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Final Report of the Borehole, Shaft, and Tunnel Sealing Test – Volume II: Shaft plugging

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Der vorliegende Bericht betrifft eine Studie, die für das Stripa-Projekt ausgeführt wurde. Die Autoren haben ihre eigenen Ansichten und Schlussfolgerungen dargestellt.Diese müssen nicht unbedingt mit denjenigen des Auftraggebers übereinstimmen.

Le présent rapport a été préparé pour le projet de Stripa. Les opinions et conclusions présentées sont celles des auteurs et ne correspondent pas nécessairement à ceux du client.

This report concerns a study which was conducted for the Stripa Project. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

Das Stripa-Projekt ist ein Projekt der Nuklearagentur der OECD. Unter internationaler Beteiligung werden von 1980-86 Forschungsarbeiten in einem unterirdischen Felslabor in Schweden durchgeführt. Diese sollen die Kenntnisse auf folgenden Gebieten erweitern:

- hydrogeologische und geochemische Messungen in Bohrlöchern
- Ausbreitung des Grundwassers und Transport von Radionukliden durch Klüfte im Gestein
- Verhalten von Materialien, welche zur Verfüllung und Versiegelung von Endlagern eingesetzt werden sollen
- Methoden zur zerstörungsfreien Ortung von Störzonen im Fels

Seitens der Schweiz beteiligt sich die Nagra an diesen Untersuchungen. Die technischen Berichte aus dem Stripa-Projekt erscheinen gleichzeitig in der NTB-Serie der Nagra.

The Stripa Project is organised as an autonomous project of the Nuclear Energy Agency of the OECD. In the period from 1980-86, an international cooperative programme of investigations is being carried out in an underground rock laboratory in Sweden. The aim of the work is to improve our knowledge in the following areas:

- hydrogeological and geochemical measurement methods in boreholes
- flow of groundwater and transport of radionuclides in fissured rock
- behaviour of backfilling and sealing materials in a real geological environment
- non-destructive methods for location of disturbed zones in the rock

Switzerland is represented in the Stripa Project by Nagra and the Stripa Project technical reports appear in the Nagra NTB series.

Le projet Stripa est un projet autonome de l'Agence de l'OCDE pour l'Energie Nucléaire. Il s'agit d'un programme de recherche avec participation internationale, qui sera réalisé entre 1980 et 1986 dans un laboratoire souterrain, en Suède. Le but de ces travaux est d'améliorer et d'étendre les connaissances dans les domaines suivants:

- mesures hydrogéologiques et géochimiques dans les puits de forage
- chimie des eaux souterraines à grande profondeur
- écoulement des eaux souterraines et transport des radionucléides dans les roches fracturées
- comportement des matériaux de colmatage et de scellement des dépôt finals
- méthodes de localisation non destructive des zones de perturbation de la roche

La Suisse est représentée dans le projet Stripa par la Cédra. Les rapports techniques du projet Stripa sont publiés dans la série des rapports techniques de la Cédra (NTB).

ABSTRACT

Shaft sealing by use of highly compacted bentonite was investigated in a 14 m long shaft in which two plugs were constructed with a central sand-filled central space for injecting water. A first reference test with concrete plugs was followed by a main test in which the plug material consisted of blocks of highly compacted sodium bentonite powder. In the latter test, the outflow from the injection chamber was only a few percent of that with the concrete plugs, which demonstrates the excellent sealing properties of the clay. The main effect was that practically no water flow took place along the rock/clay interface. The longevity of smectite clay in crystalline rock is sufficient to make bentonite plugs operative for several thousand years.

RESUME

L'obturation de puits de mine par l'utilisation de bentonite fortement compactée a été étudiée dans un puits profond de 14 m dans lequel ont été mis en place deux bouchons séparés par un espace rempli de sable destiné à l'injection d'eau. Un premier essai de référence avec des bouchons en béton a été suivi de l'essai principal où le matériau d'obturation était constitué de blocs faits de poudre fortement compactée de bentonite au sodium. Dans ce dernier essai les fuites émergeant de la chambre d'injection ne s'élevaient qu'à quelques pour-cents de celles observées avec les bouchons en béton, ce qui démontre les excellentes propriétés d'étanchement de l'argile. L'effet principal fut que pratiquement aucune circulation d'eau ne s'établissait le long du contact roche/argile. La longévité de l'argile smectique dans des roches cristallines est suffisante pour que des bouchons de bentonite soient effectifs durant plusieurs millénaires.

ZUSAMMENFASSUNG

Die Schacht-Versiegelung mit hochverdichtetem Bentonit wurde am Beispiel eines 14 m langen Schachtes untersucht. In einem durch zwei Verschlüsse abgeschotteten sandgefüllten Abschnitt im Schacht wurde Wasser injiziert und dessen Ausfluss gemessen. Einem ersten Referenztest mit Betonverschlüssen folgte ein Haupttest, bei dem das Verschlussmaterial aus Blöcken von hochverdichtetem Na-Bentonit-Pulver bestand. Im letzteren Test betrug der Wasserausfluss aus der Injektionskammer nur wenige Prozente von dem mit den Betonverschlüssen. Dies zeigt, welch ausgezeichnete Abdichtungseigenschaften der Ton besitzt. Das wichtigste Ergebnis war, dass praktisch kein Wasserfluss entlang der Grenzfläche Gestein/Ton beobachtet werden konnte. Die Langlebigkeit von smektischem Ton in kristallinem Gestein ist ausreichend, um eine Wirksamkeit der Bentonit-Verschlüsse für mehrere tausend Jahre voraussetzen zu können.

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SUMMARY

The Shaft Plugging Test comprised determination of the sealing effect of sodium bentonite by comparing it with expansive concrete. This was made by first conducting a reference test in a 14 m long and 1-1.3 m diameter shaft, with two concrete plugs separated by a sand-filled injection chamber, and then running a main test in which the concrete was replaced by blocks of highly compacted sodium bentonite.

The rock structure was carefully investigated in order to identify major potential passage-ways for the injected water and both tests confirmed that some of them discharged water from the injection chamber. Most of the outflow took place along the plug/rock interface in the reference test, while this contact turned out to be perfectly tight in the main test. This gave largely different outflow rates; about 8 liters per hour in the reference test and only a few per cent of this value when the clay plugs were in position.

The swelling pressure was measured in the test and values of up to about 3 MPa were recorded indicating that the clay interacted strongly with the surrounding rock. This must have contributed to the sealing effect by tending to close some of the water-bearing structures, although this effect was less important than the elimination of water flow along the rock/plug interface by the development of an impervious clay-infiltrated rock matrix at the interface.

A comprehensive determination of the water uptake was made at the end of the field test. It demonstrated that the general model of diffusion-type migration of water applied well to the part of the clay that was furnished with water from the pressurized sand fill. However, the water uptake appeared to have been retarded locally at the rock/clay interface, which was obviously related to a limited access to water in certain, fracture-poor parts. It was concluded that this was due to the low water pressures at the test site, which had been drained for a long time before the test began. The injection pressures were also too low to drive water through finer fractures and fissures to the shaft.

1 SCOPE OF TEST

1.1 INTRODUCTION

While boreholes may form unwanted passages between the biosphere and deeply located repositories, shafts certainly represent potential leaks and they therefore need to be effectively sealed. As in the case of boreholes, the sealing should have a hydraulic density which does not exceed that of the surrounding rock, and it must fill the shaft completely and establish a tight contact with the rock so that flow along the interface between sealing and the rock does not take place. Plugs of expanding smectite-rich clay offer these properties and are expected to retain their sealing ability for many thousand years in the pH range and groundwater environment that are characteristic of granite and gneiss bedrock, provided that the temperature does not exceed 100-150°C.

Sodiumsaturated, dense bentonite that is rich in smectite is a particularly effective sealant because of the high swelling potential and the very low permeability and diffusivity. It can be prepared in the form of blocks by compacting air-dry bentonite powder under high pressure. Its hydraulic conductivity can be as low as 10^{-14} m/s and the diffusion coefficient for most ions is only a small fraction of that of free water. Such a clay material, in the form of Na Wyoming "Volclay MX-80" bentonite, was used for the Stripa sealing tests. Its mineral composition and its basic physical and rheological properties have been fully described in earlier Stripa Project reports (1) to which the reader is referred.

1.2 PLUGGING OPERATION AND FUNCTION OF THE APPLIED PLUG

One possible way of sealing shafts effectively is to apply low-permeable, fairly short plugs at certain levels, preferably those where the surrounding rock is very poor in fractures. The remaining parts of the shafts can be filled with crushed rock that has to be effectively compacted to minimize settlement and plug displacements.

While the drilling of boreholes hardly generates or induces fractures that are parallel or subparallel to the holes, such effects appear in the vicinity of blasted and full-face drilled shafts and tunnels. Blasting, however carefully made, produces some fracturing which increases the hydraulic conductivity of the rock to within at least a few decimeters from the free surface (Fig 1-1). In addition, the stress redistribution caused by the excavation of shafts and tunnels is known to widen and cause propagation of fractures as demonstrated schematically by Fig 1-2. This effect is particularly obvious when the major principle stress is perpendicular to the shaft axis. The resulting increased hydraulic conductivity of the rock in the axial direction of the shaft means that grouting or some other effective cut-off of the permeable zone is required in addition to the plugging. Fig 1-3 shows how this can be made in practice (1).

The Stripa shaft plugging experiment involved application of plugs in the form of relatively tightly arranged blocks of highly compacted bentonite, and creation of a low-permeable surrounding rock zone by sawing a slot that was filled by such blocks. The arrangement was thus in general agreement with Fig 1-3 with the exception of the grouting.

Dense blocks of bentonite can be produced by compacting granulated Na bentonite powder under high pressure. The bulk density of such blocks will be 2.00-2.15 t/m^3 if the compaction pressure is in the range of 50-120 MPa. The water content of the blocks will be the same as that of the powder, which is in turn determined by the humidity of the atmosphere. Usually, the water content is in the interval 8-15 %, which means that the highly compacted blocks are water saturated to at least 40-50 % from the start. The huge swelling capacity of Na bentonite associated with water uptake means that plugs that are built up to form stacks of discrete blocks are expected to become homogeneous and to fill up the shaft completely after a sufficiently long time.

1.3 SCOPE OF TESTING

The suitability of Na bentonite as sealing substance per se has been documented by the Buffer Mass Test (2) and in particular by the Borehole Plugging Test (3), but some fundamental questions concerning the practicality of the investigated technique and the exact nature of the sealing function remained to be answered by the field test in Stripa. These questions were:

- Is it practical to install plugs consisting of blocks in a shaft or tunnel with the typical irregular rock surface shape that is caused by blasting? Is full-face drilling a necessary prerequisite for practical application and effective sealing?

- Is the general model of uniform water uptake over the rock/clay interface that which was derived from the Buffer Mass Test valid also when there is no thermal gradient? Thus, it may be asked if the initial saturation of the peripheral bentonite in the heater holes of the BMT led to a more rapid sealing and water-distributing capacity of discrete fractures in the rock than can be expected under isothermal conditions.

- Will the bentonite interact with the rock so effectively that no preferential flow passages are formed at their interface?

- Theoretically, there are two sealing effects on the surrounding rock that may be induced by the bentonite namely:

  * The swelling pressure is expected to compress fractures in the rock that are subparallel to the shaft

  * Bentonite is expected to penetrate rapidly and deeply into fractures which are wider than about 1 mm, by which they become sealed.

The question is whether these effects have any significant influence in practice.

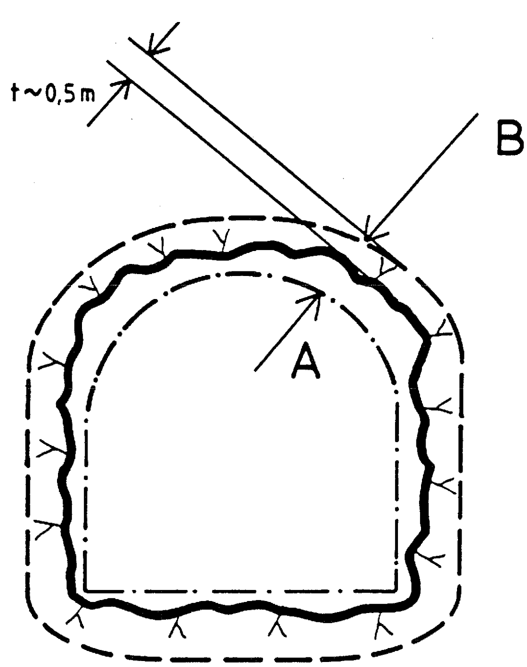


Figure 1-1. Generalized picture of the disturbed zone (B) by blasting. The A-contour represents the theoretical profile

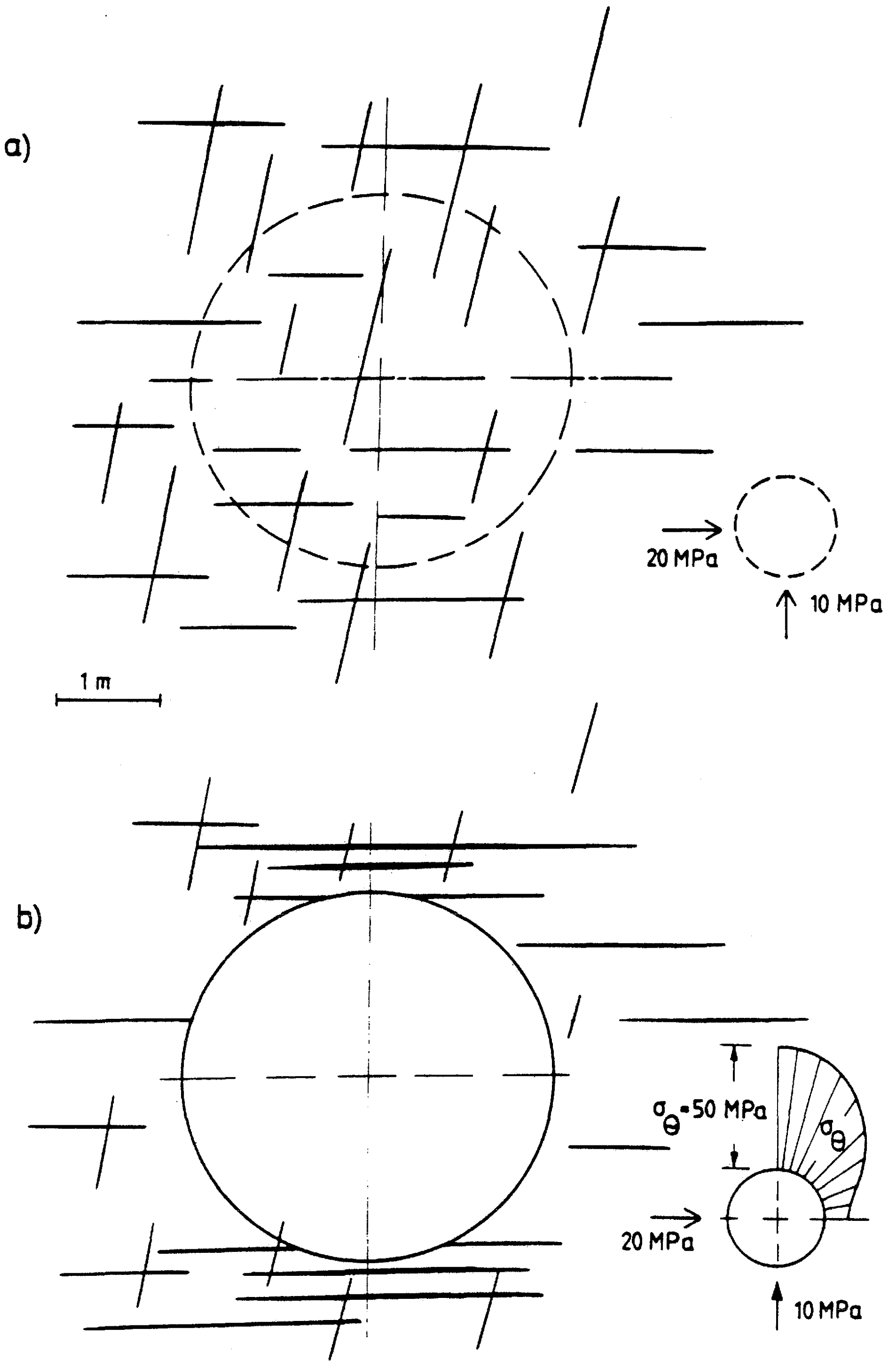


Figure 1-2. Schematic stress-induced alteration of fracture geometry. a) Initial pattern. b) Altered geometry. Notice propagation and generation of subhorizontal fractures at crown and base when the primary horizontal stress is high

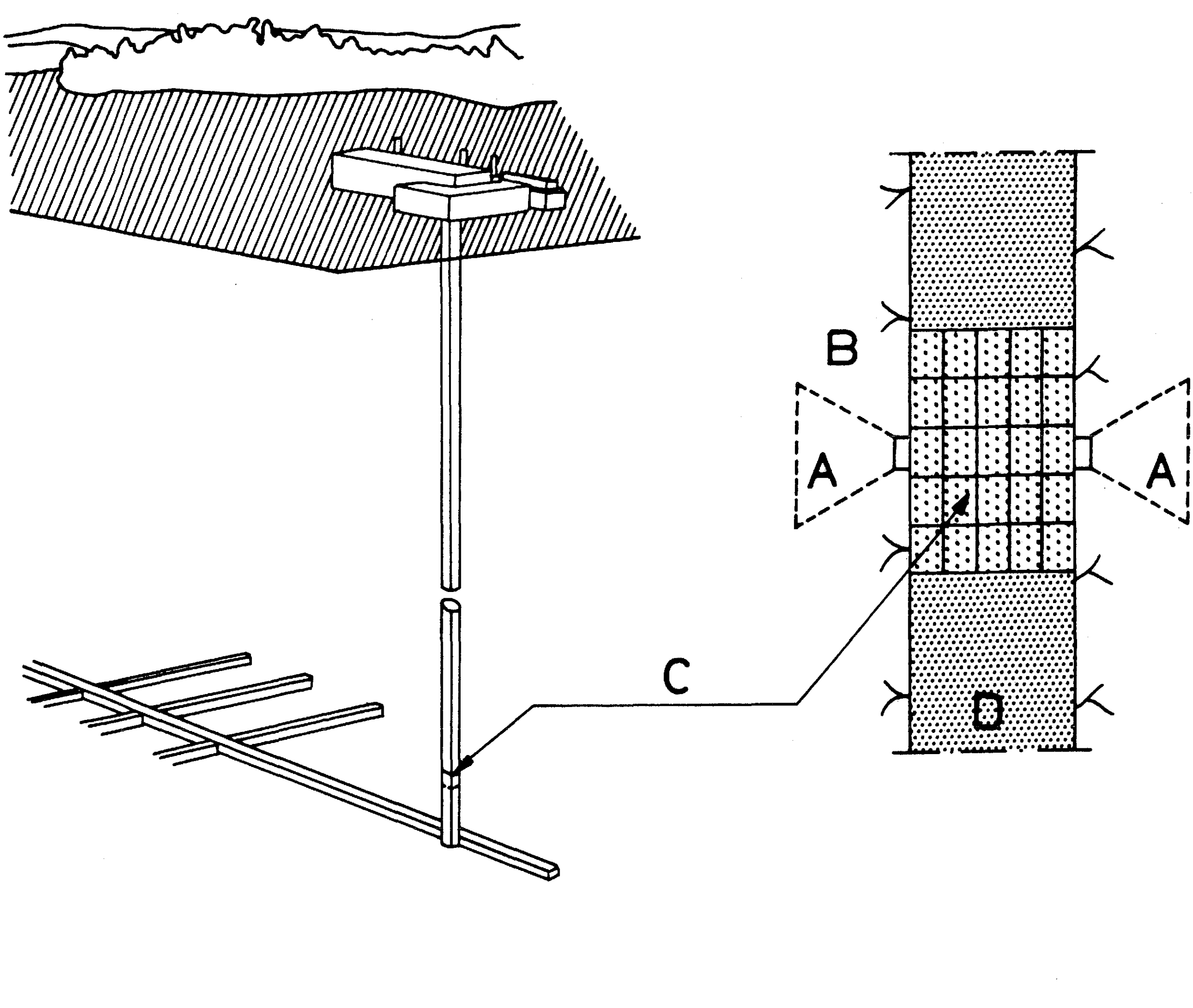


Figure 1-3. Plug of bentonite blocks in shaft and slot suggested by KBS in 1978. A) Grouted zone, B) Slot with bentonite blocks, C) Set of bentonite blocks, D) Compacted backfill. The grouting is made before constructing the plug

2 DESCRIPTION OF TEST

2.1 GENERAL FEATURES

The test had the form of measuring the outflow of water from a central, sand-filled injection chamber, which was located between two plugs that were tied together and anchored to the shaft walls. The sealing effect of bentonite was determined by comparing the outflow in a reference test using plugs made of concrete with that in the main test in which bentonite plugs were used. The plugs were equipped with pressure cells for recording the successive build-up of swelling pressures which were directly related to the water uptake.

A more complete understanding of the sealing processes required identification of the flow paths from the injection chamber. This was made through comprehensive fracture mapping and by using tracer techniques.

2.2 SITE CHARACTERIZATION

2.2.1 Location

The test site was close to that of the Ø 76 mm borehole plug experiments (cf. Fig 2-1), the shaft being located in the same, approximately 14 m thick rock slab that is penetrated by these boreholes (3).

The shaft was excavated as part of the Lawrence Berkeley Laboratory (LBL) investigations before the start of the Stripa Project. The purpose was initially to test different techniques to make deep cylindrical holes with a fairly large diameter and a relatively smooth and regular perimeter. The LBL operations yielded a 14 m deep shaft with a diameter of about 1.0 m at the upper end and 1.3 m at the lower end. The eastern part of the shaft perimeter was produced by slot-drilling, i.e. by percussion drilling of slightly overlapping, parallel Ø 50 mm holes, while the western part was made by drilling Ø 50 mm holes 20 cm apart for blasting. Both perimeter surfaces have a relatively constant radius of curvature but are, of course, far from smooth. The main geometrical features of the shaft are given in Fig 2-2.

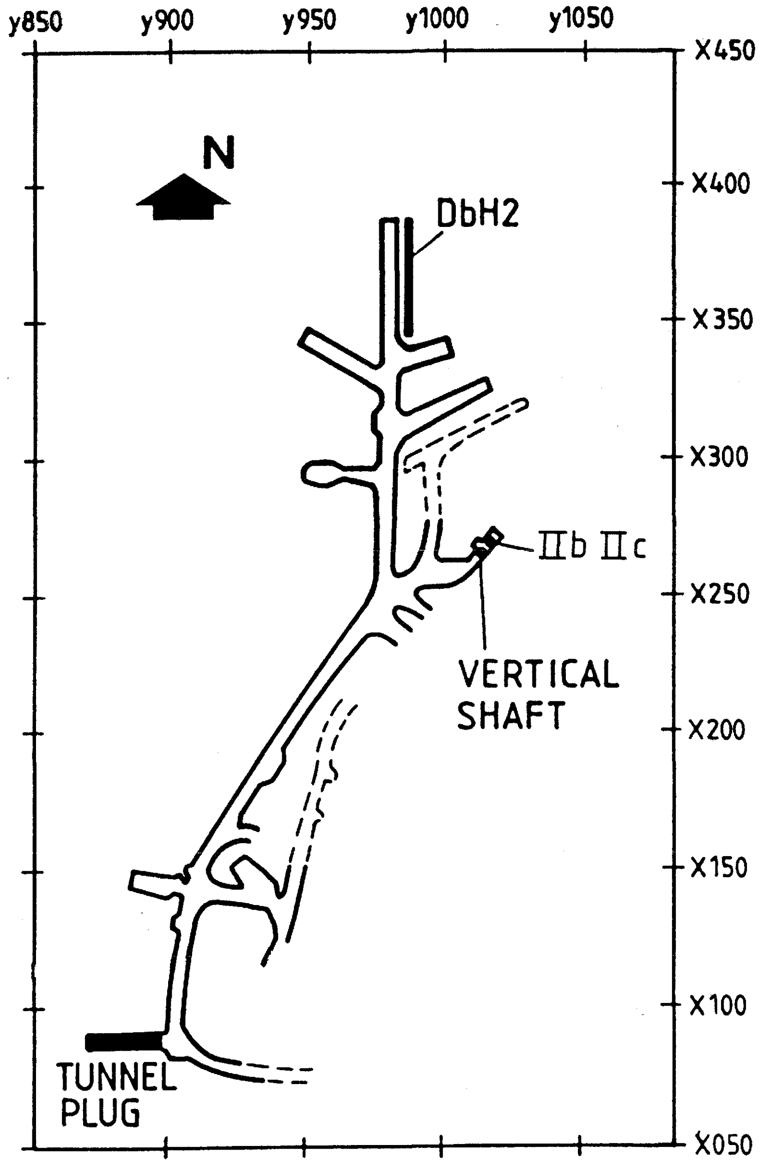
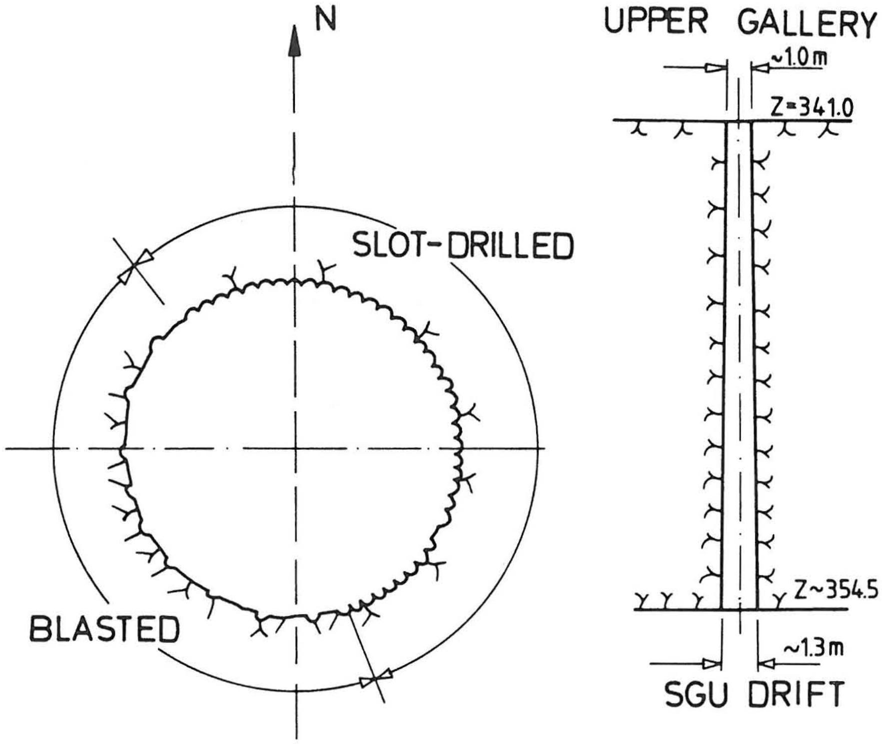


Figure 2-1. Location of the shaft plugging test, the borehole plugging tests (DbH2 and IIa and b) and the tunnel plugging test



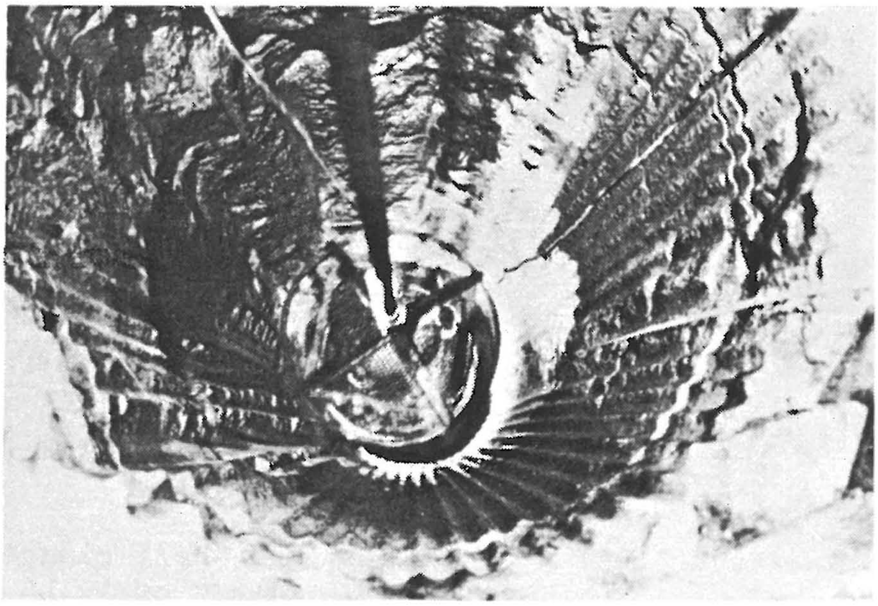


Figure 2-2. Geometry of the shaft

2.3 ROCK CONDITIONS

2.3.1 General

Detailed mapping of the fractures was made by Henrik Norlander, geologist, with the intention to identify those structural components that were of potential importance for the hydraulic conductivity of the rock and for the sealing effect of bentonite plugs in contact with the rock. The major features which could be identified in the 6 m high part of the shaft that was considered to be of major interest are indicated in Fig 2-3. This part was selected firstly because it represented the lower part of the rock slab which was supposed to be water saturated at the test start, and secondly because it had the highest number of water-bearing structures. Considering also the nature of fractures, i.e. the aperture, orientation and character (discrete fracture, "crushed" zone etc), the most suitable part for testing was found to be the one located between z=348.0 and z=352.0.

The rock matrix in this region is similar to that of the BMT area and was therefore not expected to interact chemically with the bentonite by ion exchange processes or otherwise. The composition seems to be very similar to that of the common grey/reddish granite in this part of the mine, for which LBL showed the main minerals to be quartz (35-44 %), partly sericitized plagioclase (35-39 %), and microcline (12-24 %). Minor constituents are chlorite, muscovite, biotite and epidote. SiO_2 typically varies between 74.0 and 75.3 %, while Al_2O_3 and K_2O represent 12.1-13.5 % and 4.5-4.8 %, respectively. Fe_2O_3 and CaO are in the range of 1.0-1.8 % and 0.4-0.7 %, while MgO represents 0.18-0.22 %.

2.3.2 Rock stresses

The vertical shaft is located in a rock slab in which the vertical rock stresses are insignificant but the horizontal stresses rather high, particularly in the W/E-direction. The latter stresses are estimated to be on the same order of magnitude or even higher than the major principal stress in the area, which has been estimated at about 20 MPa. Thus, recent stress measurements using overcoring techniques as well as hydro-fracturing indicate that the maximum horizontal stress, oriented W/E to NW/SE, ranges between 16 and 25 MPa (4). In the central part of the rock slab steep joints with a N/S to NE/SW strike are therefore expected to be well closed. We shall see later in the text that the major water-bearing structures have a different strike and are therefore expected to serve as effective inflow and outflow passages to the shaft.

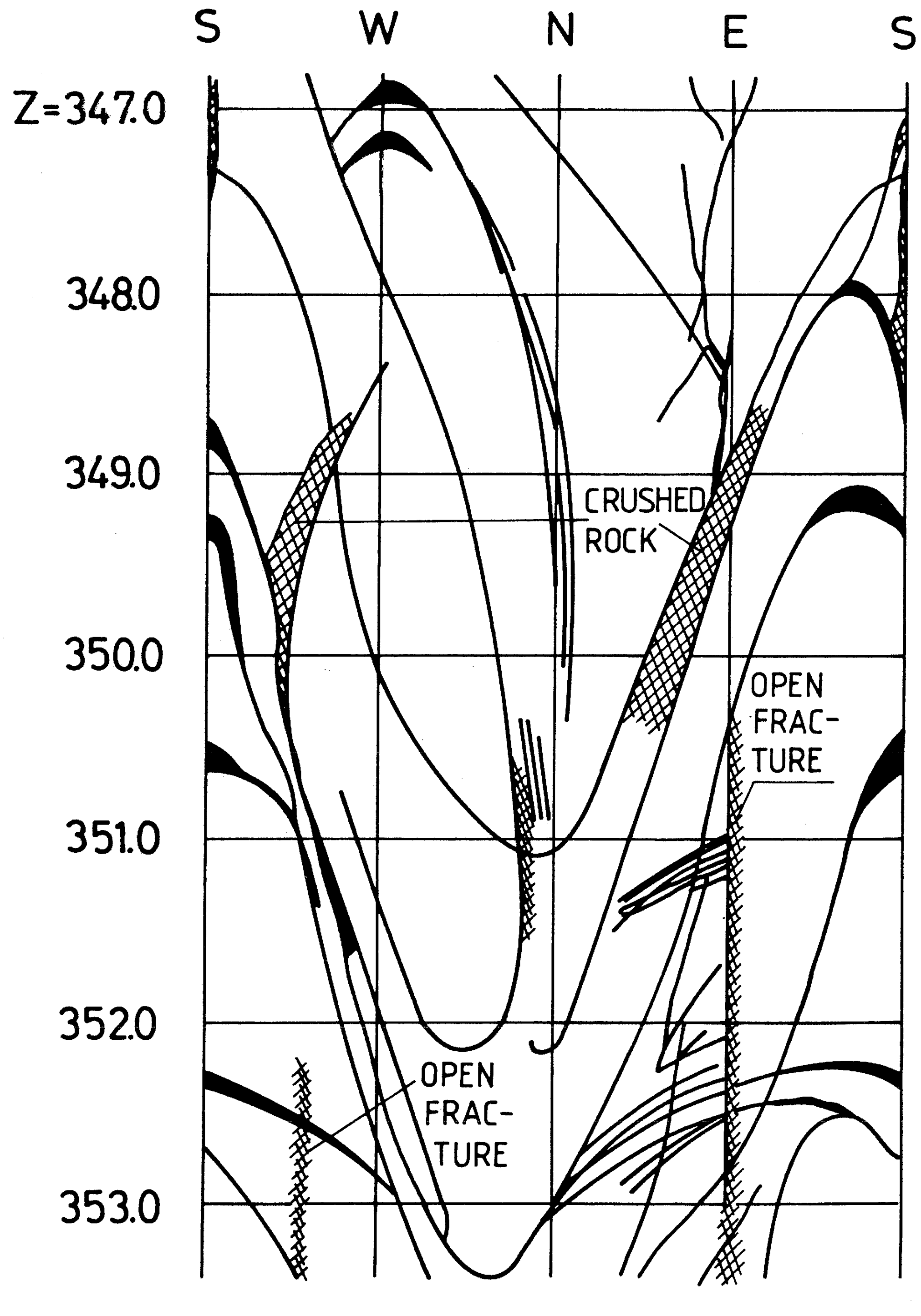


Figure 2-3. Shaft wall with major joints and fractures. The NW-SSE part is slot-drilled while the rest is blasted

2.3.3 Hydrological conditions

As in the case of the Ø 76 mm boreholes, the construction of the lower drift some 25 years before the plugging tests must have led to very low piezometric heads in the test area. However, it was clear already by ocular inspection that the fractures were water saturated before as well as during the test and that the plugs had access to water over their entire length although it was under low pressure.

The hydraulic characterization comprised identification of the major water-bearing structures in the z=348.0-352.0 region by ocular inspection of the shaft and by determining their flow properties by use of 16 Ø 56 mm boreholes close to the shaft. They were drilled almost parallel to the shaft wall and located as shown in Fig 2-4. The main water passages, as identified by watching where water appeared after drying the shallow rock by use of an ordinary contractor's air-drying device, were found to be the ones listed below and illustrated in Figs 2-5--2-8.

	Strike	Dip, degrees	Character
A	WNW/ESE	60	Crushed rock zone
B	W/E	90	Large open joint
C	NW/SE	70-90	Crushed rock zone
D	NW/SE	65	Plane joint
E	WNW/ESE	60	Plane joint

The excavation techniques applied by LBL had probably caused insignificant damage to the rock, meaning that the identified structures are largely original with exception of those appearing within 1-2 m distance from the upper floor and the lower tunnel crown. However, some fissuring must have taken place in the blasted rock, meaning that the western part of the shaft wall should have obtained a higher hydraulic conductivity than the eastern one.

The hydrological survey of the 16 observation holes aimed at identifying the major water-bearing structures which intersect the holes and also appear in the shaft wall. Even moderately comprehensive tests turned out to be tedious and not particularly accurate, however, and the study therefore had to be confined to a simple determination of whether there is any hydraulic connection at all between neighboring holes. For this purpose, each of the holes in the inner row was pressurized by use of twin packers with simultaneous recording of pressure reactions in five packer-sealed neighboring holes, two in the inner row and three in the outer one. All the holes were equipped with additional mechanical packers at about 1 m distance from the lower ends of the holes throughout the entire test so that they could be water-filled from the start of the field experiment and not serve as drainages.

At the individual water injection tests the applied nitrogen gas pressure, 150 kPa, was kept constant for a sufficiently long time to obtain steady state conditions, after which the flow and pressure reactions were observed for exactly one minute. The free distance between the packers was 2 m, the center of the injected zone being successively changed and located so as to fit the structural patterns observed in the shaft and the holes. The packers in the recording holes were kept at the same levels as in the injected one. The packer-confined gap in the recording holes was connected to transparent nylon tubings with a free water meniscus so that reactions to pressure changes in adjacent holes could be detected, thus indicating interconnectivity.

It is concluded from these tests that there are no obvious lateral hydraulic connections between the closely located holes in the tested region, except for S 3/S 4. The majority of the water-bearing discontinuities, which are particularly frequent in holes S 3, S 9, S 11 and S 13, seem to be very steeply oriented, which is in agreement with the structural pattern observed in the shaft. Two of these holes, S 9, S 11 and S 13 are located close to the blasted side of the shaft, while S 3 is close to the slot-drilled site. S 14, belonging to the outer row on the blasted side, appeared to be tight.

Table 2-1. Injection tests in the inner observation holes (cf. Fig 2-4)

Pressurized hole	section	Water flow ml/min	Observed reaction
S 1	Z=345.0-347.0	0.57	None
	347.5-349.5	0.36	
S 3	345.8-347.8	0.30	S 4 increased
	347.7-349.7	25.40	
S 5	344.3-346.3	0.20	None
	347.0-349.0	0.20	
	348.0-350.0	0.40	
S 7	344.3-346.3	0.30	None
	345.3-347.3	0.80	
	347.5-349.5	0.40	

Cont Table 2-1

Pressurized hole	section	Water flow ml/min	Observed reaction
S 9	346.0-348.0	1.30	None
	347.5-349.5	0.65	
S 11	344.9-346.9	4.00	None
	345.9-347.9	1.90	
	346.8-348.8	3.40	
S 13	345.0-347.0	0.40	None
	346.0-348.0	0.15	
	348.0-350.0	1.70	
S 15	346.2-348.2	0.46	None

The groundwater chemistry, which was discussed in detail in the final report of the Borehole Plugging Test, is characterized by a pH-value around 8-9 and a very low salinity. Sodium and calcium are major cations, the calcium concentration of about 20 ppm being approximately 50 % of that of dissolved sodium. Chlorine is by large the most abundant anion. The concentration of bicarbonate is relatively high, i.e. about 80 ppm.

2.3.4 Selection of test section

The selection of a suitable test section and the exact location of the injection chamber which separates the two plug parts, was based on the hydrological data and expected sealing effects. The following boundaries were chosen:

Upper boundary of upper plug $z = 349.30$
Lower boundary of upper plug $z = 349.80$
Injection chamber center $z = 350.05$
Upper boundary of lower plug $z = 350.30$
Lower boundary of lower plug $z = 350.80$

The special rock-sealing effect that is expected if a slot is cut and filled with clay around the plugged section, as indicated in Fig 1-3, was investigated in the main test. It was concluded that a suitable location of the center of this slot would be $z = 350.55$. By this, the shallow but rather wide B-structure would be cut off. Schematic views of the shaft with the positions of the plugs and the central injection chamber are shown in Fig 2-9.

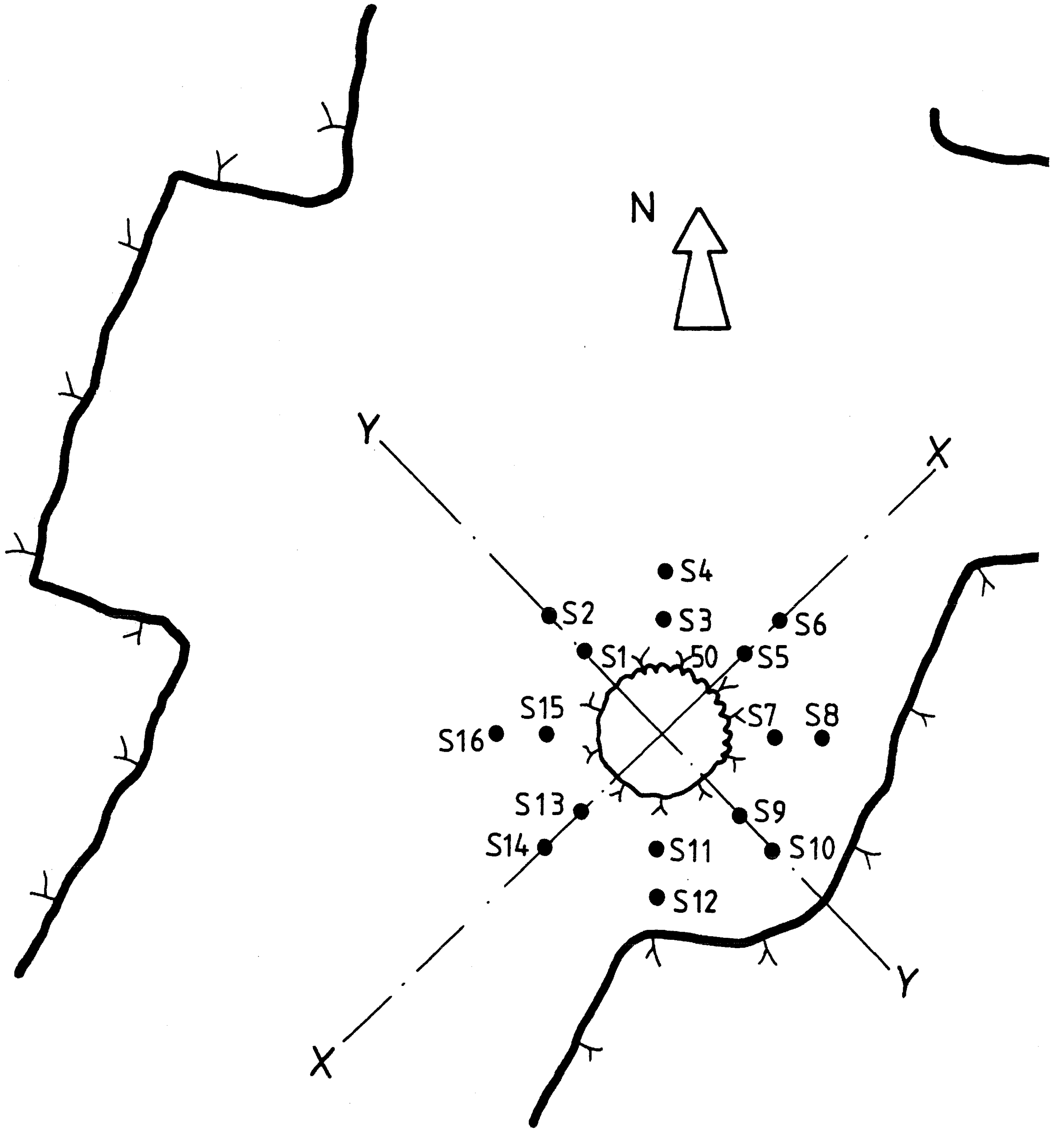


Figure 2-4. Arrangement of observation holes parallel to the shaft

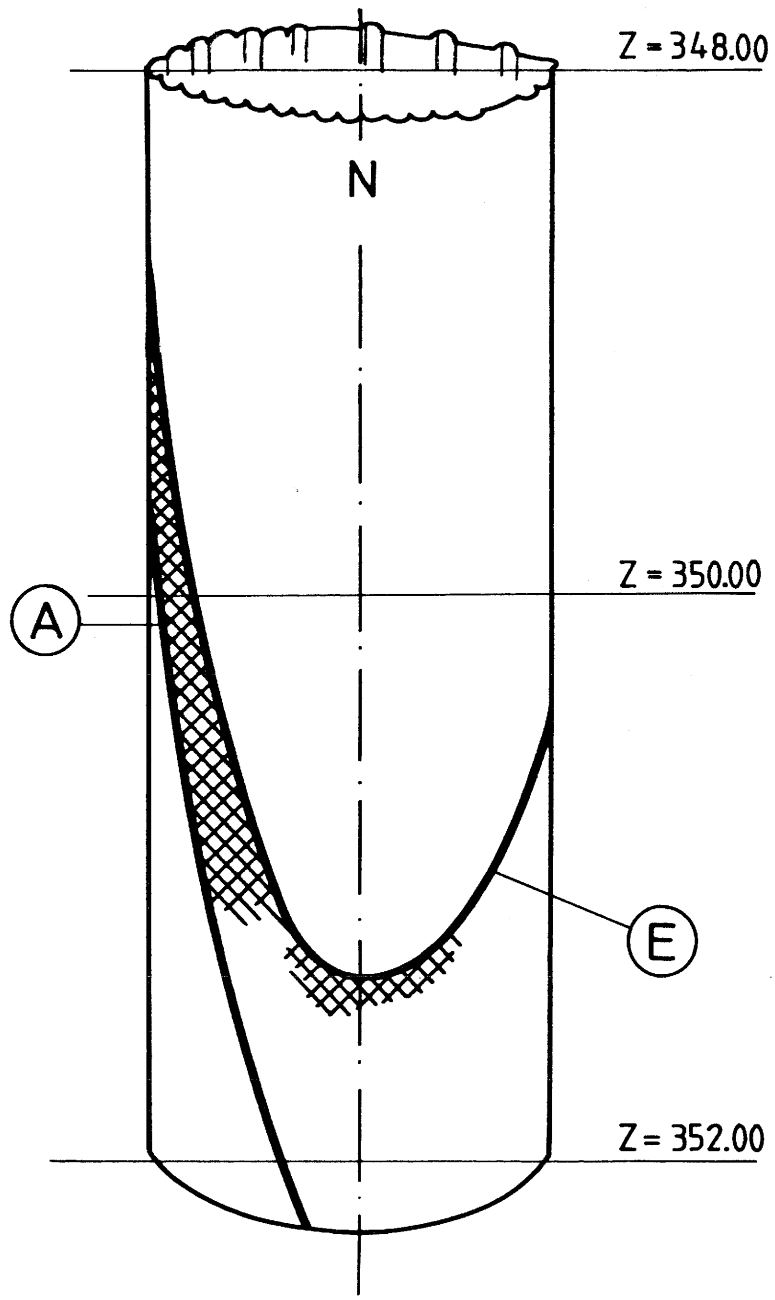


Figure 2-5. Generalized shaft model. View from north

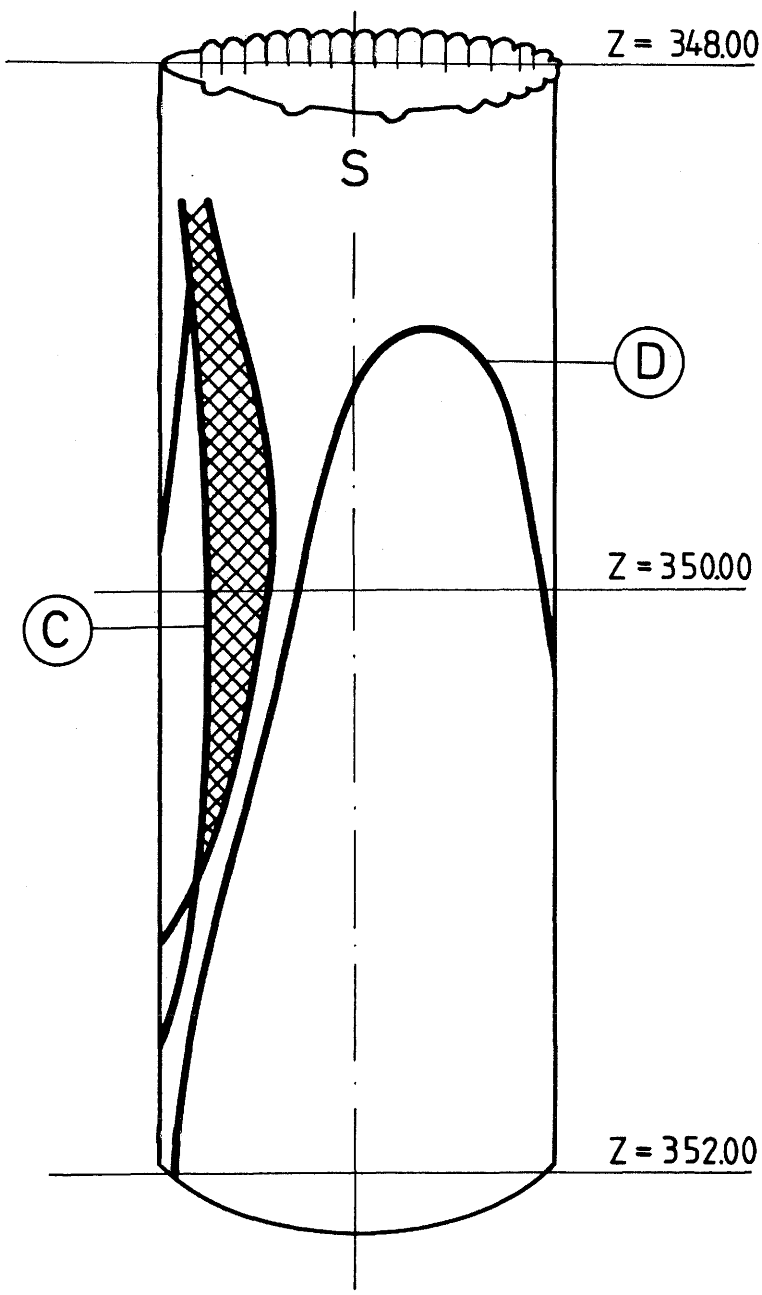


Figure 2-6. Generalized shaft model. View from south

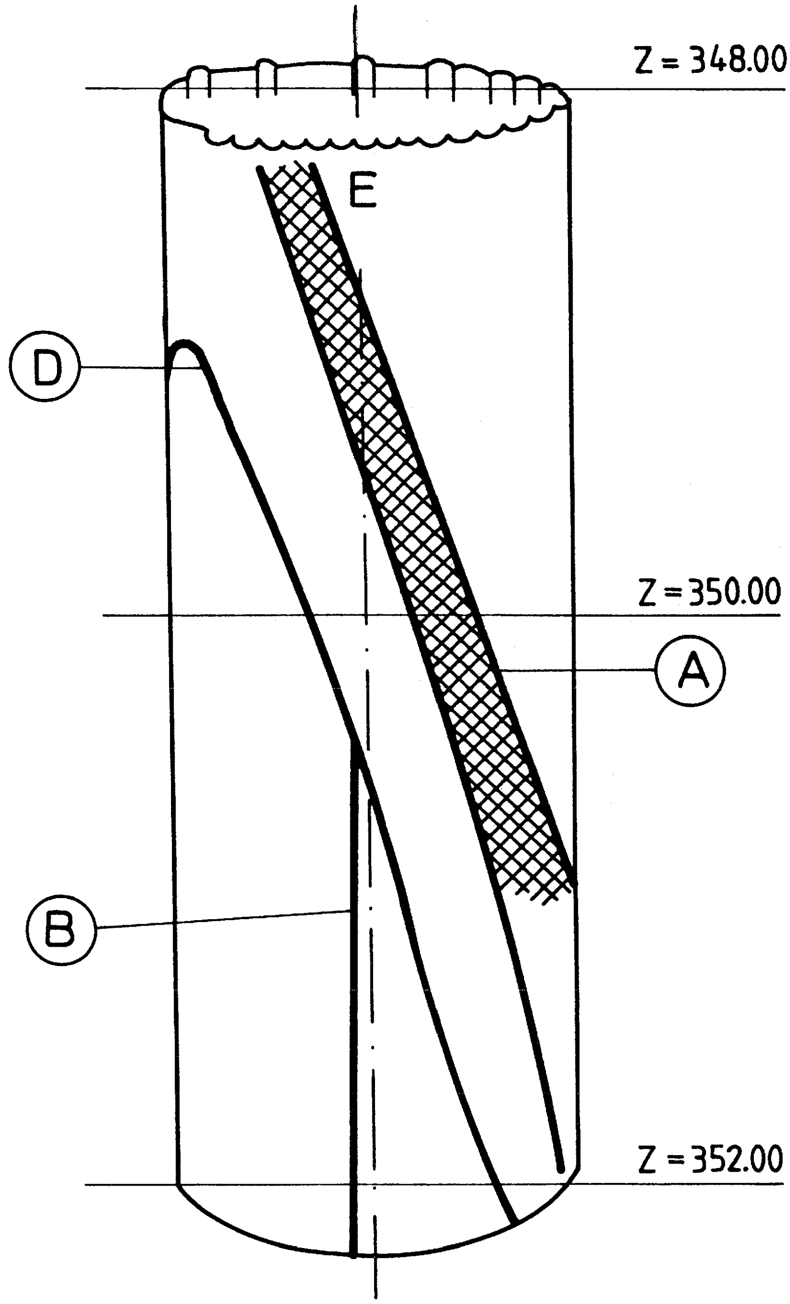


Figure 2-7. Generalized shaft model. View from east

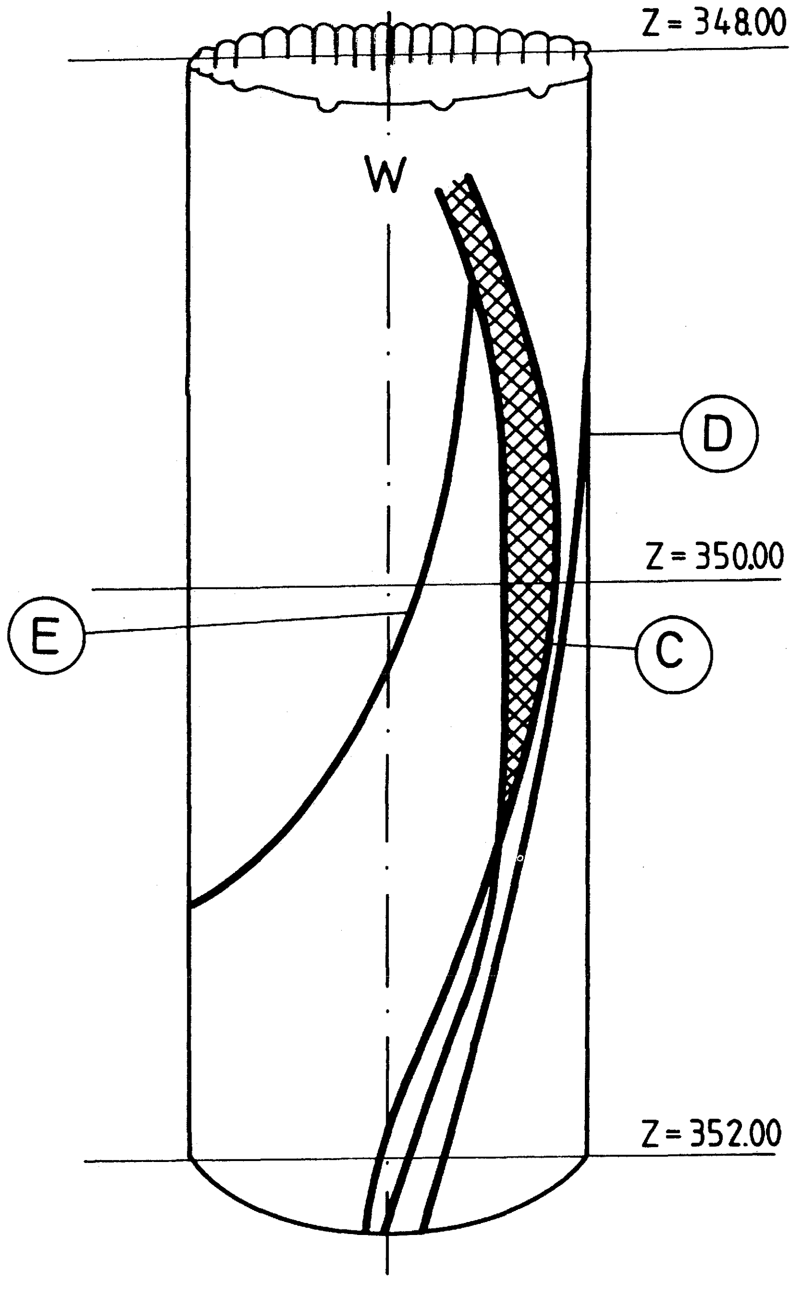


Figure 2-8. Generalized shaft model. View from west

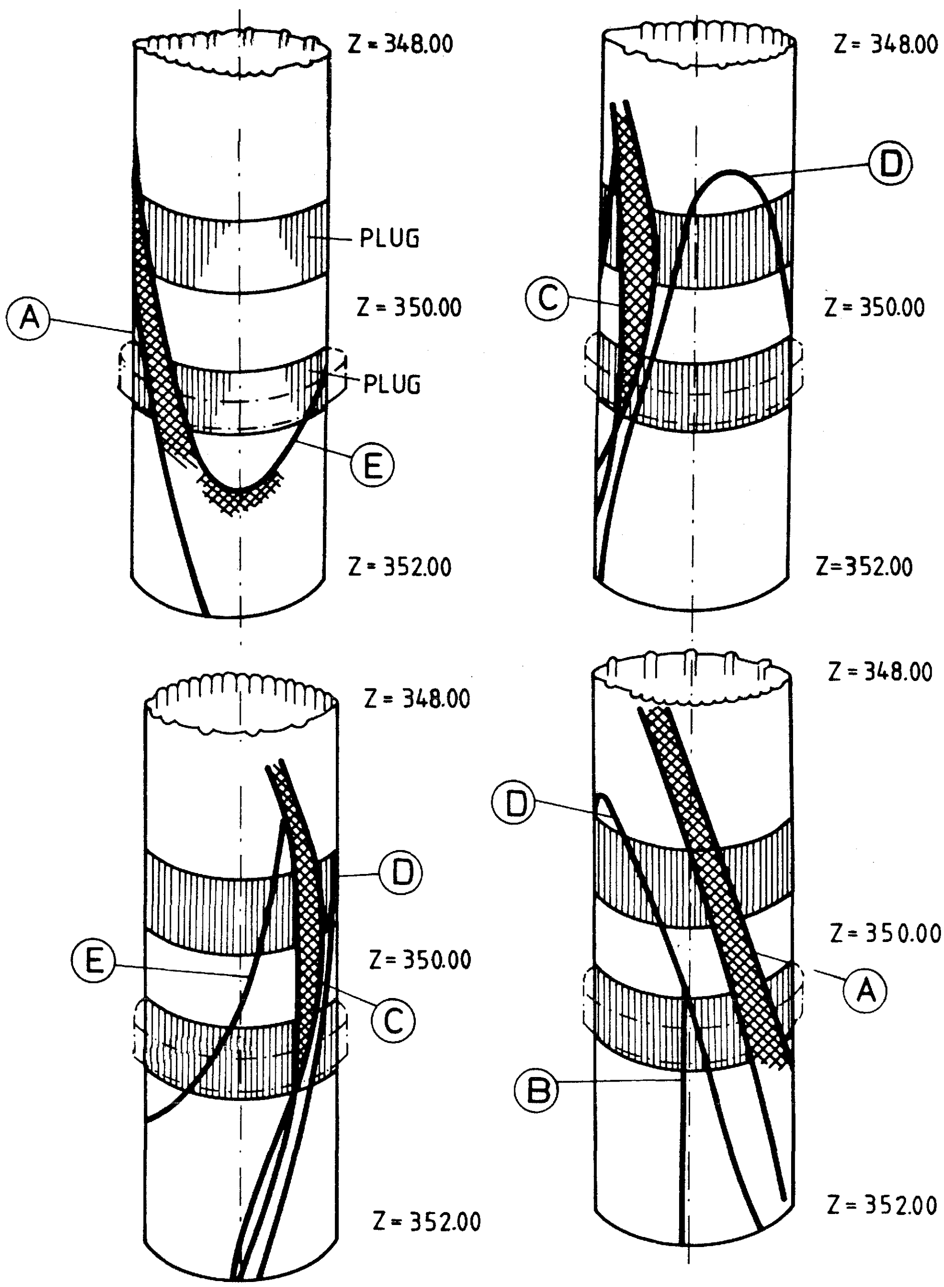


Figure 2-9. The major hydraulic active structural features A-E in the shaft

2.3.5 Preparation of the test

At the end of the hydrological characterization, the 16 Ø 56 mm holes were packer-sealed so that the sections containing major conductive structures that were assumed to be hydraulically connected to the shaft, were left open. For this purpose long inflated rubber packers were emplaced with their lower ends at the approximate level z = 353.5 and with their upper ends at the levels that are given in Table 2-2. The upper sealings were single mechanical packers with their lower ends located as specified in the table.

At a late stage of the test, the packer arrangement was altered completely in order to increase the possibility of catching water from the injection chamber. At that stage only short mechanical packers were used at the upper and lower ends of the observation holes.

Table 2-2. Final packer positions in the 16 observation holes

Hole	Upper end of lower packer	Lower end of upper packer	Length of open section, m
S 1	z = 350.3	z = 349.1	1.2
S 2	351.4	350.0	1.4
S 3	350.3	347.8	2.5
S 4	351.2	349.1	2.1
S 5	347.5	346.3	1.2
S 6	345.4	343.2	2.2
S 7	346.4	344.6	1.8
S 8	343.8	342.8	1.0
S 9	344.5	343.0	1.5
S 10	346.0	344.0	2.0
S 11	347.7	345.7	2.0
S 12	347.9	346.0	1.9
S 13	345.3	343.5	1.8
S 14	Hole S 14 is "fracture-free"		
S 15	347.5	345.3	2.2
S 16	348.9	346.0	2.9

The space between the packers was connected to a set of manometers in the upper drift so that possible pressure reactions could be recorded when the water pressure was increased in the injection chamber of the plugs. Since they were located about 11 meters above the injection chamber they were not expected to react at injection pressures lower than 150-200 kPa.

2.4 TEST ARRANGEMENT AND PROGRAM

2.4.1 General arrangement

The arrangement is illustrated in Fig 2-10. The two plugs, which consisted of concrete with expansive cement in the first "reference" test, and which were replaced by bentonite plugs in the subsequent "main" test, were separated by a sand-filled injection chamber. The reference test served to show how effectively a shaft can be sealed off by use of a high-quality concrete plug, the outflow from the injection chamber being the major parameter. The slot around the lower plug was made in connection with the preparation of the main test.

Steps were taken to identify the flow paths from the injection chamber. This was made by sawing narrow slots for water collectors in the rock at various distances from the upper and lower boundaries of the plugs. The uppermost collector prevented surface water to flow down to the plugs along the walls of the shaft, while the lower ones were applied at levels where inflow into the shaft was expected from the major water-bearing passages. The collectors were equipped with narrow nylon tubings which were connected to calibrated vessels (I-V in Fig 2-10) in the lower drift. Each collector was divided in an eastern and a western part to improve the possibility of identifying the location of these passages. Tracers were used at certain intervals to identify the exact position of the passages which led water into the shaft above and below the plugs, as well as to find out possible flow paths from the injection chamber to the observation holes.

The main test also comprised measurement of swelling pressures in the bentonite to get information about the maturation rate and the magnitude of the swelling pressure.

2.4.2 Plugs

a. Concrete plugs in reference test

The drawing in Fig 2-11 shows the design of the two concrete plugs. Their height was 0.5 m while the diameter was about 1.2 m. The lower plug, which was built on a form resting on 8 bolts anchored in the wall, was traversed by the central pipe hosting the tubings from the upper collectors and from two injection tubings. After solidification of the concrete, sand was applied and compacted in layers with simultaneous flooding of water to yield saturation of the sand. The upper plug was then cast and the two plugs finally locked in position by applying a low tension stress in the 4 Ø 25 mm bolts that passed through the plugs.

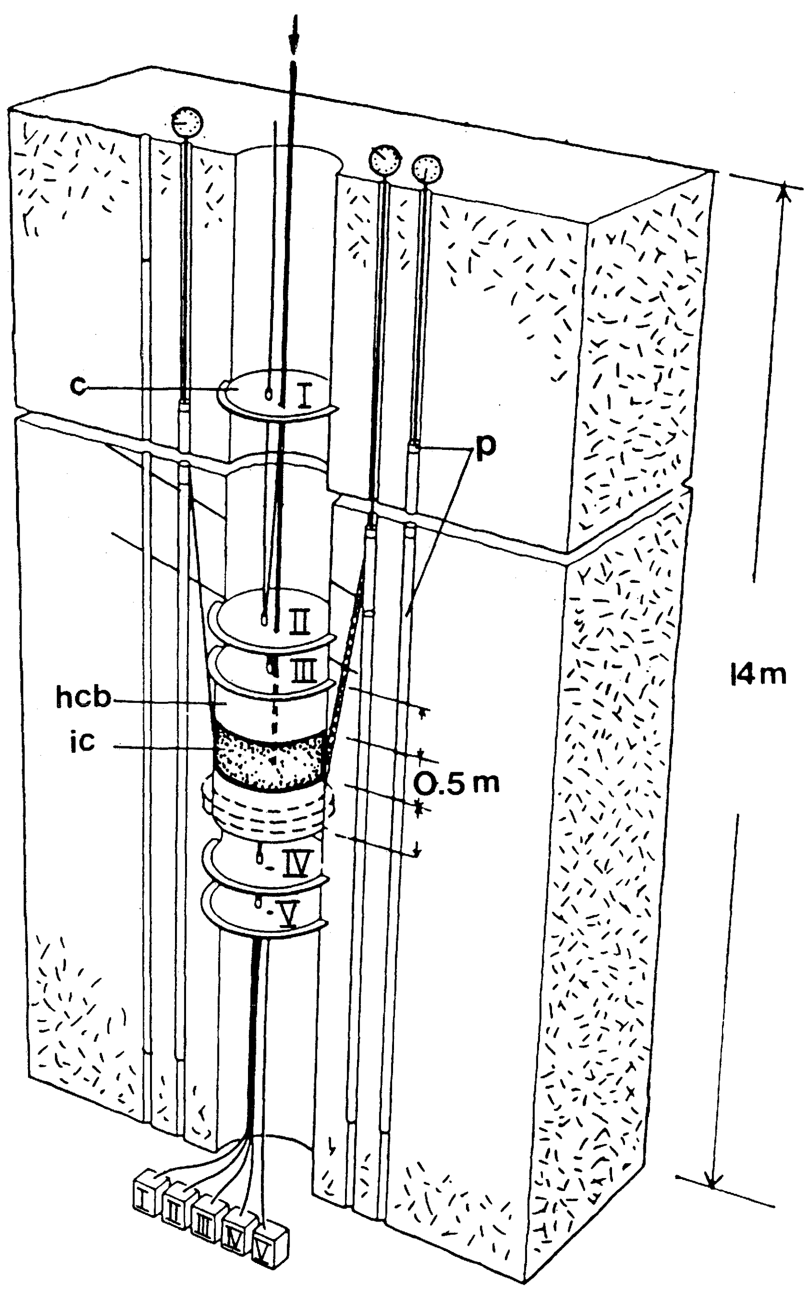


Figure 2-10. General test arrangement

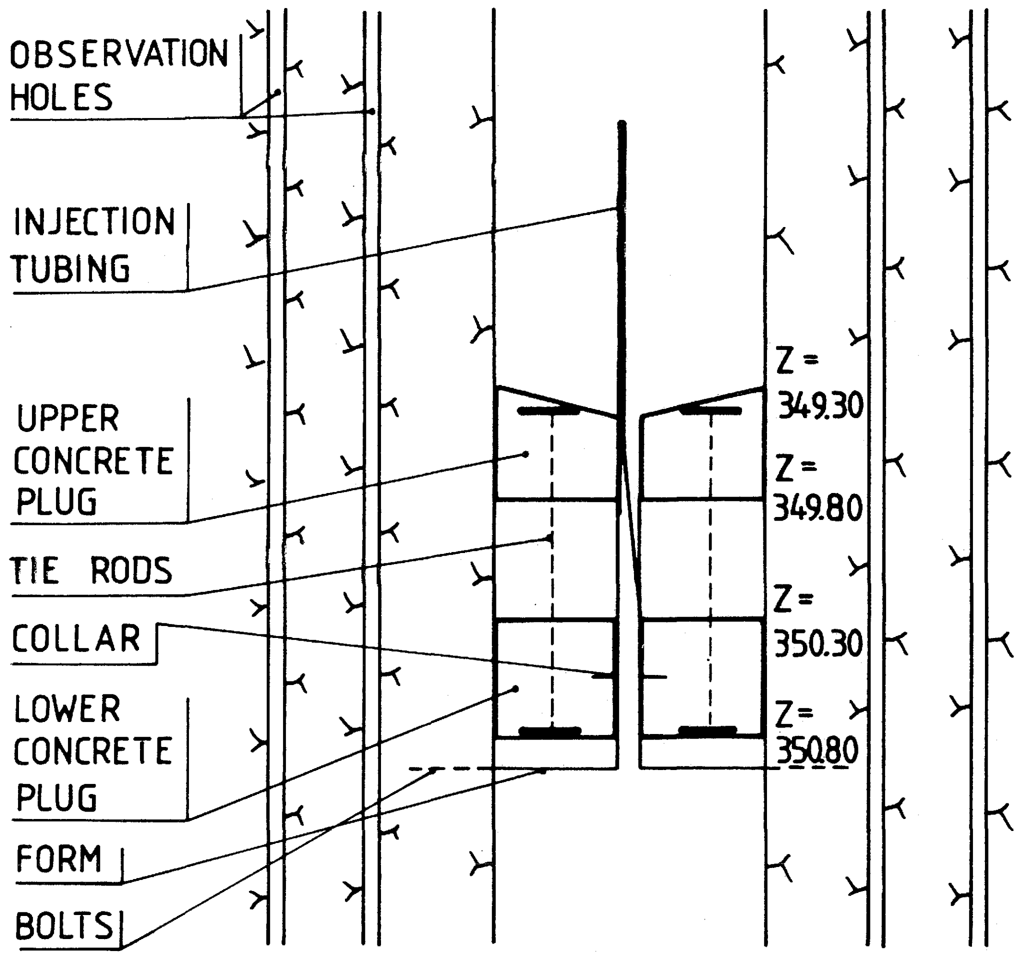


Figure 2-11. Design of the concrete plugs

b. Bentonite plugs in main test

Fig 2-12 shows the arrangement of the bentonite plugs. The maximum swelling pressure that was expected to be developed in the course of the test was 3 MPa, for which the beams and tie-rods had to be designed. Rather heavy components were found to be required as indicated by the photograph in Fig 2-13, which shows one of the beam supports forming the upper and lower ends of the twin plug.

The slot surrounding the lower plug was cut by means of a rotating diamond-coated steel disc. The machine was mounted in the shaft so that a number of parallel 250 mm deep slots could be cut, the upper and lower ones having a distance of 254 mm.

The rock between the cuts was then removed by use of a steel wedge that was driven into the narrow openings. This yielded a relatively even inner wall of the slot, the height of which made it possible to bring in prefabricated 250 mm thick blocks of bentonite. Hagby Bruk AB was responsible for all the rock cutting operations.

The bentonite blocks were prepared from the set of larger blocks that was left over from the Buffer Mass Test. They had been produced by compacting Volclay MX-80 bentonite powder with an initial water content of 10-13 %, so that a bulk density of 2.07-2.14 t/m^3 was obtained. The stored blocks had almost retained their physical state due to tightly fitting plastic covers but a slight reduction of the water content down to about 8 % still appeared to have taken place. The blocks were applied as densely as possible in a regular pattern, and the space between the irregular shaft wall and the central block system was filled with smaller pieces of compacted bentonite and bentonite powder. It was estimated that the net bulk density after complete water saturation would be about 2.05 t/m^3, taking into account a compression of the 0.5 m high injection chamber fill by 10 %, i.e. 5 cm. This density corresponds to a water content of 22-23 % at complete saturation. The total pore volume of the clay plugs was 0.45 m^3 of which 0.22 m^3, i.e. 220 liters, represented air-filled voids.

2.4.3 The sandfill in the injection chamber

The sand was prepared by screening a graded material to obtain one with a narrow particle size, 0.5-2.0 mm. This was because pilot tests had shown that sand containing finer particles is difficult to saturate effectively. Also, the use of coarser sand offered a possibility of observing to what extent bentonite penetrates the voids of a relatively coarse ballast material with which it is contacted.

The chamber was first filled with water to about 5 cm height and dry sand was then submerged until it reached just over the water surface. After compaction and complete saturation of this first layer, water was filled to about 5 cm height over the sand, and additional sand was then submerged to form the next, approximately 5 cm thick layer, etc.

2.4.4 Test program

The main testing principle was to run the reference and the main tests at the same injection pressure, measuring the outflow from the injection chamber and recording the inflow into the collectors. In addition, inspection was made of the shaft and observation holes after adding tracers to the water, in order to identify flow paths and differences in flow pattern between the two tests. The rate of maturation of the bentonite was illustrated by recording the pressure cells.

The test of the nearby Ø 76 mm borehole plugs had demonstrated that injection pressures exceeding 100-200 kPa tended to expand rock fractures with a certain orientation and it was therefore decided to apply a constant pressure of not more than 100 kPa. However, an increase to 200 kPa was planned in the latest phase of the main test.

A first attempt to run the reference test was made in mid February 1984, but it turned out that the outflow from the injection chamber was largely blocked by partly air-filled voids in the sand. Pressurizing, with the intention to complete the saturation, turned out to yield unconsistent results and the test had to be rearranged. The upper concrete plug was removed by percussion drilling, the sand excavated and the chamber refilled with sand which was saturated by applying the procedure described in paragraph 2.4.3. Hereafter, a new upper concrete plug had to be cast and the water collectors were finally put in place in the shaft. These operations caused a delay and the reference test could therefore not be started until July 1984. Table 2-3 summarizes the test program.

Table 2-3. Main data of the test program

Period	Activity	Art of test
Jul-Aug, 1984	Reference test	Flow test
Aug-Sep, 1984		Tracer test
Oct-Dec, 1984	Reconstruction	-
Jan-Feb, 1985	Main test	Flow test
Mar-Jun, 1985	Main test	Tracer test
Jul-Oct, 1985	Main test	Tracer test with obs holes packed off only at upper and lower ends
Oct-85-Jan-86	Main test	Flow and tracer tests*
Feb-Mar, 1986	Main test	Excavation and sampling

* 100 and 200 kPa injection pressure. In all the preceding tests the injection pressure was 100 kPa

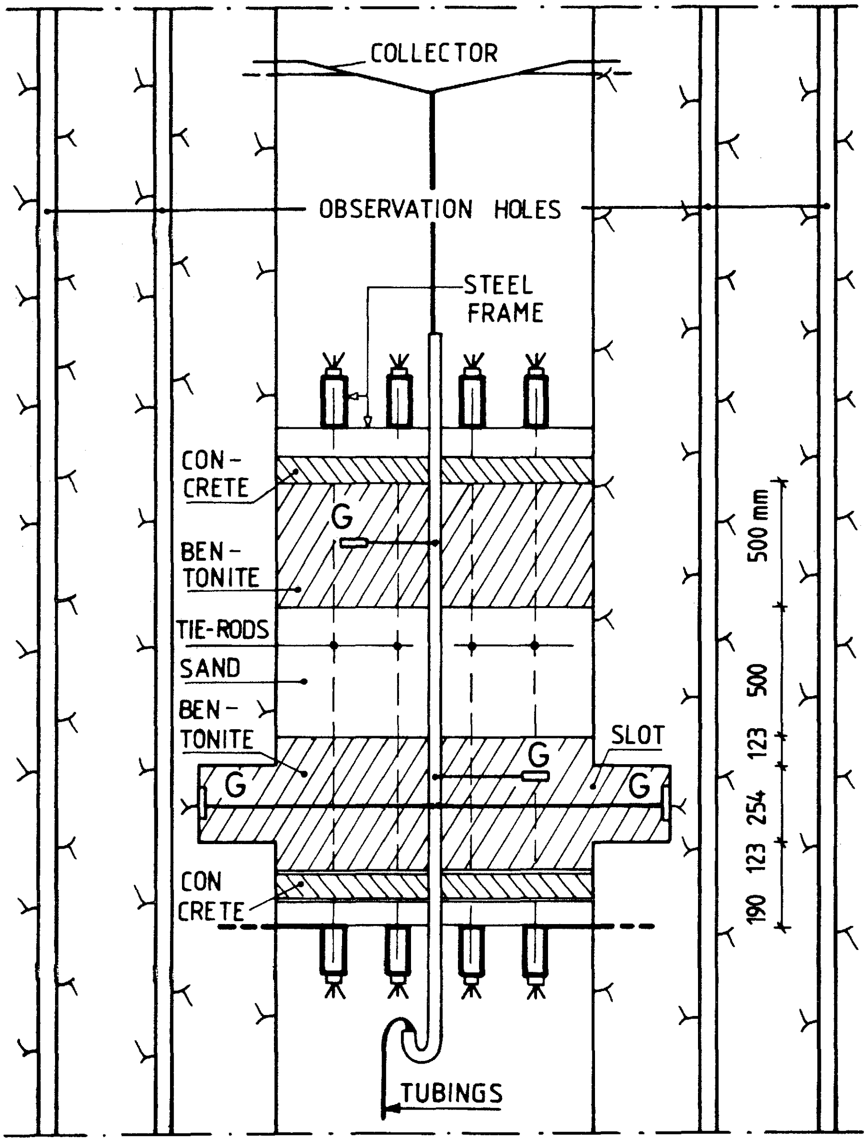
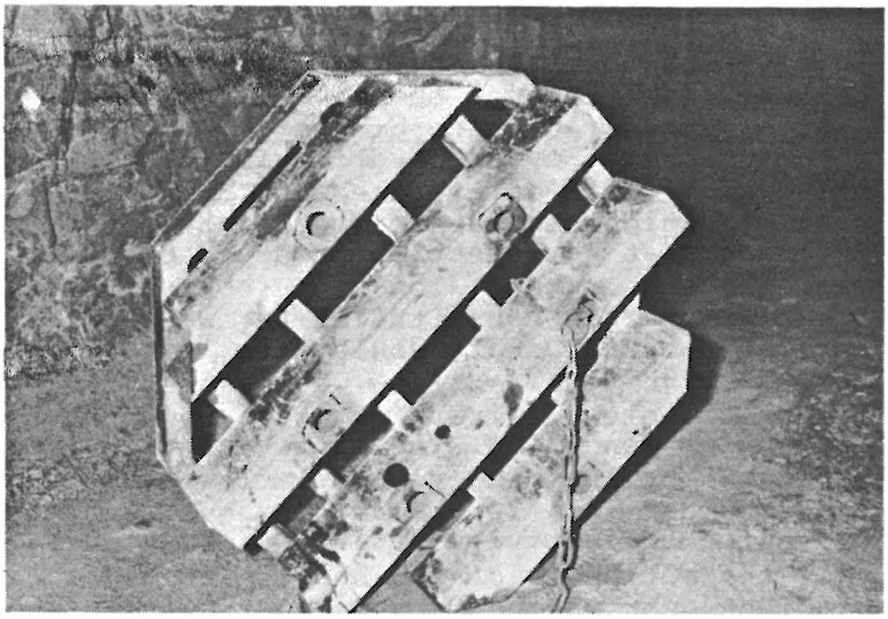


Figure 2-12. Schematic picture of the arrangement of the main test. G represents Gloetzl cell



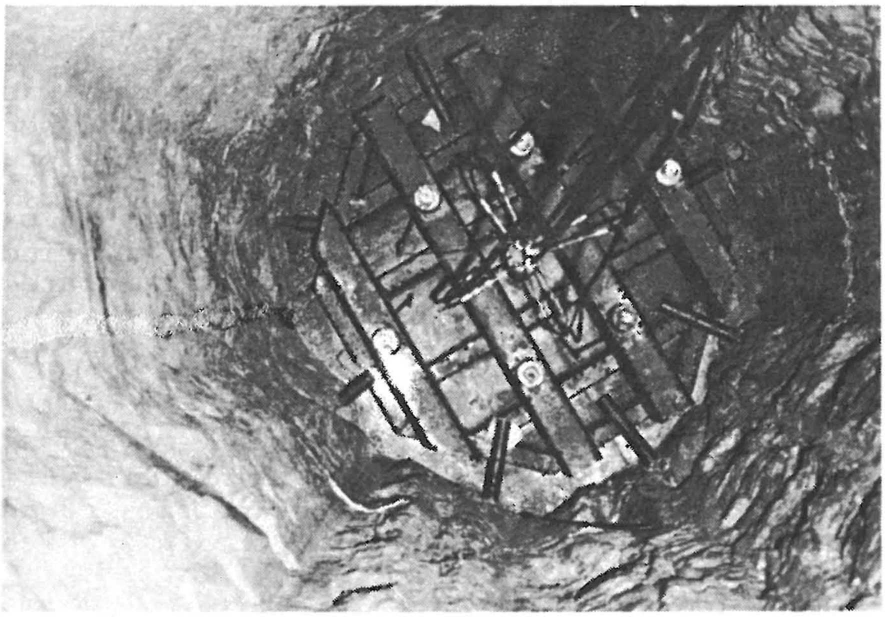


Figure 2-13. Frames of steel beams as load-carrying components of the lids

3 RESULTS

3.1 REFERENCE TEST

3.1.1 Flow rate from injection chamber

The outflow from the injection chamber was expected to take place through the five discrete structures A-E. A rough prediction of the flow was made by assuming that they are hydrologically equivalent to plane slots with an average aperture of 0.01 to 0.05 mm, which gave a predicted outflow of 0.6 to 25 l/hours at an injection pressure of 100 kPa, disregarding leakage along the rock/concrete. Since the blasted rock constituting the western perimeter of the shaft would also let some water through, the total outflow was assumed to be at least a couple of liters per hour under steady state flow condition. The latter contribution was estimated by assuming vertical flow from the injection chamber in a 10 cm wide "porous" zone with a hydraulic conductivity of 10^{-6} to 10^{-8} m/s along half the periphery of the shaft. The hydraulic gradient over the upper and lower parts of the zone, each of 0.5 m axial length, would be roughly 20, thus yielding a flow on the order of 0.15 to 15 liters per hour.

The actually measured flow was initially more than 10 l/h but dropped to about 5 l/h after 4 days and to about 2 l/h after 10 days (Fig 3-1). A further drop in flow was recorded after a few weeks, probably due to clogging of the filter of the injection pipe, but the initial flow rate was again observed when water was injected through the second pipe. The average outflow rate under stationary conditions was thus concluded to be 8-9 l/h in the reference test, indicating that the larger part of the leakage took place through the identified, larger structures or along the rock/concrete interface.

3.1.2 Flow paths

While the water flow into the collectors varied considerably with time and never exhibited any distinct quantitative pattern, the collection of water from the various parts of the shaft simplified the identification of the major flow passages. The observations, which are summarized in Table 3-1, were made by injecting water with 100 ppm uranine tracer solution.

The following conclusions were drawn from the study:

- No flow occurred from the injection chamber to the upper part of the shaft

- Structure B, i.e. a steep, wide fracture extending from the injection chamber and downwards was the major water passage as indicated by the appearance of the tracer substance

- Significant leakage took place through the "crushed" rock zone A and the fracture E along the lower plug as demonstrated by the appearance of tracer substance

- No uniform flow through the blasted rock along the plugs upwards or downwards had taken place as concluded from the absence of tracers. This demonstrates that practically all the outflowing water from the injection chamber had been discharged through structures A, B and E where they contacted the concrete

- No water had migrated to the observation holes as demonstrated by the complete absence of tracer substance in water samples from these holes

- Effective reduction of the flow was expected in the main test by truncating the B-structure with the clay-filled slot. The A- and E-structures were likely to be sealed by penetrating clay.

Table 3-1. Tracer experiment in the reference test

Collector			Structure relation	Observation
I	Upper		None	None
II	0.5 m above upper plug	E (eastern)	-	None
		W (western)	C,D,E	None
III	On top of upper plug	E (eastern)	C	None
		W (western)	C,D,E	None
IV	0.5 m below lower plug	E (eastern)	A,E	Strong coloring
		W (western)	B,C,D	Strong coloring
V	1.0 m below lower plug	E (eastern)	A	Very weak coloring
		W (western)	B,C,D	Strong coloring

3.2 MAIN TEST

3.2.1 Test conditions

The shaft walls had been carefully cleaned by cutting and carving after the removal of the concrete plugs so that no cement remained, and flushing of the shaft walls had removed all signs of tracer substance, dust and loose rock fragments. The test conditions were thus practically the same in the reference and main tests and the results therefore directly comparable.

3.2.2 Flow rate from injection chamber, 100 kPa injection pressure

The outflow from the injection chamber in the main test was expected to be considerably smaller than in the reference test already at the onset of the first-mentioned test because of the blocking of the shallow, major flow passage (B), but this was assumed to be largely compensated by the much better fit between the plug material and the rock in the reference test. The initial flow rate was therefore assumed to be approximately the same in both tests, but a significant reduction was expected in the course of the main test because of various sealing mechanisms of the maturing bentonite. The outflow from the chamber under steady state conditions in the main test at 100 kPa pressure was predicted to be in the range of 0.1-1 l/h, and the lower value was actually approached after a couple of months (Fig 3-2). A direct comparison between the reference and main tests shows that the flow in the latter test was approximately 50 % of that in the reference test in the first ten days, which is in reasonable agreement with the predictions. Hence, the sealing effect was moderate to begin with, while it became very significant after a couple of months. This suggests a close relationship between the leakage and the saturation of the bentonite, which is known to be a time-consuming process.

The total outflow from the injection chamber in the main test with 100 kPa pressure was approximately 1500 liters, i.e. about 7 times the available empty pore space in the bentonite. Thus, the large majority of the water that left the injection chamber was discharged through rock structures which were in contact with the bentonite but which also served as drainage passages. Only a very small fraction of the discharged water could have been absorbed by the bentonite.

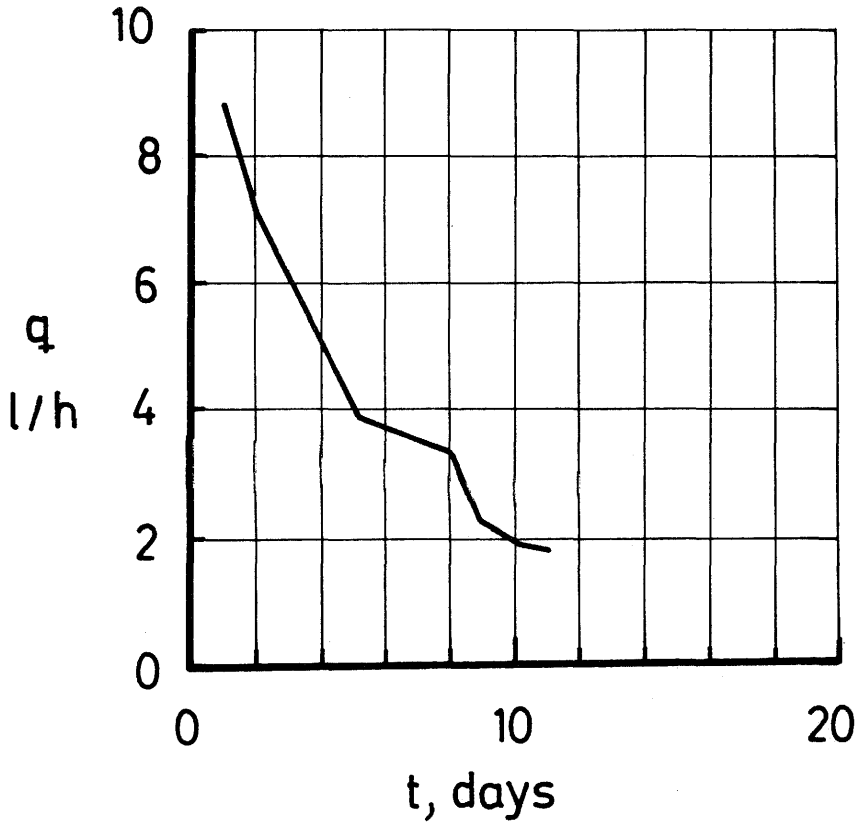


Figure 3-1. Outflow from the injection chamber in the reference test

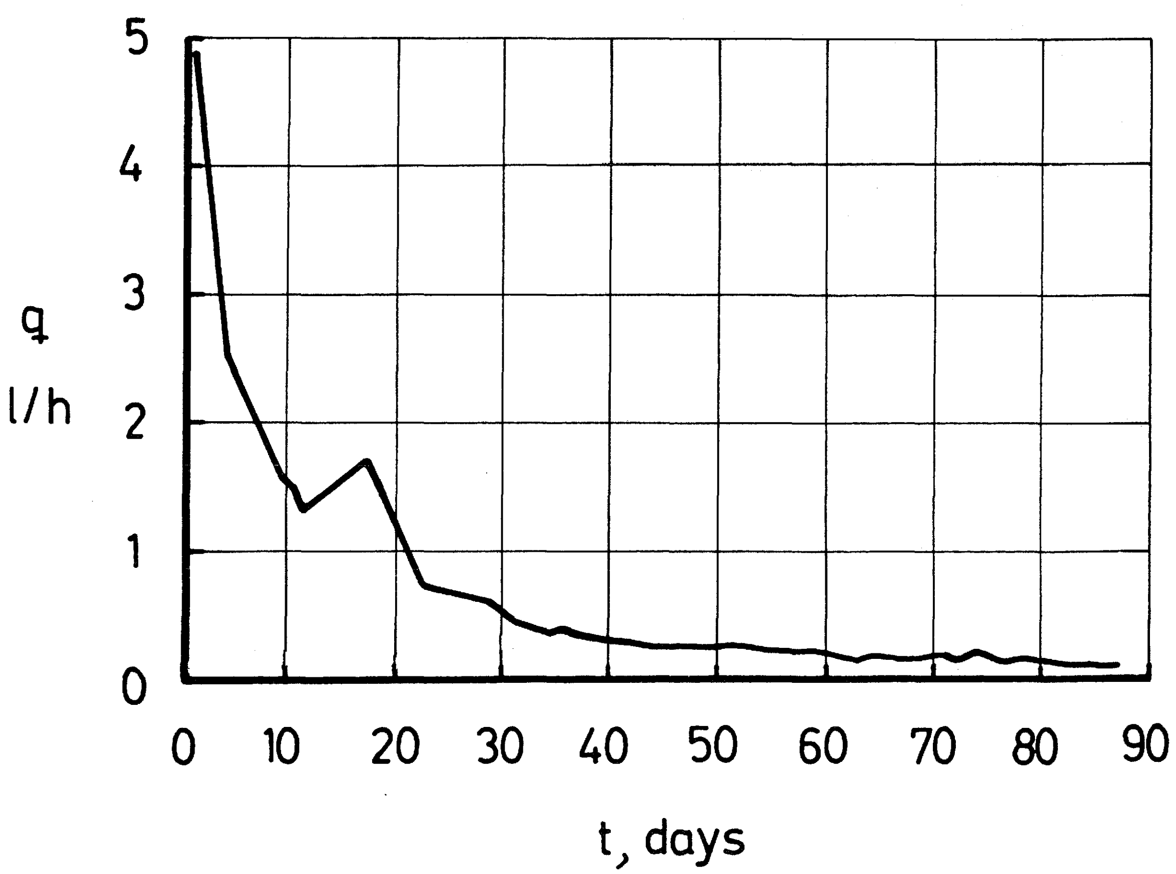


Figure 3-2. Outflow from the injection chamber in the main test

3.2.3 Flow paths, 100 kPa injection pressure

No flow into the collectors took place during the main test, which certified that leakage did not occur along the rock/bentonite interface or through the adjacent rock. The collectors were therefore removed and uranine solution with a concentration of 1000 ppm injected in order to identify the flow paths, which were obviously not identical with those in the reference test. Tracers were not found on the shaft wall or in the observation holes but appeared in the central tube, which turned out to be caused by a slight leakage at the lead-through of the injection pipe. This leakage was estimated at a few tenths of a liter per hour, meaning that the net outflow of water from the injection chamber to the rock had almost ceased after about one month.

The first tracer test series, which lasted from March to July, 1985, was followed by a second series in which the long packers in the lower part of the observation holes were replaced by short mechanical packers at the upper and lower ends of the holes. Uranine solution was used in a first injection phase, which indicated connectivity between the injection chamber and the observation holes S1, S3, S4, S7, S11 and S15. No connection appeared to exist between the chamber and the holes numbered S2, S6, S9, S10, S12, S14. Most of these latter holes were located on the eastern side of the shaft while 50 % of the first-mentioned holes were located west of the shaft, which shows that the blasting of the western perimeter of the shaft had not caused far-reaching fractures.

It was concluded from this investigation that the rock structures A and E represented the major flow paths from the injection chamber in the main test, through which the injected water was driven downwards towards the lower drift. The fact that there was no sign of tracers at the crown of this drift suggests that the discharged water was effectively distributed and diluted, and that the tracer substance was partly adsorbed in many fine fractures in the blasted rock.

Phloxine B tracer solution with a concentration of 1000 ppm was used in a second injection phase. Although this investigation lasted for about two weeks, even a very careful analysis of water samples from the observation holes showed no presence of tracers. This was in agreement with the observation that the outflow from the injection chamber had almost ceased and no further valuable information from this test could be expected. The injection pressure was therefore increased to 200 kPa.

3.2.4 Flow rate, 200 kPa injection pressure

When the injection pressure was raised to 200 kPa the flow did not increase substantially as shown by the diagram in Fig 3-3. We see that it was less than 50 % of the recorded values at 100 kPa pressure at corresponding times after onset of the respective tests. This demonstrates that the sealing effect of the bentonite had increased considerably in the course of the test.

3.2.5 Flow paths, 200 kPa injection pressure

The injection pressure was maintained at 200 kPa over the greater part of the approximately 2 months test period that ended the shaft plugging test. Uranine tracer solution with a concentration of 1000 ppm was used in the last week of the test in order to investigate whether new flow passages were opened by the increased pressure or if the A and E paths had been activated again. The appearance of tracer substance at the exit of structures A and E in the shaft wall gave evidence of the latter process. Careful inspection of the shaft verified that no leakage had taken place along the interface between the rock and the bentonite plugs.

The character of "crushed rock" of the A-structure was clearly seen in the wall of the slot surrounding the lower plug (Fig 3-4). The detailed features of the C- and D-structures were also revealed, the first-mentioned being similar to the A-structure (Fig 3-5). The E-structure is a discrete fracture (Fig 3-6) which intersects the shaft wall at a relatively high angle.

3.2.6 Swelling pressure

The development of swelling pressures was expected to be relatively slow. Thus, applying the diffusion-type model of water uptake that was derived in the Buffer Mass Test, and which is further discussed in the subsequent chapter, it was realized that water saturation of a 5 cm wide clay zone adjacent to the sand-filled injection chamber would require at least 3 months. This would also be the time needed for saturating a zone of the same width adjacent to the rock, provided that the rock leads water to the clay interface at a sufficiently high rate. Assuming this condition to apply, the swelling pressure should increase from a few hundred kPa in February/March 1985 to about 2-3 MPa at the end of the test in early February 1986, provided that the fitting of the blocks was perfect. Since there was a fairly large variation in the continuity of the block sets and the density of the bentonite fill close to the rock was considerably lower than that of the blocks, a slower build-up of the swelling pressure was foreseen. The wetting of the bentonite at the sand/bentonite interface was expected to cause slight expansion of the bentonite associated with compression of the sandfill in the injection chamber. The low bulk density of the sand would correspond to a high compressibility, and the net displacement of the interface was therefore expected to be as much as 2-4 cm.

As demonstrated by the diagram in Fig 3-7, the actual development of the pressures was in reasonable agreement with the predicted ones for cells no 2 and 4, which recorded pressures developed by the uptake of water from the sand. Cell no 3 gave the maximum pressure 3 MPa for which the tie-rods of the twin plug had been designed. The rapid pressure build-up at this cell, which was located in the northern part of the slot, and the much slower pressure development recorded by cell no 1 on the southern side are not readily explained. The variation was probably due to differences in the fitting of blocks and to a certain spread in density of the backfilled bentonite powder.

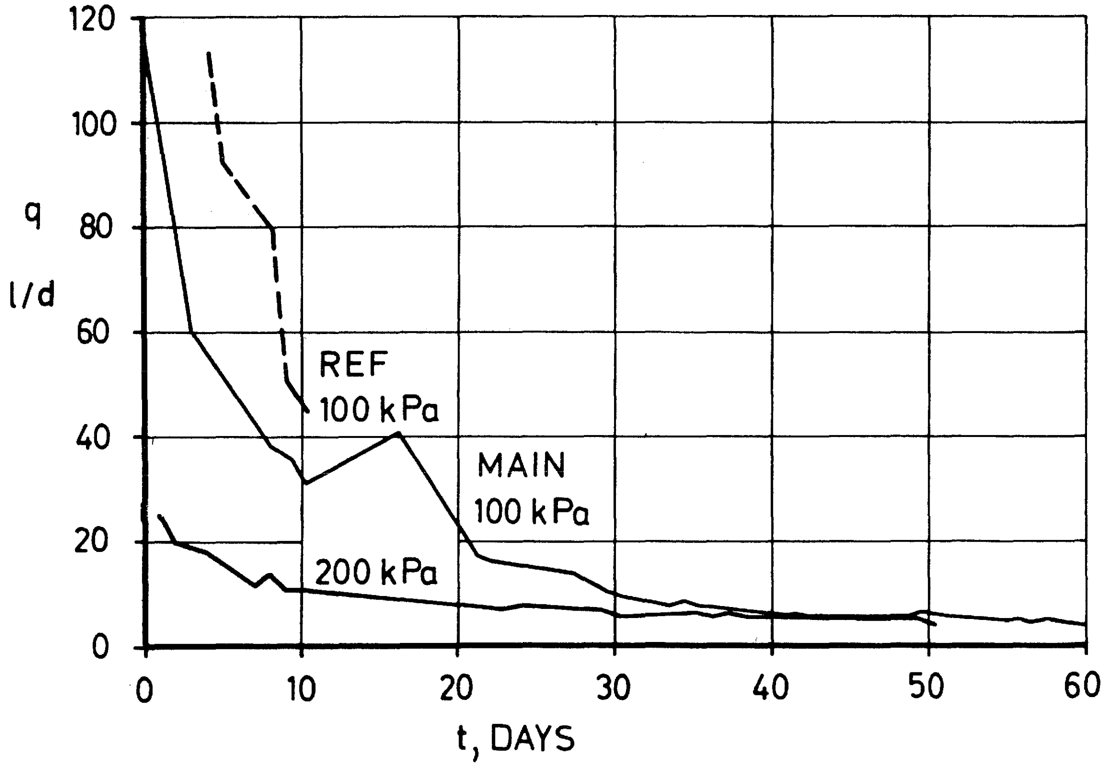


Figure 3-3. Diagram showing the outflow at reference and main tests

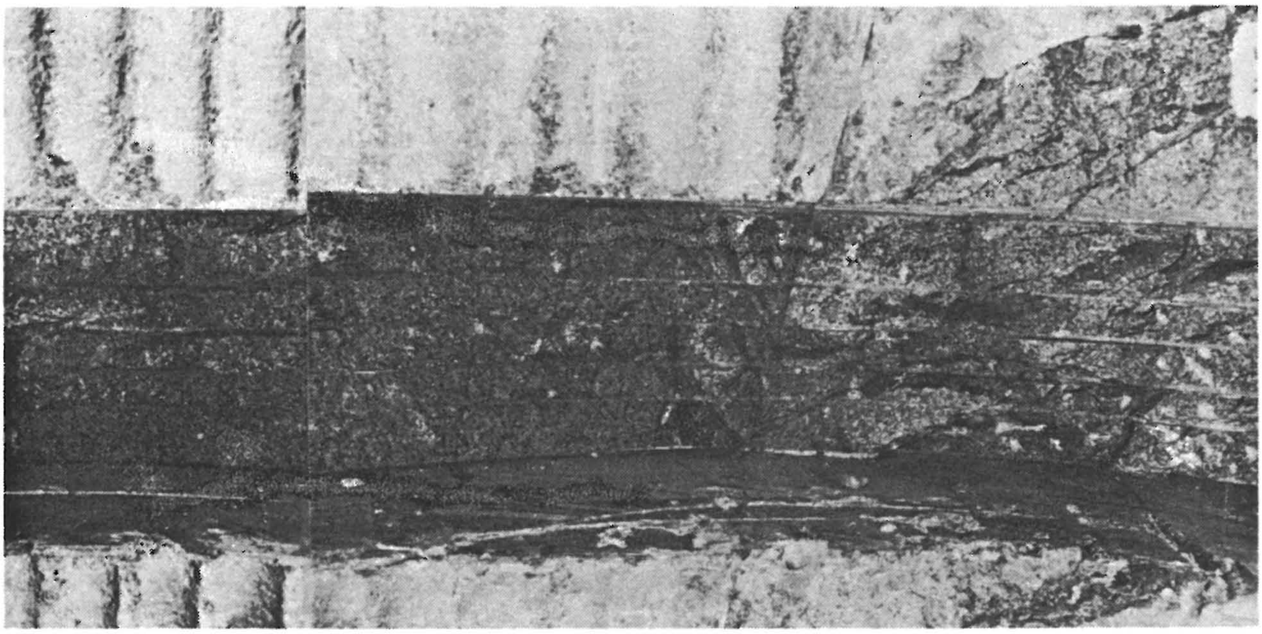


Figure 3-4. Photograph of the A-structure

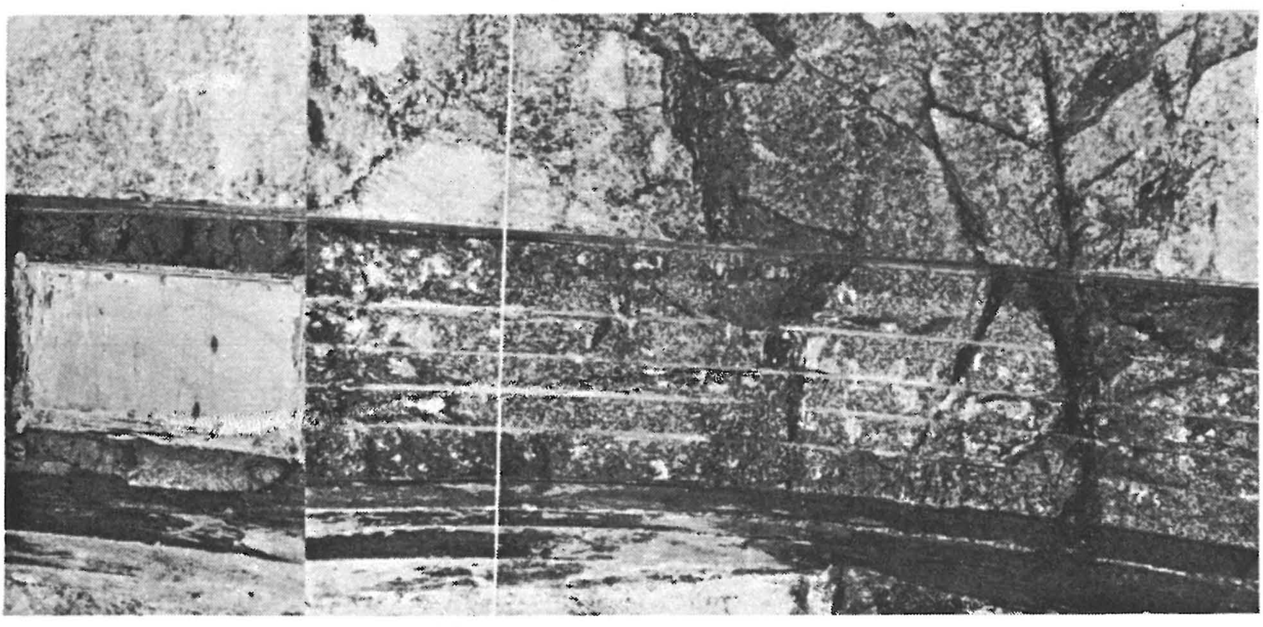


Figure 3-5. Photograph of the C- and D-structures

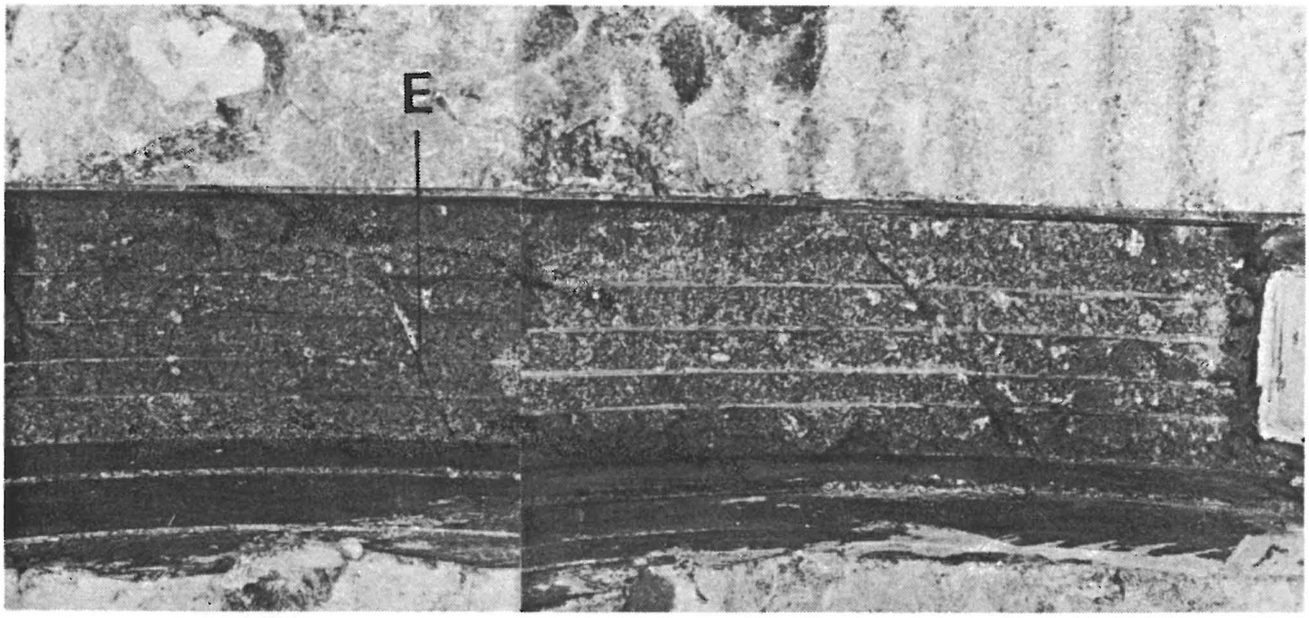


Figure 3-6. Photograph of the E-structure

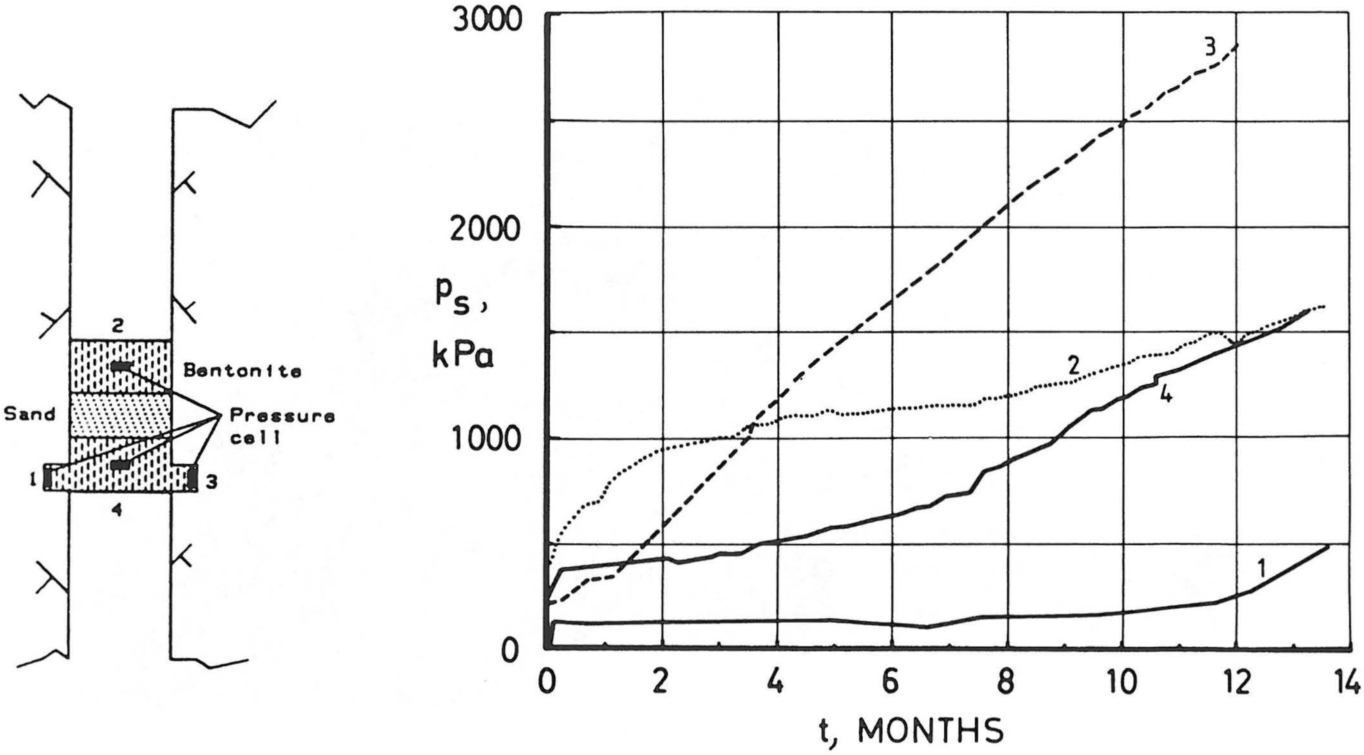


Figure 3-7. Recorded swelling pressures

3.2.7 Water uptake and distribution

Predictions

At the planning of the presently discussed test, the Buffer Mass Test was not yet fully evaluated and the understanding of the water transport through normally fractured rock to non-saturated dense smectite clay was still rather limited. Thus, large variations in the rate of uptake and in the distribution of absorbed water were expected early in the test preparation. However, it became obvious in the course of the test, particularly at the evaluation of the Buffer Mass Test and the Borehole Plugging Test, that the general diffusion-type model was likely to apply also in the present case, provided that the piezometric heads in the rock surrounding the plugs were sufficiently high to maintain a water pressure also in the finest fissures.

The main features of the model for water uptake, which is presented and discussed in detail in the final report of the Borehole Plugging Test, are as follows. Water first enters the clay from water-bearing fractures, which tend to be blocked rather soon by penetrating clay. Water under pressure in the surrounding rock then follows "second order" passages, i.e. fine fissures, which in turn become blocked by expanding clay. Finally the narrow joints of the crystal matrix lead water to the shaft and this yields a rather uniform wetting over the clay/rock interface. Where the rock is relatively fractured and water available all over the clay/rock interface the rate of water uptake proceeds, in principle, according to the diffusion-type migration specified by Eq. (1):

$$\frac{\delta w}{\delta t} = D\nabla^2 w \qquad (1)$$

where w = water content
t = time
D = "diffusion coefficient"

Laboratory investigations as well as the conclusions from the BMT study suggest an average D-value of 4×10^{-10} m^2/s (2, 3).

The uptake of water was calculated by use of the computer program ENERGY (Chalmers University of Technology, Gothenburg, Sweden), the boundary conditions being unlimited access to water at the clay/rock and clay/sand interfaces and no transfer of water at all across the outer ends of the plug. The latter assumption was in agreement with the conditions represented by the 5 cm thick reinforced concrete layer which transferred the swelling force from the clay to the heavy steel frame at each outer end of the plugs. Since the concrete layers were kept drained they actually represented dry boundaries.

A few predicted wetting stages are illustrated in Figs 3-8--3-10. It is seen that the calculations yielded zones with unaltered water content, even at the end of the almost 1 year long test. However, at that time at least 80 % saturation, corresponding to about 18 % water content, was expected to within about 10 cm distance from the wet boundaries. The total water uptake would amount to about 80 liters in the twin plug.

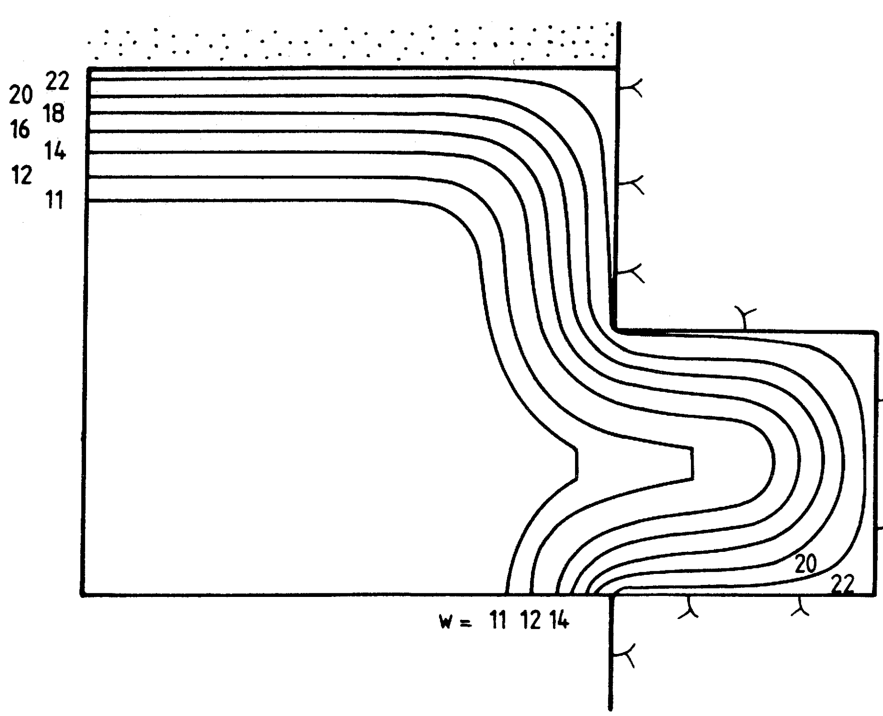


Figure 3-8. Predicted water content distribution after 2 months. Lower plug

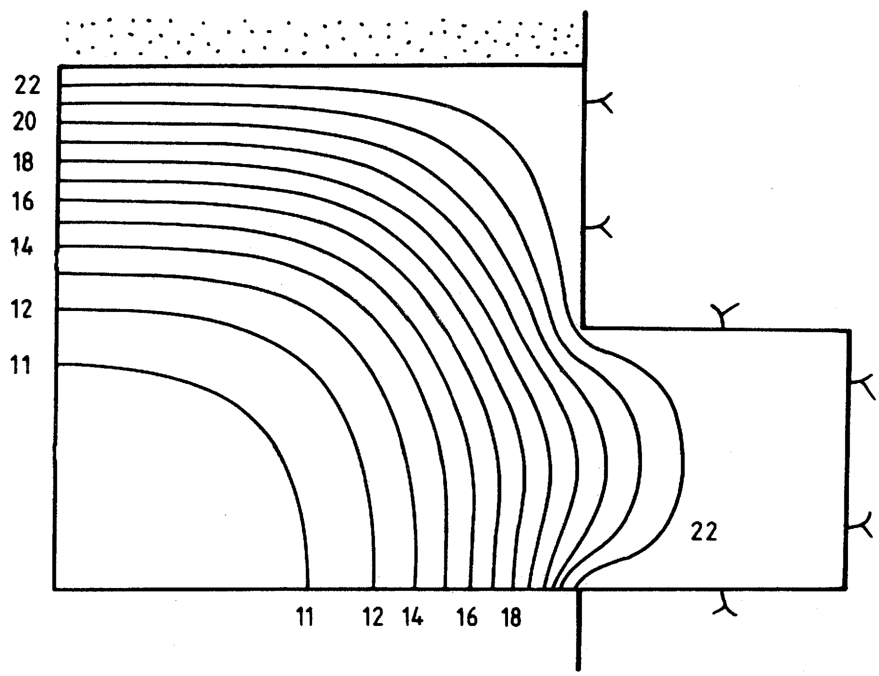


Figure 3-9. Predicted water content distribution at the termination of the test, 1 year after the start. Lower plug

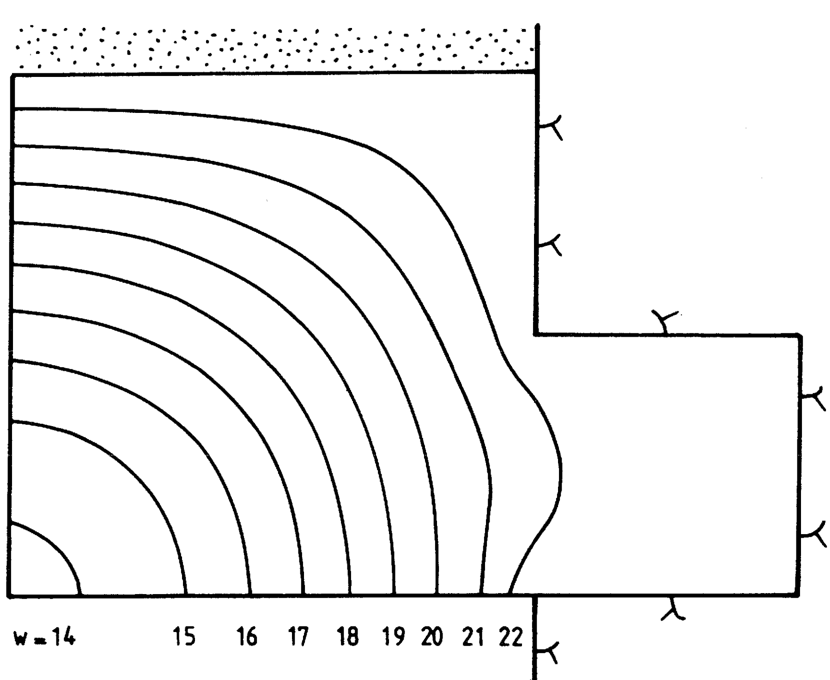


Figure 3-10. Predicted water content distribution 2.8 years after the start if the test had continued. Lower plug

Field investigation

After removal of the upper steel frame and concrete cover, the clay was excavated from above and samples taken for determination of the water content. The positions of the samples were preset by applying a jig on the sampling levels, which were located about 12 cm apart in the vertical direction (Fig 3-11). The samples were taken with the same equipment as that used in the Buffer Mass Test. The total number of samples was about 250 in the upper plug and about 300 in the lower one. Fig 3-12 illustrates the sampling operation and tools.

The appearance of the bentonite is illustrated by Figs 3-13 and 3-14. It had established a tight contact with the rock and had no open joints or fractures at any of the sampling levels. The bentonite turned out to be perfectly homogeneous with no visible joints within about 10 cm distance from the rock wall and the sand chamber, respectively, while closed joints were seen in the rest of the plugs.

As predicted, the central part of the upper half of the top plug had retained its original water content (Fig 3-15). A closer look at this iso-moisture plot reveals that local parts along the north-eastern and north-western peripheries were significantly dryer than the rest of the perimeter which appears to have been uniformly wetted. The next lower sampling level showed a similar but more uniform pattern, the higher figures at the edge indicating that slight expansion towards the sand chamber had taken place (Fig 3-16). The presence of local, relatively dry peripheral parts seems to be related to the lack of clearly water-bearing rock fractures in these parts, where none of the major structures are located. Still, also these fracture-poor parts should have been effectively wetted if the water pressure had been sufficient to feed the fine fissures with water. It is therefore concluded that the natural piezometric heads and those generated by the water injection were too low to bring water through to the clay/rock interface.

A more regular pattern of concentric iso-moisture curves is exhibited by the corresponding plottings for the lower plug (Figs 3-17 and 3-18). This may be explained by somewhat higher water pressures in the rock surrounding the lower plug although the conditions cannot have been significantly different from those at the upper plug. This is actually demonstrated by the sections in Fig 3-19 from which it can be seen that the upper edge of the slot had not served as an effective water source for the wetting of the clay. The number of water content data of the blocks in the slot was very limited because of the difficulty of extracting the clay in such a way that the exact position of the clay samples could be determined and the curves are dotted to indicate that they are somewhat uncertain. It should be noticed that the lower boundary represented by the concrete had offered some water to the clay. It is also clear that leaching along the central pipe had taken place early in the test, thereby producing the local increase in water content in the central parts of the lower and upper plugs. In general, however, Figs 3-19 to 3-22 show very regular patterns, verifying that the wetting was best developed at the clay/sand interface and at the clay/rock interface at the inner part of the slot. It was almost equally well developed at the clay/rock interface of the upper plug. The total water uptake was found to be about 90 liters, i.e. not very far from the predicted figure.

A direct comparison between the predicted and recorded water contents is offered by Fig 3-23. We see that there is fair agreement at the clay/sand boundary and at the clay/rock contact in the slot, which verifies that the theoretical model applies where the access to water is not limited. The obvious misfit for the rest of the clay/rock contacts demonstrates that the access to water had been a limiting factor in the wetting process. The reason for this is concluded to be the low water pressures in the rock, which failed to drive water through finer fissures. The test conditions were thus representative of very shallow parts of repository shafts and of such parts of deeply located repositories in which the piezometric heads are low due to draining activities.

3.2.8 Clay migration in ballast material

At an early stage of the development of the presently investigated shaft plugging technique it was assumed that highly compacted bentonite contacting sand backfills will not only produce compaction of the sand but also cause penetration of the voids by expanding clay. It was shown later in experiments with clay penetration into narrow slots (5) that this effect is insignificant when the aperture is smaller than 0.1 mm, which would practically eliminate such infiltration of clay into well graded ballast materials. The shaft plugging test offered a possibility of verifying this experimentally. Since the sand consisted of grains with a size ranging between 0.5 and 2 mm the average diameter of pores exposed to the clay was on the order of 0.3 mm. Applying the semi-empirical relationship in Eq. (2) for estimating the penetration depth (cf. 5) we find it to be less than 3 mm.

$$x = Ad^2 \log(t+1) \quad (2)$$

where x = movement of gel front
d = aperture
t = time after onset of propagation
A = constant. For x and d in meters and t in years, A can be set at 10^5

Samples were taken from the clay/sand interface for microstructural investigations. They were frozen in freon and fractured at LN_2 temperatures to expose sections oriented perpendicularly to the clay/sand interface. These were then dried by vacuum sublimation, mounted, and coated with both carbon and gold for subsequent investigation in a scanning microscope. The preparation and microscopy was made by Gentronix Laboratories, Inc., Rockville, Maryland, USA.

Ocular inspection of the fractured specimen showed that clay could not have penetrated into the sand by more than 1-2 millimeters. This was clearly demonstrated also by the micrographs, of which Fig 3-24 is a representative example. The character of the penetrated clay was rather massive, indicating that it had been forced into the voids of the sand by the swelling pressure rather than having expanded into them by volume increase. This is in good agreement with the general physical model for clay penetration into rock fractures (5).

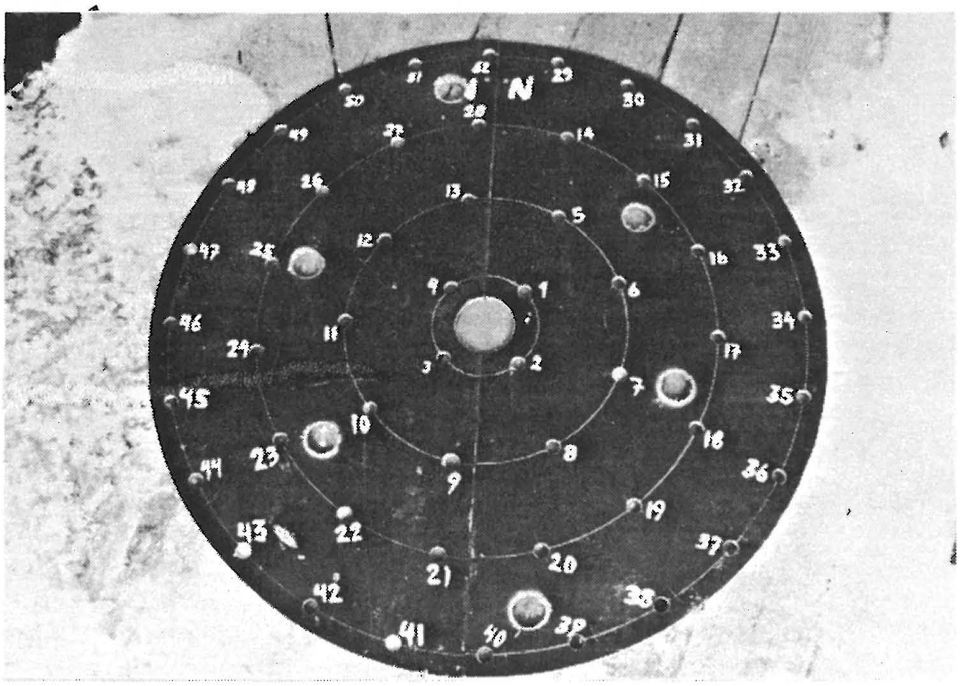


Figure 3-11. Jig for location of sampel holes

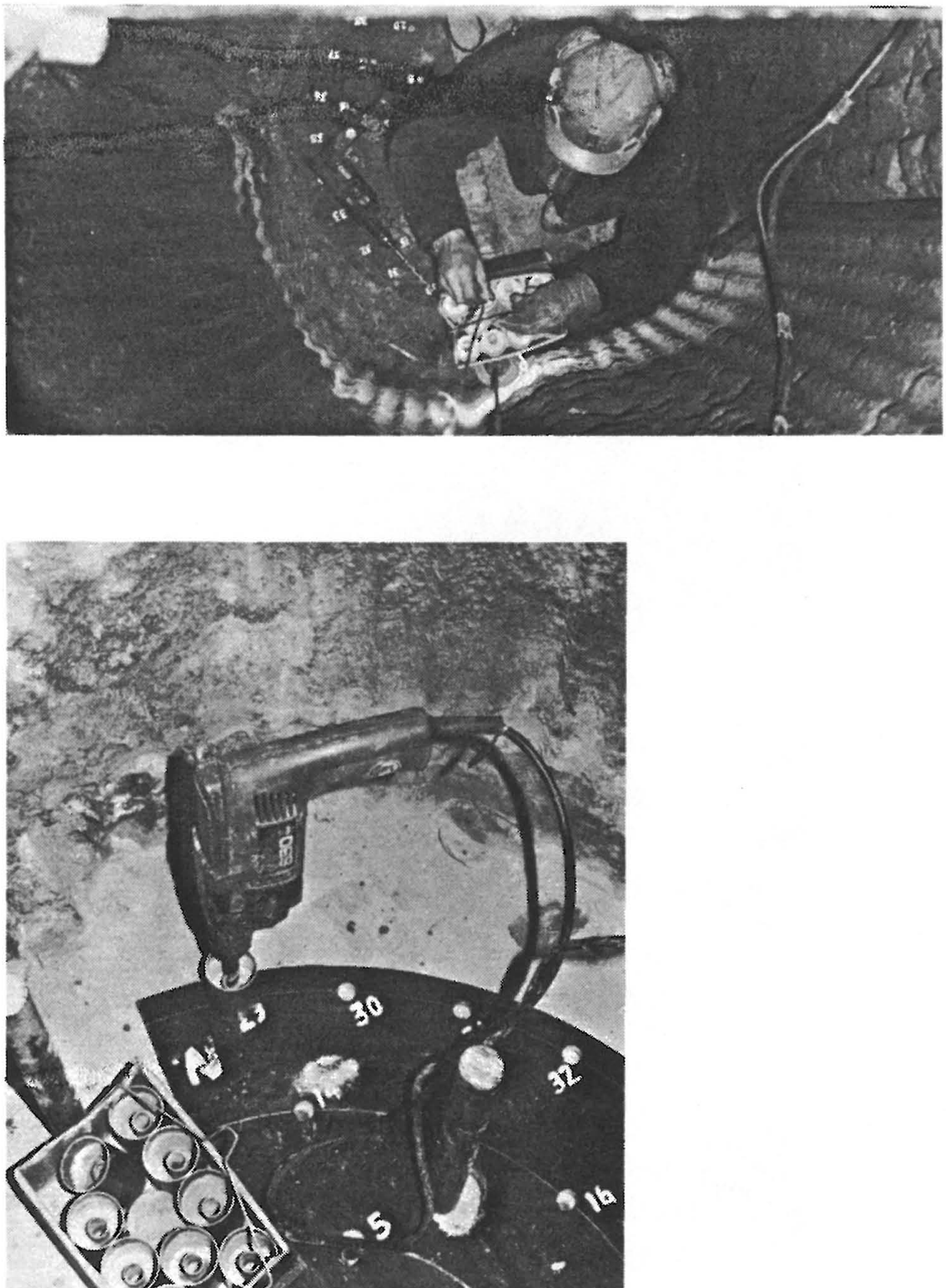


Figure 3-12. Sampling operation

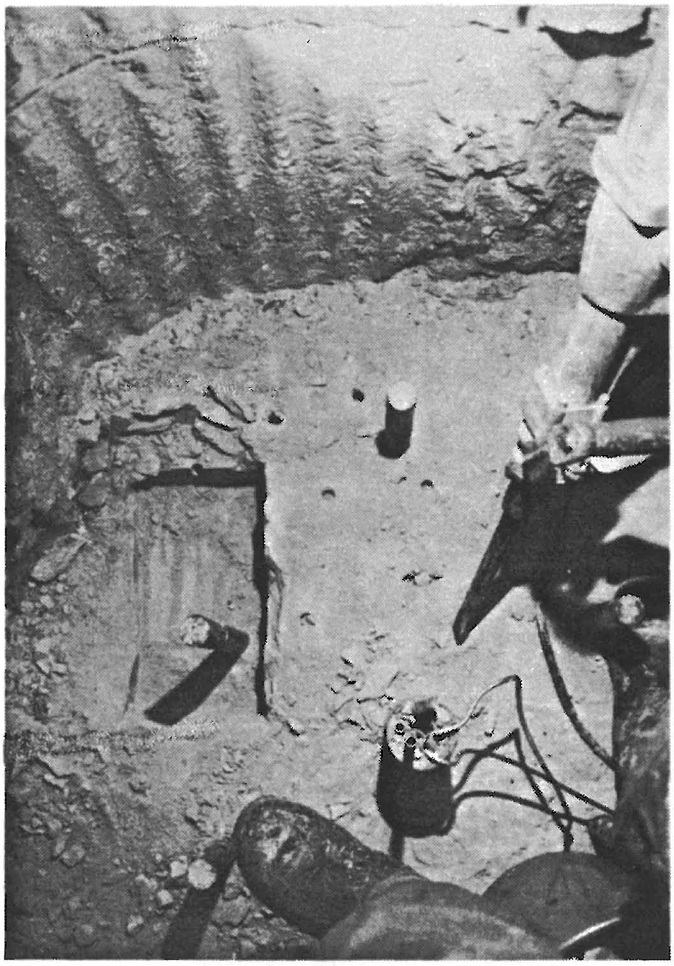


Figure 3-13. Breaking up the upper bentonite plug.
Notice the complete, tight contact
between the bentonite and the rock

Figure 3-14. Joints could not be seen between the blocks but they broke up along these planes of weakness

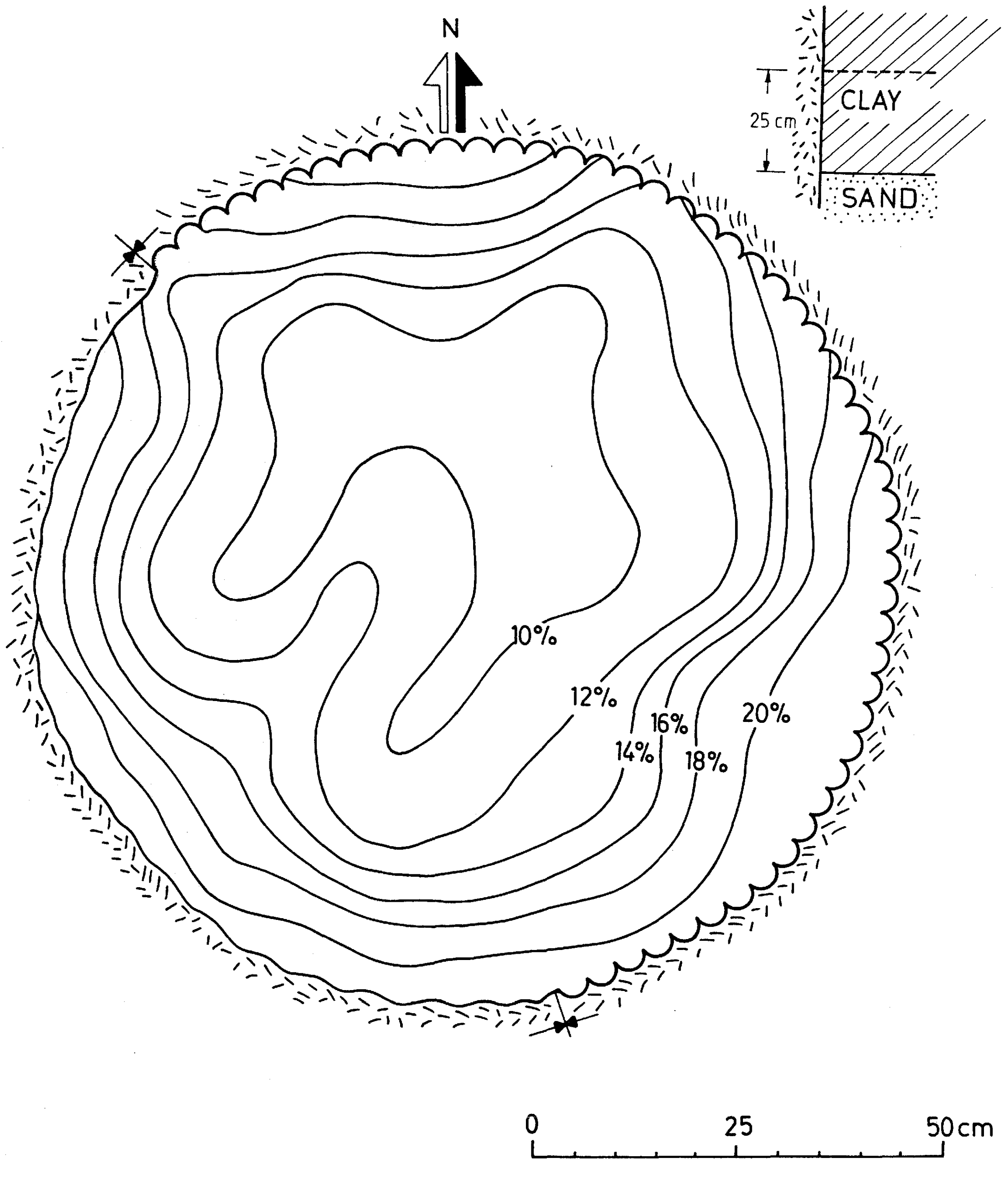


Figure 3-15. Isomoisture plot at mid-height of the upper plug

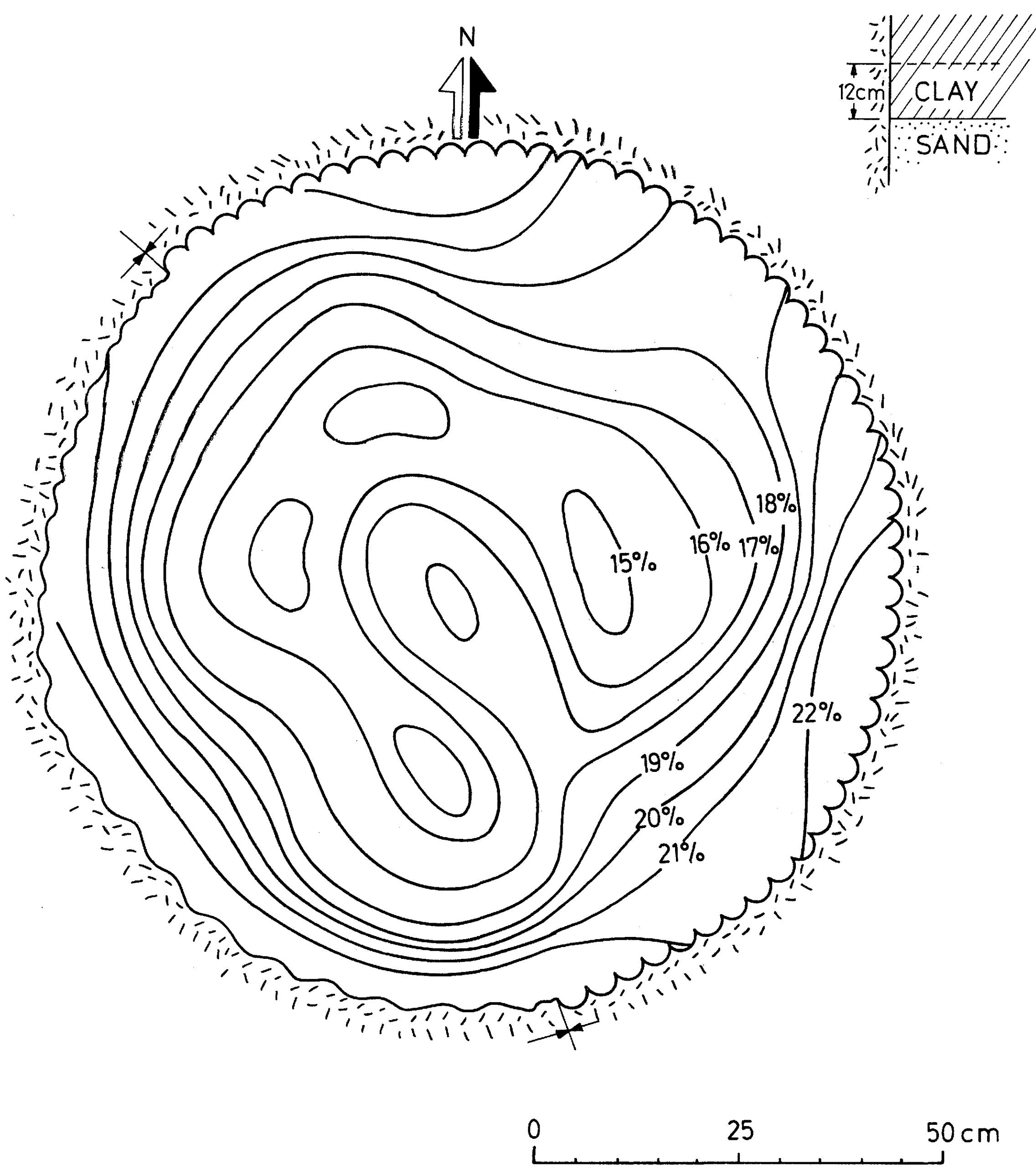


Figure 3-16. Isomoisture plot at 12 cm distance from the clay/sand interface in the upper plug

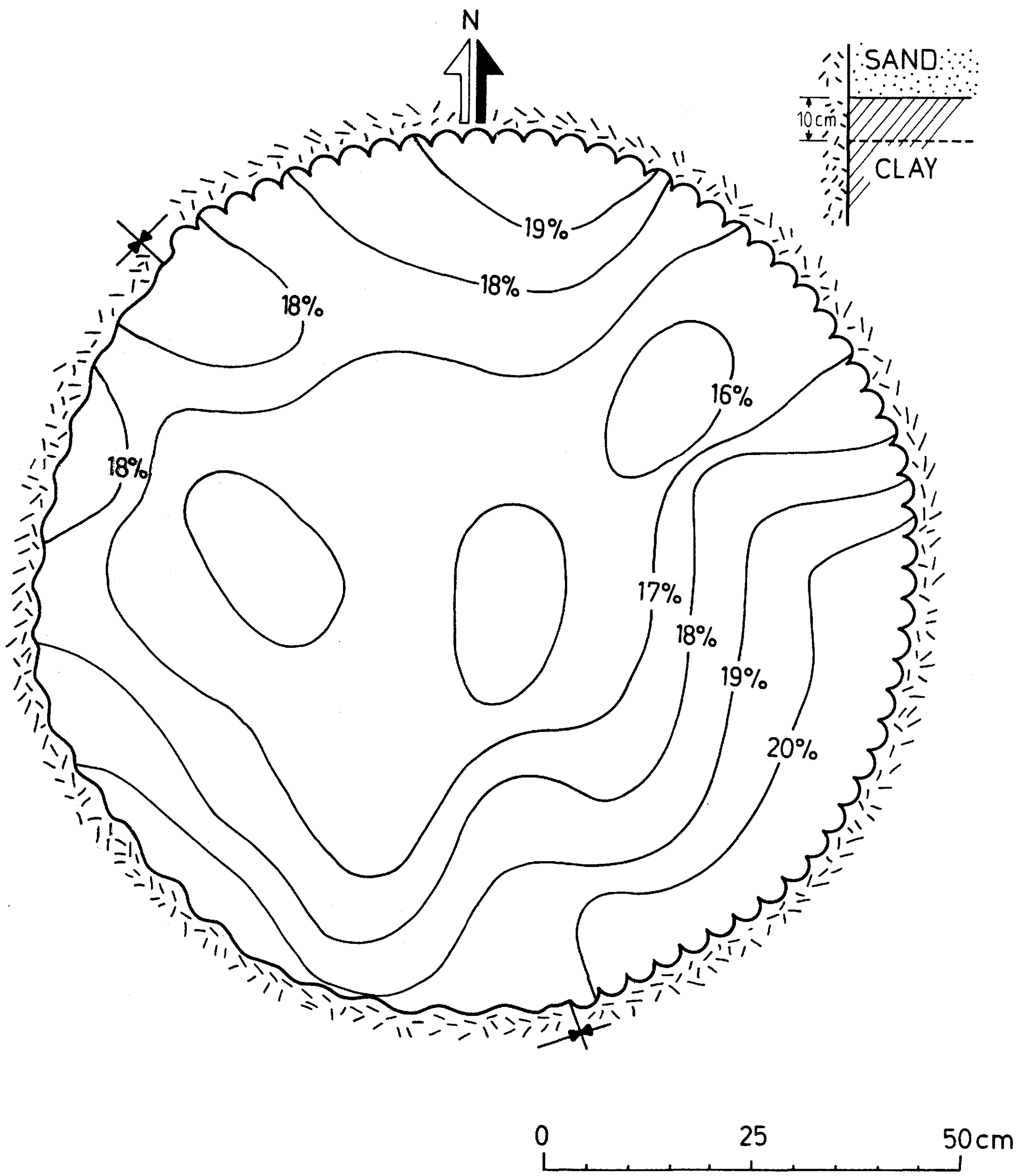


Figure 3-17. Isomoisture plot at 10 cm distance from the clay/sand interface in the lower plug

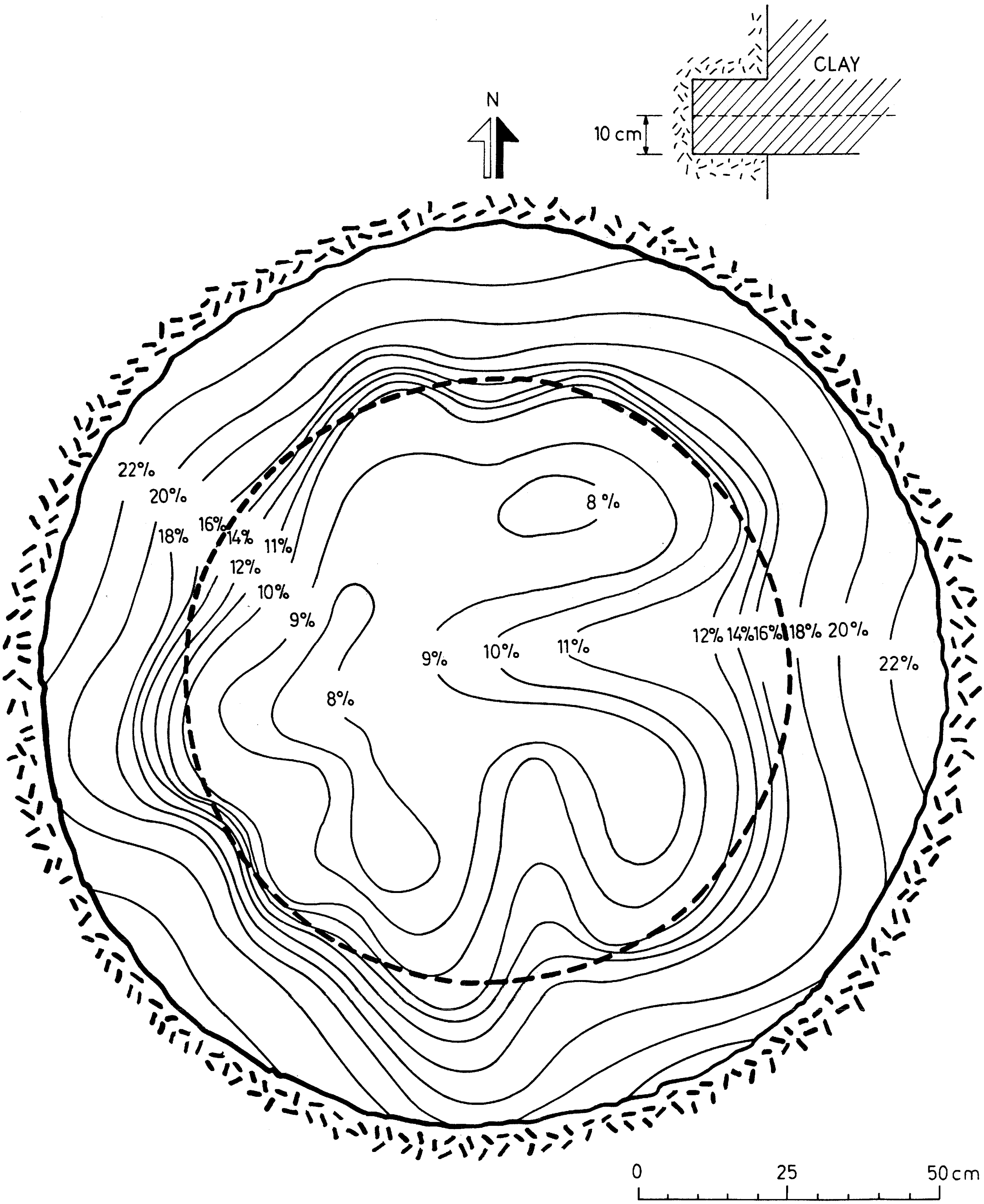


Figure 3-18. Isomoisture plot at mid-height of the slot in the lower plug

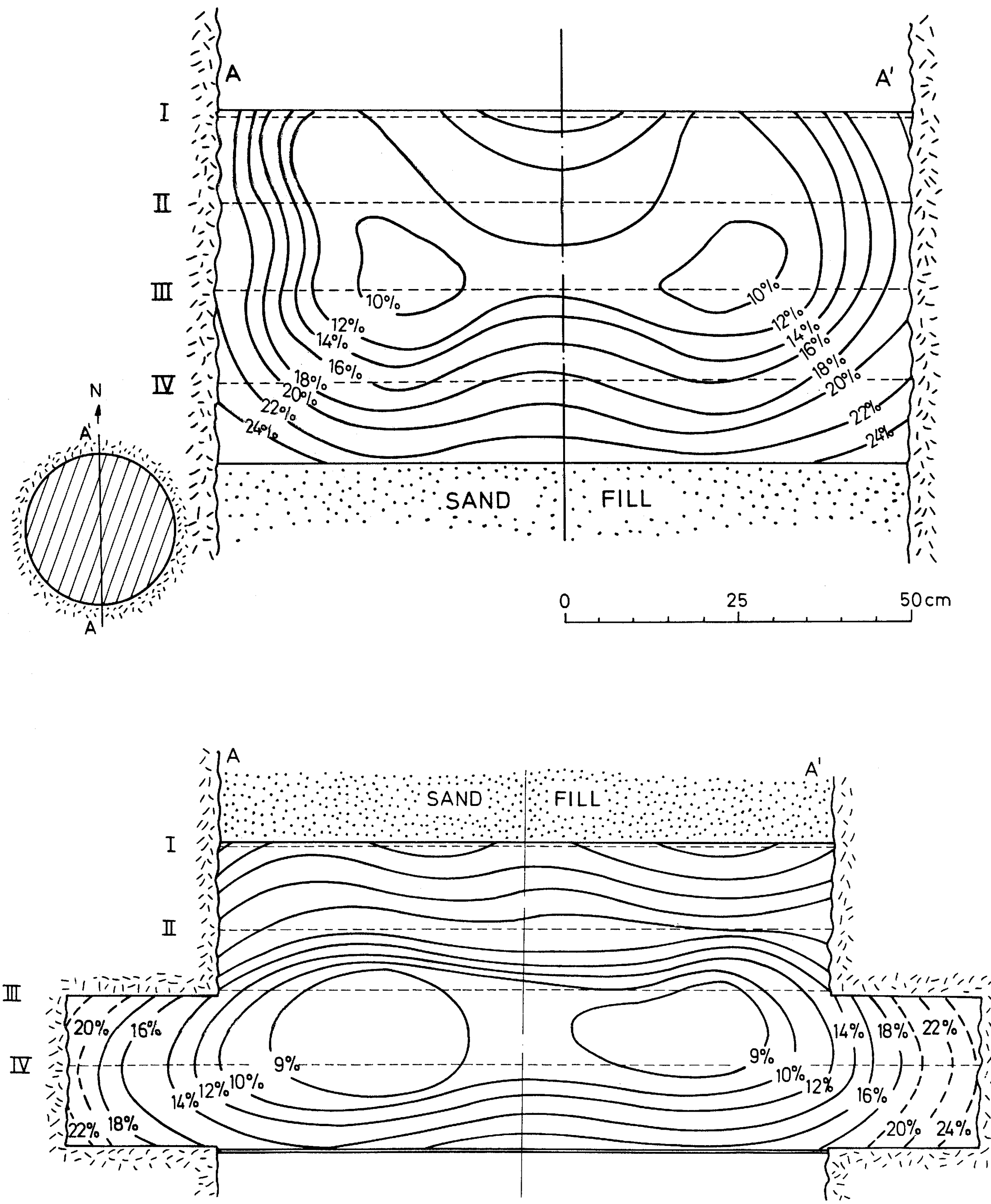


Figure 3-19. N/S cross section through the plugs; isomoisture plottings

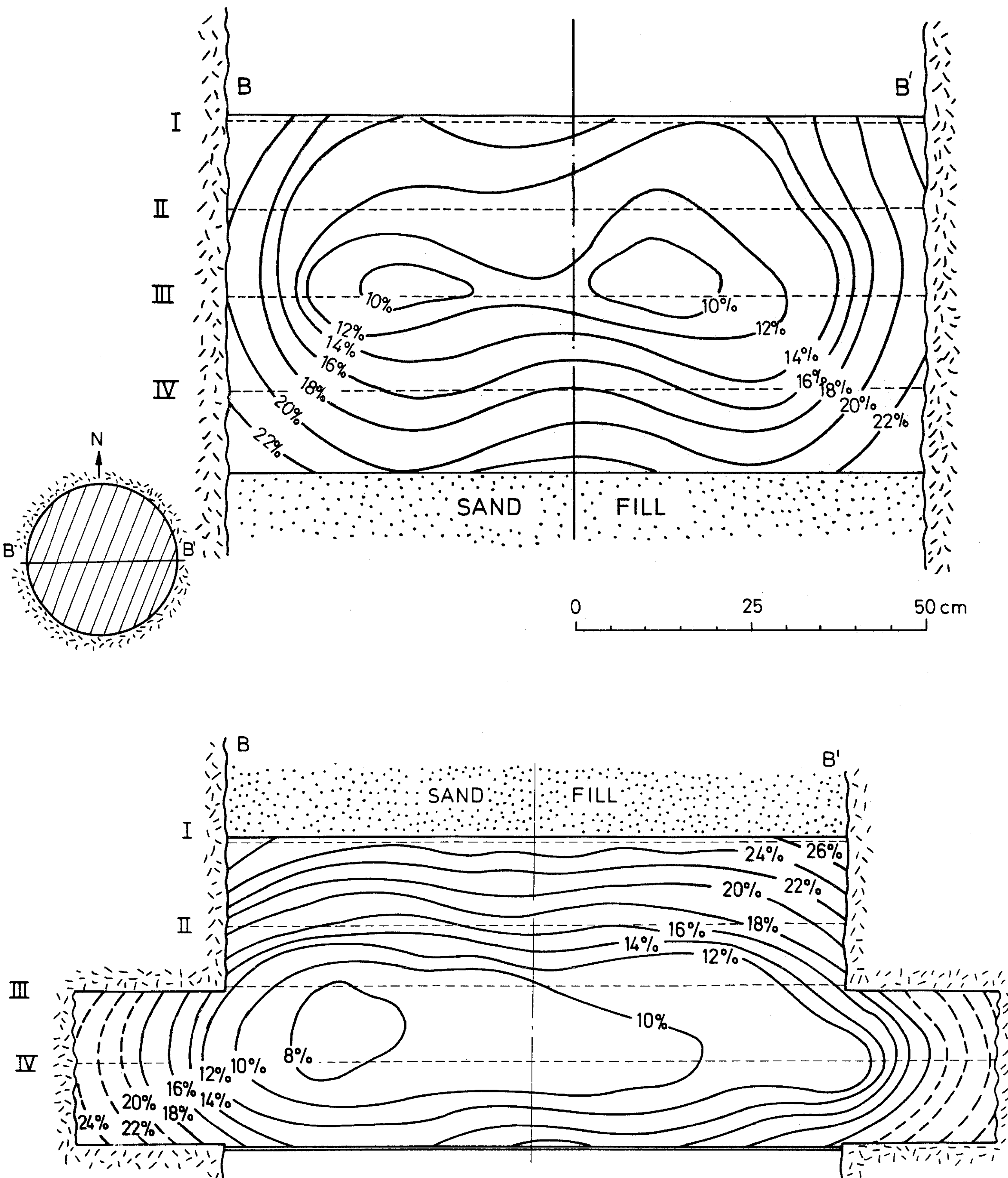


Figure 3-20. W/E cross section through the plugs; isomoisture plottings

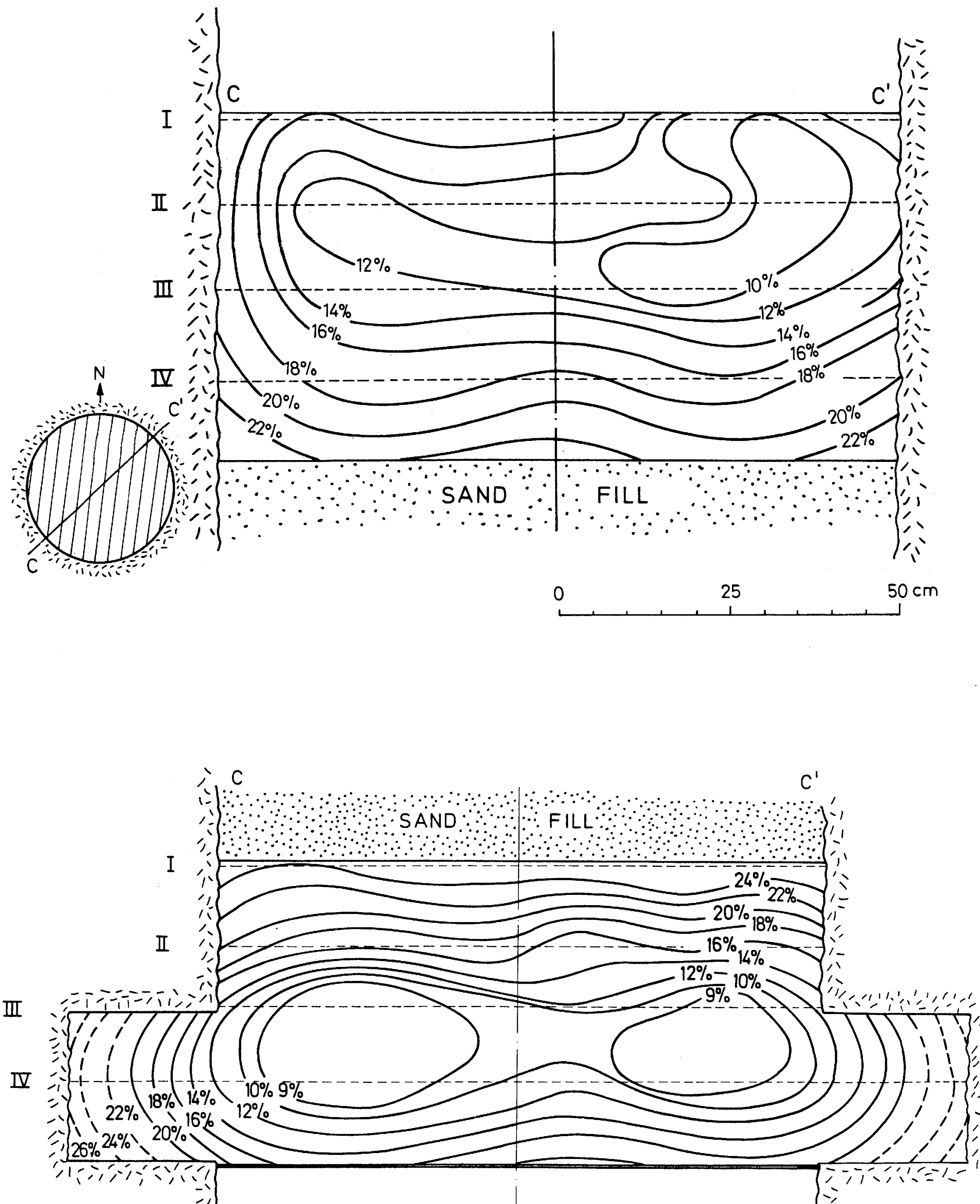
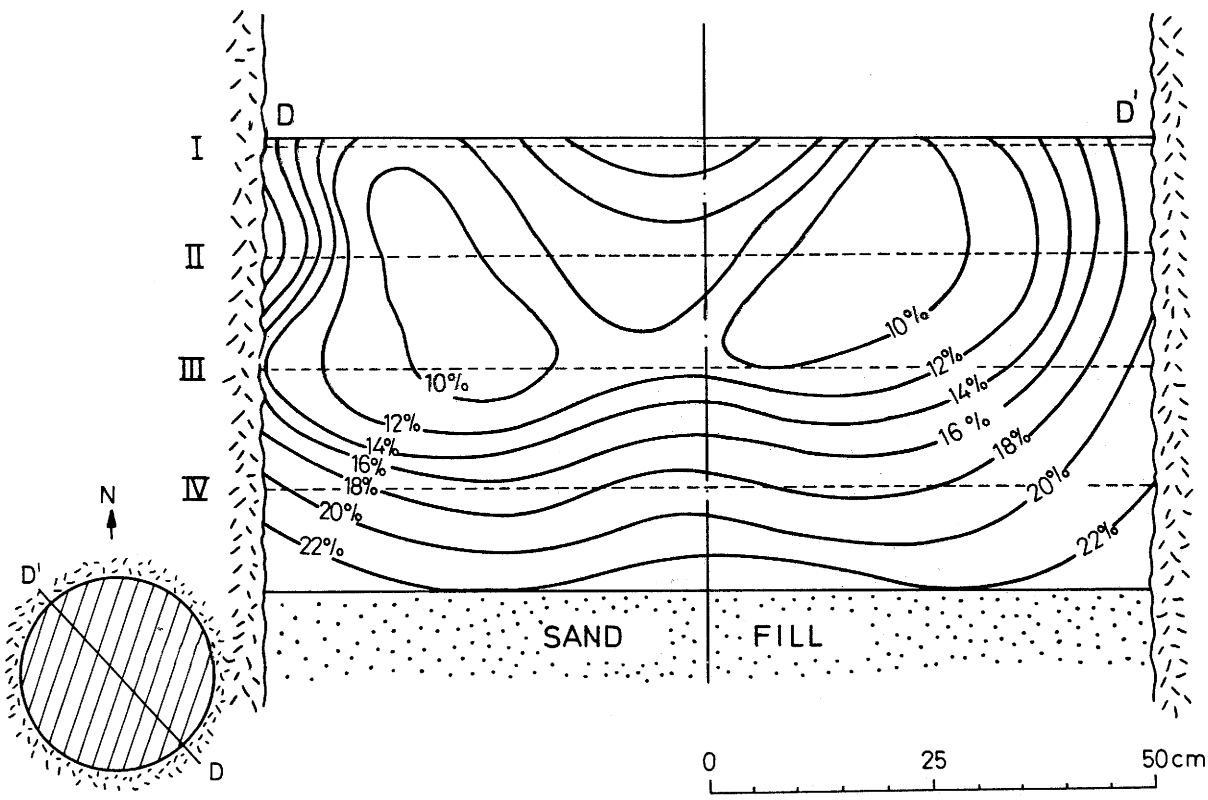


Figure 3-21. SW/NE cross section through the plugs; isomoisture plottings



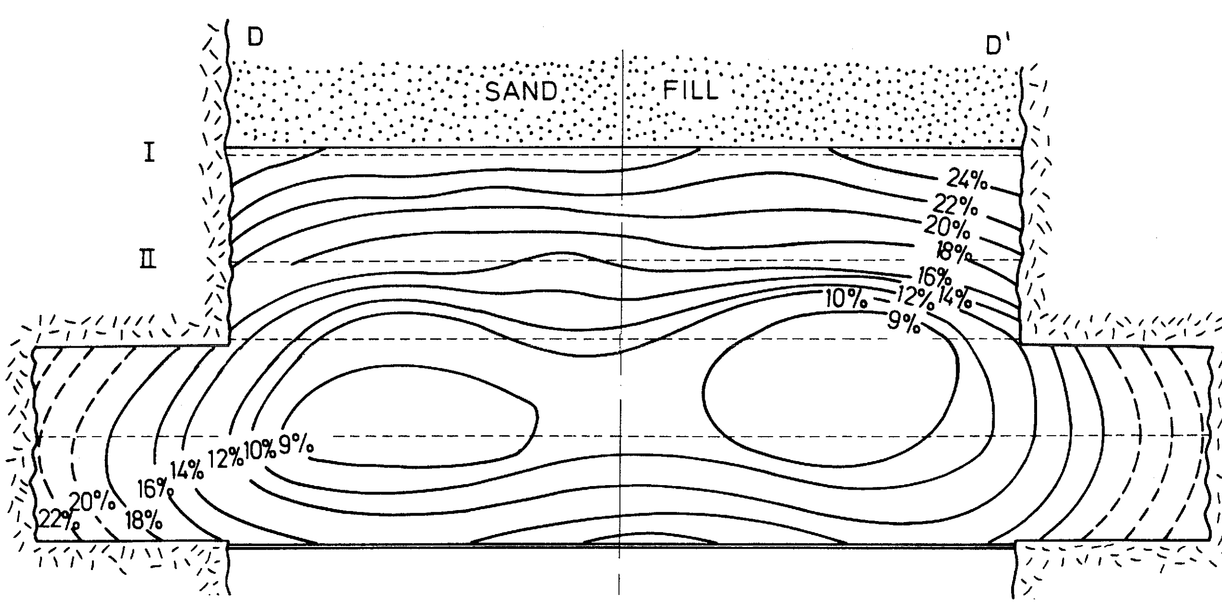


Figure 3-22. NW/SE cross section through the plugs; isomoisture plottings

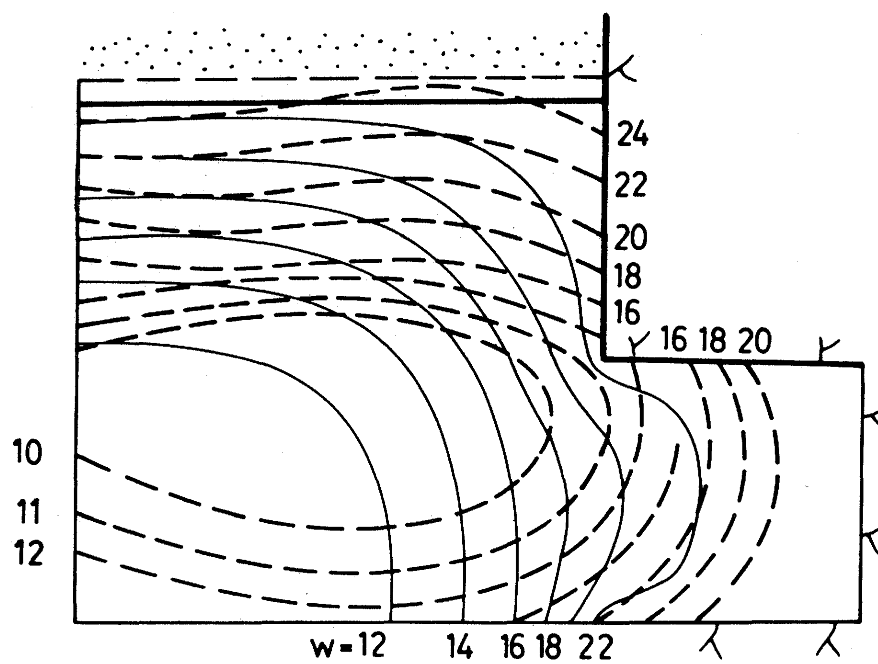


Figure 3-23. Commparison between predicted (full lines) and recorded (broken lines) water content distributions

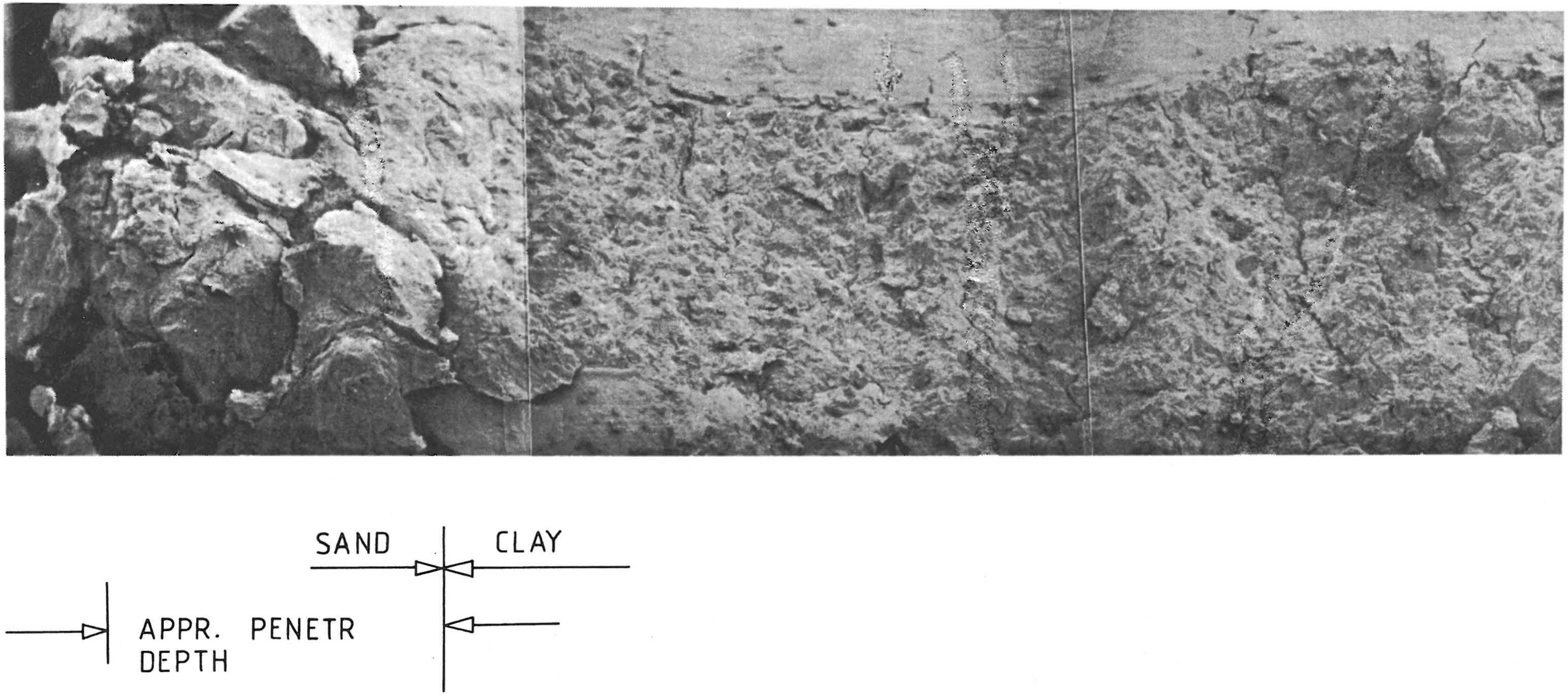


Figure 3-24. SEM panorama micrograph showing sand to the left with clay penetrated from the massive clay body to the right. Magnification about 30x

4 DISCUSSION AND CONCLUSIONS

4.1 PRACTICALITY

The test demonstrated that the application of precompacted blocks is a simple and straightforward process, and that filling the space between regular sets of blocks and an irregular rock surface with bentonite powder does not have to be made very carefully to obtain a largely homogeneous clay zone adjacent to the rock after saturation.

The compaction of the sandfill and the associated expansion of the clay, which were small and within the predicted intervals in the present test, need to be considered in the design of actual repositories. The matter will be dealt with in detail in the forthcoming report on the Tunnel Plugging Test.

4.2 SEALING EFFECT

The drop in outflow from about 8-9 liters per hour at the start of the reference test with 100 kPa injection pressure to about 0.3 liters per hour at the end of the main test with 200 kPa injection pressure demonstrates the excellent sealing power of the bentonite plugs. We conclude from the present test that this can be ascribed to several functions which will be discussed here in some detail. They are:

1 The bentonite plugs are almost non-permeable

2 The plugs block flow passages along the rock/plug interface

3 The clay-filled slot truncates shallow flow passages in the rock and increases the length of flow paths

4 The swelling pressure tends to compress certain fractures in the rock

5 Clay tends to expand into and block certain fractures and shallow openings

<u>1</u> The hydraulic conductivity of sodium bentonite is very low also at relatively low densities, which makes the plug material very tight. Thus, water saturated Na bentonite with a bulk density of about 2 t/m^3, which was the

approximate value for the bentonite close to the rock, has a hydraulic conductivity of about $2x10^{-14}$ m/s. This value is much lower than that of concrete.

2 The contact between the bentonite and the rock became completely tight as concluded, firstly from the fact that tracer-doped water did not flow along the clay/rock interface, and secondly from the fact that the clay was found to adhere strongly to the rock, thus forming an intimate, impermeable contact. The reason for this is the swelling pressure of the clay, which pressed the clay against the rock, and also the tendency for clay gels emerging from the dense clay blocks to migrate into open voids.

3 The clay-filled slot in the test was 25 cm deep and served to force water to flow around the slot, which reduced the leakage by extending the flow paths. The major sealing effect of the clay-filled slot was to cut off one of the major water-bearing structures (B). It also replaced practically all of the fractured zone that had been generated by the blasting of the western perimeter by low-permeable clay, but this contribution to the sealing was probably not a major one.

4 The swelling pressure that was successively exerted by the clay on the surrounding rock, cannot have had any significant effect on fractures which intersect the shaft wall at right angles. Thus, the B- and D-structures at the lower plug and the E-structure at the upper plug were not compressed by the swelling pressure, while this must have been the case for the D-structure at the upper plug and the E-structure at the lower plug. The effect of compression can be roughly estimated by applying simple flow models (6), which indicate that an increase in normal stress from zero to 3 MPa on fractures of the presently discussed type cannot have reduced the average hydraulic conductivity of the rock around the plugs to less than 10-50 % of the original value. This clearly demonstrates that the actual dramatic reduction of the outflow from the injection chamber when bentonite replaced concrete was due to the disappearance of flow paths along the rock/plug interface.

5 Clay penetrating fractures reduces their flow capacity substantially even if the density is very low. Since the sealing effect is strongly related to the penetration depth the fracture width is a determinant and as demonstrated by Eq. (2) this depth is insignificant for very narrow fractures. The actual aperture of the major water-bearing structures A-E or of any other fracture could, of course, not be accurately measured, but their

approximate, hydraulically equivalent apertures were estimated at 0.01 to 0.05 mm, which would yield a negligible penetration depth of clay into the structures. However, the typical variation in fracture aperture, ("channeling") implies that certain parts of the structures, particularly those exposed at the rock surface, were up to one to two millimeters wide. This would lead to local penetration depths of several centimeters in one year, which was actually confirmed by the test (Fig 4-1). It is clear that this largely reduced the flow of water through the major hydraulically active structures along the clay/rock interface and forced the water to flow at a larger distance from this interface. This effect, which contributed to the formation of an almost impermeable plug/rock contact, was the major sealing effect. The mechanism is schematically shown in Fig 4-2.

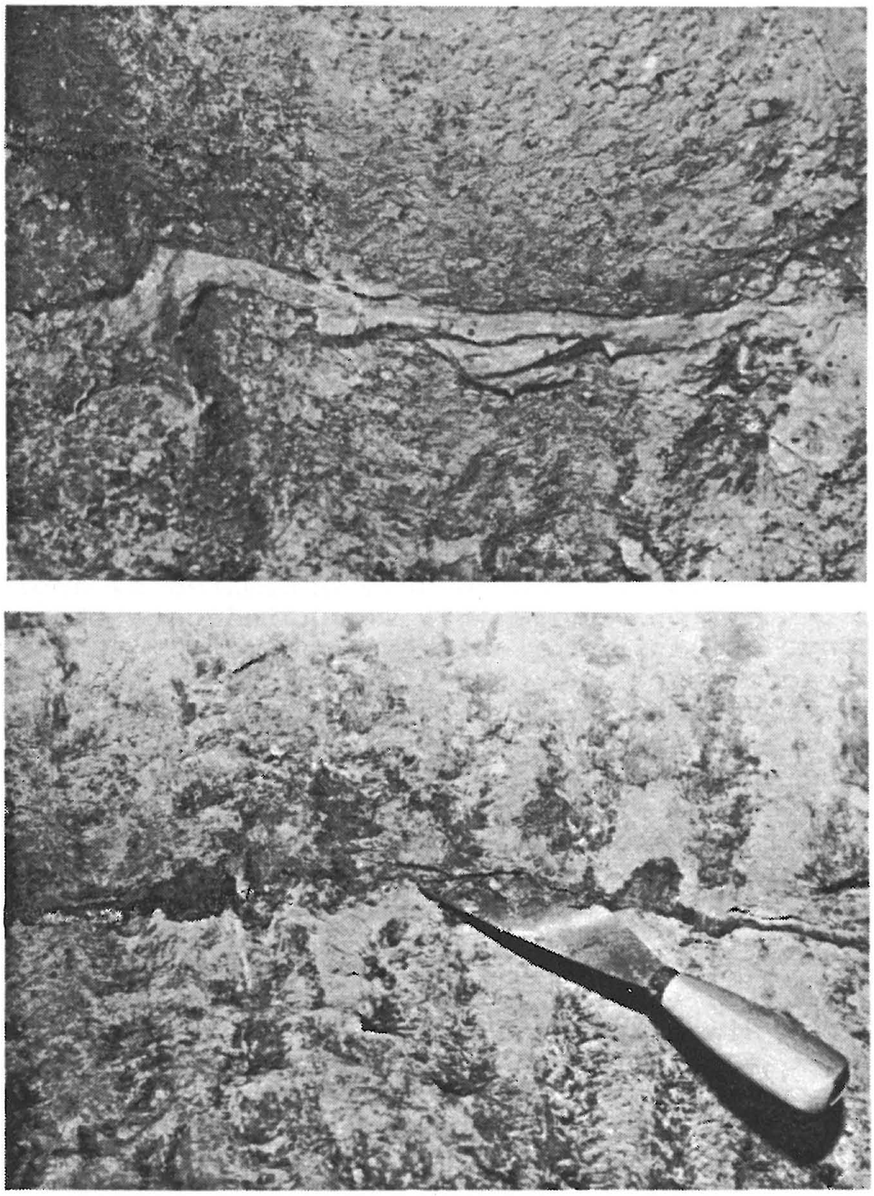


Figure 4-1. Clay-filled fractures

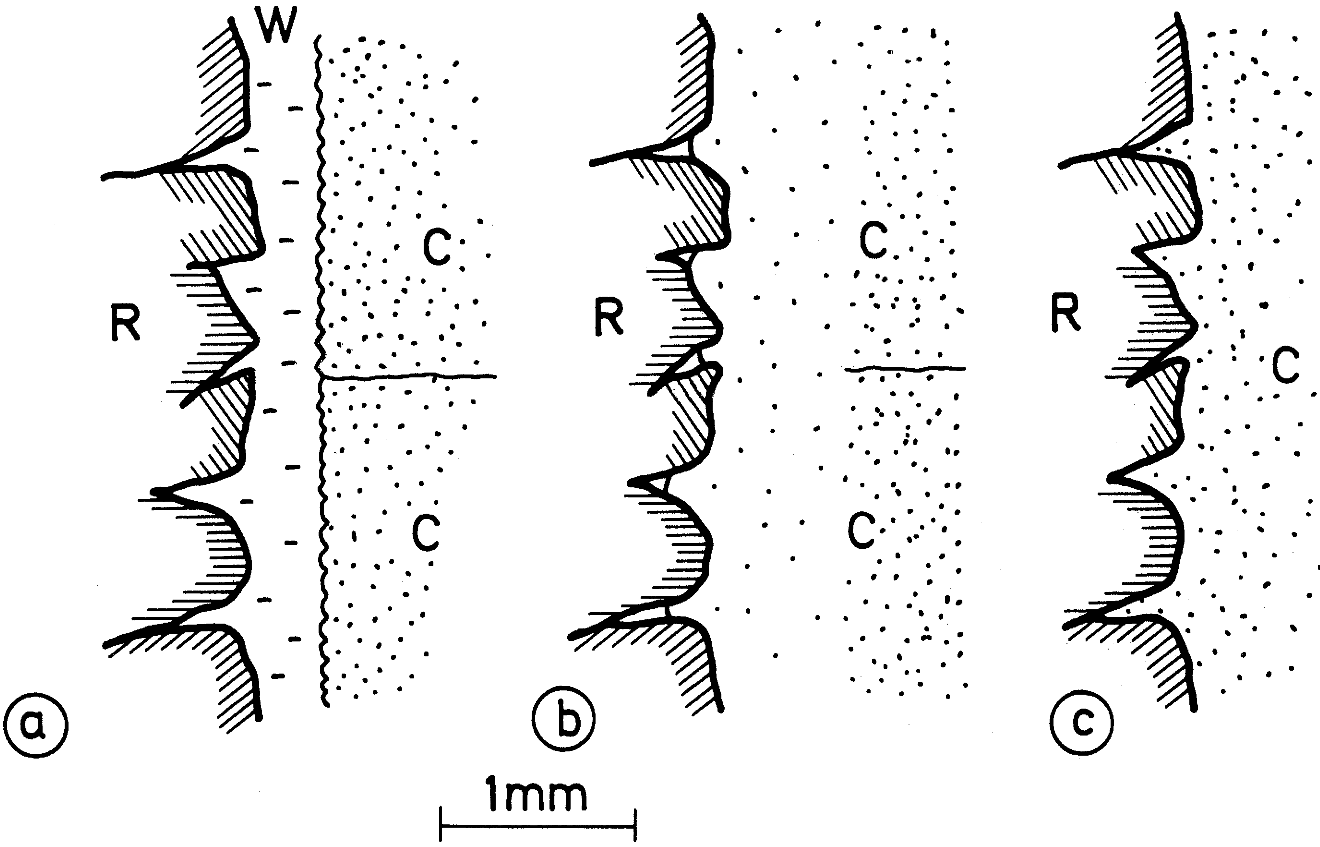


Figure 4-2. Schematic picture of clay penetration into the rock matrix and formation of a tight clay/rock contact. a) clay blocks in position, starting point. b) Early stage of expansion. c) Final stage with integrated clay (c) and crystal matrix (R). W represents water, C bentonite, and R rock

4.3 THE MATURATION PROCESS

The main conclusion from the extensive determination of the water uptake in the plugs was that the bentonite rapidly absorbed water where it was exposed to wider fractures. Thus, the relatively small difference between the outflow in the reference and main tests in the first few days is partly explained by the uptake of water in the bentonite, although the main reason is that water initially flowed along the rock/plug contacts in both tests. The strongly water-bearing wide fractures which initially fed the bentonite with water became blocked by the expanding clay, which forced water under pressure in the rock to flow towards the shaft through finer fractures, which in turn became sealed. The water pressure was not sufficient, however, to drive water through the finest fissures and the water uptake was therefore retarded in those parts where the fracture frequency was low. It is evident that the water uptake from the rock, which was abouot 90 liters at the end of the test and thus only represented 5-10 % of the total discharge from the injection chamber, cannot have affected the outflow rate significantly after about one to two weeks. Hence, the conditions were different from those of the "wet" heater holes of the Buffer Mass Test and the DbH2 borehole test, where the high water pressures forced water also through fine fissures and effectively wetted the rock/clay interface, leading to fast saturation. We can conclude from the present test that the ability of sodium bentonite to seal shafts in rock with low groundwater pressures was well documented, the major principle being that the bentonite swells and establishes a tight contact with the rock where water appears and where sealing consequently is required.

4.4 LONG TERM FUNCTION

4.4.1 General

The erodibility of clay-based plugs needs to be considered as well as the chemical stability of the clay material. They will be shortly commented on in this chapter.

4.4.2 Physical conditions

Shafts excavated from the ground surface to large depths by necessity will pass through strongly fractured rock zones. They may be percolated by relatively rapidly flowing groundwater which can produce erosion. While loss of clay material that penetrates into wider fractures and is removed by eroding groundwater may be critical to the density of borehole plugs and canister overpacks in deposition holes, the large bentonite mass in shaft or tunnel plugs is not very sensitive. A significant fraction of the clay material, i.e. at least 10-20 % (cf. (5) can actually be lost without reducing the bulk density of the plug to a critical level, especially since at least some of the eroded material will remain in the fractures of the surrounding rock.

If large fractures intersect the plug site it is recommended to grout them before the plug is constructed and this yields the state outlined in Fig 1-3. The erosion resistance and chemical stability of the grout should be at maximum, which suggests the use of silica flour as one component.

4.4.3 Chemical processes

The high net bulk density of bentonite plugs that can be obtained in large plugs make them relatively insensitive to changes in groundwater chemistry. Thus, as long as the density exceeds about 2 t/m^3, the swelling pressure will not be altered at all if the groundwater salinity would be increased to that of the oceans, and the associated increase in hydraulic conductivity would be very moderate.

Other processes may have a stronger impact on the physical properties of the clay and this is the inflow of surface water of low pH from swamp areas to relatively shallow shaft plugs, and the effect of high temperatures on deeply located plugs. Acid groundwater from swamps will cause alteration of montmorillonite to kaolinite, while high temperatures may yield mineral transformation and cementation. Both alterations result in an almost complete loss in swelling power and a very marked increase in hydraulic conductivity. However, the very strong buffering capacity of the large clay mass that constitutes plugs of the presently discussed sort means that the alteration to kaolinite is extremely slow, which leaves the temperature effect as major threat to a proper sealing function of bentonite plugs. This matter is dealt with in the reports from the Buffer Mass Test (7) and is currently being investigated in Sweden and several other countries. It is assumed that alteration to the smectite family member beidellite is the primary risk because transformation to hydrous mica (illite) will then only be a matter of the availability of potassium in the porewater. There are theoretical reasons to assume that beidellitization, which has the form of replacement of silica in the SiO_4 tetrahedrons by aluminum, takes place at a temperature of about 100-150°C.

Except for the charge change which is produced by this process and which is the reason for the fixation of potassium, there is also a risk of cementation by precipitation of silica, which would transform the plastic clay into a brittle, non-swelling medium with very poor sealing properties. It should be added here that higher temperatures than 100°C may not yield complete transformation of montmorillonite to hydrous mica. It may only be partial and very slow and may therefore still be accepted.

5 ACKNOWLEDGEMENTS

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Special thanks are due to Jeanette Stenelo for the typing and taming the word processor, and to Birgitta Hellström for preparing the drawings.

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