1973).

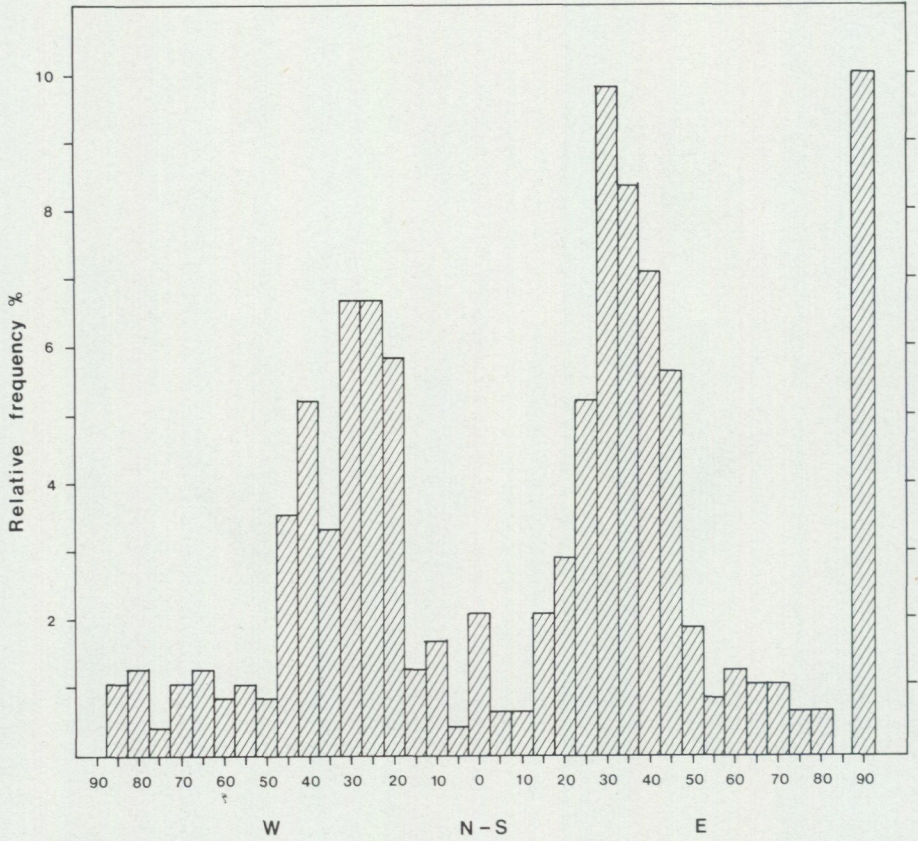


Fig 9. Distribution of directions of vertical and nearly vertical fractures. 1 means most frequent directions, 2 frequency below randomly distributed fractures, 3 distribution when all fractures should be randomly distributed (A. Carlsson 1979).

FRACTURE CHARACTERISTICS

As regards the individual fractures, the gneiss-granitic rock mass is dominated by four joint sets, three of which form an almost orthogonal system. Figure 8 shows a semispherical projection of the normals of the fracture planes. This figure is based on measurements of more than 500 fractures in the area of Unit 3. Figure 9 shows the distribution of directions of vertical and nearly vertical fractures. According to these figures the four existing joint sets have the following directions:



Fig. 10. View of the superficial rock mass with extremely wide apertures which are filled with a silty sediment. Photograph by G. Hansson/N.

- S1, vertical, E-W,
- S2, vertical, NW-SE,
- S3, vertical, NE-SW,
- S4, horizontal,
- R, randomly oriented fractures.

The horizontal and the vertical sets, striking NE-SW, are the most developed in the superficial rock mass. The joint set running NW-SE has a direction similar to the foliation of the gneiss-granite.

A characteristic feature of the gneiss-granitic rock mass in the Forsmark area is the occurrence of horizontal and subhorizontal fractures intersecting the steeply dipping structure of the rock mass (A. Carlsson 1979). The fractures occur throughout the area but are not found within the sedimentary gneiss. The horizontal fractures are concentrated to the upper part of the rock mass where they often have openings of considerable width (more than 500 mm are recorded with a maximum of 820 mm). These wide apertures are commonly filled with unconsolidated sediments of silty composition (cf. Figure 10).

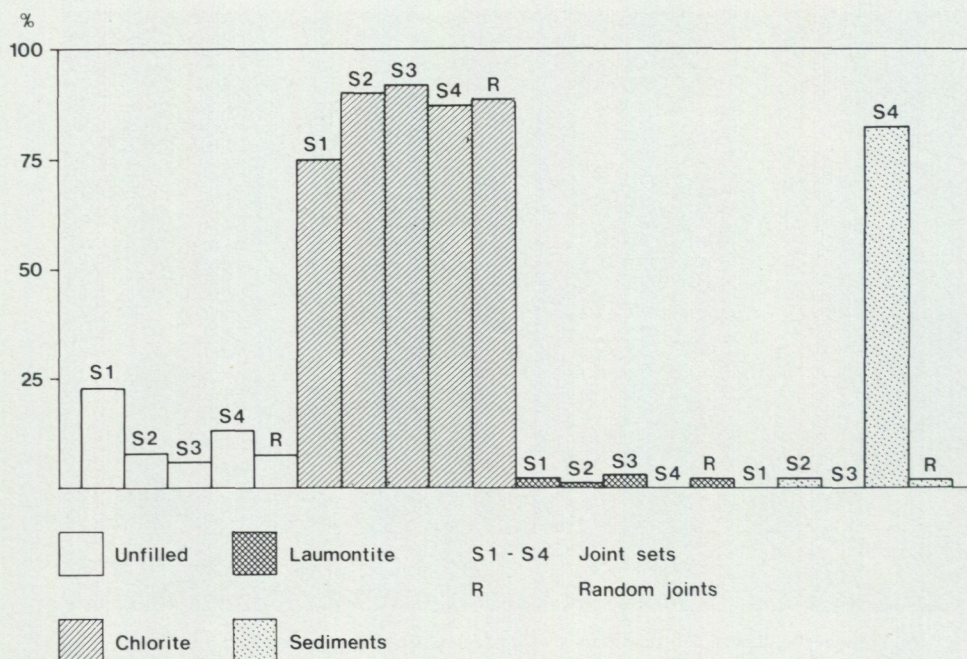


Fig. 11. Type of filling material and the distribution of this material within each joint set and random joints. Per cent of all fractures included in the set. In sediment-filled fractures additional mineral coatings also occur. (A. Carlsson 1979.)

In the area of Unit 3 an investigation was carried out of the fracture characteristics (A. Carlsson 1979, A. Carlsson and T. Olsson 1980), some of which are of importance for the water-bearing ability of the fractures. These parameters are

orientation,
filling and coating material,
aperture,
spacing,
roughness,
continuity.

The orientation of the fractures included in the study is shown in Figures 8 and 9 above.

Most of these fractures have some kind of infilling material or mineral coating. Figure 11 shows the types of filling material in the fractures, related to the different joint sets. The most common type is chlorite which occurs in almost all (75–90 per cent) of the fractures. The occurrence seems to be

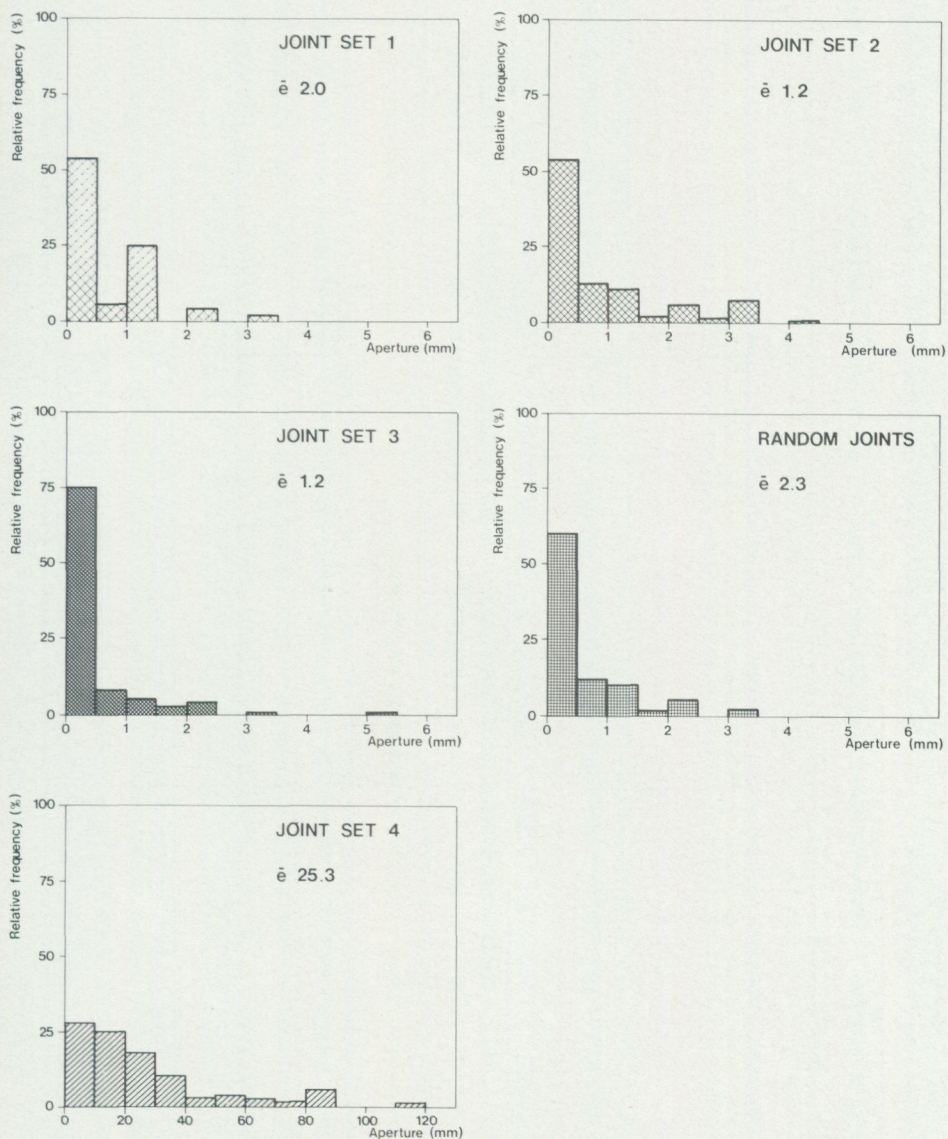


Fig 12. The distribution of aperture values within each joint set (A. Carlsson 1979).

independent of the joint sets. Sediment material is mainly found in the horizontal set (S4) and about 80 per cent of all fractures included in this set have sediment fillings. Sediment fillings occur to a very small extent in the vertical sets, and only when there is an interconnection between vertical and horizontal fractures.

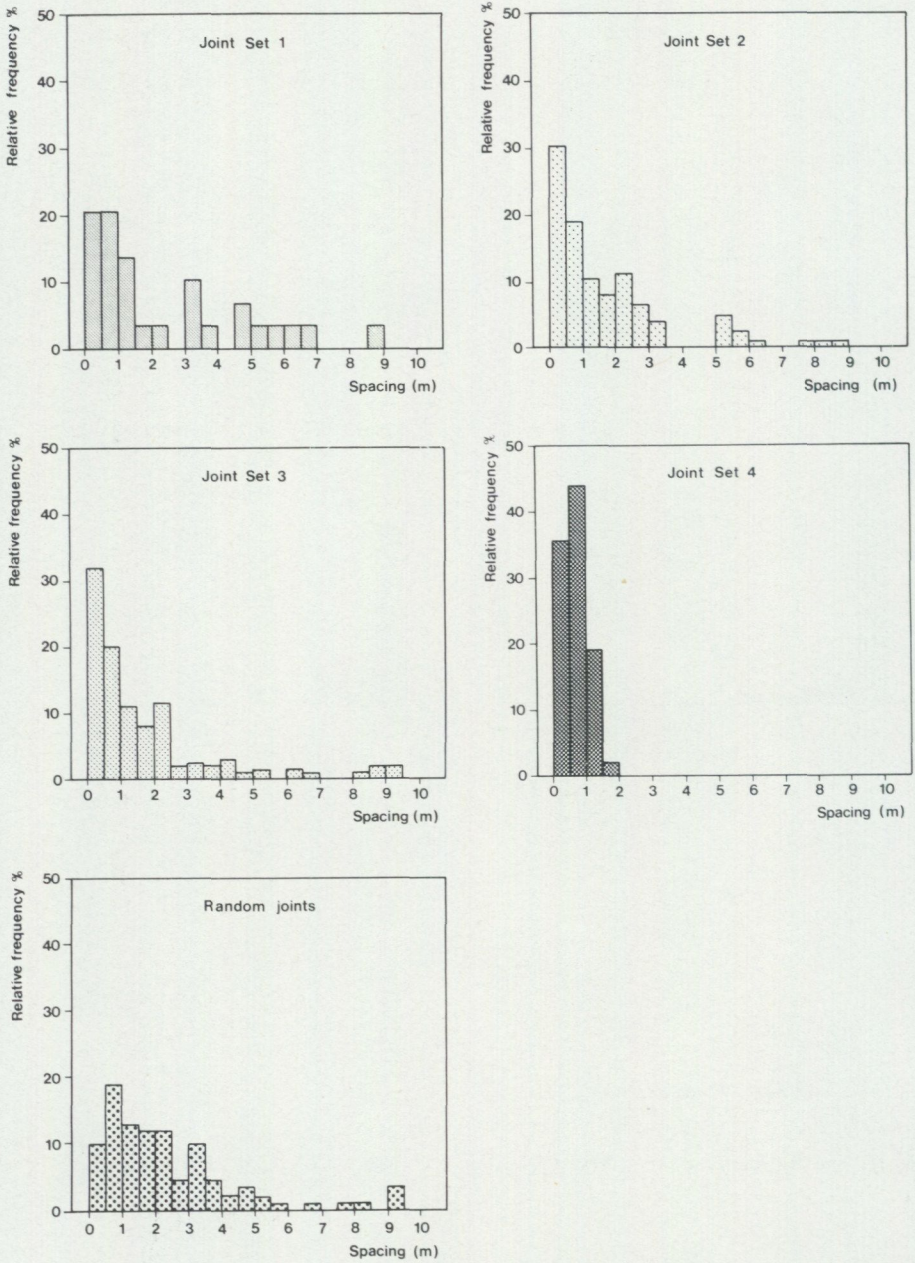


Fig. 13. Histogram of the spacing in the superficial rock mass for each joint set and random joints (A. Carlsson 1979).

TABLE 1. Result of the measurements of fracture apertures in the area of Unit 3.

Joint set	Fracture aperture (mm)					Number of apertures in per cent	
	Maximum	Minimum	Mean	Median	Standard	< 0,1 mm	> 10 mm
1	40	<0,1	2,0	<0,1	6,3	47,9	8,3
2	30	<0,1	1,2	<0,1	3,1	39,2	5,4
3	60	<0,1	1,2	<0,1	6,5	55,7	2,7
4	220	1,0	25,3	14,0	33,8	0	73,0
Random	40	<0,1	2,3	<0,1	7,1	49,2	8,3

The distribution of fracture apertures within each joint set is illustrated in Figure 12, and the characteristic values of the apertures are presented in Table 1. As indicated, there is a considerable difference between the apertures of the horizontal and vertical sets. The horizontal set has a median aperture which is more than 100 times greater than those of the vertical sets. Beside these physical measurements of the apertures which are presented in Figure 12 and Table 1, the fracture apertures have also been determined by means of hydraulic tests in drill-holes (A. Carlsson and T. Olsson 1978). The results of this treatment are given in Table 2, and as seen they are in the same order of magnitude as those reported in Table 1.

TABLE 2. Values of the fracture aperture calculated from hydraulic tests.

Maximum	Minimum	Fracture aperture (μm)			$e_{75} - e_{25}$
		Mean	Standard deviation	Median	
1100	3	71	82	47	63

The distribution in spacing of each joint set is shown in Figure 13 and Table 3, and again there is a striking difference between the horizontal and the vertical joint sets. The horizontal set has the closest spacing of all, about 50 per cent of that of the vertical sets. This is a consequence of the dense fracturing of the superficial rock mass. Figure 14 shows spacing versus depth obtained in drill-holes in the Forsmark area. There is a tendency to increased spacing with increasing depth.

TABLE 3. Result of the measurements of the fracture spacing in the area of Unit 3.

Joint set	Spacing (m)				
	Maximum	Minimum	Mean	Median	Standard deviation
1	8,5	0,1	2,4	1,3	2,4
2	8,7	0,05	1,7	1,2	1,8
3	10,0	0,05	1,8	1,0	2,2
4	1,7	0,05	0,6	0,7	0,4

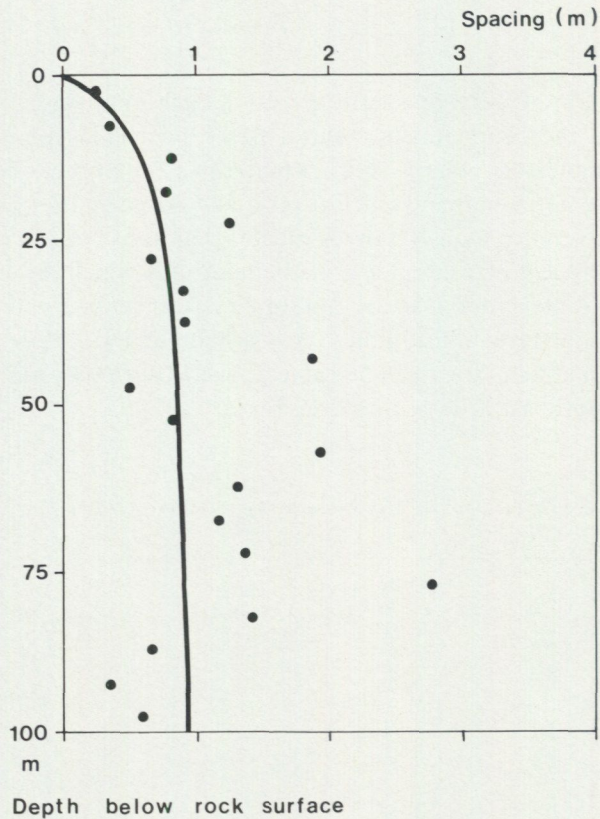
Fig. 14. Spacing *versus* depth obtained in drill-hole DBT-1 (A. Carlsson 1979).

Table 4 gives the roughness values for each of the joint sets. As regards this parameter, the horizontal set has the roughest fracture planes, but this difference between the sets is not as significant as for the apertures and spacing.

TABLE 4. Roughness values obtained at Unit 3.

Joint set	Roughness value			Number of surfaces measured
	Non-coated	Mineral-coated	Total mean	
1	0,30	0,24	0,27	60
2	0,32	0,22	0,27	60
3	0,24	0,19	0,22	51
4	0,33	0,29	0,31	54
Random	0,30	0,27	0,29	57

There seems to be a good interconnection between the different joint sets. The blocky structure and the relatively high frequency of open fractures indicate that this assumption is correct. Figure 15 gives an example of good interconnection between fractures included in different sets.

The above-mentioned results from the fracture investigation are of interest for the present study as the physical characteristics can be used to explain some of the irregularities obtained in the hydraulic treatment. All the reported parameters are of significance for the ability of a single fracture in the rock mass to transmit groundwater.



Fig. 15. Gneiss-granite with fractures which are well interconnected. Photograph by G. Hansson/N.

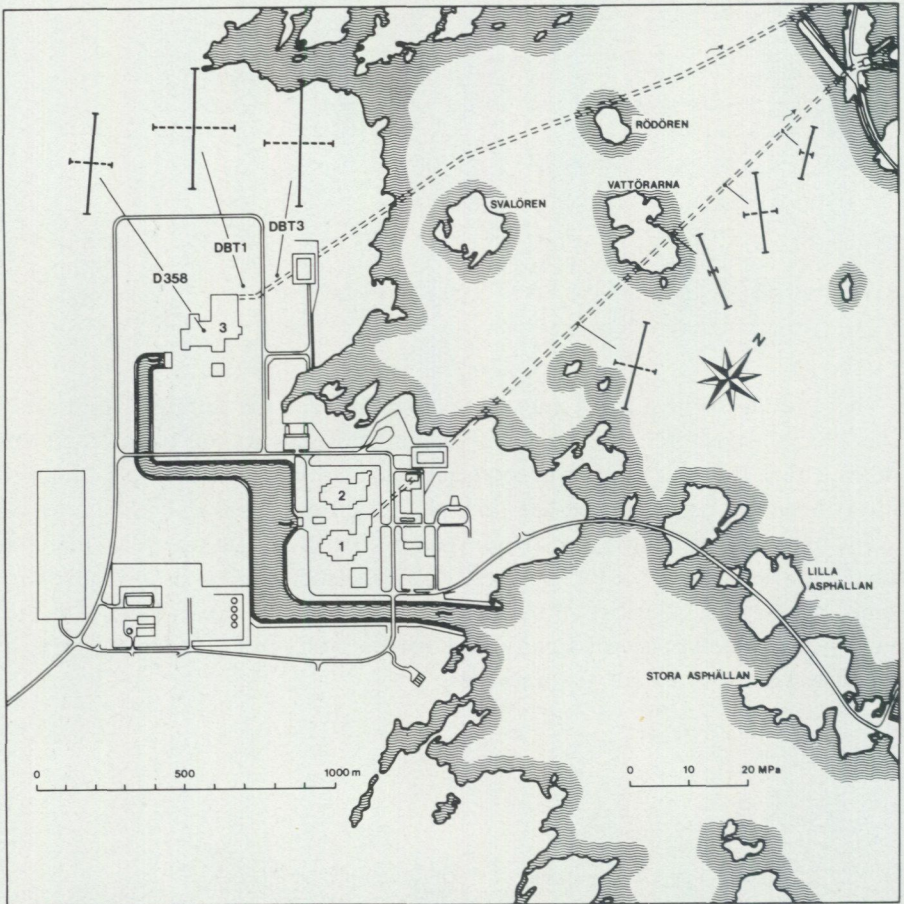


Fig. 16. The mean magnitudes in MPa and the direction of the horizontal principal stresses obtained by measurements in drill-holes in the Forsmark area (A. Carlsson 1979).

ROCK-STRESS DISTRIBUTION

In situ rock-stress measurements were carried out at Forsmark (Hiltscher and Strindell 1976, Hiltscher, Strindell and Martna 1979). These measurements were made in 7 drill-holes as shown in Figure 16. The measuring method used was developed by the Swedish State Power Board and allows measurement of the directions and magnitudes of the principal stresses, whereby the three dimensional stress tensor can be determined.

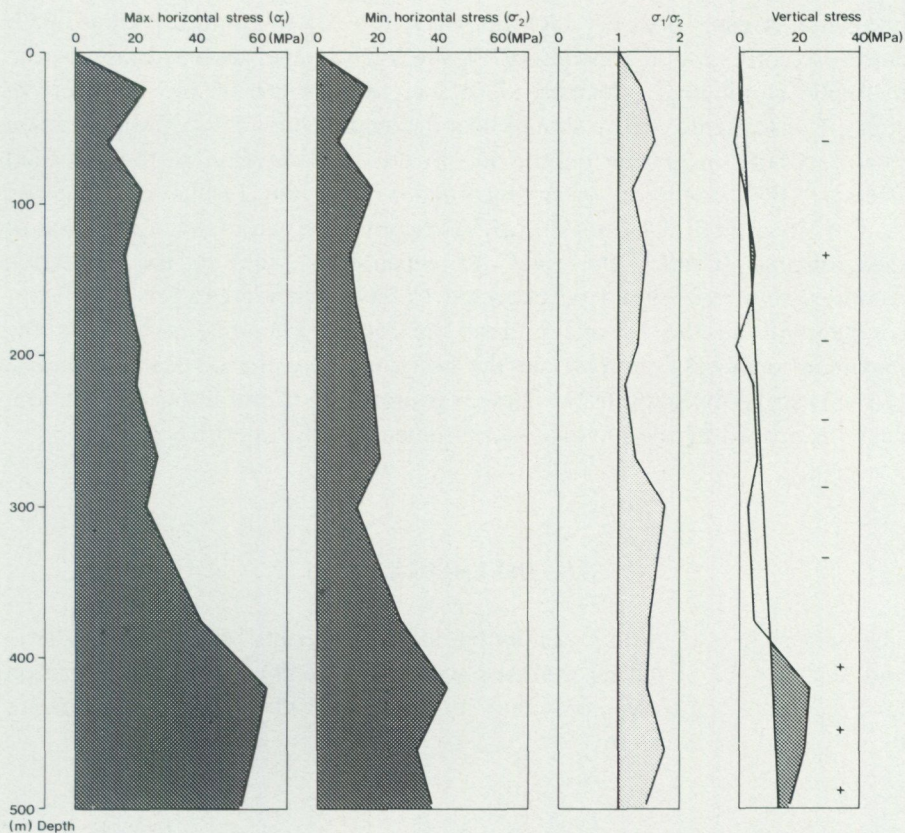


Fig. 17. Principal stresses *versus* depth obtained in drill-hole DBT-1 in the Forsmark area.

In three drill-holes at Unit 3, measurements of the triaxial rock stresses were made at different depth. In two of these drill-holes the measurements have been made at certain intervals down to about 500 m below the rock surface. The result from drill-hole DBT-1 is given in Figure 17. They indicate that the horizontal stresses in the superficial rock mass are very high, generally with a magnitude of 20–30 MPa. As regards directions, there seems to be a clear correspondence between the directions of the principal stresses and the structure of the rock mass. As pointed out by A. Carlsson (1979), the measurements show a close correspondence between the direction of the highest compressive stress and the fracture zones in the area, the fracture orientation and the foliation.

The rock-stress distribution *versus* depth indicates an increase in the vertical stress vector, which is approximately in accordance with the weight of the overburden, although tensile stresses exist even at great depth. The

horizontal stresses are very high but they, too, show a minor increase with depth. According to T. Olsson (1979), the fracture apertures and thereby the hydraulic conductivity decrease with increasing value of the compressive stress. Consequently, there should be a decreased conductivity for all existing joint sets with increasing depth, due to the total increase in the principal stresses. This condition is in accordance with the results obtained by A. Carlsson and T. Olsson (1977a). As regards the variations in direction of the principal stresses, the joint set which is parallel to the maximum compressive stress should be expected to have wider apertures and higher conductivity. In the Forsmark area, the sets which strike parallel to the maximum compressive stress are the horizontal and the vertical sets with a NW-SE strike direction (S2). These sets are likely to fulfill this expectation, which is proved by the physical measurements of the apertures.

SITE INVESTIGATIONS

The present investigation is mainly based on the results obtained by Larsson and Moberg (1975) during the geophysical and geological site investigation for Forsmark Unit 3. Here only those explorations will be described which are directly used for the study.

GEOLOGICAL AND GEOPHYSICAL SITE EXPLORATION

Extensive geophysical investigations provided the basis for the more detailed exploration. In all, over 100 km seismic profiling has been carried out in the Forsmark area, primarily to identify zones of weakness in the rock mass, but also to produce information on the soil cover.

Based on the geophysical measurements, core drillings were executed, some located in zones where the geophysical results indicated weak rock but the majority derived from the layout of the unit. For the three units more than 10 km of core and percussion drilling have been carried out to date.

Core drilling in combination with water-injection tests was used for the first part of the drilling program. After the final location of the units a second stage of drilling was carried out but this time as percussion drilling combined with TV-inspection and water-injection tests.

Three core drillings (two vertical and one inclined) were made for the purpose of research on the state of stress in the rock mass. These drillings are of special interest as they reach a depth of about 500 m and the state of stress was measured at fixed intervals along the holes. In accordance with the

exploration drillings, these drill-holes were also hydraulically tested. To date the water-pressure tests have been made down to about 150 m, but the measurements will later be continued to full depth.

WATER-INJECTION TESTS

As this study is based in large measure on results obtained from water-injection tests, it seems valuable to give a fairly extensive description of the method, its positive and negative conditions and various sources of error. A more detailed account may be found in A. Carlsson and T. Olsson (1979).

GENERAL

The measurements of water loss to determine the relative imperviousness of a bedrock is a test method which has long been used in geological and geophysical site explorations for construction projects. The aim of these tests (Lugeon-tests) was to obtain a comparative value of the imperviousness while the absolute hydraulic conductivity in standardized dimensions was not determined.

In the course of many years of construction work, the Swedish State Power Board has devised routines for testing and judging which are directly adapted to specific problems. Some of these routines can be modified for use in other hydrogeological investigations, such as determination of the hydraulic conductivity.

The water-pressure test (or water-injection test) can be defined as a reversed pumping test. In the pumping test (pumping out) the level of the groundwater is lowered, which results in a potential gradient. In the water-pressure test (pumping in), however, water under a certain pressure is forced into the rock mass, which also gives rise to a potential gradient. Both methods cause a controlled disturbance of the normal state of groundwater flow. The hydraulic properties of the water-bearing medium can be determined from the effect of a given disturbance.

The use of the water-pressure test for determining the rock imperviousness was first described by Lugeon (1933) and has ever since been used worldwide for engineering purposes. The water flow around a test section during a water-pressure test is shown in Figure 18. This flow pattern is valid, provided that the water-bearing medium is homogeneous and isotropic. In a fractured medium the water flow will be governed by the intersecting fractures.

Assuming that the tested rock mass is homogeneous and isotropic, and that

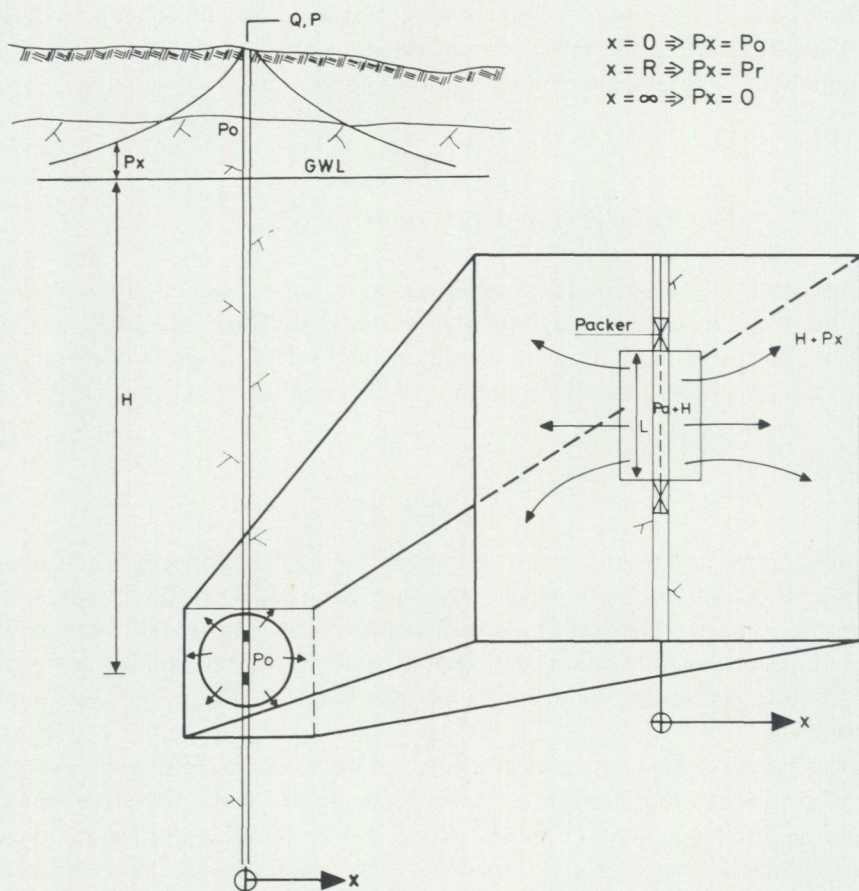


Fig. 18. The principle of the flow conditions in a rock mass during a water-injection test. In the vicinity of the test section the flow is radial from the drill-hole (A. Carlsson and T. Olsson 1979).

steady-state flow is obtained, the following relation may be derived, which gives the hydraulic conductivity of the tested section of the rock.

$$k = \frac{Q}{2\pi HL} (1 + \ln L/d), \quad (1)$$

where k = hydraulic conductivity (LT^{-1}),
 Q = water consumed during the test (L^3T^{-1}),
 H = hydraulic pressure (L),
 L = length of the test section (L),
 d = diameter of the test section (L).

This equation is applied in the present paper in order to determine the conductivity. The obtained conductivity then allows calculation of the fracture conductivity, aperture and kinematic porosity.

SOURCES OF ERROR

Stationary flow conditions must prevail for this method to be valid. Usually, due to the very short measuring times, transient conditions exist, which is the basic disadvantage of the water-pressure test. With more exact instrumentation it is possible to analyse the transient groundwater flow, which would increase the application of the method.

A faulty flow-meter or a leakage, either in the pipe system or at the packers, will lead to an incorrect value of the water intake of the rock mass. It is possible to diminish the risk of leakage at the packers by means of a multiple packer system which yields three separate test sections where the centre one is used for the test while those on each side provide long leak routes around the packers (cf. Maini 1971).

The head loss within the testing equipment causes a decrease in the hydraulic pressure. At low flow rates, the head loss is comparatively small but it increases with increasing water flow. Since the difference between the initial hydraulic pressure at the ground surface and the true pressure down in the test section is caused by this head loss it is essential to consider this effect either by measurements downhole or by corrections due to the losses.

The skin effect is known from pumping tests and causes a marked drop in the draw-down curves in the vicinity of the drill-hole, i.e. within the skin. Here the conductivity is significantly lower or higher than in the rest of the formation. This effect is generally supposed to result from the drilling operation, the completion technique and pumping practices used, which damage the aquifer (cf. van Everdingen 1953 and Hurst 1953).

The calculation method is based upon Darcy's Law and therefore derives from the same assumptions as regards validity. One of the most important of these assumptions is the demand that a laminar state of flow exists. The essential difference between laminar and turbulent flow is that the velocity of the laminar state is in proportion to the potential gradient, while that of the turbulent state is in proportion to the square root of the gradient. In addition, all intermediate stages occur as well. To correct for this effect it is necessary to make the tests with gradually increasing hydraulic pressure.

In connection with the water-pressure test, several effects are produced by the increase in the hydraulic pressure. These effects cannot be attributed to losses or turbulence, but probably to changes and impact on the water-bearing formation. Figure 19 illustrates some of the relationships between the hydraulic head and the flow which are due to such impacts on the formation.

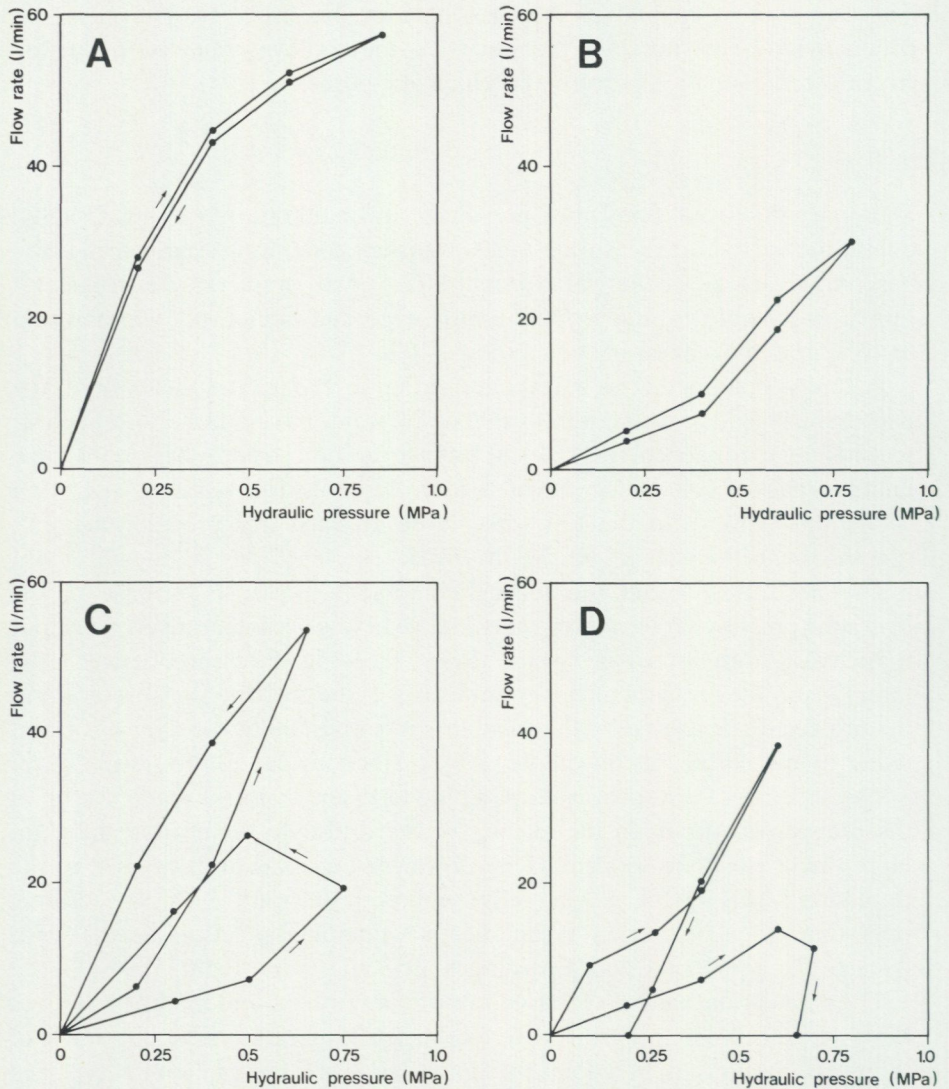


Fig. 19. Different kinds of test influence. A means turbulence, B rock deformation, C wash-out, D wash-out with re-deposition and compaction. (Modified after A. Carlsson and T. Olsson 1979.)

Figure 19 B shows curves which describe a steep rise in the flow rate at a fairly moderate increase of the head. These measurements were made at depths of 10 m and 20 m in the Forsmark area. The effect is probably due to a widening of the fractures and a consequent increase in conductivity. Depending on the hydraulic pressure, a deformation of the rock appears. During the gradual decrease of the head, the consequence of this rock

deformation may either persist or result in a re-tightening of the fractures. In the first case, the flow rate will have a higher value during the head decrease than during the increase. If the fractures re-tighten, the flow rate at the decrease will, on the whole, follow the increase (either as an elastic deformation of the rock mass or as a sudden tightening).

Figure 19 C describes a relation between the hydraulic pressure and the flow rate, where each load increment produces an increasing water flow which is not in proportion to the increase of the pressure. In contrast to the rock-heaving, where the increase of the flow rate was momentary, the increase is here continuous. This effect ensues when the joint system incorporates easily eroded, filling material as at Forsmark. Another effect of filling is illustrated in Figure 19 D. Here the curves at the onset present the same wash-out as indicated in Figure 19 C, but higher pressures will be accompanied by redeposition and compaction of the eroded material and thereby a decrease in flow rate. This combined effect ensues during the increase of pressure and is due to wash-out, redeposition and compaction of the filling material.

All these effects are proportional to increasing hydraulic pressure in the test section; therefore it is crucial that determinations are made at low acting heads in order to reflect the natural conditions of the rock mass in the best way. However, the increased pressure is of interest in order to elicit further information concerning the state of flow and the characteristics of the rock mass and its fractures.

HYDRAULIC PROPERTIES OF FRACTURED AQUIFERS HYDRAULIC CONDUCTIVITY

There are several different methods of obtaining the hydraulic conductivity of an aquifer, both *in situ* and laboratory tests. However, in this paper the said water-pressure test is used. The conductivity can be determined from the following equation (cf. A. Carlsson and T. Olsson 1979).

$$k = \frac{Q}{LH} \left(\frac{1 + \ln(L/d)}{2\pi} \right), \quad (1)$$

- where k = hydraulic conductivity (LT^{-1}),
 Q = injected water flow (L^3T^{-1}),
 L = length of the test section (L),
 d = diameter of the test section (L),
 H = hydraulic head in the test section (L).

This equation gives the conductivity of the rock mass in the test section under the presumption that stationary flow conditions prevail and the water-bearing formation is isotropic and homogeneous. Neither of these presumptions are fulfilled as a rule, but nevertheless, the equation more or less holds good as shown by, *inter alia*, A. Carlsson and T. Olsson (1979) and L. Carlsson *et al.* (1979).

The hydraulic conductivity provides the basis for further calculations of other characteristic properties, such as apertures and porosity.

FRACTURES AND FRACTURE PROPERTIES

In order to evaluate the quality of the individual fractures which intersect the rock mass in the Forsmark area, some characteristic properties of the fractures were determined. Assuming that the fracture frequency or spacing is known, it is possible to calculate the fracture aperture and conductivity. In addition, the kinematic porosity of the rock mass can be estimated.

In a rock mass consisting of rock material and transecting discontinuities, the hydraulic conductivity will constitute an integrated mean value of the conductivity of the different elements. The conductivity of a section with the length L and unit breadth will be

$$k = \frac{1}{L} (b_1 k_1 + b_2 k_2 + \dots + b_n k_n), \quad (2)$$

where k = hydraulic conductivity of the section (LT^{-1}),

L = length of the section (L),

b_i and k_i = width and hydraulic conductivity of the single elements (L and LT^{-1}).

This relation is illustrated in Figure 20.

Assuming that all fractures included in the section have the same apertures and spacing, equation (2) becomes

$$k = \frac{1}{S} (ek_j + (S-e)k_r), \quad (3)$$

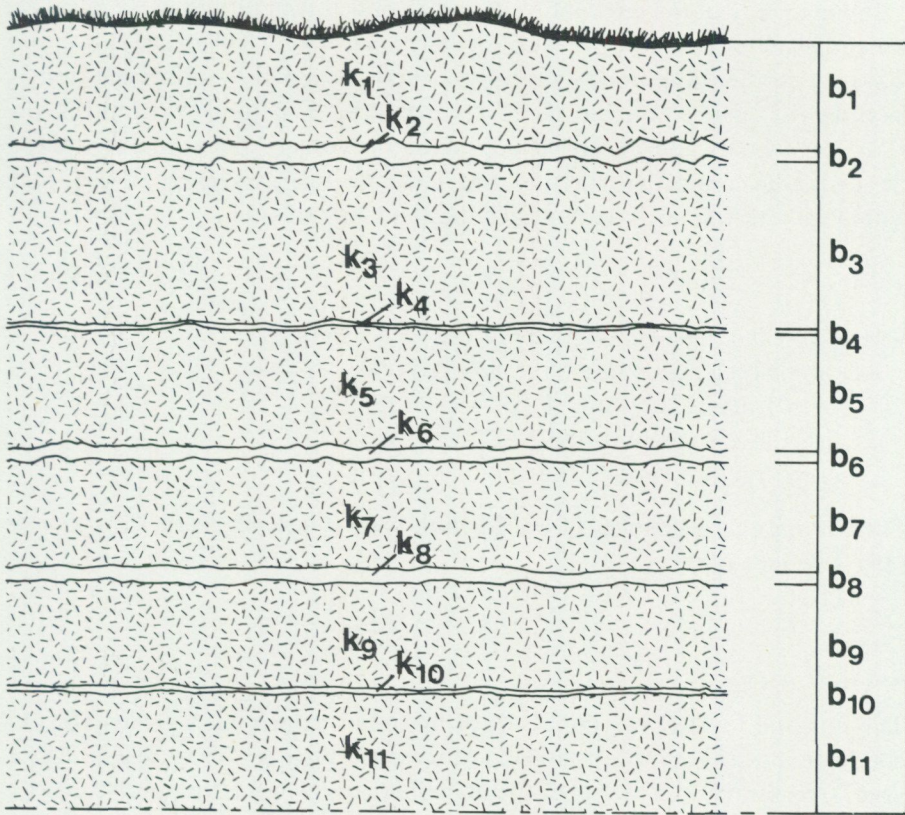
where k = hydraulic conductivity of the rock mass (LT^{-1}),

k_j = hydraulic conductivity of the fractures (or joints) (LT^{-1}),

k_r = hydraulic conductivity of the rock matrix (LT^{-1}),

S = fracture spacing (L),

e = fracture aperture (L).



$$L = \sum_{i=1}^n b_i \quad k = \frac{1}{L} \sum_{i=1}^n b_i k_i$$

Fig. 20. Schematic view of the structural elements in a rock mass and their implications for the rock-mass conductivity (T. Olsson 1979).

The conductivity values for the rock mass and the rock matrix reported in the literature (k about $10^{-8} - 10^{-6}$ m/s and k_r about $10^{-15} - 10^{-10}$ m/s) imply that $k_r \ll k_j$, and also that $e \ll S$. Hence, it is possible to reduce equation (3) to

$$k = \frac{e}{S} k_j, \tag{4}$$

which is equal to

$$k = n e k_j, \tag{5}$$

where $n =$ fracture frequency (L^{-1}).

Thus, the hydraulic conductivity of the rock mass is a function of fracture spacing/frequency, fracture aperture and fracture conductivity.

In the middle of the last century Poiseulle and Hagen produced a derivation which describes laminar, parallel flow in narrow slots. This basic derivation was later further developed by means of theoretical and experimental studies in order to elicit a suitable description of flow in natural fractures. Snow (1965) and Louis (1967) carried out laboratory tests of the relation between the hydraulic conductivity and fracture characteristics. Assuming parallel flow within smooth fractures Snow states the following relation.

$$k = \frac{ge^3}{12vS}, \quad (6)$$

where k = hydraulic conductivity of the rock mass (LT^{-1}),

g = acceleration due to gravity (LT^{-2}),

e = fracture aperture (L),

v = kinematic porosity (L^2T^{-1}),

S = fracture spacing (L).

Considering the roughness of the fracture walls which divert the flow, Louis (1967) deduced that

$$k = \frac{ge^3}{12vCS}, \quad (7)$$

where $C = (1 + 8.8 \xi^{1.5})$.

The function C describes the effect of the relative fracture roughness on the conductivity, as derived from laboratory experiments. According to Louis (1967) the term ξ is probably of the magnitude 0.4 – 0.5 for natural fractures, which gives a value for the C -function approaching 4. This means that the conductivity in a rough fracture is about 25 per cent of that in a smooth one.

Groundwater flow in natural fractures normally takes place under non-parallel conditions, which indicates that equation (7) best satisfies natural conditions. Solving this equation with respect to the fracture aperture, e , gives

$$e = \left(\frac{12kvCS}{g} \right)^{1/3}, \quad (8)$$

which may be used to obtain a value of the fracture aperture. The relation is graphically shown in Figure 21. This method of determining the fracture aperture from the hydraulic conductivity was used by, *inter alia*, Bianchi and Snow (1969), A. Carlsson and T. Olsson (1978).

Nevertheless, the equation gives the aperture of a number of fractures situated within a single test section. A more accurate value of the fracture aperture calls for individual test of each fracture, and the validity of the calculated aperture decreases with increasing size of the test section. In water-pressure tests the measurements are made in test sections of constant length in which at best only a few fractures occur. Thus, the fracture aperture

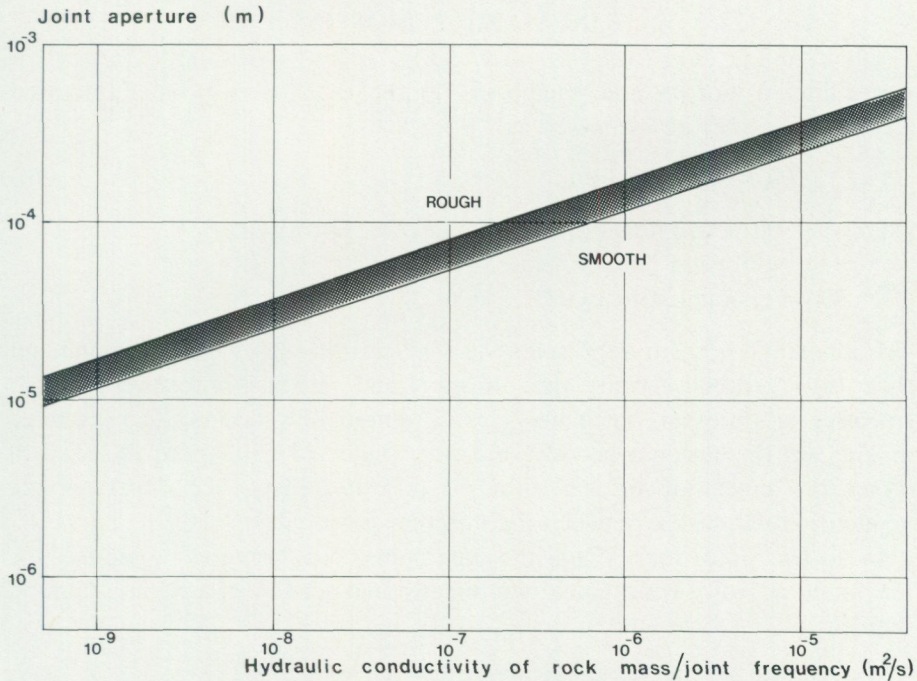


Fig. 21. The relation between the hydraulic conductivity of the rock mass, the fracture frequency and the fracture aperture for rough and smooth fractures. (A. Carlsson and T. Olsson 1978).

obtained is a mean value of all the fractures within the section. Furthermore, it is not feasible to consider the variation in aperture because of irregularities in the fracture planes within a single fracture. The aperture calculated by equation (8) is equal to the essential aperture of a fictive fracture with a continuous, equal opening which can replace the natural fracture without changing the conductivity of the test section.

With a known value of the fracture aperture it is possible to determine the fracture conductivity as seen in equation (5). Solving this equation with respect to the fracture conductivity gives

$$k_j = \frac{k}{ne}. \quad (9)$$

This relation is here used to determine this parameter for each performed test. The parameter, however, will be a hydraulically exact mean value for the test section independent of the fact that the aperture was fictive.

Rocha and Franciss (1977) adopted a similar approach in order to determine the anisotropic conductivity from measurements of the aperture and the fracture orientation. The opposite principle was applied by A. Carlsson and T. Olsson (1978) to determine the apertures from conductivity values.

KINEMATIC POROSITY

According to Norton and Knapp (1977) the total porosity in a fractured medium, Θ_T , may be expressed as

$$\Theta_T = \Theta_K + \Theta_D + \Theta_R, \quad (10)$$

where Θ_K = effective flow porosity or kinematic porosity (1),

Θ_D = diffusion porosity (1),

Θ_R = residual porosity (1).

The kinematic porosity represents the fractures through which the dominant fluid flow proceeds, while the diffusion and residual porosities refer to fractures or pores in which no or very limited flow occurs. The fractures making up the residual porosity are not connected with those included in either the kinematic or the diffusion porosity. Figure 22 illustrates the geometric relationship between the different porosities.

In a fractured rock mass the interconnected fractures comprise the kinematic porosity which in a two-dimensional section of unit area can be defined as

$$\Theta_K = e_1 + e_2 + \dots + e_n. \quad (11)$$

With equal fracture apertures and spacing, equation (11) becomes

$$\Theta_K = ne, \quad (12)$$

and with three sets of water-bearing joints with equal properties the kinematic porosity will be

$$\Theta_K = 3ne. \quad (13)$$

Calculations of the porosity based on measurements in drill-holes will result in different porosity values depending on the penetration of the drill-hole in different sets. Moreover, the existing joint sets in fact have different fracture properties, a point discussed by Parsson (1972) and A. Carlsson (1979).

Snow (1968) reports a study of fracture spacing, fracture apertures and kinematic porosity, and presents a method of determining the kinematic porosity from water-pressure tests. With equal penetration in three equal joint sets, the following relation was obtained

$$\Theta_K = 2.4 ne. \quad (14)$$

This equation, together with those above, demonstrates a relationship between the kinematic porosity, fracture spacing and fracture apertures.

An attempt will be made in this work to determine the kinematic porosity from data on fracture frequency and apertures. The theory is based on the

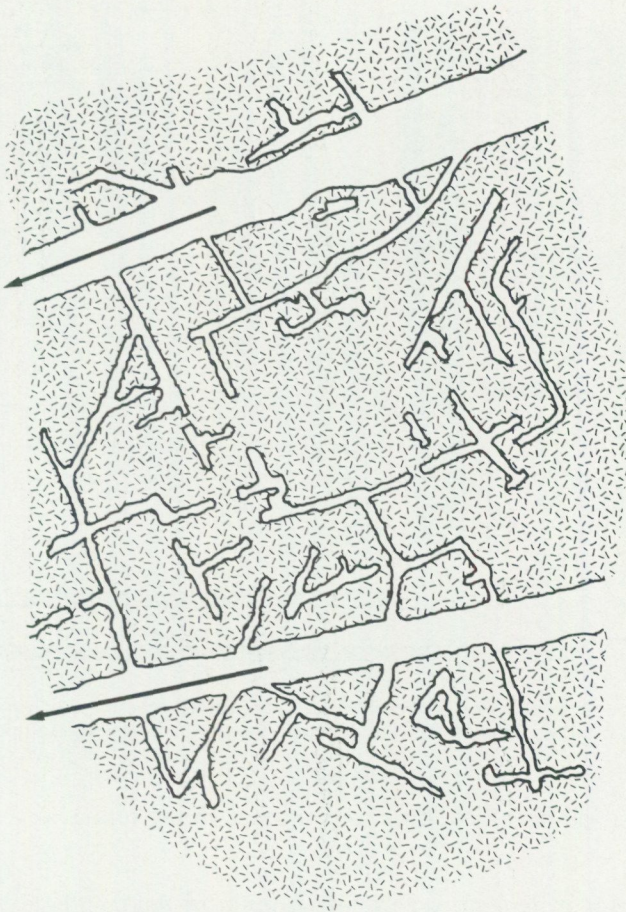


Fig. 22. Schematic representation of the geometric relationship between the different porosities in a rock mass. The arrows denote an arbitrarily chosen direction of water flow within fractures forming the kinematic porosity. The smaller fractures and pores represent the diffusion and the residual porosity (Norton and Knapp 1977).

fact that vertical and inclined drill-holes penetrate the joint sets in different ways. A vertical drill-hole in a rock mass dominated by an orthogonal joint system, like that at Forsmark, will from a theoretical point of view penetrate only the horizontal joint set. Consequently, an inclined drill-hole will penetrate two or three sets depending on the direction of the drill-hole compared with that of the vertical joint sets. These differences are schematically illustrated in Figure 23. As indicated by equation (11), the porosity of a rock mass may be expressed as

$$\Theta_K = \sum n_i e_i. \quad (15)$$

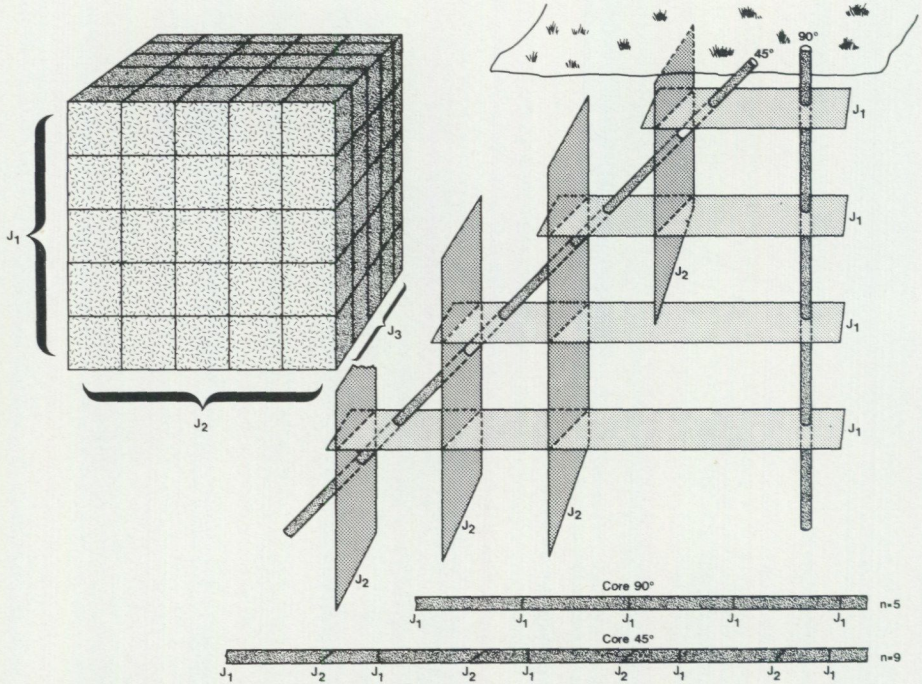


Fig. 23. Differences in penetration between vertical and inclined bore-holes in a rock mass with an orthogonal joint system composed of one horizontal and two vertical sets of fractures.

Data from a single bore-hole may be combined in the following expression.

$$\Theta_K = \sum \delta n_i e_i, \tag{16}$$

where the factor δ depends on the penetration of the drill-hole in different joint sets. Thus it is not possible to determine the porosity if only vertical drill-holes exist. The reason is naturally that the vertical drilling only penetrates the horizontal set, so that no information is obtained about the vertical sets of the orthogonal joint system. In order to simplify the calculations it is possible to disregard the differentiation of the sets and obtain a relation valid for each single drill-hole. This relation is assumed to take the form

$$\Theta_K = \alpha ne, \tag{17}$$

where α = a function which depends on the penetration in the different sets and the differences in frequency and apertures between the sets, n and e = frequency and aperture within a specific section in a specific drill-hole.

With equal frequency, aperture and penetration the α -factor will be 3 as shown by equation (13). (Cf. Snow 1968.)

In the gneiss-granitic rock mass in the Forsmark area with a dominant horizontal set in the superficial rock mass, this set will govern the porosity. As a result of this condition, all drill-holes, both vertical and inclined, will penetrate the dominant set and the α -value will be lower than 3.

These conditions may be verified by a study of the obtained conductivity values with respect to the differences between vertical and inclined drill-holes.

It seems reasonable to assume that the vertical drill-holes in fact only penetrate the horizontal joint set, which implies that the obtained values of frequency and aperture are representative of this set. Accordingly, as regards the inclined holes, it appears feasible that these penetrate both the horizontal and at least one of the vertical sets. The obtained values from the inclined bore-holes will therefore be representative of all existing sets.

In this study it is postulated that the two vertical sets have identical properties. The fracture frequency in an inclined drill-hole with a direction parallel to any vertical set will be composed of the frequency of the horizontal and one of the vertical sets. Thus, the following relation may be applied.

$$(n_h + n_v)\sin\beta = n, \quad (18)$$

where n_h = frequency of the horizontal set,

n_v = frequency of the vertical set,

β = inclination of the drill-hole.

The value of n_v may be determined from this relation since n_h can be regarded as known from the vertical holes. By analogy, it is also possible to determine the apertures of the vertical set

$$(n_h e_h + n_v e_v)\sin\beta = ne. \quad (19)$$

The theoretical real value of the kinematic porosity may be derived from equation (15) while comparison with this value gives an α -value as a function of different inclinations of the drill-holes.

For the Forsmark area these determinations have given $\alpha = 1.26$ for vertical drill-holes and $\alpha = 1.58$ for holes inclined 45° to the horizontal. Analysis of the sensitivity of these determinations resulted in the following ranges for the α -values.

Vertical 1.07–1.52,
inclined 1.35–1.91.

Thus, there is a well defined difference between the various sets. The horizontal set clearly predominates and the additional contribution from the vertical sets to the kinematic porosity normally falls short of 15 per cent for each set.

DATA BASE

The results of the site investigation yielded the following parameters, either directly or via calculation from the information given.

- Fracture frequency or spacing,
- rock type,
- filling or coating material,
- seismic velocity,
- hydraulic conductivity of the rock mass,
- fracture conductivity,
- fracture apertures,
- kinematic porosity.

Apart from the seismic velocity, all parameters are related to individual recordings in drill-holes. This condition makes it possible to obtain both the variation with depth and the mean value for the entire penetrated rock mass. The hydraulic conductivity and fracture frequency were determined for each test section and also as a mean value for each bore-hole. As both double and single packer tests were performed in some of the drill-holes, the conductivity for the bore-holes was determined against the test length as a weighted mean value (cf. A. Carlsson and T. Olsson 1977a). The fracture conductivity, fracture aperture and kinematic porosity were derived from the individual values for the conductivity and fracture frequency in each test section.

The depth values used are generally the vertical distance between the rock surface and the centre of each test section. However, the vertical total depths of the drill-holes were used, so there is a difference in principle between the test sections and the bore-holes as regards the depth.

The seismic velocity is determined as valid for the rock mass at each drill-hole. In the following section of the paper, the results obtained will be summarized and discussed.

This study is based on a large number of water-pressure tests, there being about 1 000 determinations in all 364 test sections distributed over 29 drill-holes.

In order to study this very large stock of data, about 1 000 values of 11 parameters, it was necessary to base the processing and data storage on a computer. A Hewlett-Packard computer was used. Each of the parameters may serve as a search concept for the statistical treatment. The following parameters were included in the processing.

- Drill-hole number,
- inclination of drill-hole,
- test performance, single or double packer measurement,

depth, drill depth or depth of the test section,
hydraulic conductivity of the drill-hole,
hydraulic conductivity of the test section,
fracture frequency,
fracture apertures,
fracture conductivity,
kinematic porosity,
seismic velocity.

The values of the drill-holes for the hydraulic conductivity are given in Table 5 as an example of the deviation.

STATISTICAL TREATMENT

In the main, two different kinds of statistical calculation were performed, basic sample statistics in order to produce mean values and deviation for the individual parameters and regression analyses for the purpose of studying the interconnection of different parameters. As regards the regression analysis, it is of special interest to examine the assumed depth dependence of the hydraulic parameters. The hydraulic conductivity has already been found to be depth dependent (A. Carlsson and T. Olsson 1977a), where a marked decrease in conductivity with increasing depth was deduced.

Some of the afore-said parameters are calculated from the same test results so that a clear correlation exists between the parameters. It is therefore of the greatest interest to calculate the interconnection between the independent parameters, such as, for instance, the seismic velocity and the hydraulic parameters. This of course is essential for the suitability of the seismic measurements as a measure of the water-bearing ability of a fractured rock mass.

CHARACTERISTIC VALUES OF THE PARAMETERS

RESULTS AND DISCUSSION

The sample statistics of all parameters included yielded the characteristic values of the parameters. Table 6 shows basic statistics on the different parameters obtained for the individual test sections. Table 7 presents the corresponding figures for the drill-holes.

A comparison of these two tables demonstrates that the mean and median values of the parameters are of the same order of magnitude. However, the standard deviation, the quartiles and the total deviation (max.-min.) are

TABLE 5. Hydraulic conductivity values representative of each of the bore-holes included in this study.

Bore-hole No	Hydraulic conductivity (m/s)			
	Minimum [†]	Maximum	Weighted mean	Median
D61	$5 \cdot 10^{-8}$	$2 \cdot 10^{-5}$	$6 \cdot 10^{-6}$	$5 \cdot 10^{-8}$
D62A	$5 \cdot 10^{-8}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-7}$
D63	$3 \cdot 10^{-8}$	$3 \cdot 10^{-6}$	$5 \cdot 10^{-7}$	$8 \cdot 10^{-8}$
D64	$4 \cdot 10^{-8}$	$1 \cdot 10^{-5}$	$7 \cdot 10^{-7}$	$7 \cdot 10^{-7}$
D68	$5 \cdot 10^{-8}$	$1 \cdot 10^{-5}$	$6 \cdot 10^{-7}$	$2 \cdot 10^{-7}$
D304	$5 \cdot 10^{-8}$	$1 \cdot 10^{-3}$	$2 \cdot 10^{-7}$	$9 \cdot 10^{-8}$
D305	$5 \cdot 10^{-8}$	$4 \cdot 10^{-6}$	$8 \cdot 10^{-7}$	$4 \cdot 10^{-7}$
D306	$5 \cdot 10^{-8}$	$2 \cdot 10^{-6}$	$6 \cdot 10^{-7}$	$5 \cdot 10^{-8}$
D309	$9 \cdot 10^{-7}$	$9 \cdot 10^{-7}$	$9 \cdot 10^{-7}$	$9 \cdot 10^{-7}$
D311	$5 \cdot 10^{-8}$	$4 \cdot 10^{-7}$	$2 \cdot 10^{-7}$	$5 \cdot 10^{-8}$
D312	$5 \cdot 10^{-8}$	$2 \cdot 10^{-6}$	$4 \cdot 10^{-7}$	$5 \cdot 10^{-8}$
D332	$5 \cdot 10^{-8}$	$8 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$4 \cdot 10^{-7}$
D333	$1 \cdot 10^{-7}$	$2 \cdot 10^{-5}$	$3 \cdot 10^{-6}$	$3 \cdot 10^{-6}$
D334	$2 \cdot 10^{-8}$	$5 \cdot 10^{-8}$	$5 \cdot 10^{-8}$	$5 \cdot 10^{-8}$
D335	$5 \cdot 10^{-8}$	$2 \cdot 10^{-5}$	$1 \cdot 10^{-6}$	$7 \cdot 10^{-8}$
D336	$5 \cdot 10^{-8}$	$8 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-7}$
D337	$5 \cdot 10^{-8}$	$8 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$7 \cdot 10^{-8}$
D341	$5 \cdot 10^{-8}$	$2 \cdot 10^{-5}$	$7 \cdot 10^{-6}$	$6 \cdot 10^{-6}$
D342	$5 \cdot 10^{-8}$	$6 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$6 \cdot 10^{-7}$
D343	$7 \cdot 10^{-8}$	$2 \cdot 10^{-5}$	$5 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
D344	$5 \cdot 10^{-8}$	$2 \cdot 10^{-5}$	$3 \cdot 10^{-6}$	$7 \cdot 10^{-8}$
D345	$5 \cdot 10^{-8}$	$2 \cdot 10^{-6}$	$3 \cdot 10^{-7}$	$2 \cdot 10^{-7}$
D346	$3 \cdot 10^{-8}$	$2 \cdot 10^{-5}$	$3 \cdot 10^{-6}$	$3 \cdot 10^{-6}$
D347	$5 \cdot 10^{-8}$	$2 \cdot 10^{-5}$	$5 \cdot 10^{-6}$	$3 \cdot 10^{-6}$
D348	$5 \cdot 10^{-8}$	$9 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-6}$
D349	$1 \cdot 10^{-7}$	$2 \cdot 10^{-5}$	$4 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
D350	$5 \cdot 10^{-8}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-7}$	$5 \cdot 10^{-8}$
DBT-1	$1 \cdot 10^{-10}$	$3 \cdot 10^{-7}$	$2 \cdot 10^{-8}$	$6 \cdot 10^{-10}$
DBT-3	$2 \cdot 10^{-11}$	$8 \cdot 10^{-7}$	$4 \cdot 10^{-8}$	$4 \cdot 10^{-10}$

† The minimum values usually correspond to the lower limit of the test method. This limit varies due to differences in equipment and purpose of the investigation.

generally greater for the individual test sections. This effect occurs because the values of the bore-holes are based on mean values which *per se* incorporate considerable deviation.

The hydraulic conductivity and the porosity range over several powers, at most eight for the conductivity and three for the porosity. These wide ranges

TABLE 6. Characteristic values obtained by sample statistics for the different parameters based on each single test section.

Parameter		Maximum	Minimum	Mean	Standard deviation	Median	Quartiles		Number of samples
							Q ₇₅	Q ₂₅	
Depth	(m)	154,5	1,8	30,4	33,0	18,0	34,0	11,0	364
Hydraulic conductivity	(m/s)	$1 \cdot 10^{-3}$	$2 \cdot 10^{-11}$	$5 \cdot 10^{-6}$	$6 \cdot 10^{-5}$	$7 \cdot 10^{-8}$	$1 \cdot 10^{-6}$	$2 \cdot 10^{-8}$	358
Fracture conductivity	(m/s)	$6 \cdot 10^{-1}$	$7 \cdot 10^{-6}$	$5 \cdot 10^{-3}$	$3 \cdot 10^{-2}$	$1 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	$4 \cdot 10^{-4}$	328
Kinematic porosity	(l)	$3 \cdot 10^{-3}$	$1 \cdot 10^{-6}$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$8 \cdot 10^{-5}$	328
Aperture	(μ m)	1100	4	66	79	50	90	30	328
Fracture frequency	(No/m)	18,0	0,1	3,4	2,8	2,7	4,1	1,7	333
Seismic velocity	(m/s)	5700	3000	4777	707	4860	5460	4150	364

cause the mean values of these parameters to lie close to the upper limit, as the higher values carry great weight in the determination – the mean value of $2 \cdot 10^{-4}$ and 10^{-10} is $1 \cdot 10^{-4}$. Of all measurements included in this study about 55 per cent show conductivity values below $1 \cdot 10^{-7}$, which gives an overall median value of less than $1 \cdot 10^{-7}$ m/s. This large number of low conductivity values exerts but little influence on the mean value, which amounts to about $2 \cdot 10^{-6}$ m/s. This great weight of the larger values is somewhat misleading, as the mean value may result from one or a few single fractures while the remainder of the rock mass has a very low conductivity or porosity. Drill-hole D 350 for example has a mean conductivity of $1.3 \cdot 10^{-7}$ m/s, which depends on one single zone. The rest of this hole has a conductivity below the limit of the

TABLE 7. Characteristic values obtained by sample statistics of the different parameters based on the mean values of the drill-holes.

Parameter		Maximum	Minimum	Mean	Standard deviation	Median	Quartiles		Number of samples
							Q ₇₅	Q ₂₅	
Depth	(m)	151,4	19,8	41,1	29,9	29,0	44,0	25,0	29
Hydraulic conductivity	(m/s)	$7 \cdot 10^{-6}$	$9 \cdot 10^{-9}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$7 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	29
Fracture conductivity	(m/s)	$2 \cdot 10^{-2}$	$3 \cdot 10^{-4}$	$5 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	$7 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	24
Kinematic porosity	(l)	$7 \cdot 10^{-4}$	$4 \cdot 10^{-5}$	$4 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$6 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	24
Aperture	(μ m)	170	22	90	42	100	200	50	24
Fracture frequency	(No/m)	5,4	1,3	2,8	1,0	2,7	3,4	2,1	24
Seismic velocity	(m/s)	5700	3000	4586	674	4580	5280	4000	29

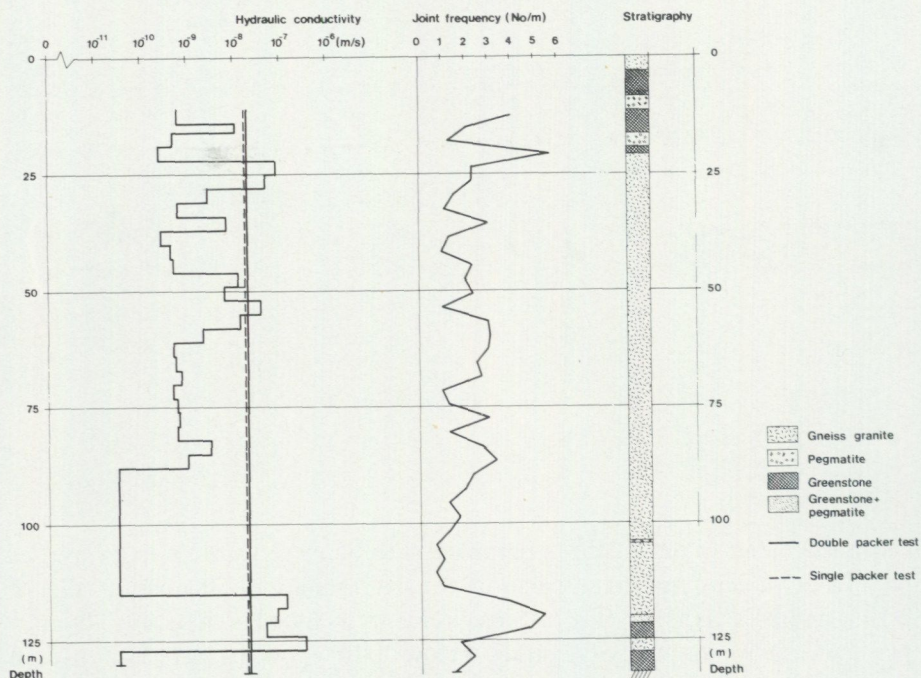


Fig. 24. Hydraulic conductivity values obtained in the bore-hole DBT-3 (A. Carlsson *et al.* 1977).

determination method. Nevertheless, the mean value gives a correct description of the water-bearing ability of the specific section of the rock mass which corresponds to the bore-hole, but for regional estimations the median value is more representative.

The bore-hole DBT-3 may serve to illustrate the correct picture obtained by the mean value (A. Carlsson *et al.* 1977). The results of both single and double packer tests down to 130 m are shown in Figure 24. In all, 40 test sections were used for the double packer tests, which gave a mean value of $2.1 \cdot 10^{-8}$ m/s. Single packer measurements of the entire bore-hole yielded a conductivity of $2 \cdot 10^{-8}$ m/s, which agrees surprisingly closely with the double packer tests.

As regards the reliability of the different parameters, it is necessary to compare the values obtained with other investigations. A great number of determinations of the conductivity are reported in the literature, but it is difficult to find any information on the other parameters for comparison.

Figure 25 consists of a compilation of normally obtained conductivity values in different rock types (L. Carlsson and T. Olsson 1979). As the ranges included in this figure are based on values from bore-holes and valid for the entire bore-hole, it seems appropriate to use the mean conductivity value

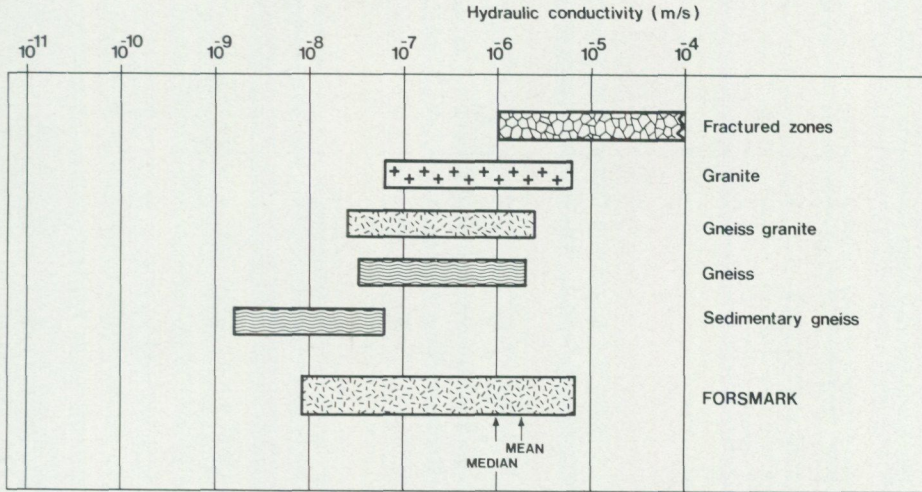


Fig. 25. Values of the hydraulic conductivity of different rock types. The mean value from the present study and its total range are included for reference. (Modified after L. Carlsson and T. Olsson 1979.)

given in Table 7. Thus, this value together with the entire range (max.-min.) is inserted in the diagram. As seen, the values obtained in this study are in good agreement with those in the diagram.

Values of the kinematic porosity are rarely reported in the literature. A previous study along similar lines (L. Carlsson and T. Olsson 1979) shows values of the same order of magnitude as those reported here. A tracer test made in the Finnsjö area (L. Carlsson *et al.* 1979) close to Forsmark shows values which are also in agreement with those presented here.

Several of the determinations of the kinematic porosity which are reported in the literature are summarized in Table 8. The present values are also included in this table and as seen from this comparison, the correspondence between the different values is good, but the variation or the span is wide. However, a minor trend of underestimation may be found for the calculated values compared with those obtained by for instance tracer tests. This effect may be due to the determination method. The values based on tracer tests are probably more accurate. Figure 26 shows some of the reported values together with some from this study related to the hydraulic conductivity. A fair correlation seems to prevail between those parameters, not only for those calculated from the conductivity but also for those produced by other methods.

The same conditions hold for the fracture apertures and the fracture conductivity, although reported values are rare. A. Carlsson and T. Olsson

TABLE 8. Compilation of data of the kinematic porosity reported in the literature.

Rock type	Kinematic porosity	Reference
Gneiss	$1 \cdot 10^{-3} - 2 \cdot 10^{-3}$	1
Granodiorite	$2 \cdot 10^{-3}$	2
Granite	$1 \cdot 10^{-4}$	3
Gneiss	$8 \cdot 10^{-4}$	4
Granite	$2 \cdot 10^{-5}$	5
Quartzdiorite	$2 \cdot 10^{-3} - 3 \cdot 10^{-5}$	6
Granite	$8 \cdot 10^{-4}$	7
Granite	$1 \cdot 10^{-4}$	8
Granodiorite	$2 \cdot 10^{-3} - 7 \cdot 10^{-5}$	9
Gneiss granite	$8 \cdot 10^{-5} - 6 \cdot 10^{-6}$	9
Granite	$2 \cdot 10^{-4} - 2 \cdot 10^{-5}$	9
Gneiss	$4 \cdot 10^{-5} - 1 \cdot 10^{-5}$	9
Gneiss granite	$3 \cdot 10^{-3} - 1 \cdot 10^{-6}$	Present

1. Landström et al. (1978), 2. L. Carlsson et al. (1979), 3. Lundström and Stille (1978), 4. Webster et al. (1970), 5. Pratt et al. (1974), 6. Villas (1975), Rasmussen (1963), 8. Stewart (1962), 9. L. Carlsson and T. Olsson (1979).

(1978) and L. Carlsson and T. Olsson (1979), however, report a number of determinations. The first of these works is based on material from the Forsmark area while the second is a compilation of data from different areas. The reported values and the results of this study are related to the conductivity in Figures 27 and 28. The correlation between the parameters appears valid for these parameters too.

The values of the fracture frequency and seismic velocity are in full agreement with those normally found (cf. Helfrich *et al.* 1979).

CHARACTERISTIC PROPERTIES OF THE FORSMARK AREA

Considering the values obtained for the different parameters and the discussion of each parameter, the rock mass in the Forsmark area may from a hydraulic point of view be characterized as shown in Table 9. Moreover the range of each parameter is obviously wide. Figure 29 gives the distribution of each parameter.

These values may be compared with those presented in another study (A. Carlsson and T. Olsson 1977a), which produced a regional conductivity of

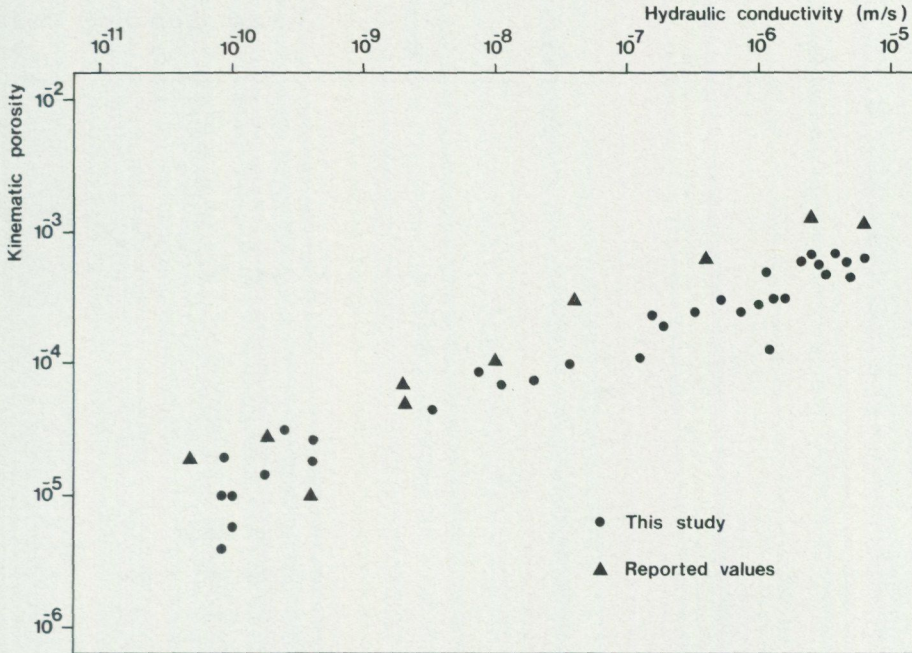


Fig. 26. Kinematic porosity *versus* hydraulic conductivity.

$2 \cdot 10^{-6}$ m/s which is hereby verified. Test pumpings in the area resulted in $2 \cdot 10^{-5}$ m/s (Andersson and Olsson 1978). The test pumpings were however only executed in wells located in large zones of fractured or crushed rock, which of course should yield higher conductivity.

TABLE 9. Characteristic properties of the rock mass at Forsmark

Parameter	Magnitude	Range (Minimum—Maximum)
Hydraulic conductivity (m/s)	$5 \cdot 10^{-6}$	$1 \cdot 10^{-11} - 1 \cdot 10^{-3}$
Fracture conductivity (m/s)	$5 \cdot 10^{-3}$	$7 \cdot 10^{-6} - 6 \cdot 10^{-1}$
Fracture aperture (μm)	70	1 — 1100
Kinematic porosity (l)	$3 \cdot 10^{-4}$	$1 \cdot 10^{-6} - 3 \cdot 10^{-3}$
Fracture frequency (No/m)	2,7	0,1 — 18,0
Seismic velocity (m/s)	4600	3000 — 5700

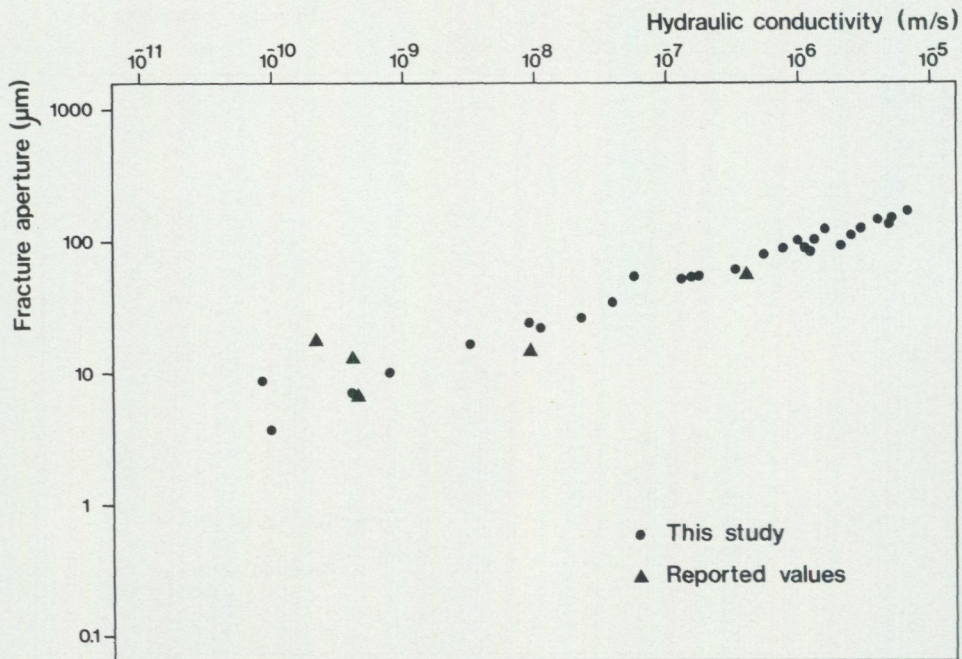


Fig. 27. Fracture aperture *versus* hydraulic conductivity.

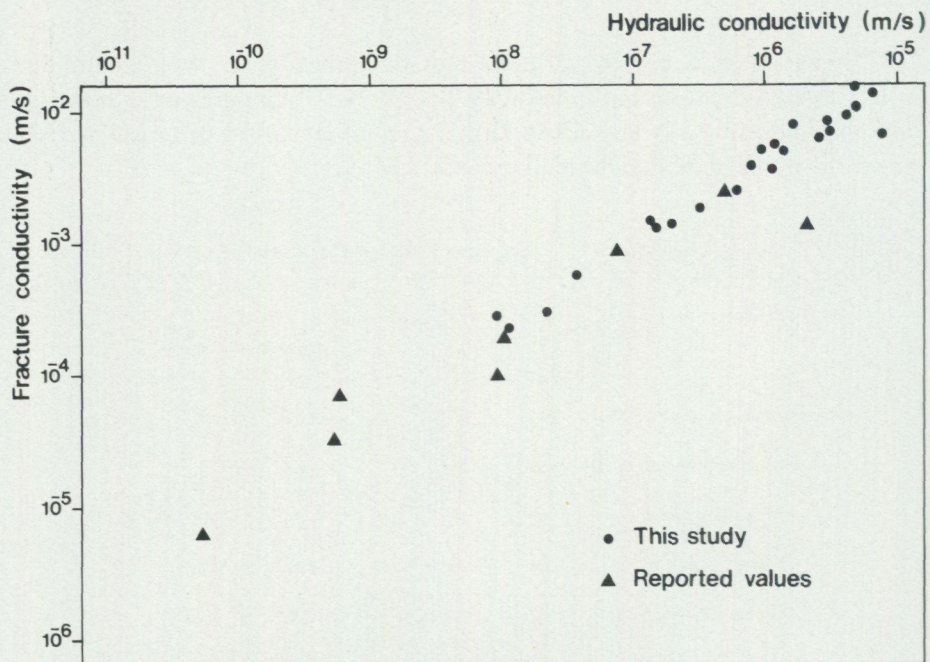


Fig. 28. Fracture conductivity *versus* hydraulic conductivity.

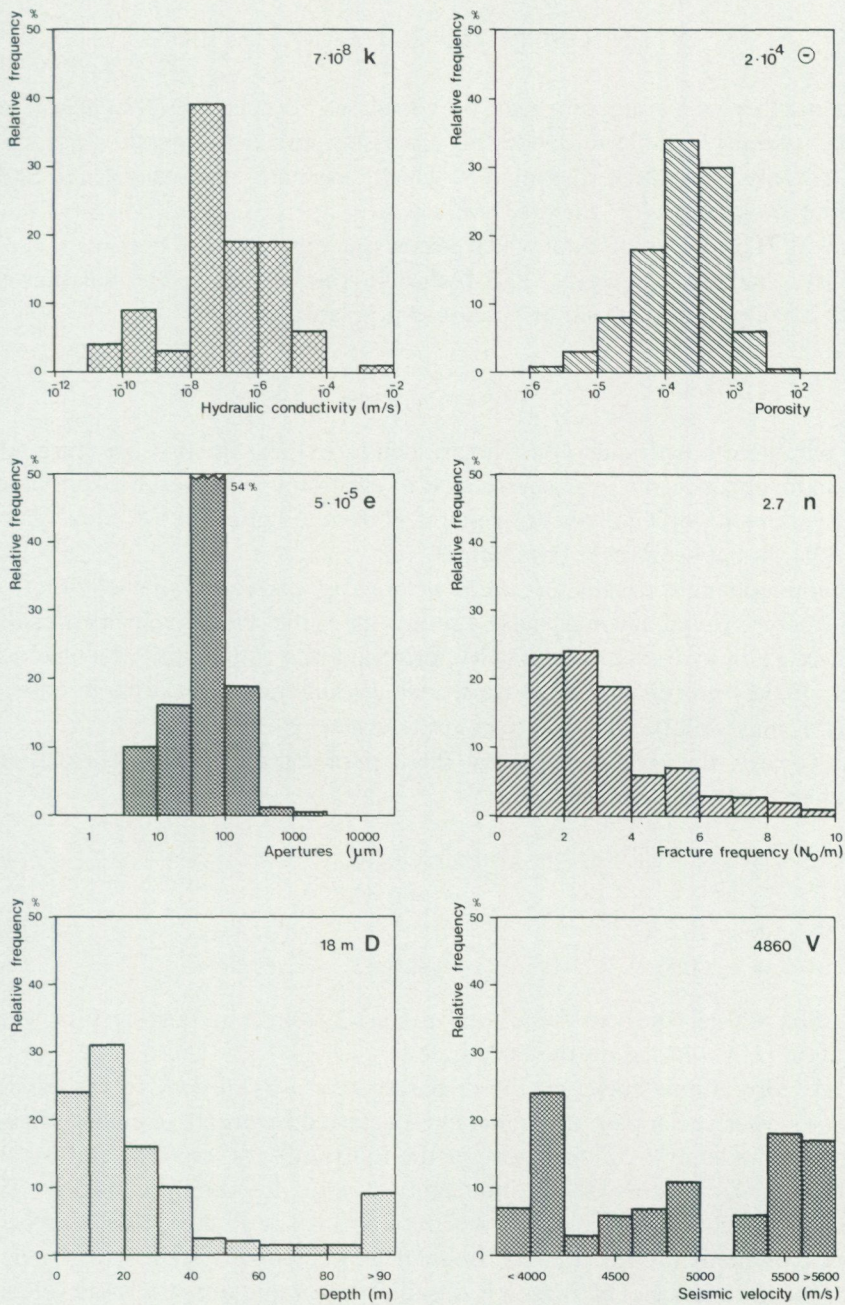


Fig. 29. Distribution of the obtained parameters: hydraulic conductivity, fracture aperture, bore-hole depth, kinematic porosity, fracture frequency, and seismic velocity.

INTERCONNECTION OF PARAMETERS

As a number of parameters may be correlated to each other somehow or other, it seems suitable to divide this discussion into two separate parts, one which deals with those parameters which originate from the same basis (hydraulic conductivity, fracture conductivity, apertures, and porosity), and one with those parameters which were independently obtained (seismic velocity, fracture frequency, and hydraulic conductivity). The relation to depth of all parameters will be discussed in a later section.

CORRELATIONS

The parameters hydraulic and fracture conductivities, fracture aperture and kinematic porosity *per se* are correlated to each other. But results from other independent reports follow the general pattern. Figures 26–28 above show the relation between these parameters.

The independent parameters are in no way pre-correlated to each other. A high fracture frequency may cause a reduction of the seismic velocity and also an increase in hydraulic conductivity, provided that the existing fractures are open. If they are disseminated by secondary minerals or have large contact areas, it may well be that no effect at all ensues.

As regards the relation between these parameters, the best correlations obtained take the following forms.

$$k = 3.2 \cdot 10^{-8} n^{1.3}, \quad r^2 = 0.12, \quad (20)$$

$$k = 1.7 \cdot 10^{-8} n^{3.7}, \quad r^2 = 0.42, \quad (21)$$

$$k = 10^{12} v^{-5}, \quad r^2 = 0.17, \quad (22)$$

$$v = 6086 - 9.26 \sqrt{n}, \quad r^2 = 0.13. \quad (23)$$

Equation (20) is derived from total material from each test section while equation (21) is based on the bore-holes.

The correlation between these parameters was tested by regression analyses where each pair of parameters was tested according to eight different models. The analyses were made for the individual test sections and for the drill-holes as regards the conductivity *versus* fracture frequency. The regressions where the seismic velocity was included, the seismic velocity *versus* conductivity and fracture frequency, were only tested with the data from the bore-holes. The reason is that only one value of the seismic velocity was obtained for each bore-hole, thus, this value should correspond to the properties of the rock mass at the bore-holes. Hence great care must be taken in these correlations because of the indirect nature of the seismic method and the fact that only one measurement was made at each drill-hole. The seismic

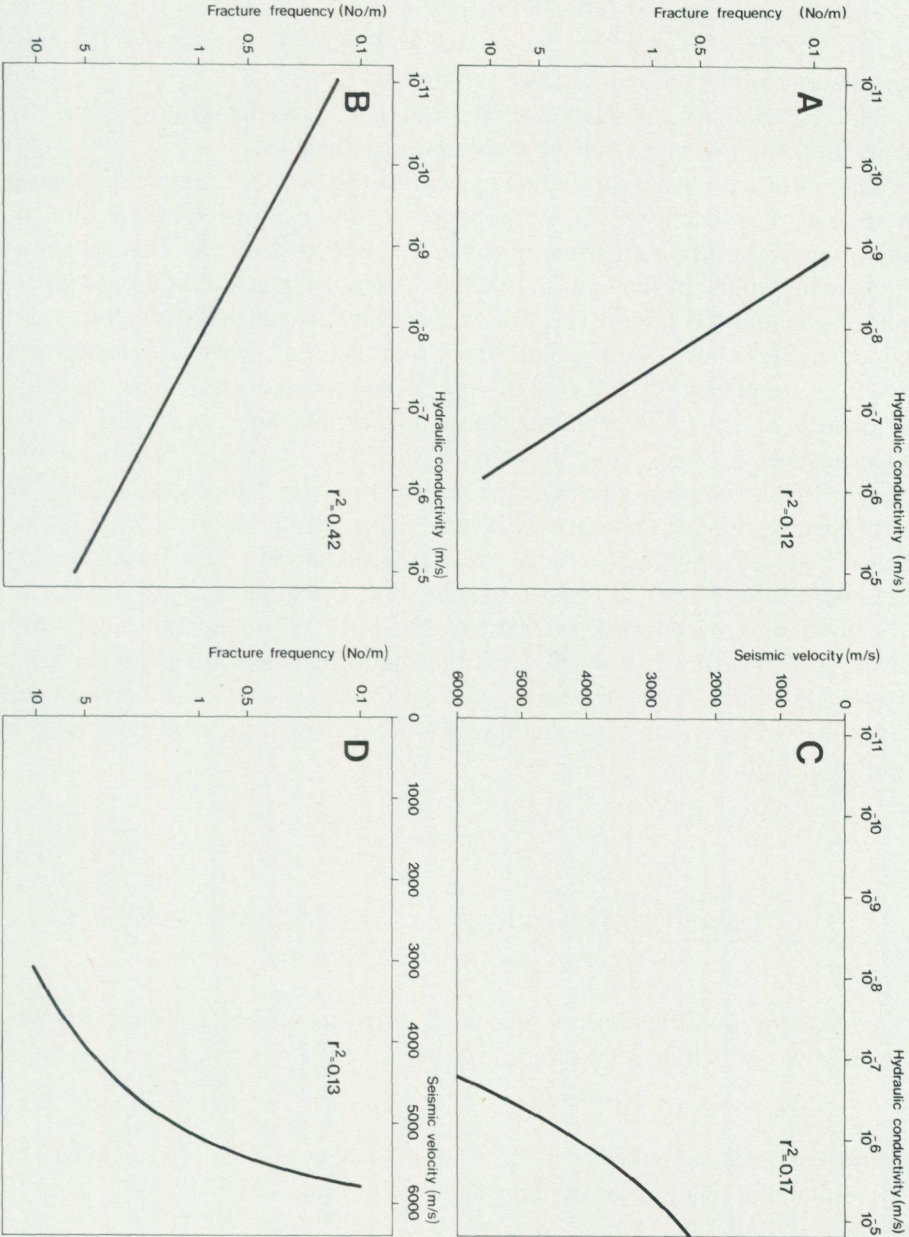


Fig. 30. Relations between seismic velocity, hydraulic conductivity and fracture frequency. A means hydraulic conductivity *versus* fracture frequency based on the test sections, B do. based on the bore-holes, C hydraulic conductivity *versus* seismic velocity, D fracture frequency *versus* seismic velocity.

velocity is also greatly dependent on the direction of the seismic profile related to the direction of the fractures. Figure 30 a-d shows the best correlations obtained between the parameters.

The correlations obtained are not too good, as demonstrated by the comparatively low values of the correlation coefficients.

The most clear-cut correlation concerns the fracture frequency *versus* hydraulic conductivity, which implies that the existing fractures are of importance for the water-bearing ability of the rock mass. This fact also implies that many of the existing fractures are partly open although normally mineral coated (cf. Figure 11). The correlation between seismic velocity and conductivity is also fairly good while that between seismic velocity and fracture frequency is surprisingly poor. As pointed out above, a high frequency of fractures should increase the conductivity and decrease the velocity, but as seen from the correlations, the frequency carries greater weight for the conductivity than the seismic velocity. This condition may be explained by the fact that narrow fractures have only a minor influence on the seismic velocity although crucial for the conductivity. This indicates that seismic investigations are most suitable for detection of large zones of fractured or crushed rock intersecting the rock mass and not small such features. However, in order to pass final judgement on this matter a more systematic study of the relations must be made. The relation between the hydraulic conductivity and the fracture frequency from one bore-hole is shown in Figure 31.

DEPTH DEPENDENCE OF THE PARAMETERS HYDRAULIC CONDUCTIVITY

The present investigation produced a correlation *versus* depth for the conductivity which is as follows.

$$k = 7.3 \cdot 10^{-7} e^{-0.07D} \quad (24)$$

with a correlation coefficient of 0.51 based on all individual test sections. The corresponding relation for the bore-holes is

$$k = 2.2 \cdot 10^{-6} e^{-0.03D} \quad (25)$$

with a coefficient of 0.28.

Hence, these relations differ in kind from those reported by A. Carlsson and T. Olsson (1977a). Their main relation is

$$k = 10^{-(1.65 \log D + 4.5)} \quad (26)$$

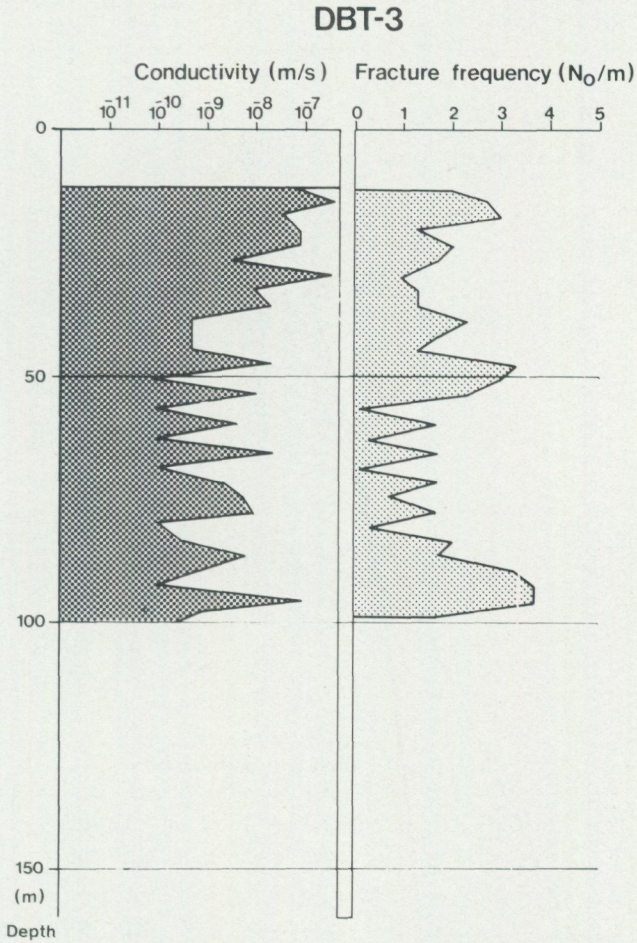


Fig. 31. The relation between hydraulic conductivity and the fracture frequency obtained in DBT-3.

or the equivalent

$$k = 3.2 \cdot 10^{-5} D^{-1.65} \quad (27)$$

However in the present study similar relations were also obtained:

$$k = 5.7 \cdot 10^{-5} D^{-2.2} \quad (28)$$

for the individual test sections with a coefficient of 0.46. The corresponding relation for the bore-holes was

$$k = 2.2 \cdot 10^{-4} D^{-1.6} \quad (29)$$

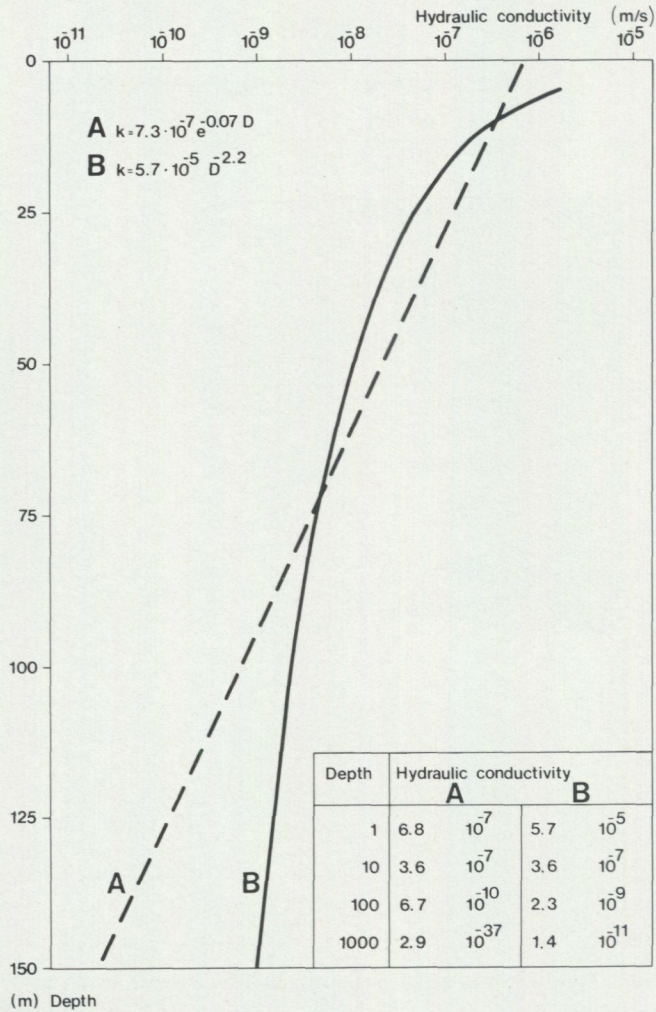


Fig. 32. Hydraulic conductivity versus depth, with two different relations obtained from the individual test sections.

with a coefficient of 0.27. These latter equations are in good agreement with those presented by A. Carlsson and T. Olsson (1977a). It should also be noted that equations (26) and (27) are derived from information from five different areas, one of which is Forsmark, and that the relations are based on the total number of measurements from all areas. As pointed out above, the bore-holes and the test sections are not treated similarly as regards the depth. The depth used for the drill-holes is equal to the vertical projection of the total depth, which values are related to the integrated mean value of the rock mass down to this depth. As regards the test sections, the depth is the actual

TABLE 10. Conductivity values for different depth according to equation (29) (k) and equation (27) (k^+).

Depth	k	k/k_{1m}	k^+	k^+/k_{1m}^+
1m	$3,2 \cdot 10^{-5}$	1	$5,7 \cdot 10^{-5}$	1
10m	$7,2 \cdot 10^{-7}$	$2,2 \cdot 10^{-2}$	$3,6 \cdot 10^{-7}$	$6,3 \cdot 10^{-3}$
100m	$1,6 \cdot 10^{-8}$	$5,0 \cdot 10^{-4}$	$2,3 \cdot 10^{-9}$	$3,9 \cdot 10^{-5}$
1000m	$3,6 \cdot 10^{-10}$	$1,1 \cdot 10^{-5}$	$1,4 \cdot 10^{-11}$	$2,5 \cdot 10^{-7}$

vertical distance to the centre of the section. This difference impairs the accuracy of the relation obtained for the drill-holes; consequently equations (24) and (28) best reflect the actual hydraulic properties of the rock mass.

The best correlation obtained in the present study produces a decrease in conductivity which is not reliable, as seen in Figure 32. This relationship states a very low conductivity at a depth below 100 m, which has no support in observations to date. The close correlation obtained according to that relation probably results from some deep seated low conductive parts of the rock mass, which exert a considerable influence of the correlation. Consequently, as the second best obtained relation also has a fairly high correlation coefficient and this is in accordance with earlier reported results (A. Carlsson and T. Olsson 1977a), it seems reasonable to assume that this relation (equation 28) is the most accurate.

The main difference between the results reported by A. Carlsson and T. Olsson (1977a) and those presented here is the gradient *versus* depth. This condition is summarized in Table 10, where both relations are treated similarly. Table 10 shows that the starting values at 1 m depth are about the same, but the decreases with depth differ. The gradient obtained in the present study is steeper indicating a faster decrease in conductivity with increasing depth. This is graphically illustrated in Figure 33.

In order to visualize the variations in conductivity with depth, the two deepest drill-holes included in the study were also analysed. The best correlations obtained are

$$k = 1.4 \cdot 10^{-8} D^{-6} \text{ (DBT-1)}, \quad (30)$$

$$k = 1.9 \cdot 10^{-4} D^{-2.8} \text{ (DBT-3)}. \quad (31)$$

The correlation coefficients are 0.02 and 0.40. These relations as well as the individual test results are shown in Figures 34 and 35. As seen from the correlation coefficients and the equations, the variation between different bore-holes may be significant. The best agreement with the general view

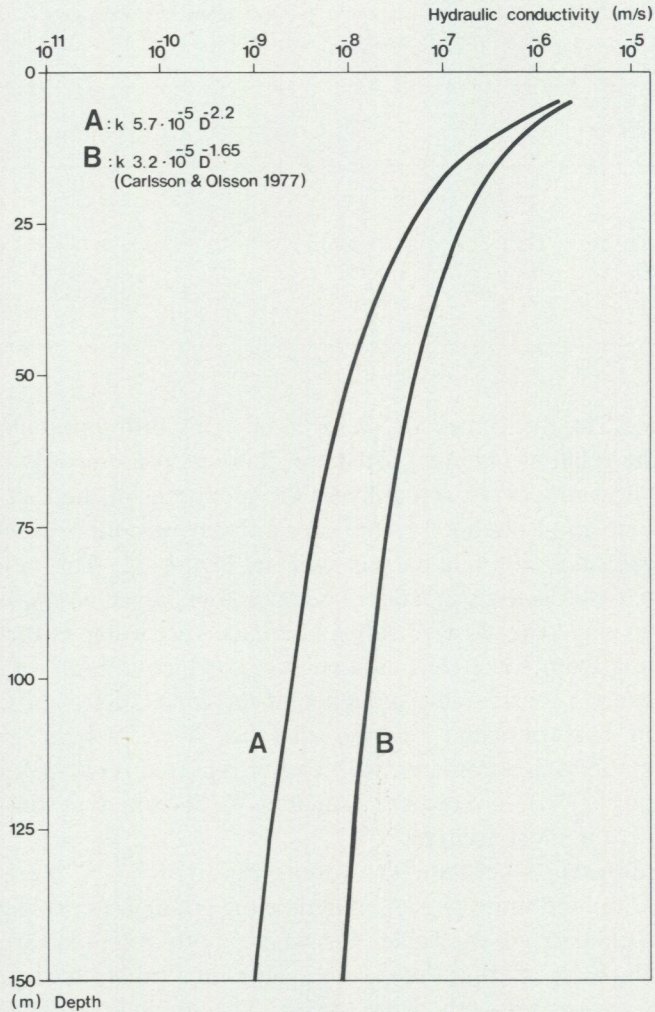


Fig. 33. The depth dependence obtained in this study compared with that deduced by A. Carlsson and T. Olsson (1977a).

relates to bore-hole DBT-3 while DBT-1 shows a very distant correspondence with an extremely weak gradient. The reason for these discrepancies is that for most of its length bore-hole DBT-1 traverses a rock mass with very low conductivity, but some minor zones of more conductive rock are also present. In the impervious rock mass, the existence of conductive zones carries great weight. This may be seen in Figure 34. On the other hand, bore-hole DBT-3 penetrates a more commonly found rock mass. These bore-holes illustrate the very great differences which may occur within the same rock mass. Therefore

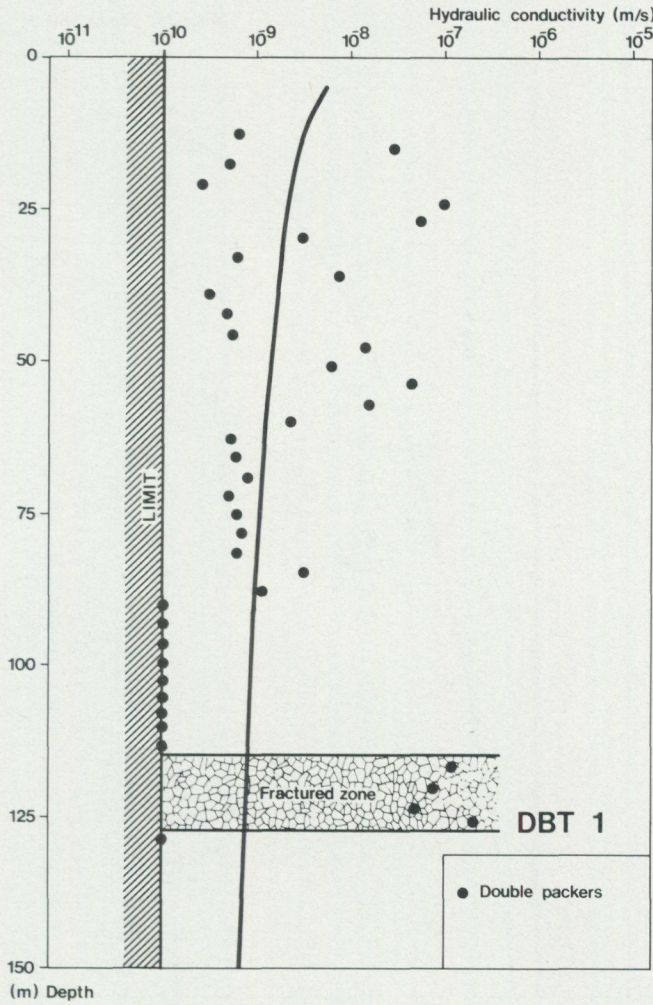


Fig. 34. Hydraulic conductivity versus depth at bore-hole DBT-1.

it must be stressed that the relations obtained are only statistically significant, while a specific bore-hole may have its peculiar features. Statistically speaking, however, it is obvious that the general trend is decreasing conductivity with increasing depth.

FRACTURE CONDUCTIVITY, APERTURES, FREQUENCY, AND KINEMATIC POROSITY

For these parameters the best and the second best obtained correlations are shown in Table 11. With the exception of the fracture frequency, the relations

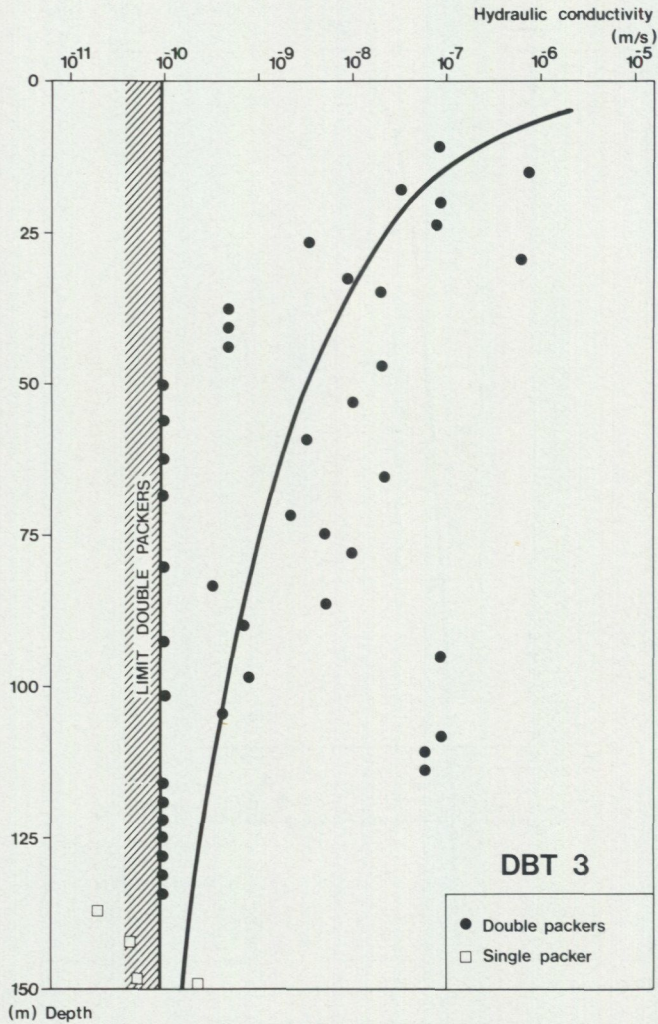


Fig. 35. Hydraulic conductivity *versus* depth at bore-hole DBT-3.

derived from the individual test sections show much better correlation than those based on the bore-holes. This situation prevails despite the far greater number of values included in the correlation of individual data. According to the Table, three models for the regression dominate. These are

$$Y = A e^{-BX}, \quad (32)$$

$$Y = A X^{-B}, \quad (33)$$

$$Y = A + \frac{B}{X}. \quad (34)$$

TABLE 11. The obtained best and second best correlations for the parameters versus depth, both for the test sections and for the bore-holes.

Parameter	Best correlation Correlation	r^2	Second best correlation Correlation	r^2
Test sections				
k_j	$3,2 \cdot 10^{-3} \cdot e^{-0,05D}$	0,41	$3,1 \cdot 10^{-2} \cdot D^{-1,2}$	0,37
e	$8,1 \cdot 10^{-5} \cdot e^{-0,02D}$	0,41	$2,6 \cdot 10^{-4} \cdot D^{-0,06}$	0,38
n	$4,8 D^{-0,22}$	0,07	$2,9 + 5,25D^{-1}$	0,05
θ	$3,5 \cdot 10^{-4} \cdot e^{-0,03}$	0,36	$1,7 \cdot 10^{-3} \cdot D^{-0,84}$	0,35
Bore-holes				
k_j	$6,2 \cdot 10^{-1} \cdot D^{-1,22}$	0,24	$6,3 \cdot 10^{-3} \cdot e^{-0,02D}$	0,24
e	$6,2 \cdot 10^{-4} \cdot D^{-0,6}$	0,23	$1,1 \cdot 10^{-4} \cdot e^{-0,009D}$	0,23
n	$1,5 + 37,5 D^{-1}$	0,16	$4,3 - 0,06D$	0,14
θ	$4 \cdot 10^{-5} + 0,008D^{-1}$	0,22	$1,1 \cdot 10^{-3} - 2 \cdot 10^{-4} \cdot 1nD$	0,21

In addition two more regression models were obtained. Of these models the first obviously cannot represent the actual conditions of rock mass, since it indicates that the values of the parameters will be too low compared with actual observations. The most reliable correlations are therefore those which are specially marked in Table 11. Hence, for six of the eight correlations, the best fitting model is the same as for the hydraulic conductivity *versus* depth. A. Carlsson (1979) found that the spacing (S) versus depth in the Forsmark area had the following relation.

$$S = \frac{D}{0.99D + 8.55}, \quad (35)$$

which is in accordance with the relations of the fracture frequency in the present study. Equation (35) yields a decreasing frequency with an asymptotic frequency of 1 fracture per metre. The corresponding results of the obtained correlations here yield frequencies of 2.9 and 1.5 fractures per metre. These conditions from the Forsmark area are in agreement with the results presented by Johnson (1970), who states that the spacing increases with increasing depth down to a critical depth. In deeper seated rock masses the spacing is more or less constant.

A special study was made of the spacing *versus* depth in bore-hole DBT-3. This contains three zones of denser fracturing while the remainder of the rock mass is more moderately fractured. The depth relations of the spacing for the

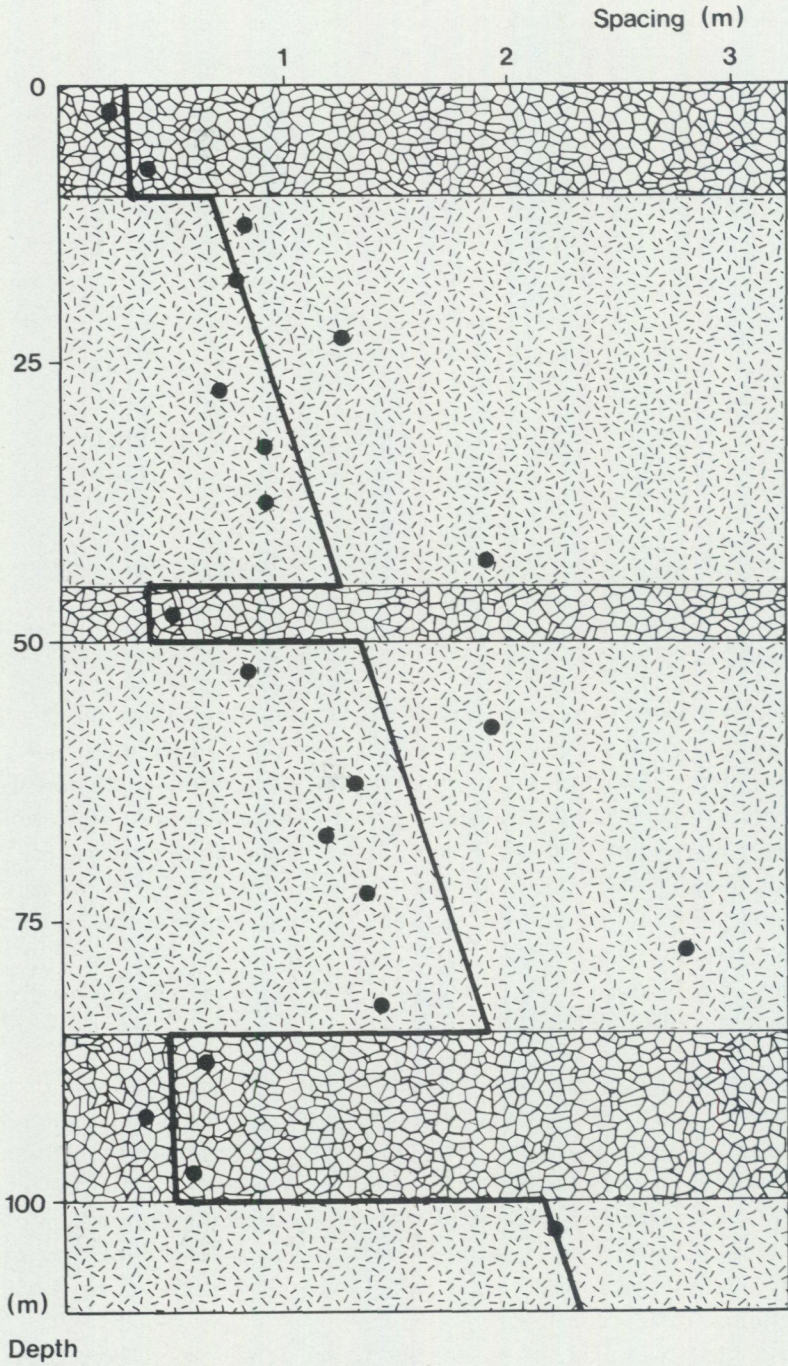


Fig. 36. Spacing versus depth in bore-hole DBT-3.

TABLE 12. A comparison between the actual gradient versus depth (exponent -B) and gradients calculated from the proportionality between the parameters.

Gradient	k	k_j	e	n	θ
Exponent -B	-2,2	-1,2	-0,6	-0,2	-0,8
Proportionality	-2,0	-1,4	-0,6	—	-0,8

homogeneous rock and the denser fractured zones were calculated. The relations were as follows.

$$S = 0.02 D + 0.4, \quad (36)$$

$$S = 0.003 D + 0.3 \quad (\text{fractured zones}) \quad (37)$$

with correlation coefficients of 0.51 and 0.47. Figure 36 shows the spacing *versus* depth, the location of the more densely fractured zones and a combined function taking into account both the homogeneous rock mass and the fracture zones. The results show that the fracturing in zones only to a minor extent decreases with depth. This condition suggests that water-bearing zones may exist even at great depth.

A comparison between the different relations obtained allows evaluation of the accuracy of the results obtained. In this respect it seems suitable to use the correlations based on the individual test sections. The same model for regression appeared for all parameters:

$$Y = AX^{-B}, \quad (38)$$

where the exponent $-B$ governs the gradient *versus* depth. The mathematical relations between the different parameters state the following proportionality between the parameters.

$$k - ne^3, \quad (39)$$

$$k_j - ne^2, \quad (40)$$

$$\theta - ne. \quad (41)$$

The values of the gradients are reported in Table 12. The theoretical exponents according to the proportionality between the parameters are calculated and inserted in the table. As seen, the correspondence is fairly close which indicates that these correlations are reliable.

DISCUSSION AND CONCLUSIONS

It is obvious that from a statistic point of view the hydraulic properties of the rock mass are depth dependent. The hydraulic conductivity, together with these parameters which were calculated from it, clearly decreases with increasing depth. The fracture frequency, too, manifests a decreasing trend, but not as clear-cut as for the conductivity. The obtained relations *versus* depth are in agreement with other studies in this field. The decrease of the conductivity and related parameters with increasing depth were illustrated in other areas by Snow (1968) and A. Carlsson and T. Olsson (1977a). For the fracture frequency, similar tendencies were obtained by Jahns (1943), Johnson (1970) and A. Carlsson (1979).

The reason for the decrease in conductivity with increasing depth is thought to be an increase in compressive stress (Olsson 1979). The relation between hydraulic conductivity and effective stress or pore pressure was discussed by several authors, but usually attributed to induced stresses on rock samples and not to the existing primary stress field in the rock mass (*inter alia* Serafim and del Campo 1965, Snow 1968, Brace 1978, Zoback and Byerlee 1975). The effect of the stress on the conductivity depends on whether the stress field closes or tightens the fractures. Pratt *et al.* (1974) showed by *in situ* tests that the conductivity decreased by a factor of 4 when normal stress was applied across the fracture. But normal stress parallel to the fracture increased it by a factor of 2.5. Investigations of petroleum technology indicate that the conductivity of fractures is stress dependent (cf. *inter alia* Fatt and Davis 1952). The results show that high closing pressure can reduce the fracture conductivity near a well. This reduction is due to the decrease in pore pressure during pumping. A similar effect is also demonstrated by A. Carlsson and T. Olsson (1979) in connection with water-pressure tests in fractured rock masses using high testing pressures.

The discussion indicates that the apertures of a fracture, and thereby the hydraulic conductivity, are dependent on the existing stress field. In an otherwise isotropic rock mass with identical fracture properties of different joint sets, the conductivity will differ in different directions due to variations in the stress field. A joint set parallel to the greatest principal stress will have wider fractures and higher conductivity, while a joint set perpendicular to the greatest stress will have a lower conductivity. This relation is shown in Figure 37.

In this context rock-stress measurements at different depth below the rock surface are useful. The measurements made in Forsmark may serve this purpose. Some of these measurements were taken every 20 m in deep drilled bore-holes. The measurements have shown that the increase in vertical stresses become greater with depth, approximately in accordance with the

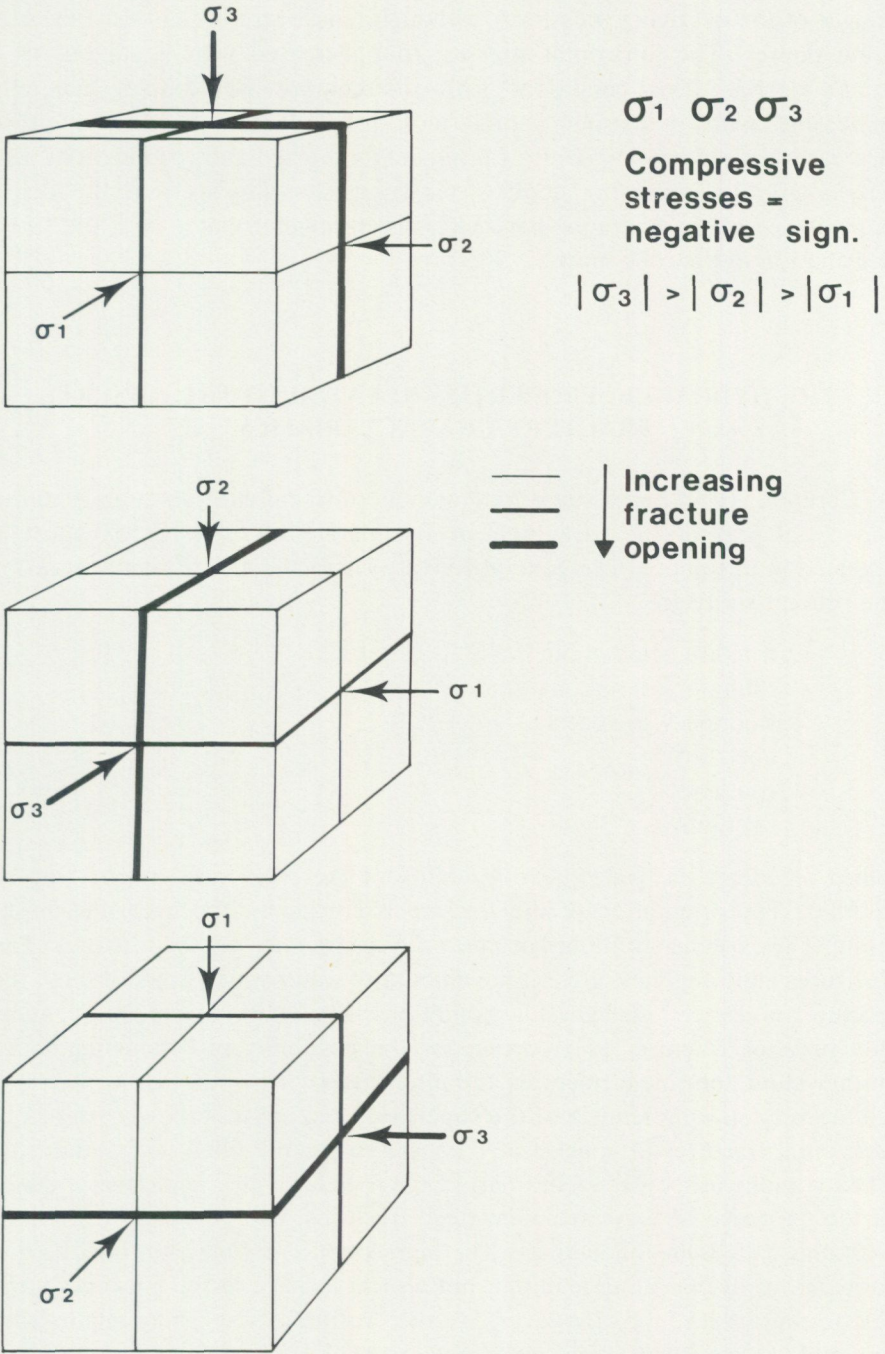


Fig. 37. Schematic illustration of the relation between the magnitudes of the principal stresses and the water-bearing ability of different fractures (T. Olsson 1979).

weight of the overlying rock mass, although tensile stresses did exist even at great depths. The horizontal stresses, too, increased with depth but to a minor degree. This condition, with the compressive stresses generally increasing with increasing depth, indicates that the fracture aperture decreases with increasing depth. Consequently the hydraulic conductivity also decreases with increasing depth. This conclusion implies that the depth dependence of the hydraulic parameters is closely correlated with the stress distribution in the rock mass.

THE HYDRAULIC PROPERTIES RELATED TO THE GENERAL FRACTURE CHARACTERISTICS

A. Carlsson (1979) processed a great amount of fracture information from the superficial part of the rock mass at Forsmark Unit 3, some of which is adduced in this paper. The general fracture characteristics of significance for the present study are

- fracture orientation,
- filling or coating material,
- frequency or spacing,
- aperture,
- roughness,
- continuity,

which all affect the water-bearing ability of the rock mass in one way or another. The orientation of the fracture is crucial for the hydraulic anisotropy. The existence of fillings or mineral coatings may seal the fractures. The apertures and roughness govern the amount of water which flows through the fractures under certain hydraulic conditions. The continuity or interconnection between fractures is important for the possibility of conducting water further along the single fractures and into others.

One very striking feature of the superficial rock mass is the occurrence of horizontal fractures of considerable width, commonly filled with sediments. The hydraulic properties of this part of the rock have given no clear evidence of the existence of these sediment-filled fractures, except for a few sections with unusually high conductivity. The high conductivity may not only be due to wash-out of the filling material, but also to leakage at the packers during the testing procedure. However, as the hydraulic tests were made with gradually increased pressure, it is obvious that wash-out has occurred (cf. Figure 19). It is not possible to discern this kind of fractures from the hydraulic parameters.

A. Carlsson (1979) reports a number of conductivity determinations of the filling material which give a mean conductivity of about $1 \cdot 10^{-7}$ m/s with a variation in the range $1 \cdot 10^{-8}$ – $4 \cdot 10^{-6}$ m/s dependent on the composition of the sediments. Thus, a water-pressure test in a section of the rock which contains one 10 cm wide filled fracture yields the same conductivity as if the zone contained one unfilled fracture with a continuous mean aperture of 10 μ m. Due to the fine-grained composition of the sediments the filling probably seals the fractures unless layers of coarser material are present.

As regards the anisotropy of the rock it seems likely that the horizontal joint set is the most conductive, due to generally wide apertures, high fracture frequency and incomplete filling. As regards the vertical sets, the set which strikes NW–SE seems to be the most conductive and that which strikes NE–SW the least conductive. This judgement is supported by the reported values of the fracture apertures (Table 1) and of the fracture spacing (Table 3).

The NW–SE striking set has the greatest mean apertures as it contains least number of fractures with an aperture less than 0.1 mm. This set also has a fairly high fracture frequency. Accordingly the set which strikes NE–SW has the smallest apertures and a lower fracture frequency.

These conditions imply that the rock mass is probably anisotropic with the highest conductivity running NW–SE, and the lowest in the perpendicular direction. The difference in conductivity between these directions depends on the relation between the conductivity of the horizontal set and those of the vertical ones. Probably the difference between the main directions is slight, at least in the superficial rock mass, while at greater depth it will be more pronounced as the effects of the horizontal set will become less dominant. The direction of the anisotropy is also supported by the rock-stress measurements given in Figure 16.

As regards the roughness (Table 4) the horizontal set has the roughest surfaces and the vertical, NE–SW, the smoothest. Thus, this parameter also indicates the highest conductivity for the horizontal set and consequently the lowest for the NE–SW striking set. The asperities are larger in a rougher fracture which tends to cause greater dilatation of such a fracture.

SUMMARY

The aim of the present work is to investigate in what sense different parameters, such as gross hydraulic conductivity, fracture conductivity, porosity, fracture openings and so forth are interrelated. In consequence of a former work (A. Carlsson and T. Olsson, 1977 a) on the determination of the conductivity-depth relation, it is of interest to investigate this relation in the case of other parameters, too.

In order to fulfil these aims, a specific area was studied, namely the construction area of the Forsmark Power Plant in northern Uppland, Sweden. This area is

adjudged suitable as extensive geological and hydrogeological investigations have been carried out.

From a morphologic point of view, the Forsmark area is remarkably flat with only minor topographical variations. The ground level at the area investigated lies 1 to 5 m above sea level. The bedrock is mainly made up of old Svecokarelian intrusive, schistose rocks, so-called gneiss-granites. In addition, mica gneisses and mica schists occur on the islands off the mainland. The gneiss-granite includes greenstones of amphibolitic composition and pegmatites. The Power Station is situated between two major fracture zones with a strike direction of NW-SE and steeply dipping. The intervening rock mass demarcated to NE and SW shows evidence of a secondary tectonization.

As regards the individual fractures, the gneiss-granitic rock mass is dominated by four joint sets, three vertical and one horizontal set. An investigation of the fracture characteristics was carried out in the area of Unit 3. The parameters investigated are orientation, filling, aperture, spacing, roughness, and continuity. The most common type of filling material is chlorite and the occurrence seems to be independent of the joint sets. Unconsolidated sediment material is mainly found in the horizontal set. There is a considerable difference between the apertures of the horizontal and the vertical sets. The horizontal set has a median aperture which is more than 100 times greater than those of the vertical sets, and there is a tendency of increased spacing with increasing depth. As regards the roughness, the horizontal set has the roughest fracture planes, but this difference between the sets is not as significant as for the apertures and the spacing.

In situ measurements of the triaxial rock stresses in drill-holes were made down to a depth of 500 m. The results indicate high horizontal stresses in the superficial rock mass, generally with a magnitude of 20–30 MPa. As regards direction, the measurements show a close correspondence between the direction of the highest compressive stress and the fracture zones in the area, the fracture orientation and the foliation. The rock-stress distribution *versus* depth indicates an increase in the vertical stress vector, which is approximately in accordance with the weight of the overburden, although tensile stresses exist even at great depth.

There are several different methods of obtaining the hydraulic conductivity of an aquifer. In this paper the water-injection test (Lugeon test) is used. The equation used gives the conductivity of the rock mass under the presumption that stationary flow conditions prevail and the water-bearing formation is isotropic and homogeneous. The hydraulic conductivity provides the basis for further calculations of other characteristic properties, such as apertures and porosity. As the hydraulic conductivity of the rock mass is a function of fracture spacing/frequency, fracture aperture and fracture conductivity, it is possible to determine the fracture aperture from the hydraulic conductivity. The value obtained gives the aperture of a number of fractures situated within a single test section. A more accurate value of the fracture apertures calls for individual test of each fracture, and the validity of the calculated aperture decreases with increasing size of the test section. In water-injection tests the measurements are made in test sections of constant length in which at best only a few fractures occur. Thus the fracture aperture obtained is a mean value of all the fractures within the section. The aperture calculated is equal to the essential aperture of an fictive fracture with a continuous, equal opening which can replace the natural fracture without changing the conductivity of the test section.

The kinematic porosity has been derived from data on fracture frequency and apertures. The theory is based on the fact that vertical and inclined drill-holes

penetrate the joint sets in different ways. The determinations show that there is a well defined difference between the various sets. The horizontal set clearly predominates and the additional contribution from the vertical sets to the kinematic porosity normally falls short of 15 per cent for each set.

The results of the site investigation yielded the following parameters either directly or via calculation from the information given: fracture frequency/spacing, rock type, filling, seismic velocity, hydraulic conductivity of the rock mass, fracture conductivity, fracture aperture, and kinematic porosity. The hydraulic conductivity and fracture frequency were determined for each test section and also as a mean value for each bore-hole. The fracture conductivity, fracture aperture and kinematic porosity were derived from the individual values for the conductivity and fracture frequency in each test section. This study is based on a large number of water-pressure tests, there being about 1 000 determinations in all in 364 test section distributed over 29 drill-holes.

A comparison of the characteristic values of the parameters demonstrates that the mean and median values of the parameters are of the same order of magnitude. However, the standard deviation, the quartiles and the total deviation (max.-min.) are generally greater for the individual test sections. This effect occurs because the values of the bore-holes are based on mean values which *per se* incorporate considerable deviation.

The hydraulic conductivity and the porosity range over several powers, at most eight decades for the conductivity and three for the porosity. Of all measurements included in this study about 55 per cent show conductivity values below $1 \cdot 10^{-7}$ m/s. This large number of low conductivity values exerts but little influence on the mean value which amounts to about $2 \cdot 10^{-6}$ m/s. This great weight of the larger value is somewhat misleading as the mean value may result from one or a few single fractures while the remainder of the rock mass has a very low conductivity or porosity. Nevertheless, the mean value gives a correct description of the water-bearing ability of the specific section of the rock mass which corresponds to the bore-hole, but for regional estimations the median value is more representative.

If a comparison is made between obtained conductivity values, values of kinematic porosity and fracture conductivity with values reported in the literature there seems to be a good correspondence. However, values of the kinematic porosity are rarely reported and as regards this parameter a minor trend of underestimation may be found for the calculated values compared to those obtained for instance by tracer tests. There seems to be a good correspondence between values reported elsewhere and in this study regarding the fracture apertures and the fracture conductivity, the fracture frequency and the seismic velocity.

As regards interconnection between parameters, it is shown that the most clear-cut correlation concerns the fracture frequency *versus* hydraulic conductivity, which implies that the existing fractures are of importance for the water-bearing ability of the rock mass. The correlation between the seismic velocity and conductivity is also fairly good while that between seismic velocity and fracture frequency is surprisingly poor. A high frequency of fractures should increase the conductivity and decrease the velocity, but the correlations show that the frequency carries greater weight of the conductivity than of the seismic velocity.

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