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Clay particle redistribution and piping phenomena in bentonite/quartz buffer material due to high hydraulic gradients

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University of Luleå 1979-01-10

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REPORT ON

CLAY PARTICLE REDISTRIBUTION AND PIPING PHENOMENA IN BENTONITE/QUARTZ BUFFER MATERIAL DUE TO HIGH HYDRAULIC GRADIENTS

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By Roland Pusch

INTRODUCTION, SCOPE OF STUDY

The deposition of canisters with highly radioactive wastes in tunnels at 500 m depth involves application of in situ compacted bentonite/quartz buffer material in tunnels and shafts. For the KBS 1 concept such material is specified for the deposition holes as well. One possible drawback of this procedure could be that the water which enters the buffer mass from the surrounding rock may cause erosion either by washing out tiny clay particles from the mass or by creating "piping" in it. The first effect may result in the formation of a highly permeable, clay-free silt/sand/gravel zone close to the rock wall, while the second could produce open, or at least very permeable regions at the rock/buffer mass interface. Both effects lead to undesired passages which could deteriorate the barrier effect of the buffer mass.

The present report defines the problem and describes and discusses the involved physical/mechanical processes with special reference to the situation in the tunnels.

DEFINITION OF PROBLEM

Erosion by flowing water takes place when the flow rate approaches a critical value. Such a condition may be reached when ground water from rock joints flows into the buffer mass. The process is governed by Darcy's law if the mass is completely or at least largely water saturated.

A critical state may also be reached when the fill has just been, or is being applied or compacted in the tunnels. If the water pressure is built up rapidly in the joints close to the rock/buffer mass interface, water may rapidly enter the buffer mass and cause local displacement of buffer material ("piping").

Both cases will be treated here.

THE PERCOLATION CASE

Surface erosion of clay or silt sediments is known to be substantial when the flow velocity exceeds 0.1 to 0.2 m/s. Rates of this order of magnitude can easily be obtained in permeable coarse soils, such as rock-fill, even under moderate gradients. In the bentonite/quartz buffer mass extreme gradients are required, however, to yield this flow velocity. Thus, assuming the permeability to be 10^{-9} m/s the hydraulic gradient (i) has to be 10^{8} to yield the same flow rate. The maximum water pressure in the deposition plant corresponds to 5 MPa which means that a condition with $i = 10^{8}$ requires that this pressure exists in the rock at the rock/buffer mass interface while the water pressure is still zero at a distance of a fraction of a millimeter within the buffer mass. This is impossible since water will be distributed and put under pressure far into the buffer mass long before high water pressures will be established in the rock.

It is well known, on the other hand, that the critical velocity for individual clay particle movement is very much smaller than 0.1 m/s. Thus, HANSBO (1960) observed clogging effects caused by short range clay particle movement at gradients of about 1-20 and flow rates of less than 10^{-9} m/s. His studies concerned very soft postglacial and glacial, illitic clays with water contents of 70-100% and rather open pore systems. The moraine-like grain size distribution of the buffer mass, its high bulk density, its tortuosity, and its content of the more surface-active montmorillonite clay mineral suggests, however, that there should hardly be any risk of washing out the clay particles even at flow rates of the order of 10^{-7} m/s. This velocity is obtained when $i = 10^2$ for $k = 10^{-9}$ m/s, which corresponds to the conservative case where almost full water pressure at 500 m depth has been established at the tunnel periphery while it is still zero in the central part of the tunnel fill.

Literature provides a number of case histories and laboratory reports which deal with this problem but the soil compositions generally differ so much from the present case that the results are far from applicable. One report is worth mentioning, however, and this is because it describes a leaching test of a buffer mass-like, sensitive, clayey silt with i = 12 for 30 days (MOORE, BROWN & RASHID, 1977). The soil had the following characteristic parameters: w = 38%, w_P = 21%, w_L = 29%, clay content 15%, silt content 58%, and coarser fractions 27%. The authors stated that "The mechanical and hydraulic effects of the leaching did not alter the soil behaviour" which was certainly sensitive also to minor clay content changes. A definitive proof of the possible risk of such alteration caused by clay particle transportation in the buffer mass requires that a similar test series is performed but the gradient should then be at least 100.

PIPING

Piping is a well-known effect which is primarily caused by critical gradients. It is a very common phenomenon when performing permeability tests by using laboratory devices consisting of a container in which a soil sample is confined and percolated. If the applied water pressure exceeds a certain value water will find its way along the wall where a channel (pipe) may be formed. A similar phenomenon may take place along the rock/buffer mass interface or in the interior of the buffer mass as known from a number of dike and dam cases. The large number of factors which are important in the development of piping phenomena according to literature and experience ("filter criteria" technology), makes it difficult to estimate whether there is any risk of obtaining such heterogeneities in the buffer mass. Again, a series of relevant tests is required to settle the question.

EXPERIMENTAL INVESTIGATION

Two test series were made in the laboratory to investigate the clay transporting power of percolating water. Both series comprised percolation of a sample with 20% (by weight) Na bentonite and 80% quartz particles, the mixture having an initial water content of 20%. The 20% bentonite content was chosen since it is representative of the tunnel fill close to the confining rock according to the KBS concepts. Each test comprised percolation also of an initially heterogeneous soil sample in order to find out what the washing and piping effects might be if the application of the tunnel fill should lead to a separation of the bentonite and quartz constituents.

Materials

MX 80 bentonite powder was used for the preparation of the "buffer substance" while its quartz content was obtained by mixing grains belonging to the silt and sand fractions according to VBB:s suggested grain size distribution curve (FAGERSTRÖM & LUNDAHL, KBS Technical Report no. 37 page 37). Fig. 1 illustrates the obtained grain size distribution.

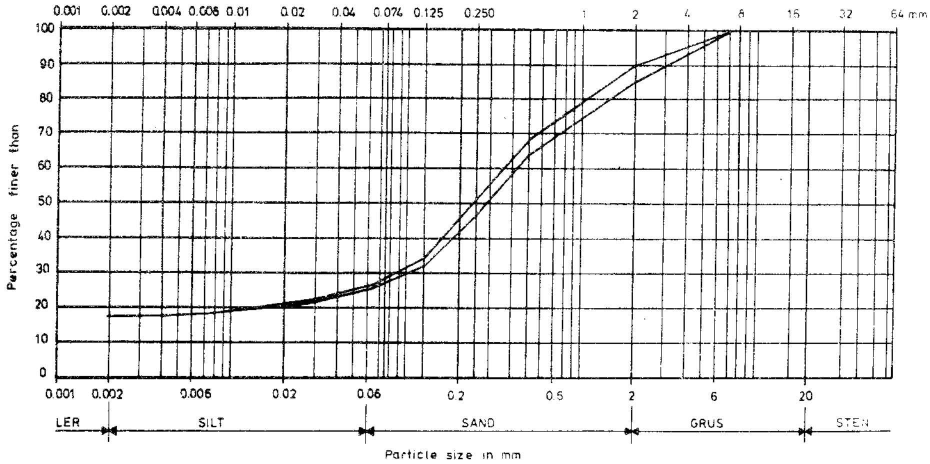

Fig. 1. Grain size distribution of "buffer material" used for the experimental investigation.

The water used in the tests was the "Orrje solution" described by RENNERFELT in KBS Technical Report no. 36.

Test performance

The buffer material was applied in columns consisting of steel cylinder sections (Figs. 2, 3 and 4). After having filled all the six sections of the two columns these were connected with a tube to which a vessel with water was attached. The water was put under pressure by compressed air by which the desired hydraulic gradient could be established (Fig. 5).

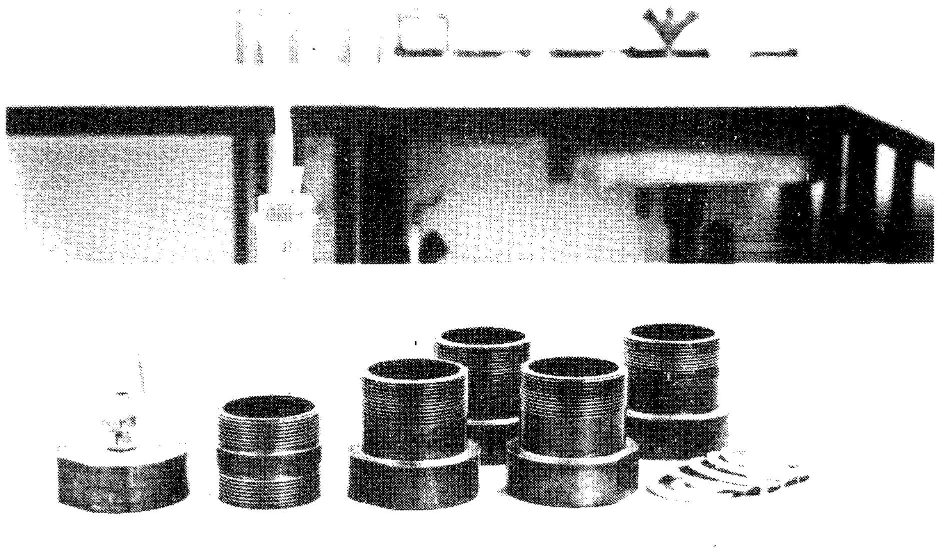

Fig. 2. Cylindrical sections and base part with valve. Aluminium rings were used to extend the flow path along the wall in Test 2.

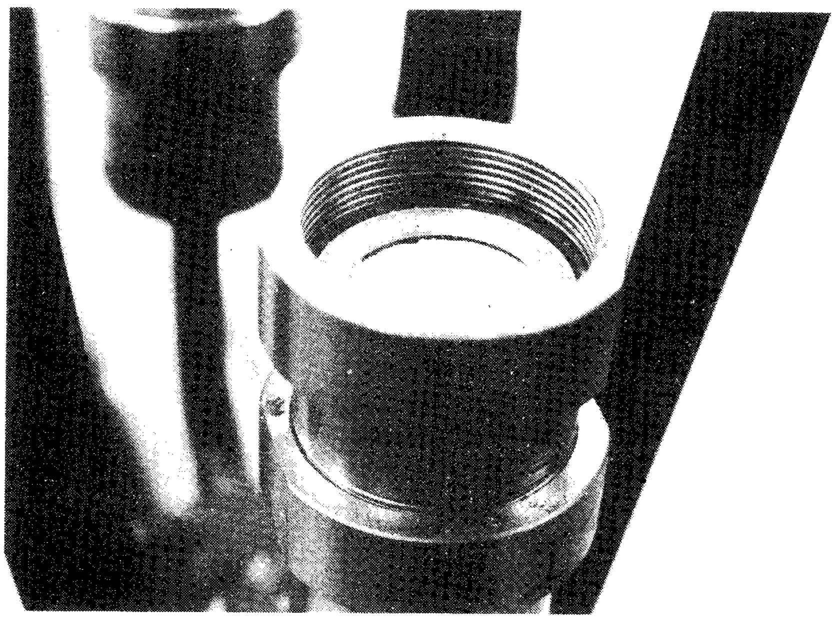

Fig. 3. View of section mounted for filling with buffer material. Aluminium ring and O-ring for sealing have been applied.

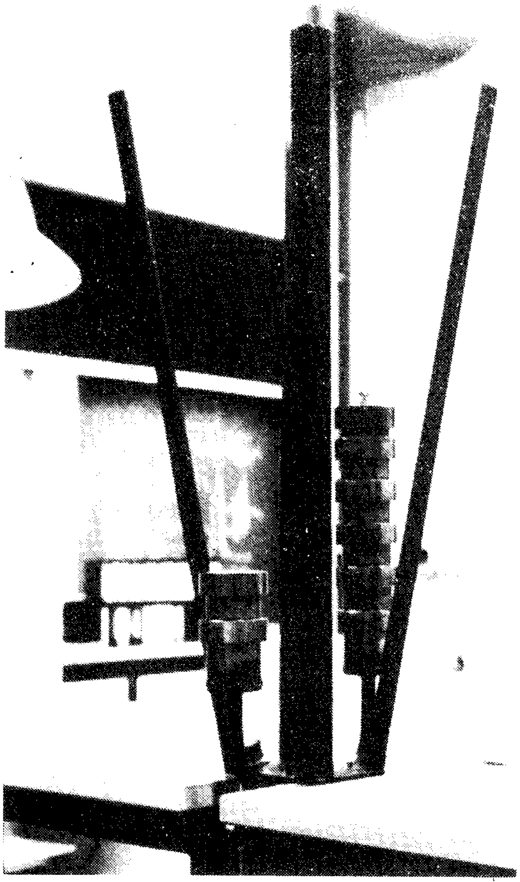

Fig. 4. Stand turned upside down during the filling operation. The right column is finished.

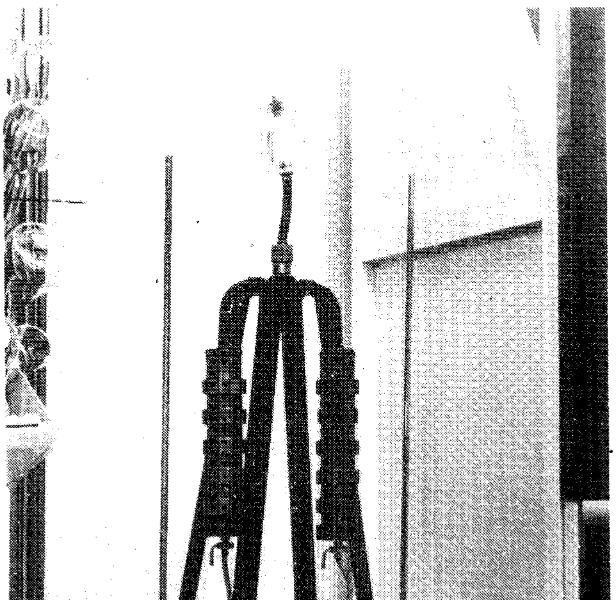

Fig. 5. The percolation device in operation.

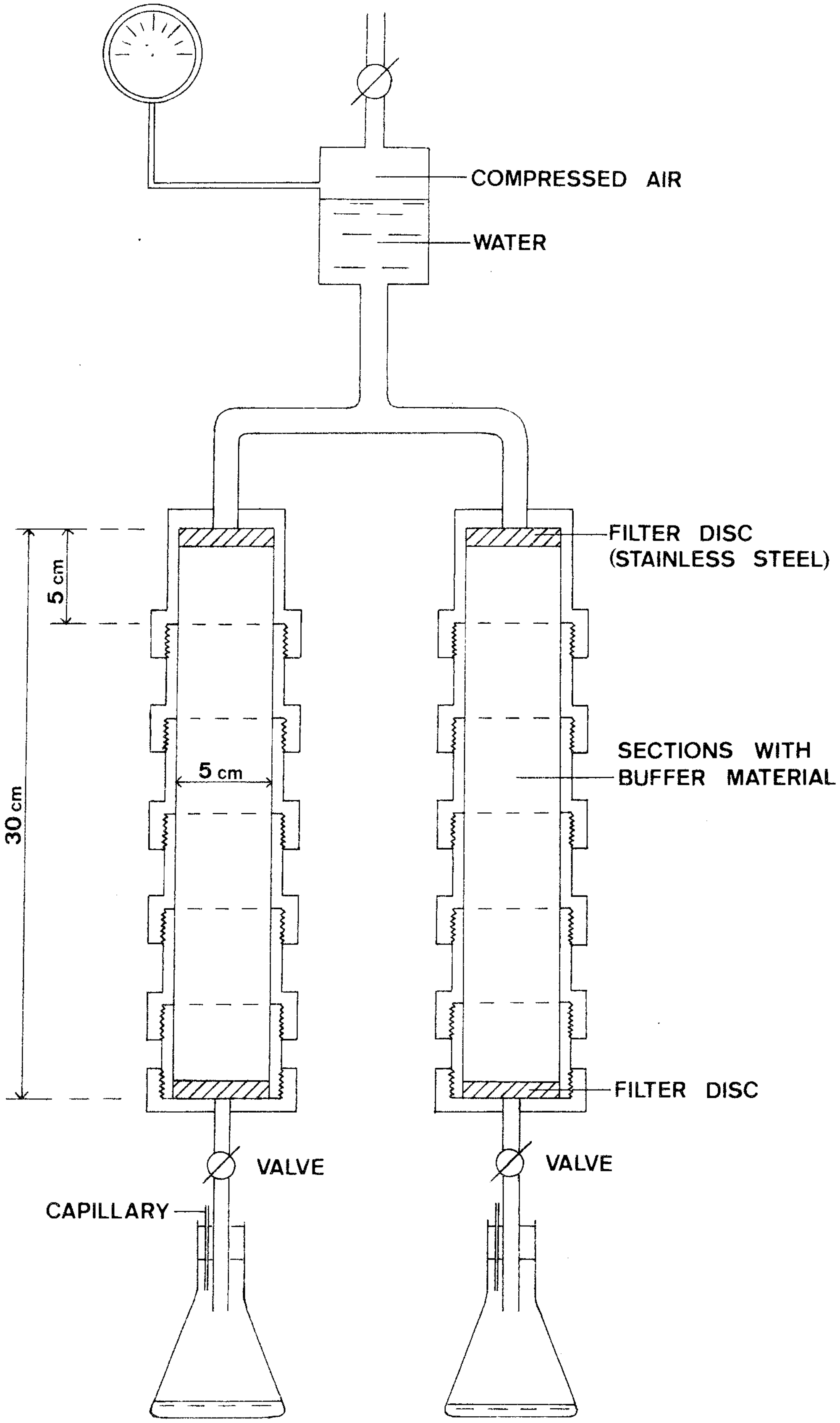

Fig. 6. Schematic view of test device.

The application of the soil was made in the following way. Thin layers of fairly dry soil material were applied and compacted in the cylinder sections and the required amount of water was added by using a spray bottle after the compaction of each layer. When one section had been filled, a new one was attached and filled etc until the 0.3 m long pipe was completely filled. Great care was taken to avoid air bubbles in the part of the system which was filled with water. One of the columns in each series was used to simulate the case with an initially heterogeneous buffer mass. This was made by filling two of the sections with quartz sand only (grain diameter larger than 60 μm). A schematic picture of this arrangement is shown in Fig. 6 which illustrates that the percolated water from the columns was collected in flasks from which practically no water could evaporate. The amount of percolated water was determined by wheighing the flasks regularly by which sufficiently accurate permeability values could be determined. After the tests, the sections were disconnected and a large number of water content and clay content determinations were made to investigate how uniform the percolation had been and to find out whether there had been any clay particle transport.

It should be pointed out that the test device represents the very conservative case of an unlimited access of water from rock joints. In practice, the inflow of such water into the tunnel fill is governed by the capacity of the joints which can be very limited due to various injection operations.

<u>Test 1</u>

The first test series was made by applying instantly a water pressure of 300 kPa. Since the soil column was 0.3 m long the hydraulic gradient was 100 which was assumed to represent the case of a rapid build-up of a high gradient in the peripheral tunnel fill.

Soon after the application of the water pressure, piping took place in the column with the sand sections and water started flowing at a considerable rate. Within about a day the flow rate decreased, however, and it then continued to drop. The calculated permeability, which was as high as 10^{-6} m/s during the first hours for the column with the quartz sand layers and about 10^{-7} m/s for the bentonite/quartz mixture, decreased to about 10^{-9} m/s for both columns after about 9 days when the test was stopped.

The situation with a constant gradient operating after a piping event can never occur in a tunnel because the water pressure instantly drops in the water-producing rock joint. This means that the applied hydraulic gradient was in fact improbably high and the test therefore represents an extremely conservative case.

The initial water content of the buffer material was 20%. The column entirely consisting of bentonite/ quartz had an initial bulk density of 1.69 t/m^3 and a dry density of 1.41 t/m^3, which means that the degree of compaction was low compared to what can be achieved by applying field compaction techniques in the tunnels. The bentonite/quartz sections of the other column had an initial bulk density of 1.83 t/m^3 and a dry density of 1.52 t/m^3, while the corresponding values for the quartz sand sections was 1.92 t/m^3 and 1.62 t/m^3 respectively. The water content distribution in the two columns at the end of Test 1 is shown in Fig. 7. It is concluded that the higher water content values along the periphery of the columns indicate that the percolation, as expected, preferably took place in the outer zones.

The initial clay content of the bentonite/quartz mixture was found to be 16-18% instead of the intended 20% according to the hydrometer analyses.

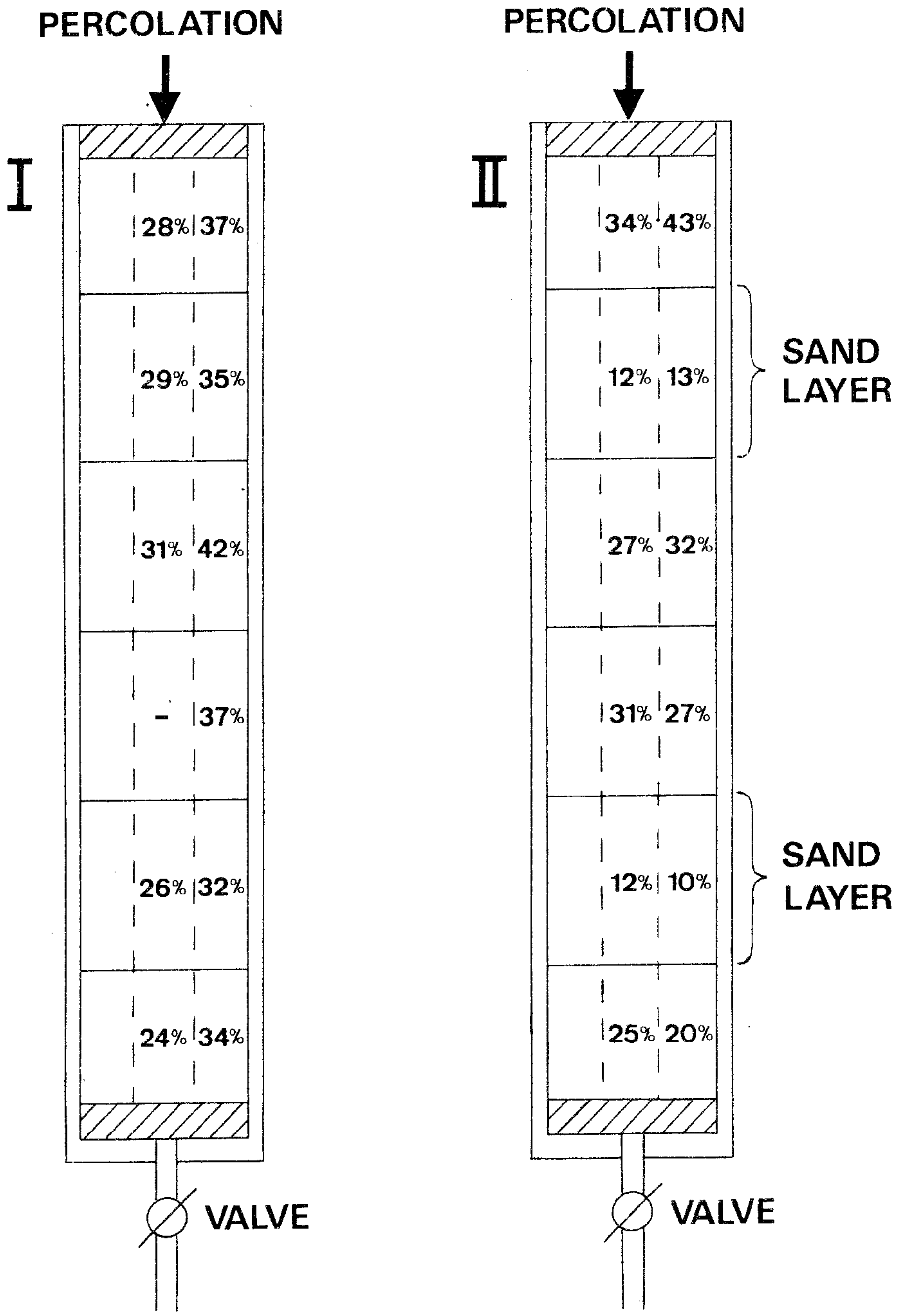

Fig. 7. Water content distribution in Test 1. Mean values for peripheral and central elements given for each section. I stands for test with 20% Na bentonite and 80% quartz powder. II stands for test with two quartz sections.

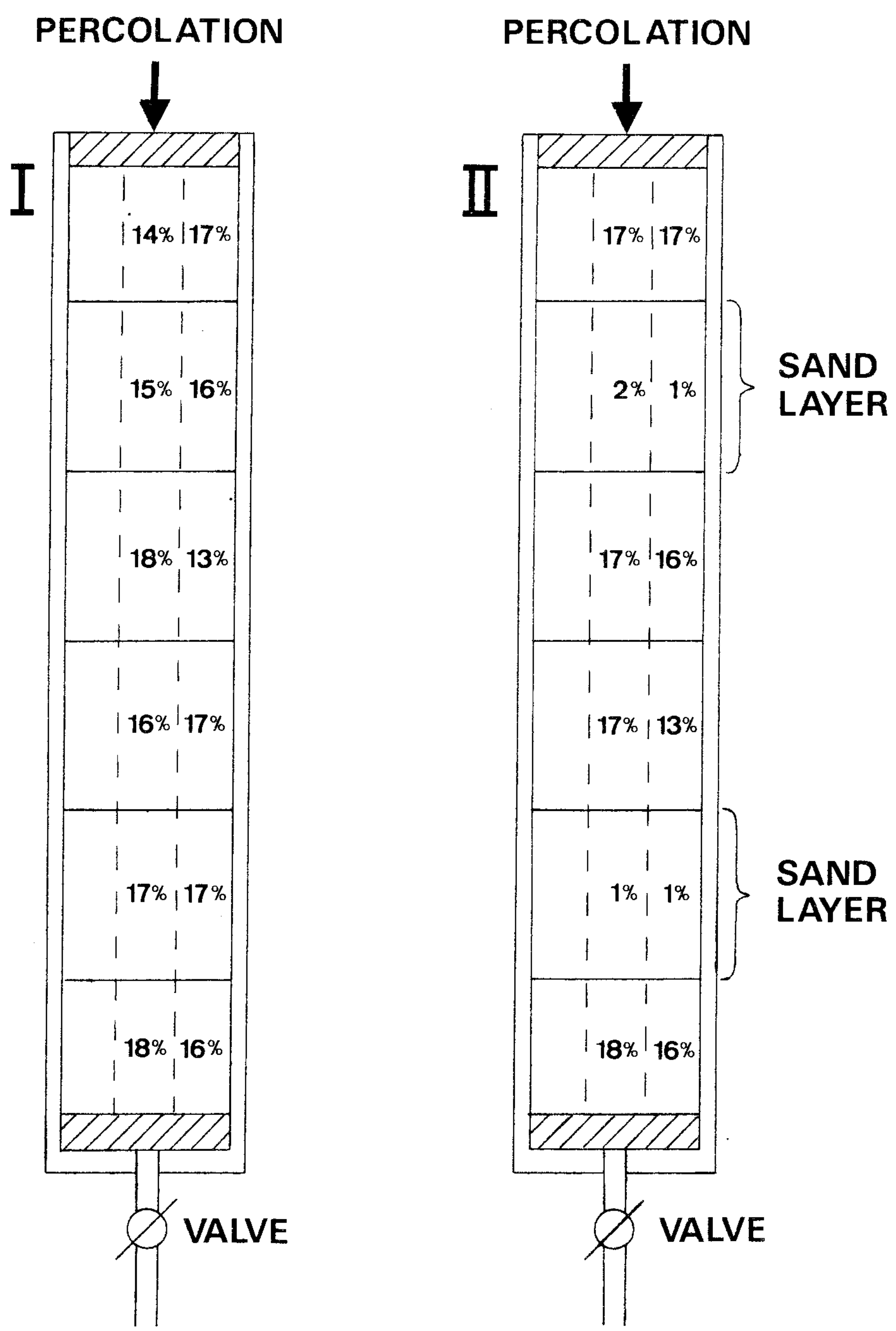

Fig. 8. Clay content distribution in Test 1. Mean values for peripheral and central elements given for each section. The sand contains a minor amount of clay also before the test.

Its distribution after the test is shown in Fig. 8. No significant tendency of washing out or enrichment of clay-sized particles can be observed even in the column with sand layers where piping occurred.

The main conclusions from Test 1 are:

- An average permeability coefficient of 10^{-9} m/s is obtained even at a fairly low degree of compaction provided that the average bentonite content is of the order of 20%. This is the case even if the bentonite is not perfectly uniformly distributed and even if local piping has taken place.

- Local piping is only temporary since self-sealing is produced. This effect is probably due to the swelling power of the bentonite component although some local redistribution of clay particles or bentonite/quartz substance may have contributed as well. No permanent highly permeable passages are created.

Test 2

In the second test series the gradient was increased stepwise, which is in better agreement with the conditions in a future deposition plant. A 100 kPa water pressure was applied instantly and it was increased by 50 kPa with 1 hour intervals until the final constant pressure of 300 kPa was obtained as in Test 1. After 3 weeks the pressure was decreased first to 150 kPa and 2 weeks later to 75 kPa to see whether the material obeyed Darcy's law.

Although the gradient was increased fairly rapidly also at the start of Test 2, no piping took place. The calculated permeability was about $2\cdot10^{-9}$ - $4\cdot10^{-9}$ m/s during the first week of percolation for the column with the sand layers, while it was 10^{-9} - $2\cdot10^{-9}$ m/s for the homogeneous bentonite/quartz column. The permeability values dropped successively and tended to be stable at about 10^{-9} m/s after 3 weeks, the homogeneous bentonite/quartz column being somewhat less permeable than the column with the sand layers.

When the water pressure had been reduced to 150 kPa, which corresponds to i = 50, the permeability dropped to less than 10^{-9} m/s. When i was finally reduced to 25 the k-values were reduced to about $2\cdot10^{10}$ to $5\cdot10^{-10}$ m/s. The material obviously does not obey Darcy's law.

The initial water content of the buffer material was 20%. The column entirely consisting of bentonite/quartz had an initial bulk density of 1.75 t/m^3 and a dry density of 1.46 t/m^3. The bentonite/quartz sections of the other column had an initial bulk density of 1.84 t/m^3 and a dry density of 1.53 t/m^3, while the corresponding values for the quartz sand sections was 2.03 t/m^3 and 1.71 t/m^3 respectively. The water content distribution in the two columns at the end of Test 2 is shown in Fig. 9. It is interesting to see that the water content in large parts of the columns indicate an almost complete water saturation. It should be noticed, however, that the degree of water saturation is fairly high (70-85%) also in large parts of the columns in Test 1, which was run for 9 days only while Test 2 was run for almost 2 months.

The initial clay content of the bentonite/quartz mixture (16-18%) was not changed by the percolation as shown by Fig. 10.

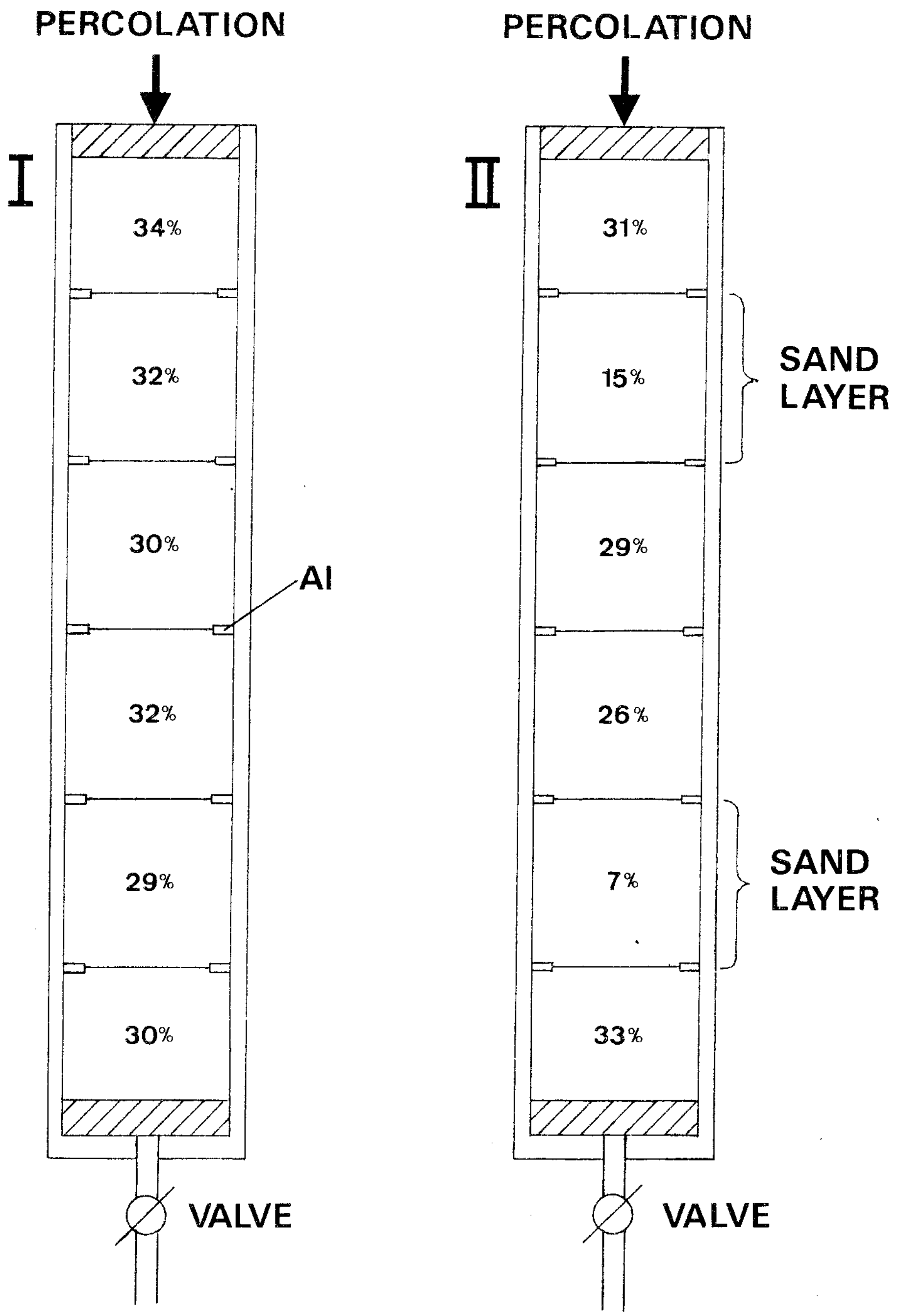

Fig. 9. Water content distribution in Test 2. Mean values given for each section. Al stands for aluminium rings which were inserted between the sections in order to prevent piping by extending the flow path along the walls.

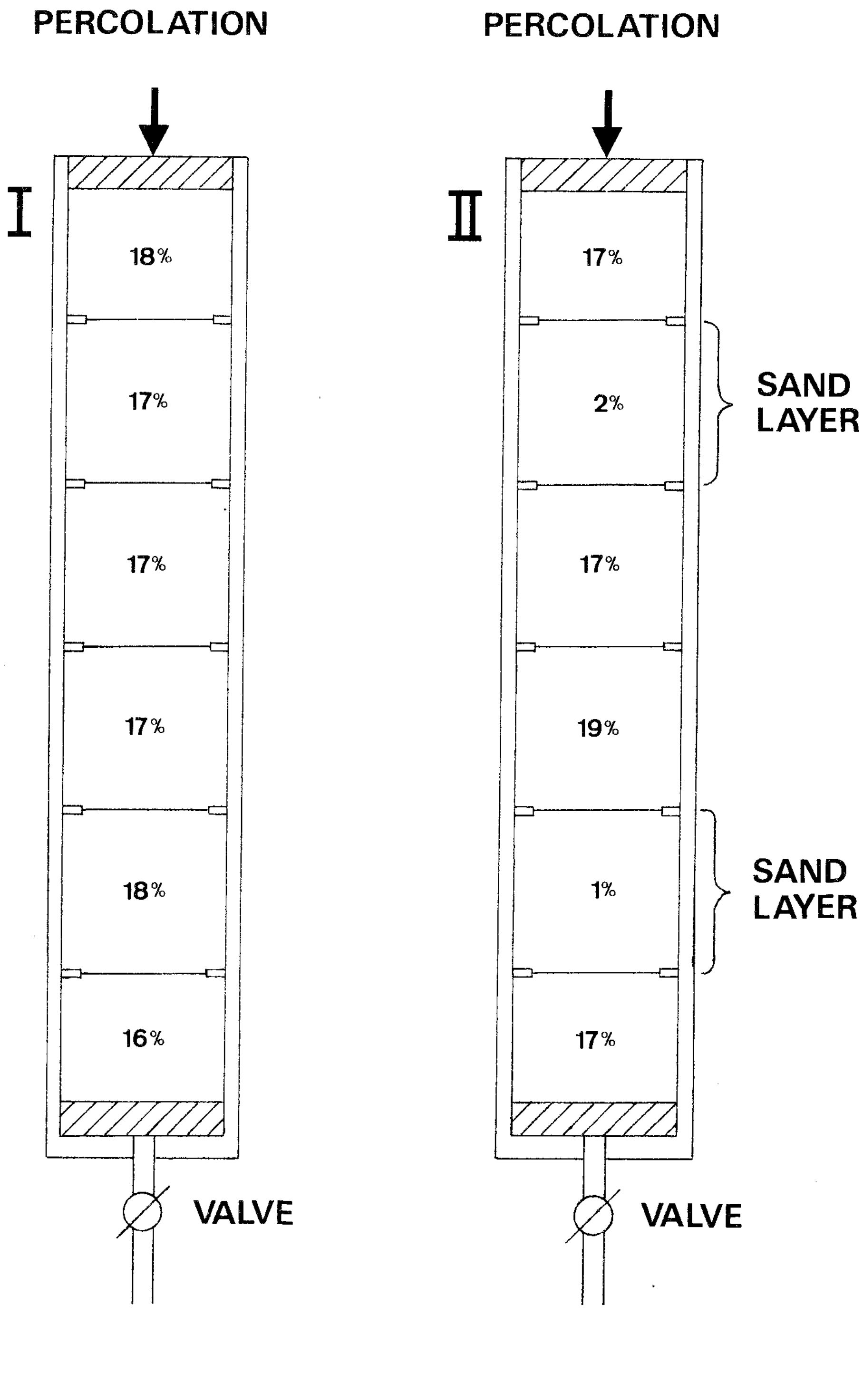

Fig. 10. Clay content distribution in Test 2.
Mean values given for each section.

The main conclusions from Test 2 are:

- The permeability is successively reduced under a constant gradient. The reason for this is the swelling power of the bentonite constituents which tend to reduce the narrow passages when expanded. This means that the coefficient of permeability will be less than 10^{-9} m/s when the buffer mass is completely water saturated even if the average dry density should be as low as 1.5 t/m^3.

- The permeability depends on the magnitude of the gradient. For small gradients the permeability drops considerably and it is reasonable to believe that the tunnel fill will be practically impervious when only regional gradients of the order of magnitude of 10^{-2} to 10^{-3} are finally in operation.

CONCLUSIONS

The percolation tests show that piping and temporarily rapid water flow may take place. It requires, however, that rather extreme and improbably high gradients are produced in the tunnel fill. Even if local piping should occur, it is found that self-sealing takes place, mainly due to the swelling power of the bentonite constituents. Permanently open or very permeable passages cannot be formed in the tunnel fill provided that the access of water through joints has been reduced by applying ordinary injection techniques.

The tests show that a steady homogeneous water flow does not transport clay particles through the grain matrix even under high gradients.

The fact that a tunnel fill with 20% Na bentonite does not obey Darcy's law, means that it will be practically impervious when only regional gradients are finally in operation.

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