R-10-70

Early effects of water inflow into a deposition hole

Laboratory tests results

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ISSN 1402-3091
SKB R-10-70

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Keywords: Buffer, Backfill, Deposition Hole, Piping, Erosion, Relative humidity, SKBdoc 1258959.

Abstract

During the installation of buffer and canister in a deposition hole a number of different problems can arise. The problems are mainly connected to water flow from fractures in the rock into the deposition hole. At some conditions it probably will be necessary to protect the installed buffer blocks with a special sheet made of rubber or plastic.

This report deals with two processes that can occur and are possible to strongly influence the buffer during installation:

1. **Erosion**. Erosion of bentonite from the deposition hole up to the voids in the tunnel backfill. This process will continue until a tunnel plug have been built and the voids in the backfill are filled with water.
2. **Heave**. Early wetting of the pellets filling may cause a heave of the buffer blocks that will decrease the density of the buffer.

An erosion model has been suggested /Sandén et al. 2008b/ which makes it possible to estimate the amount of eroded material for a certain water flow rate during a certain time. In order to verify the model and investigate how the buffer in a deposition hole behaves when exposed to a water flow, a number of different tests have been performed:

- Test type 1. Simulation of water flow out from a deposition hole. The deposition hole was made of steel and had a radial scale of 1:4 and a height of 0.6 meter. The pellets slot was scaled 1:1. After filling the deposition hole with buffer blocks and pellets, a constant water flow was applied in a point at the bottom. The discharged water at the top was collected and the amount of eroded material determined. The displacement of the blocks and pellets surfaces was also measured during the test.
- Test type 2. The influence of test length on the erosion rate was investigated by performing tests with Plexiglas tubes of different lengths (0.4 and 4 meter). The tubes were positioned vertically, filled with pellets and a point inflow was applied in the bottom. The discharged water was collected at the top and the amount of eroded material continuously measured.

The results from all tests were well within the limits of the erosion model. The erosion rate was in all tests in the lower range of the model which probably depends on the fact that the tests were performed in vertical direction with upwards flow. An interesting result from the tests (Test type 1) was that the buffer blocks moved upwards when water was filled into the surrounding pellets, but the movements did not seem to depend on swelling of the blocks. Instead the heave seemed to depend on a high relative humidity in the pellets filling which made the blocks crack and by that cause an upwards movement.

The long term test verified that the decrease of the erosion rate with time that have been measured in earlier tests and is predicted in the model seemed to continue for long time and for large water volumes.

With the performed laboratory tests as basis, analysis of the processes related to water inflow into a deposition hole have been made. The processes may lead to unacceptable reduction in buffer density during the installation and water saturation phases.

There are mainly two processes that may be detrimental to the buffer. One of them occurs during installation before the backfill has been placed on top of the deposition hole. The inflowing water will cause a heave of the buffer blocks, which may cause unacceptably decrease in density of the buffer material around the canister. The other process is erosion that will take place when water flows out from the deposition hole into the tunnel in channels formed in the pellets filling.

The criterion for acceptable heave of the buffer blocks before installation of backfill on top of the deposition hole is suggested to be one cm and the maximum allowable water inflow rate that causes such a heave within four days was found to be 0.1 l/min.

The criterion for acceptable loss of bentonite in one spot in a deposition hole is suggested to be 100 kg. The allowable inflow rate that limits the amount of eroded material from the deposition hole until the tunnel is filled with water was found to be 1.4% of the total inflow rate into the entire tunnel. In order for the erosion to be limited according to this criterion a tight plug is needed in the beginning of the tunnel.

Both criteria need to be verified in full scale tests. It may also be possible to considerably increase the latter criterion of ratio allowable inflow into a deposition hole to the total inflow.

Sammanfattning

Under installationen av buffert och kapsel i ett deponeringshål kan ett antal olika problem dyka upp. Problemen beror huvudsakligen på vattenflöde från sprickor i berget in till deponeringshålet. Vid vissa förhållande kommer det förmodligen att bli nödvändigt att skydda de installerade buffertblocken med ett speciellt framtaget ”buffertskydd” gjort av plast eller gummi.

I denna rapport behandlas tre möjliga processer som kan ha stor inverkan på bufferten under installationstiden:

1. **Erosion**. Erosion av bentonit från deponeringshålet och upp till tillgängliga porutrymmen i backfill-materialet i tunneln. Denna process kommer att fortsätta tills en tunnelplugg har byggts och allt porutrymme i backfillen är fyllt med vatten.
2. **Hävning**. Tidig bevätning av pelletsen kan leda till en hävning av buffertblocken och därmed en minskning av buffertdensiteten.

En erosions modell har föreslagits /Sandén et al. 2008b/ som gör det möjligt att uppskatta den mängd material som eroderar bort vid ett visst vattenflöde under en viss tid. För att verifiera modellen och undersöka hur bufferten i ett deponeringshål reagerar när den utsätts för ett vattenflöde, har ett antal olika tester genomförts:

- Test typ 1. Simulering av vattenflöde ut från ett deponeringshål. ”Deponeringshålet” var gjort av stål med radiell skala 1:4 och med höjden 0.6 m. Vidden på pelletsspalten var i skala 1:1. Efter att block och pellets installerats i det nerskalade deponeringshålet lades ett konstant vattentryck på i en punkt nära botten. Det vatten som kom ut i toppen samlades in och mängden eroderat material bestämdes. Rörelser os block och pellets under försökstiden mättes kontinuerligt.
- Test typ 2. Testlängdens inverkan på erosionshastigheten har också undersökts genom att göra tester i plexiglasrör med olika längd (0.4 m och 4 m). Rören placerades vertikalt, fylldes med pellets varefter ett punktinflöde lades på i botten. Det vatten som kom ut på ovansidan samlades in och mängden eroderat material bestämdes.
- Test typ 3. Ett långtidsförsök har också gjorts. En stor behållare med diametern 0.65 m och höjden 1.3 m fylldes med pellets (ca 480 kg). Ett punktinflöde lades på i botten. Det vatten som kom ut på ovansidan samlades in och mängden eroderat material bestämdes. Försöket pågick i fyra månader.

Resultaten från alla försök var väl inom gränserna för erosionsmodellen. Erosionshastigheten var i all försöken i den lägre delen (låg erosionshastighet) vilket förmodligen beror på att försöken gjordes i vertikal led med flödet uppåt. Ett intressant resultat från testerna av Typ 1, var att buffertblocken rörde sig uppåt när vatten fyllde upp porerna i pelletsspalten, men rörelserna berodde inte på svällning av bentoniten. Istället verkade rörelserna bero på att blocken sprack upp på grund av den höga relativa fuktigheten i pelletsfyllningen och att blocken därmed rörde sig uppåt.

Långtidsförsöket verifierade att minskningen av erosionshastigheten med tiden som har blivit uppmätt i tidigare försök och är predikterad i modellen verkade fortsätta under lång tid och för stora vattenvolymer.

Processer samhöriga med vatteninflöde i deponeringshål som kan leda till oacceptabel minskning av densitet hos bufferten under installations- och vattenmättnads-fasen har analyserats. Det finns i huvudsak två processer som kan vara skadliga för bufferten. En av processerna sker under installationen innan återfyllningen har kommit på plats ovanför deponeringshålet. Denna process medför att inflödande vatten orsakar en svällning och hävning av buffertblocken, vilket kan orsaka oacceptabel minskning av densiteten i bufferten runt kapseln. Den andra processen är erosion som äger rum när vatten strömmar från deponeringshålet upp i tunneln i kanaler som bildats i pelletsfyllningen.

Kriteriet för acceptabel hävning av buffertblocken föreslås vara 1 cm och maximala tillåtna inflödeshastigheten som orsakar en sådan hävning inom fyra dagar har befunnits vara 0.1 l/min.

Kriteriet för acceptabel förlust av bentonit i en punkt i ett deponeringshål föreslås vara 100 kg. Den tillåtna inflödeshastigheten som begränsar mängden material som eroderar från deponeringshålet tills dess att tunneln är vattenfylld har befunnits vara 1.4% av den totala inflödeshastigheten till tunnel och alla deponeringshål. För att erosionen skall begränsas på detta sätt krävs en tät plugg i tunnelöppningen.

Båda kriterierna behöver verifieras i full skala. Det kan också visa sig möjligt att det senare kriteriet med relationen mellan tillåtet inflöde i ett deponeringshål och total inflödet kan ökas avsevärt.

Contents

1 Introduction

During installation of the buffer and canister in a deposition hole a number of different problems can arise. The problems are mainly connected to water flow from fractures in the rock into the deposition hole, see Figure 1-1. At some conditions it will probably be necessary to protect the installed buffer blocks with a special sheet made of rubber or plastic.

Wetting of the buffer can be divided into three different phases:

1. The time until the tunnel above the deposition hole is backfilled (installation phase). The time allowed for this phase depends mainly on the water inflow rate into the deposition hole but also on the design of the buffer (slot widths, water ratio of blocks, properties of pellets etc).
2. The time from finished backfilling of the tunnel above the hole until the large voids in the pellets filling in the deposition hole and the tunnel have been filled with water. During this phase erosion of bentonite from the buffer may take place.
3. The time until the buffer is fully saturated (the saturation phase). This phase is not dealt with in this report.

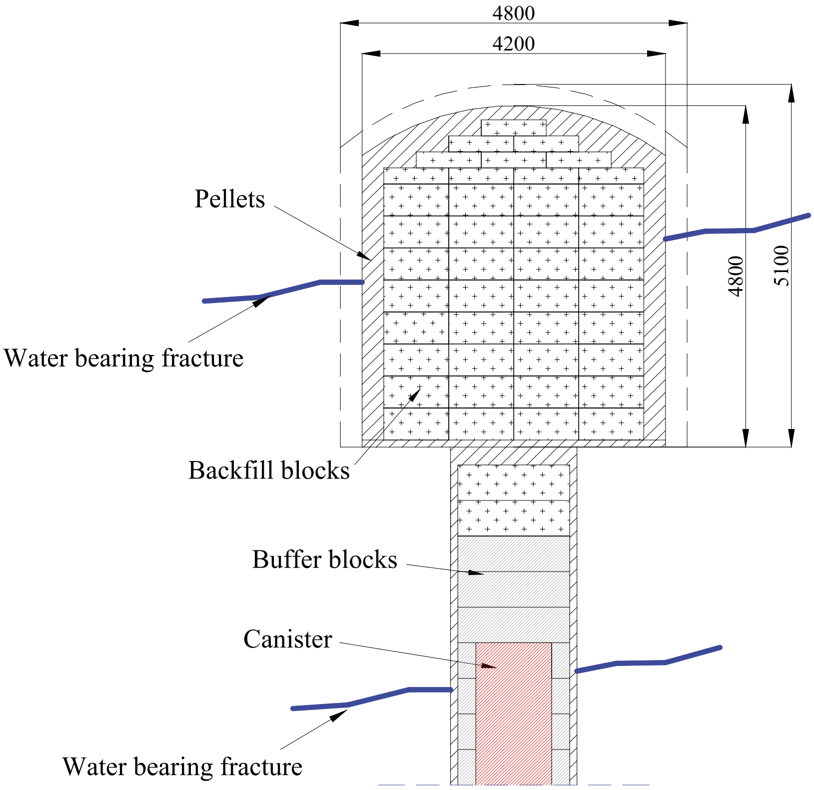

Figure 1-1. Schematic drawing showing a cross section of a deposition hole and a backfilled tunnel.

This report deals with two processes that can occur and may strongly influence the buffer during installation:

1. **Erosion**. After installation of the canister and the buffer blocks, the slot around the blocks will be filled with bentonite pellets, but they cannot stop the flowing water due to the rather low density of the filling in combination with the water pressure that will be built up. Water flowing from the deposition hole up to the tunnel can erode away bentonite from the deposition hole up to the voids in the tunnel backfill. This process will continue until a tunnel plug have been built and the voids in the backfill are filled with water.
2. **Heave**. Early wetting of the pellets filling may cause a heave of the buffer blocks that will decrease the density of the buffer.

The tests regarding item 2 described in this report have been performed in the scale 1:4 (diameter scaled 1:4 but slot scaled 1:1). Similar tests in scale 1:1 (diameter scale 1:1 and with the height 1m) have been performed at the Äspö laboratory /Åberg 2009/.

The tests regarding item 1 (erosion) are described in Chapter 4 and the tests regarding item 2 (heave) are described in Chapter 3. In Chapter 6, a scenario description is done, that analyzes the early effects of wetting of the buffer and suggestions of guide-lines for handling the inflow are provided.

2 Test prerequisites

2.1 General

All tests described in this report, except one, have been performed using MX-80 which is a sodium bentonite with a smectite content of 75–80% from Wyoming, produced by American Colloid Company.

2.2 Materials and water used in the tests

The blocks used in the tests were made of MX-80 bentonite. The blocks were manufactured in a special mold manufactured within another project (LOT). The blocks were compacted with a pressure of 100 MPa.

Pellets/granules of the following types have been used:

- **Cebogel QSE pellets**. Commercial bentonite pellets with a montmorillonite content of about 80%. The bentonite is quarried at Milos, Greece, and is converted to sodium state. The pellets are delivered by Cebo Holland BV. The material is used in ongoing field tests at Äspö. The pellets are extruded cylindrical rods with a diameter of 6.5 mm and a length of 5–20 mm. This material was only used in one test.
- **MX-80 pellets**. Pellets made of MX-80 by roller compaction. MX-80 is a natural sodium dominated bentonite. The pellets are pillow shaped with the dimensions 18 x 18 x 8 mm. In addition there are a few percent fine materials.

Water with a salinity of 1% (50/50 $NaCl/CaCl_2$) was used in all tests.

2.3 Laboratory determinations

The water content of the bentonite was determined at the end of tests. The technique is briefly described below:

Clay sample was placed in an aluminum baking tin and the bulk mass (m_b) of the specimen was determined by use of a laboratory balance. The specimen was dried in an oven for 24 hours at a temperature of 105°C. The dry solid mass (m_s) of the specimen was then determined immediately after drying. From these measurements the water ratio *w* was calculated by Equations 3-1 and 3-2:

$$m_w = m_b - m_s \tag{3-1}$$

$$w = \frac{m_w}{m_s} \tag{3-2}$$

3 Consequences of early water inflow to a deposition hole

3.1 General

A critical phase of the deposition sequence is the time between the installation of canister, buffer and pellets in a deposition hole and the backfilling of the tunnel above the deposition hole. If this time is too long and the water inflow to the deposition hole is strong, the pellets slot will be filled with water and there may be upwards displacements of the buffer. When the backfill is placed it will to a large extent prevent further movements.

The aim with this investigation was to achieve answers to the following questions/scenarios:

1. How do different water inflow rates affect the heave of the buffer?
2. At which water flow rate can the pellets be placed directly after installation of the buffer blocks and canister?
3. What erosion rate can we expect from water leaving out from the deposition hole?

3.2 Test description

The test equipment used in the experiments included a steel cylinder (inner diameter 400 mm and height 600 mm) with bottom, simulating a deposition hole. The cylinder was filled with bentonite blocks of LOT-type (diameter 280 mm and height 100 mm) which were piled around a central copper tube, see Figure 3-1. The slot between the blocks and the steel wall had a width of about 60 mm, which slightly differs from the nominal slot width in a full scale deposition hole but this is considered not to influence the results or conclusions.

A point inflow of water was applied in the bottom of the "deposition hole". At the top of the steel cylinder a number of notches with a width of about 1 mm and a depth of 50 mm were made in order to let the water reaching the top leak out and be collected in a ditch surrounding the steel cylinder on the outside. The out-flowing water was collected and analyzed in order to determine the amount of eroded material.

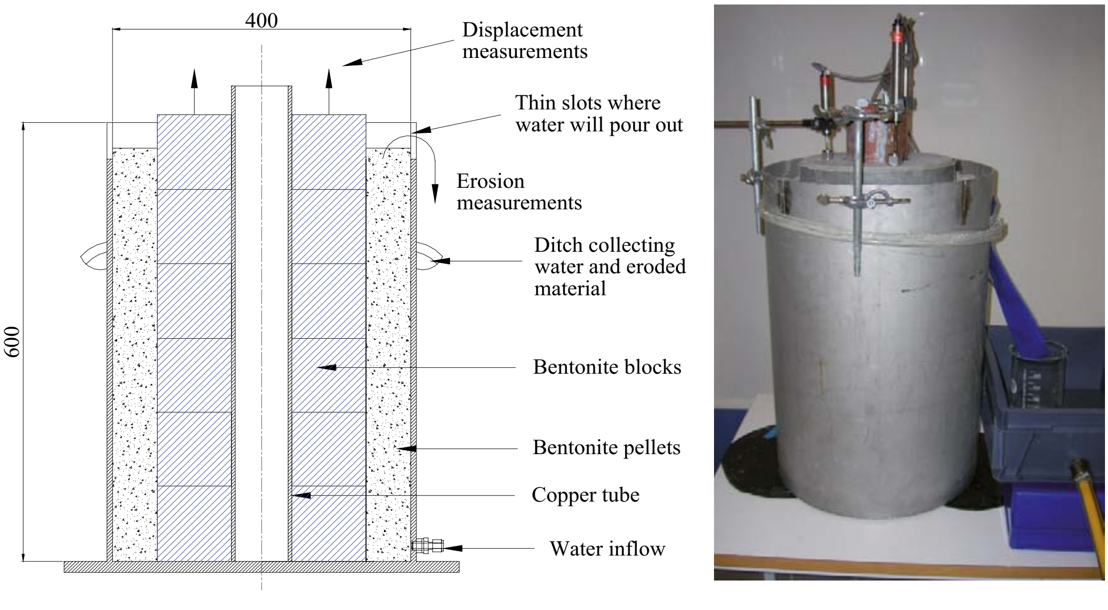

Figure 3-1. Schematic drawing (left) and photo (right) of the test equipment used for testing the influence of water inflow to a deposition hole during the installation phase.

The following was controlled or measured during the tests:

Water flow

- **Water flow into the test cylinder.** This was set to a selected value on the microprocessor controlled pump used to supply water to the test.
- **Water flow out from the test cylinder.** Samples were taken from the out-flowing water. The cups with water samples were weighed and then placed in an oven at 105° where the water was evaporated. After drying, the cup was weighed again. With this procedure the amount of out-flowing water at a certain time interval could be calculated. When the flow rate was 0.1 l/min, water samples were taken from the downstream exit at regular intervals. For flow rates of 0.01 l/min or lower all the water during a certain time period was collected as a single sample.

Buffer movements

- **Bentonite blocks.** Three displacement sensors were continuously measuring the displacements of the blocks.
- **Pellets surface.** The level of the surface of the pellets filling was measured manually in three points with a ruler at regular intervals.

Erosion measurements

- **The amount of eroded material in the water**. The water samples taken from the exiting water, as described above, were also used to determine the amount of clay in the water by evaporating the water in an oven at 105°C and determining the residue. The mass remaining was corrected for salt in the water. For water flow rates of 0.1 l/min, water samples were taken from the downstream exit at regular intervals. For flow rates of 0.01 l/min or lower all the water during a certain time period was collected as a single sample. The determined erosion rate for a certain sample was also used for the period between the two last samples taken out when calculating the accumulated amount of eroded material.
- **Observations.** A digital camera was used in order to register the behavior.

3.3 Test results

3.3.1 General

Totally nine tests have been performed. Water with 1% salt (Na/Ca 50/50, see Chapter 2) content was used in all tests. In the first test Cebogel QSE pellets was used in the slot. The reason was that this pellets type is used in some full scale tests at Äspö.

Additional diagrams and photos from the tests are provided in Appendix 1–9.

The following main test parameters were varied:

- **Water inflow rate**. The flow rate was varied between 0.1 l/min and 10^{-5} l/min. The tests with the lowest inflow rates were made in order to determine if there is an inflow rate that the buffer can stand for sufficiently long time without unacceptable expansion of blocks and outflow of water, which means that buffer protection is not needed.
- **Initial water ratio of the blocks**. The main part of the tests were performed with blocks having an initial water ratio of about 17%, which is the water ratio that has been used for the buffer blocks installed in the Prototype repository. In one test the initial water ratio of the blocks was increased to 24%.
- **Vertical load**. One test was performed with an applied overload of 208 kg (40 kPa) in order to simulate the situation in a full scale deposition hole (2 m down from the uppermost block surface).
- **Height of test**. One test was performed with double height in order to study the scale effects.

Theseparameters and main test results of all tests are compiled in Table 3-1. The table shows e.g. that all voids in the pellets were filled with water at the highest inflow rate, 0.1 l/min, before leakage started and also that at low inflow rates the portion of filled pores decreased with decreasing inflow rate.

Table 3-1. Compilation of performed tests.

Test	Block		Pellets		Flow rate	Water	Test time	Max. disp.		Time to first leakage	Macro voids in pellets	Accumulated water at leakage start	Erosion	Remark
	Material	w, %	Material	w, %	l/min		days	block mm	pellets mm	hours	liter	liter	meas.	
1	MX-80	11.4	Cebogel QSE	19.5	0.1	1 % salt	8	56	89	2.6	16	15.5	Yes	
2	MX-80	15.6	MX-80	13.0	0.1	1 % salt	8	37	51	2.6	18	15.4	Yes	
3	MX-80	15.6	MX-80	13.0	0.01	1 % salt	7	26	66	17	18	10.3	Yes	
4	MX-80	17.0	MX-80	13.0	0.00125	1 % salt	12	16	60	19.9	18	1.5	Yes	
5	MX-80	17.0	MX-80	13.0	0.01	1 % salt	7	18	57	11.4	18	6.9	Yes	Vertical load 40 kPa
6	MX-80	17.0	MX-80	13.0	0.0001	1 % salt	86	95	130	–	18	–	No	Low inflow I
7	MX-80	17.0	MX-80	13.0	0.01	1 % salt	8	25	50	19.9	36	12.0	Yes	Double height
8	MX-80	24.0	MX-80	13.0	0.01	1 % salt	9	18	41	12.7	18	7.6	Yes	High S_r in blocks
9	MX-80	17.0	MX-80	13.0	0.00001	1 % salt	93	8	4	–	18	–	No	Low inflow II

3.3.2 Block movements (heaving)

The axial displacement or heave of the blocks with time was measured in all tests. A compilation of the results is provided in Figure 3-2 and 3-3. The test results yield the following conclusions:

- The influence of inflow rate is very clear; higher flow rates result in larger heave of the buffer blocks. This depends on the fact that the number of affected blocks are higher when the water flow rate is higher, see description and photos from the dismantling in next section.
- Also with very small water inflow rates a displacement could be measured. The rate of the movement was however very low, see Figure 3-3. The wetted volume is in this case very small and any significant effects of the locally increased humidity could not be seen.
- The movements are decreased when an overload (other blocks or backfill) is applied at the top, see result from test 5 where an overload of 40 kPa was applied.
- If the buffer blocks are manufactured with high initial water content they are more resistant against the wetting and the movements will be smaller.

When the tests were finished the buffer blocks were carefully examined. It was found that the upwards movements were not caused by water entering the joints between the blocks and a following swelling. Instead it seems like the movements upwards were caused by cracking of the blocks. When water fills up the voids between the pellets the relative humidity increases and the bentonite blocks starts to take up water from the air. This process affects the blocks in a way that make them crack and also make them bent so that the volume occupied by the blocks increases. This phenomena has also been seen in other projects /Sandén et al. 2008a/. The cracks are large and goes through the blocks, see Figure 3-4. Cracks of this type could be seen on one or several blocks in all tests.

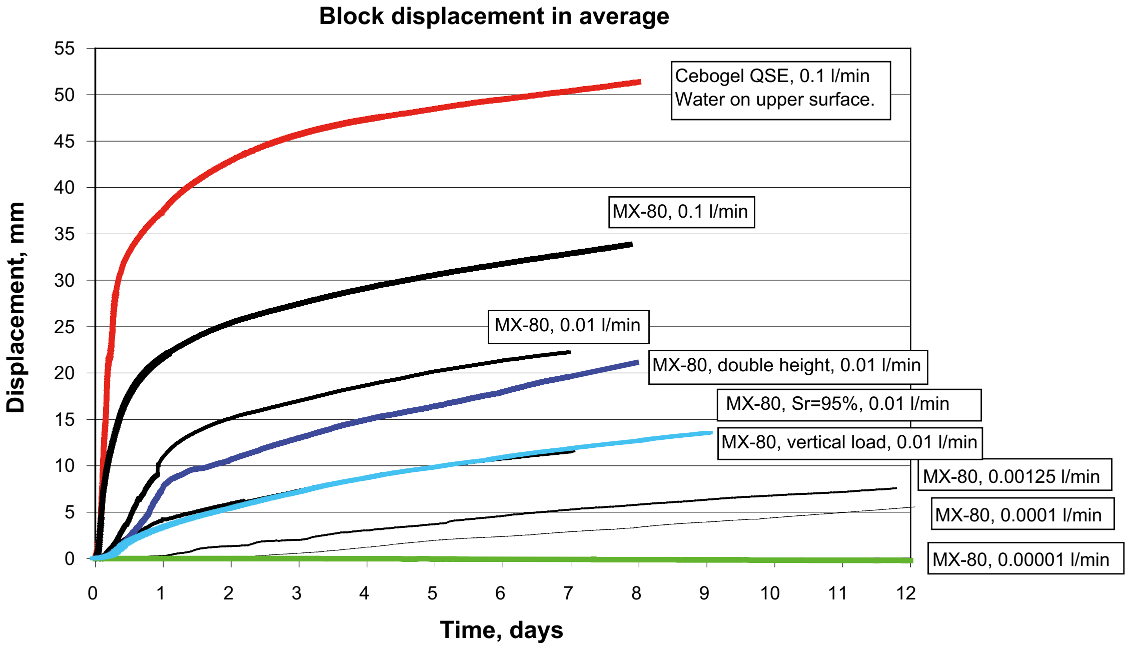

Figure 3-2. *Average displacement plotted vs. time. The curves represent an average of the displacement measured by three sensors for the nine tests.*

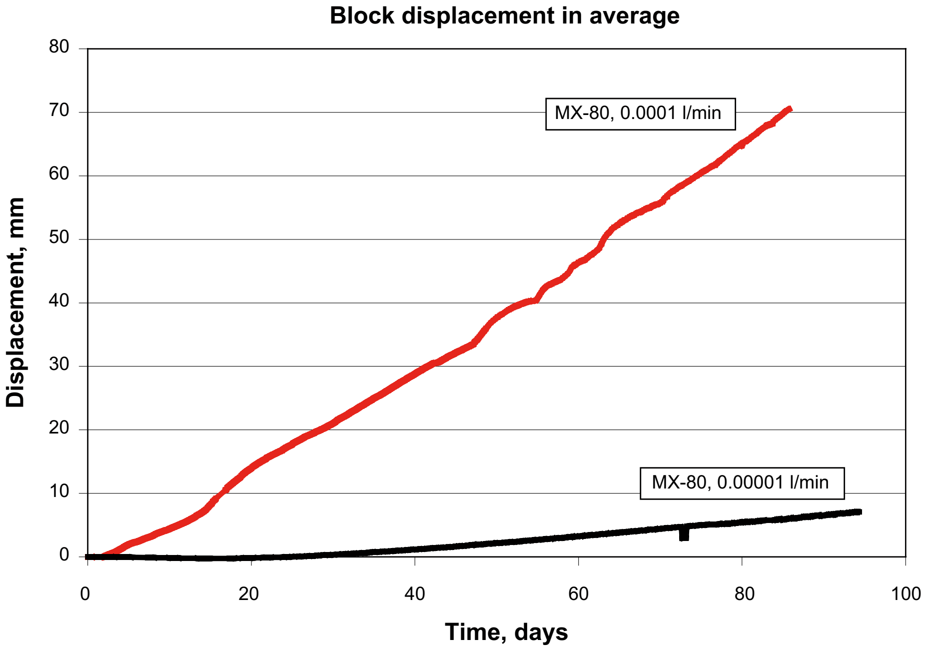

Figure 3-3. Average displacement for the two tests with lowest water inflow rates and longest test period.

3.3.3 Wetting behaviour

During dismantling it was noticed that the wetting behavior of the pellet fillings differed at the different inflow rates. Figure 3-4 shows pictures taken during dismantling. The following influence of inflow rate could be seen:

- 0.1 l/min: The filling has started from the bottom and all voids seem to be filled with water.
- 0.01 l/min. About half of the pellet filling was wetted. The water has ascended along one side without affecting the opposite side.
- 0.001 l/min. Only a small part of the filling is wetted. The water has flow upwards in a small channel only affecting the pellets close to the channel.

The difference in behavior for the different flow rates is not well understood. One explanation could be that at low flow rates, the bentonite has time to swell and seal, which means that the downward and sideways directions are blocked early This difference has an impact on the time until water can be expected to reach the top of the deposition hole. In a full scale deposition hole, where canister, buffer and pellets are installed, water that has reached the top will not leak out like in the performed tests, but will stay on the surface and affect the top of the uppermost block which then can swell freely. This effect limits the time until the backfilling above the deposition hole must be finished.

In a full scale deposition hole the pellet filling will contain a macro void volume of about 1,000 liters. Assuming that the water behaves in the same way in full scale as in the scale tests the time from installation of pellets until water enters the top of the deposition hole can be estimated. Table 3-2 shows the results of such estimation where the following assumptions have been made:

- 0.1 l/min. The whole pellets filling is filled with water.
- 0.01 l/min. Water is filling up a channel with a width of about 500 mm.
- 0.001 l/min. Water is filling up a small channel along the rock wall.

Table 3-2 shows that although there is an influence of the inflow rate on the time needed in order for the water to reach the top, the influence is not very strong due to the difference in behaviour. These scenarios have been further investigated at full scale in Chapter 6.

Figure 3-4. Photos taken during dismantling of the tests with different inflow rates. ***Upper****. 0.1 l/min: The whole pellet filling is wetted. There are distinct cracks in the blocks.* ***Middle****. 0.01 l/min: Half of the pellet filling is wetted. Also in this test distinct cracks can be seen in the blocks.* ***Lower****. 0.001 l/min: Only a small part of the filling is wetted. The water has ascended in a channel along the "rock" wall.*

Table 3-2. Table showing estimated time for water to reach the top of a full scale deposition hole at different water inflow rates.

Water flow rate at the bottom of the deposition hole, l/min	Calculated time until water reaches the top of the deposition hole, hours
0.1	167
0.01	240
0.001	280

3.3.4 Erosion measurements

Erosion was measured in seven of the nine tests. In the two tests with the lowest water inflow rates, 0.0001 and 0.00001 l/min, no water leaked out during the test time.

In Figure 3-5 the accumulated dry weight of material is plotted vs. time. The results can also be presented as the accumulated dry weight of material plotted vs. the accumulated water flow in logarithmic scales, see Figure 3-6.

Within the Baclo project a number of erosion tests have been performed, mainly on different bentonite pellets but also on compacted blocks. Based on the results from these tests an erosion model has been proposed /Sandén et al. 2008b/. The model assumes a linear relation between the accumulated amount of eroded material and the accumulated water flow in a double logarithmic diagram. The model also includes that there is an evident decreasing of the erosion rate by time. The black bold lines in the diagram in Figure 3-6 show the limits of the erosion model. It is shown in the diagram that all results from this test series are in the lower part of the suggested model i.e. the erosion rate is proportionately lower in these tests. An explanation for this can be that in this test series the water flow direction has been vertical upwards while all other tests, on which the model is based, have had a horizontal flow.

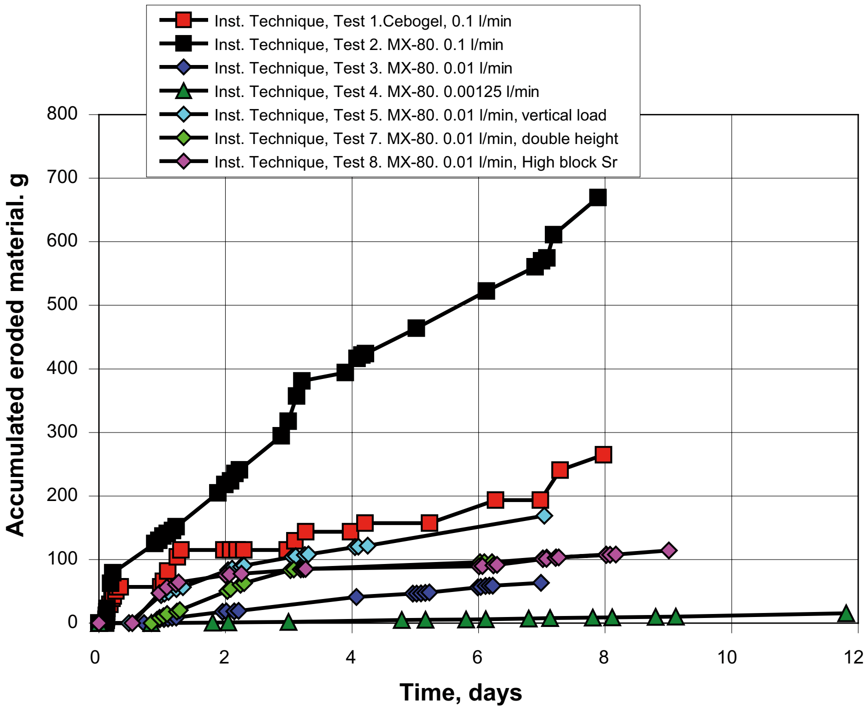

Figure 3-5. The accumulated dry weight of eroded material plotted vs. time.

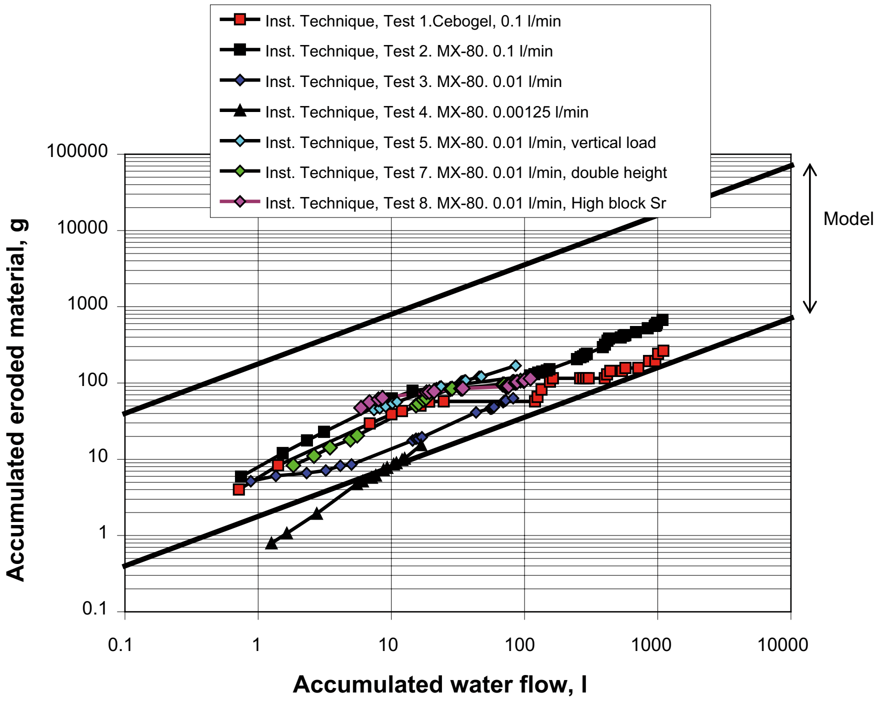

Figure 3-6. *The accumulated dry weight of eroded material plotted vs. the accumulated water flow.*

3.4 Comments and conclusions

The results from the scale tests can be summarized as follows:

- There is a very clear influence of the applied water inflow rate regarding the rate and magnitude of the heave of the buffer.
- The heave depends mainly on the fact that the buffer blocks are cracking due to the high relative humidity in the pellet filling. Similar cracking has been observed when blocks are exposed to high RH and seems to be caused by local swelling at the block surface.
- Also very small inflow rates (0.0001 and 0.00001 l/min have been tested) affects the buffer. The rate of the move is however very low.
- Different portions of the pellets volume is affected at different water inflow rates. At the highest inflow rate, 0.1 l/min, all voids between the pellets will be filled with water, but with a low inflow rate, 0.001 l/min, the water will seek it´s way upwards, only affecting a small part of the pellets filling.
- The measured erosion rates are well inside the limits of the suggested erosion model /Sandén et al. 2008b/. The measured erosion rates are close to the lower limit of the model which probably depends on the difference in flow direction, which is vertical in the tests while the model is based on tests with horizontal flow.

4 Erosion tests with bentonite pellets

4.1 General

As mentioned in Chapter 3 the erosion properties of bentonite pellets have been investigated within the BACLO project. Based on the results from these tests an erosion model has been suggested /Sandén et al. 2008b/. The model assumes a linear relation between the accumulated amount of eroded material and the accumulated water flow in a double logarithmic diagram.

Since the tests so far have been made with rather short duration (less than a week) and with rather short flow paths it was decided that complementary tests were needed. The following test types have been made:

- The influence of the length of the flow paths have been investigated by performing tests in tubes with different lengths, 0.4 m and 4 m.
- A long term test has been performed in order to check if the model can be extrapolated to actual figures. The earlier tests performed have shown that there is a rather strong decease in erosion rate with time and accumulated water flow. This parameter is very important in order to calculate the total amount of eroded material during a certain time period.

4.2 Influence of the length of the flow path

4.2.1 General

The influence of the length of the flow path has been investigated earlier, /Sandén et al. 2008b/ in a single test but it was not possible to detect any large influences on erosion rate. Six new tests have been performed in order to further investigate the influence of the flow length.

4.2.2 Test description

The tests have been made in Plexiglas tubes, which makes it possible to follow the course of events from the outside and also to take photos, see Figure 4-1. The tubes have an inner diameter of 0.1 m. The test series included two test lengths, 0.4 and 4.0 m, and two water flow rates, 0.01 and 0.1 l/min. All tests were performed with water having a salinity of 1%, see Chapter 2.

The tests were performed with the tubes standing i.e. the inflow point was in the bottom and the water was flowing upwards. At the upper end of the test equipment, a number of slots were sawed in the Plexiglas, see Figure 4-2, where the water could pour out and down to a ditch positioned around the tube. The water could then be collected in a vessel. The test design is similar to the one described in Chapter 3. The vertical flow direction is the same and also the technique for collecting water samples. The flow direction is different compared to earlier tests made within the Baclo project. The difference in flow direction represents the difference in behaviour in a deposition hole and in the deposition tunnel. The tests described in Chapter 3 showed that the erosion rate seems to be lower when the flow direction is upwards compared to the earlier tests performed within the Baclo project that included horizontal flow in Plexiglas tubes.

Figure 4-1. *Photos showing the test equipment used in the tests. The left photo shows the 4 meter long test equipment. The right photo shows a close up view after filling the tube with pellets.*

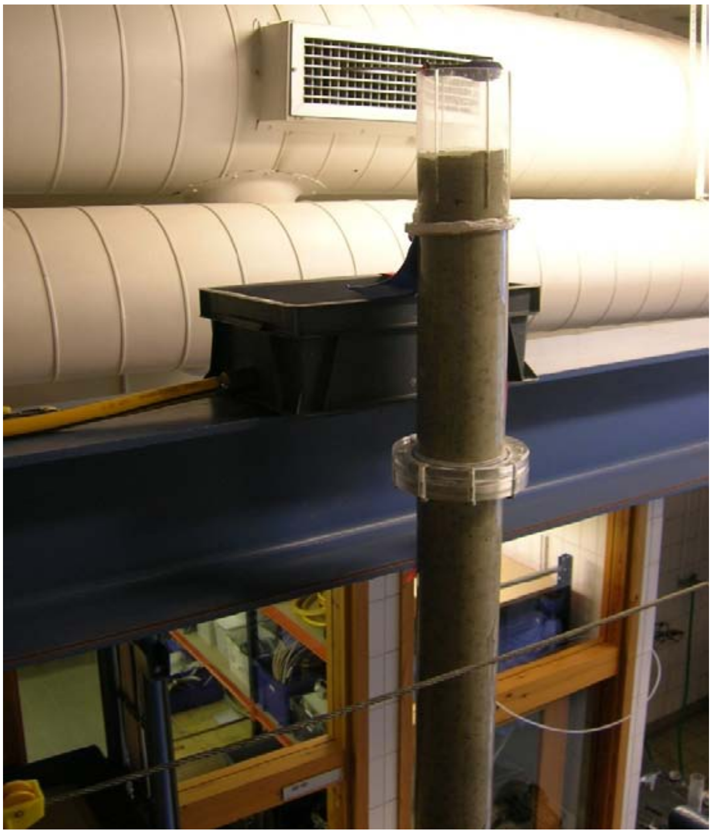

Figure 4-2. *Photo showing the upper end of the 4 meter high test equipment where the water was collected.*

4.2.3 Measurements

The water flow and erosion were controlled and measured in the same way as the tests described in section 3.2. A separate pressure transducer was registering possible water pressure built up. The aim was to apply a constant flow that remained constant independent of the resisting water pressure that was built up during the saturation of the pellet material.

4.2.4 Test results

General

Totally six tests have been performed in this test series. The data and results are compiled in Table 4-1. Erosion was measured in four of the tests.

Resistance to water inflow

At the water flow rate 0.01 l/min and test length 4 meters, a counter pressure (resistance to further water inflow) was built up which made it impossible to continue the tests. The bentonite pellets sealed which resulted in a resistance to further water inflow. The water pressure increased and since the pressure acted on the whole cross section the pellets column above was pushed upwards. Figure 4-3 shows the measured water pressure in both tests and Figure 4-4 shows the water filled space created by the high water pressure. This phenomenon has been seen also in the earlier investigations and is believed to be caused by valve formation and controlled by factors such as the grain size distribution, the size of available voids and the geometry of the confinement.

Figures and photos from the tests are provided in Appendix 10–14.

Also in the other tests a significant water pressure could be measured, see Appendix 10–14. In the tests performed with the shorter test length, 0.4 m, the counter pressure was very low (about 20 kPa) but in the tests with the longer test length, 4 m, the pressure was rather high (between 50 and 250 kPa). Low water inflow rates and long test sections increases the resistance to water pressure.

Erosion measurements

Erosion was measured in four of the tests, see Table 4-1. The results are not entirely conclusive and some are difficult to explain. All erosion measurements fits however very well to the suggested model /Sandén et al. 2008b/.

Figure 4-5 shows the accumulated amount of eroded material plotted vs. time. The results can also be presented as the accumulated amount of eroded material plotted vs. the accumulated water flow in logarithmic scales, see Figure 4-6. The black lines in the diagram show the limits of the suggested erosion model. The measured erosion rates are in the middle and in the lower part of the model.

Figure 4-7 shows the bentonite content in the discharged water plotted vs. different flow rates. The erosion rate was evaluated after 48 hours test duration.

These results don't show any evident influence of the test length.

A main channel has been formed after a certain time in all tests and the main part of the out-flowing water seems to follow that channel. Figure 4-8 shows a picture of a channel. The channel has in all tests mainly been formed in the interface between pellets and the wall of the test equipment which probably depends on that the flow resistance is lower in this region. The behaviour is believed to be the same in full scale i.e. in a deposition hole. The difference between a rock wall and a Plexiglas wall is not believed to influence the erosion properties.

Table 4-1. Compilation of performed erosion tests.

Test	Pellets Material	w, %	Flow rate l/min	Flow length m	Water	Test time days	Time to first leakage hours	Macro voids in pellets liter	Accumulated water at leakage start liter	Erosion meas.	Remark
1	MX-80	13.0	0.01	0.4	1 % salt	4	2h 28 min	3.2	1.5	Yes	
2a	MX-80	13.0	0.01	4	1 % salt	1	–	32.0	–	No	No erosion measurements depending on high counter pressure.
2b	MX-80	13.0	0.01	4	1 % salt	1	–	32.0	–	No	No erosion measurements depending on high counter pressure. Repetition of test 2a.
3	MX-80	13.0	0.1	0.4	1 % salt	8	13 min	3.2	1.3	Yes	
4a	MX-80	13.0	0.1	4	1 % salt	11	2h 10 min	32.0	13.0	Yes	
4b	MX-80	13.0	0.1	4	1 % salt	7	1h 56 min	32.0	11.6	Yes	Repetition of test 4a.

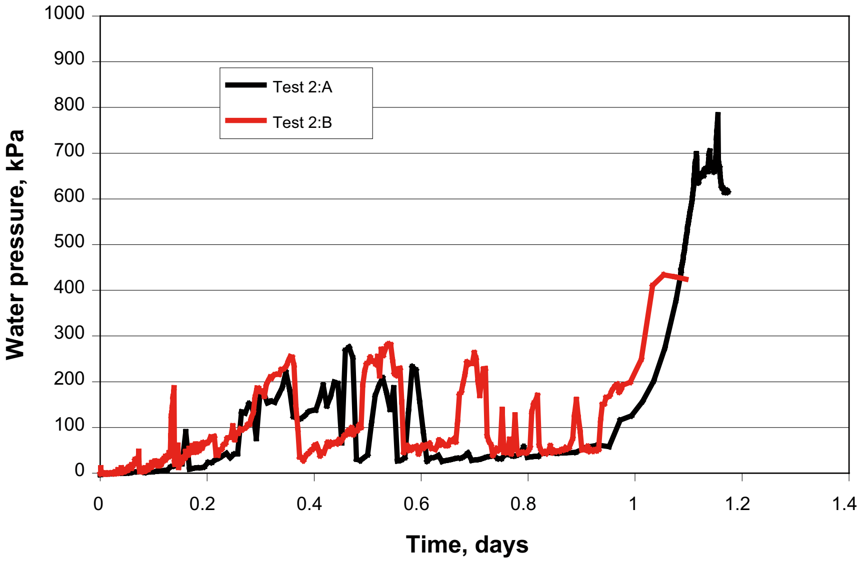

Figure 4-3. *Water pressure measured at the two tests with the flow rate 0.01 l/min and the test length of 4 meters. The bentonite sealed at these test conditions and a high water pressure was built up.*

Figure 4-4. *When the bentonite had sealed at one level, the water pressure could act on the whole cross section and the pellets column was pushed upwards.*

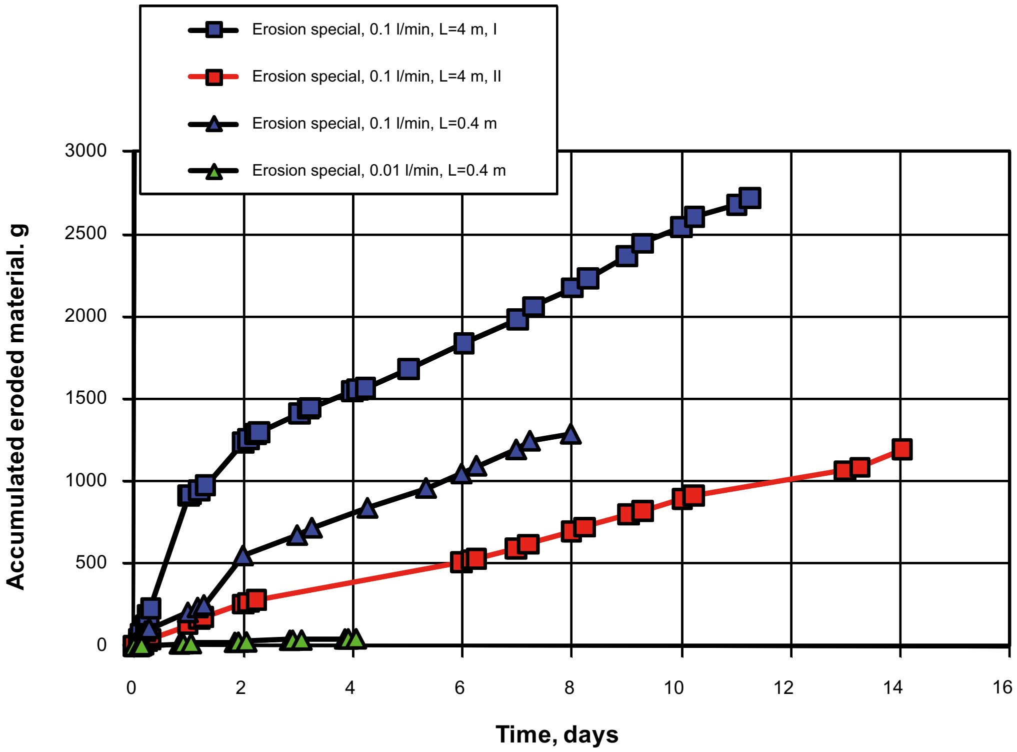

Figure 4-5. Accumulated amount of eroded material plotted vs. time.

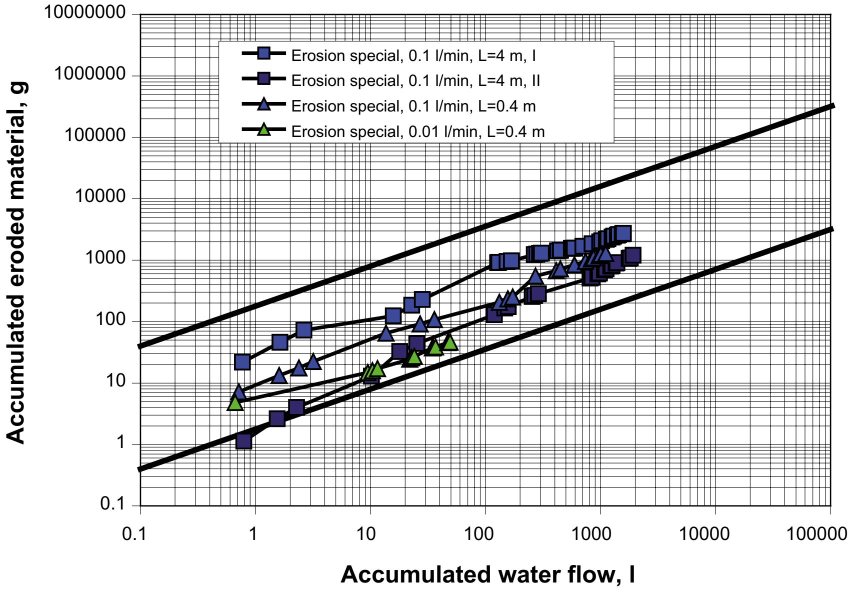

Figure 4-6. Accumulated amount of eroded material plotted vs. accumulated water flow in logarithmic scales.

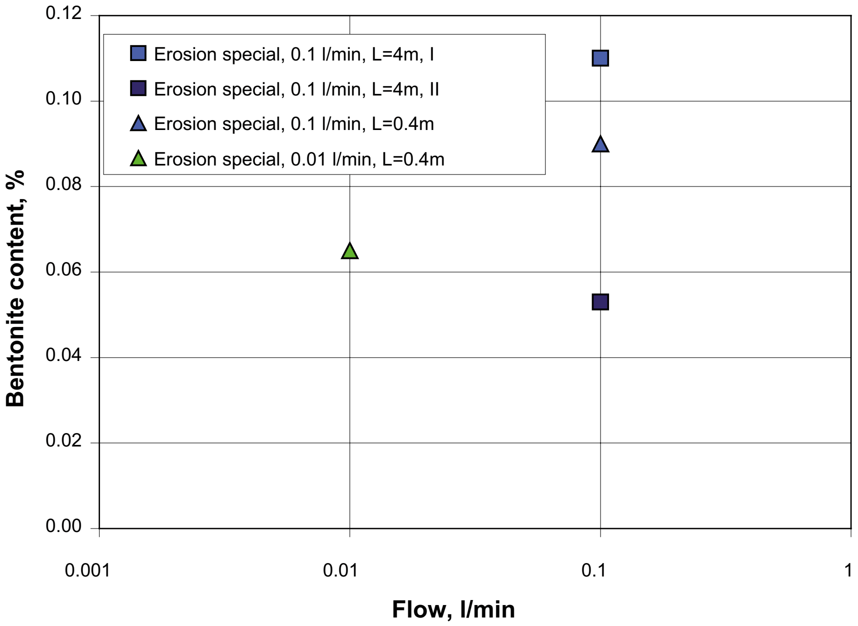

Figure 4-7. *Bentonite content in the out flowing water in percentage plotted vs. different water flow rates. The erosion rate was evaluated after 48 hours test duration.*

Figure 4-8. *Photo showing a typical channel where all water is flowing.*

4.3 Long term test

4.3.1 General

The suggested erosion model assumes a linear relation between accumulated eroded material and accumulated water flow in a double logarithmic diagram. The α-parameter in the model (see model description in Chapter 6) corresponds to the inclination of the linear relation and does not seem to be affected of the test conditions. According to earlier measurements the α-parameter is constant with the value 0.65 i.e. the erosion rate decreases by time.

The earlier tests had duration of one to two weeks with a maximum water flow of 2 m^3, and it was therefore decided to perform a long term test in order to verify that the results can be extrapolated to actual field conditions.

4.3.2 Test description

The test equipment consisted of a large plastic vessel with the diameter 0.65 m and the height 1.3 m, which was placed in a steel frame, see Figure 4-9. The vessel was filled with about 480 kg MX-80 pellets. In the middle of the bottom plate of the vessel a point inflow was applied. The plastic tube, supplying the tests with water was pushed through the connector during installation, which means that the inflow point was positioned about 200 mm above the bottom plate. This was made in order to avoid water flow along the interface between pellets and vessel.

At the upper part of the vessel, around the periphery, notches were made. On the outside of the vessel a ditch was placed in order to collect the out-flowing water, see Figure 4-9.

The water used in the test had a salinity of 1% (50/50, $NaCl/CaCl_2$). A constant flow of 0.1 l/min was applied. Altogether about 16,000 litres flow through the bentonite pellets. In order to supply the test with water, special equipment consisting of two large vessels and pumps, was made, see Figure 4-10.

Figure 4-9. *Left: Arrangement for collecting water in order to measure the erosion. Right: Pellets surface about 20 hours after test start. Water has entered the surface in the middle. The white plastic lids are placed on the pellets surface measuring movements.*

Figure 4-10. *Vessels and pumps for mixing and supplying the test device with water.*

4.3.3 Test results

About 20 hours after test start, water reached the top surface, see Figure 4-11. This means that about 120 litres had been injected which should be compared with the available macro voids (voids between pellets) which was about 195 litres. This means that parts of the voids between pellets were unfilled when water reached the upper surface. This is not in accordance with the results achieved in Chapter 3 where it was stated that filling of a pellet filling with this flow rate will lead to a complete filling of water in all macro voids, which shows the random elements that exist in these processes.

The upper surface swelled rather fast during the first 48 hours after test start, see Figure 4-11. About 40–45 litres of bentonite gel had to be removed from the top in order to avoid it from flowing over the edge.

Due to the applied constant rate of water inflow a counter pressure was built up, see Figure 4-12. The pressure varied between 20 and 50 kPa.

Figure 4-11. *Left: Pellets surface after 24 hours. Right: Pellets surface after 40 hours.*

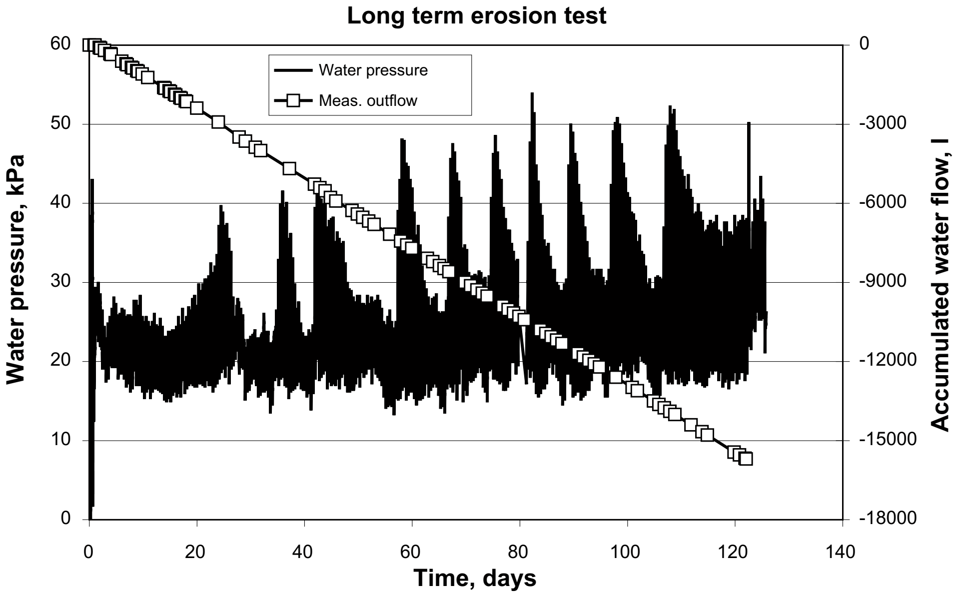

Figure 4-12. Water pressure and measured outflow plotted vs. time.

Erosion measurements

Erosion and water flow was controlled and measured in the same way as described in section 3.2.

Figure 4-13 shows the accumulated amount of eroded material plotted vs. time. The results can also be presented as the accumulated amount of eroded material plotted vs. the accumulated water flow in logarithmic scales, see Figure 4-14. The black lines in the diagram show the limits of the suggested erosion model.

The results from the erosion measurements are very well in between the limits of the suggested model and the decrease with time has continued during the entire test time.

Test termination

The test was intended to run for six months but had to be finished after about four months test duration. During a weekend, the uppermost 0.8 meter of the pellets column had displaced about 100 mm upwards, see Figure 4-15. The displacement is probably caused by similar phenomenon that was seen in earlier tests, see section 4-2. The column continued to move upwards and it was decided to terminate the test. In opposite to the other tests no increase in the water pressure occurred during this event, see Figure 4-12.

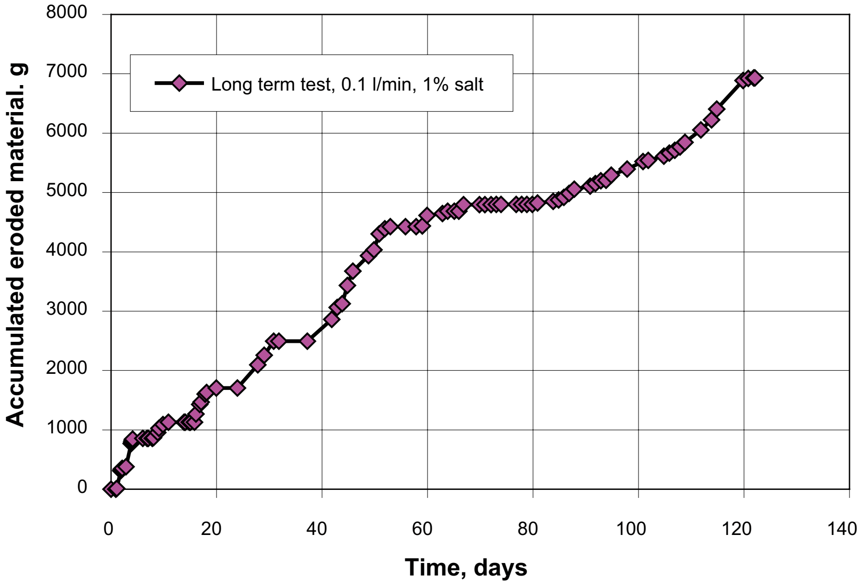

Figure 4-13. Accumulated amount of eroded material plotted vs. time.

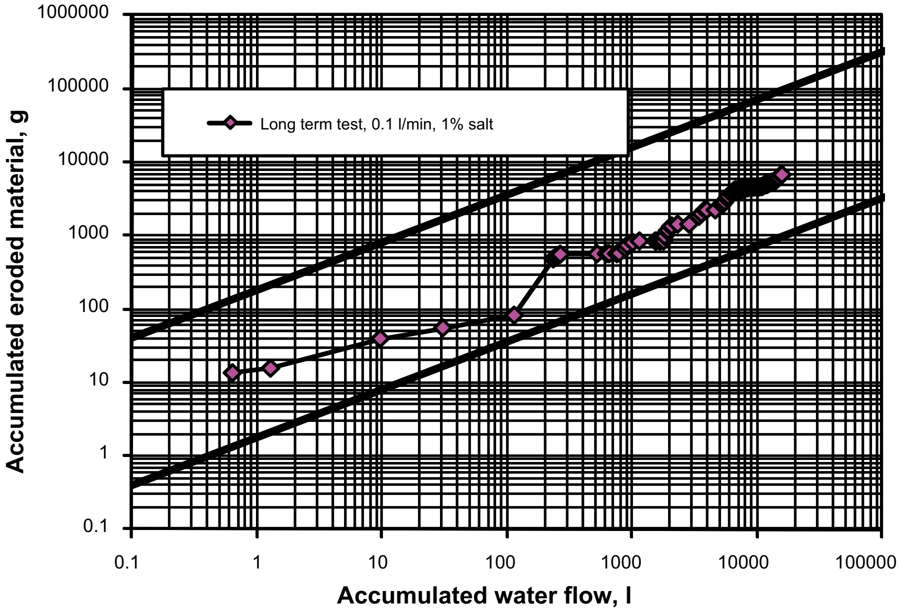

Figure 4-14. Accumulated amount of eroded material plotted vs. accumulated water flow in logarithmic scales.

Figure 4-15. *After 4 months test duration and measurement of erosion the pellets column rose about 100 mm during a weekend.*

4.4 Erosion and piping channels

In all tests performed in Plexiglas tubes it has been noticed that rather soon after test start almost all water was flowing in one main channel. It is actually possible to see and study how bentonite particles are eroded away with the flowing water in this channel, see Figure 4-16. After a certain time, the amount of particles decreases and it looks like almost clear water flowing in the channel. At some locations however, a residue consisting of more coarse grained particles, which are not flowing away with the water but whirls around at one position can be seen, see Figure 4-16. In the 4 meter high test described in section 4-2, about 8 to 10 whirls of this type could be seen along the test tube.

Samples of this coarse grained material were taken (from Test 4, described in section 4-2). The samples were used to perform two hydrometer analyzes in order to determine the grain size distribution. The results are shown in the diagram in Figure 4-18 together with the reference material. The diagram shows that there is a very clear difference in grain size distribution between the samples taken out from the "whirls" and the reference material. In the reference material 100% is finer than 0.05 mm while in the reference material the figure is about 75%. This means that parts of the finest material had eroded away leaving the coarser grained in the channel.

Figure 4-16. *In the beginning of a test it is possible to actually see the eroding material. All water seems to flow in one main channel.*

Figure 4-17. *Typical whirls with coarse particles that are not transported away with the flowing water.*

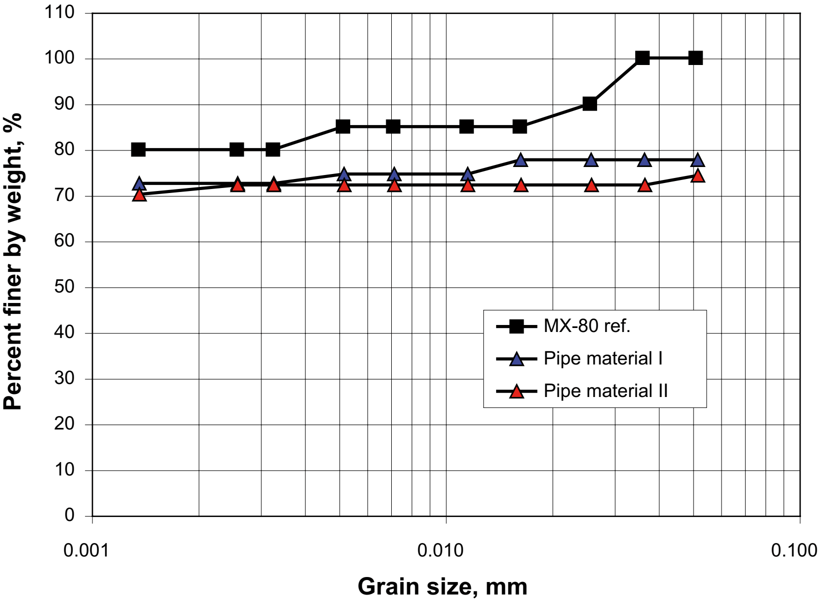

Figure 4-18. *Grain size distribution for the reference material and the two samples taken from the "whirl" material.*

4.5 Comments and conclusions

The results from the erosion tests with bentonite pellets can be summarized as follows:

- All results from the erosion measurements are well between the limits of the erosion model.
- Erosion rate in vertical direction i.e. in a deposition hole seems to be lower than in horizontal direction. The influence of gravity can be one explanation for this behaviour.
- The influence of test length on the erosion rate is still not known. The results are not conclusive and more tests are probably necessary. However, there does not seem to be a proportional relation between test length and erosion rate.
- The decrease in erosion rate by time, characterized by the constant $\alpha = 0.65$, continued also in the long term test (four months). This is an important factor in order to understand and calculate the loss or redistribution of material, during the installation phase.
- Piping channels are formed and they seem to stabilize by time i.e. all water is flowing in one channel.
- The fine material in a channel is washed out and there is a residue left with coarser grains.
- There is a principal problem that occurs at some parameter combinations. In the test tubes (plexiglas tubes with an inner diameter of 100 mm) and in the larger long term test equipment (d = 600 mm) arches were formed which sealed the flow channels. This sealing led to separation between pellets in a section. After a short time the water pressure could act on the whole cross section area and push the pellets column forward. This phenomenon is believed to be controlled by factors such as grain size distribution, size of the available voids and the geometry of the confinement. The phenomenon is not believed to appear in a full scale deposition hole, but needs to be further studied.

5 Scenario descriptions

5.1 General

Water inflow into the deposition hole and the deposition tunnel will take place mainly through fractures and will contribute to the wetting of the buffer and backfill. However, before full water saturation has occurred the inflowing water may cause detrimental effects on the buffer material especially in the case of large water inflow rates into a hole.

Some of these harmful effects have been investigated and were reported in Chapter 2 to 4. In this chapter the consequences will be analyzed and suggestions for handling will be given. The pellets filled slots in the deposition holes and in the tunnel cannot stop the water inflow due to the high water pressure, which means that water will continue to fill up the hole and also the tunnel until either a high swelling pressure or a high water pressure is formed that can prevent the water inflow.

An analyse of the processes related to water inflow into a deposition hole that may lead to unacceptable reduction in buffer density during the installation and water saturation phases has been done. There are mainly two processes that may be detrimental to the buffer. One of them occurs during installation before the backfill has been placed on top of the deposition hole. The water may cause a heave of the buffer blocks, which may cause unacceptably decrease in density of the buffer material around the canister. The other process is erosion that will take place when water flows out from the deposition hole into the tunnel in channels formed in the pellets filling.

Suggestion of allowable limits of such processes in terms of loss of bentonite will be made and the related inflow criteria that may lead to those consequences will be analyzed and suggested limits motivated.

Only problems with high water inflow rates into the deposition holes will be analyzed. Potential problems with drying in very dry rock are not treated.

5.2 Sequence of buffer and backfill installation and initial states

The buffer and backfill installation will take place in a well defined sequence according to the following schedule.

1. Before the backfill is placed the buffer blocks and the canister in all deposition holes in the entire deposition tunnel will be installed in the following way:
    a. Installation of buffer protection bag.
    b. Placement of bentonite bottom block and rings.
    c. Installation of the canister into the buffer.
    d. Placement of the upper buffer blocks and the upper two blocks of backfill material.
    e. Closing and sealing of the buffer protection bag.
2. When the installation in all deposition holes has been finished the backfilling will start. The backfilling will be made step wise with removal of buffer protection and filling of pellets in each deposition hole before the backfill is placed in the tunnel above the deposition hole:
    a. Removal of the buffer protection.
    b. Filling of pellets in the slot around the buffer blocks.
    c. Filling of pellets around the backfill blocks and in the bevelled floor.
3. Now the backfilling of the tunnel section located above the hole can be done:
    a. Placement of pellets on the floor.
    b. Placement of backfill blocks.
    c. Filling of pellets in the slot between the blocks and the rock surface.
4. The backfill is placed until about one meter from the next deposition hole after which the process continues with action 2 at the next hole.

The plan is to deposit one canister each working day which yields about 200 canisters per year. Depending on if one tunnel is filled at a time or if two tunnels are filled in parallel a backfilling sequence will take 1.5 or 3 days in average. Adding one day for unexpected events yields that the maximum time a deposition hole can stay open from the removal of the buffer protection until all backfill is placed is 4 days.

The layout of the tunnel and deposition hole and a possible situation, when the backfilling work will start after removal of the buffer protection, is shown in Figure 5-1.

If the water inflow is strong water will at first fill up the open pore space in the pellets filling both in the buffer and in the backfill before any significant amount of water is absorbed by the buffer or backfill blocks since there is no resistance against water flow in the pellets while the very low hydraulic conductivity in the blocks limits the water uptake rate in the blocks. Thus the volume of the open pore space available for water in the pellets filling is an important parameter.

Experiences from work with pellets filling show that the dry density of the filling will be about 1,000 kg/m^3.

$\rho_d = 1{,}000$ kg/m^3

$e = 1.78$ (void ratio)

$n = 0.64$ (porosity)

The porosity is thus 64% but some of this space is located in the pellet granules. A pellet granule has the following average properties:

$\rho_d = 1{,}980$ kg/m^3

$e = 0.40$

$n = 0.28$

which yields an average porosity of large pores between the pellets of about 50%.

The total pellets volume in the buffer part of the deposition hole is

$7.0 \cdot 0.06 \cdot 1.69 \cdot \pi = 2.23$ m^3, which yields an **empty pore volume of the deposition hole** (V_{pd}) available for inflowing water of about

$V_{pd} = 1.1$ m^3.

The total pellets volume in the tunnel is (assuming 300 m long tunnel and 40% pellets filling)

$300 \cdot 4.95 \cdot 4.5 \cdot 0.4 = 2{,}673$ m^3, which yields an **empty pore volume of the tunnel** (V_{pt}) available for inflowing water of about

$V_{pt} = 1{,}300$ m^3.

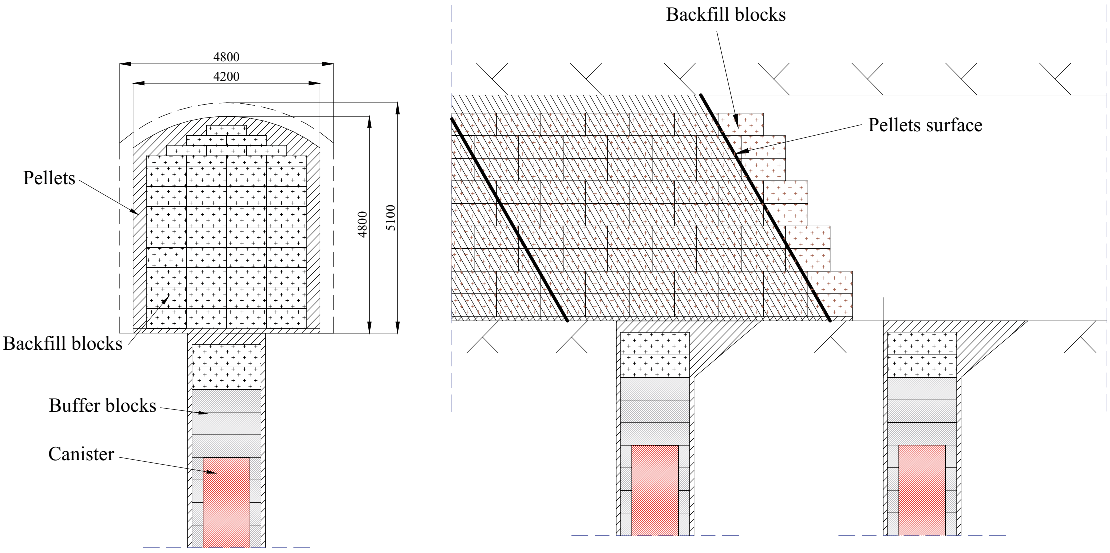

***Figure 5-1.** Reference layout of the repository and illustration of the progressed backfilling just after pellets filling of the next deposition hole.*

5.3 Processes and criteria related to water inflow into a deposition hole

5.3.1 General

There are some general understandings of how flowing water interacts with bentonite after installation at great depths that are very important for the behaviour of the buffer material in the deposition hole after exposure to the natural ground water inflow:

- The pellets filling can never stop the water inflow since the water pressure that will occur if the water inflow is stopped is in the order of several MPa and the swelling pressure of the pellets filling is only about 100 kPa.
- It will take several years for the buffer and even more for the backfill to generate a swelling pressure that is high enough to stop the water inflow. It has not been proven and is not sure that a large water flow can ever be stopped by self sealing of bentonite unless the high water pressure gradients that may occur at repository depth is reduced by a tight plug. The limit in water inflow rate, when the bentonite may self seal without the help from a tight plug, is not known. The limit is probably low and it is assumed in this report that all inflowing water enters the deposition hole or the tunnel.
- The consequence of this is that when a plug is built in the end of a deposition tunnel the pellets slots in both the deposition holes and the tunnel will be filled with water since the pellets cannot stop the inflow but new channels that distribute the water to empty parts will steadily be formed until the slots are filled with water. When the slots are filled the water pressure in the tunnel will start to rise and the hydraulic gradients will be taken by the plug instead of by the bentonite and the inflow will be strongly reduced.
- Since the pellets filling cannot stop the water inflow there will consequently be channels in the pellets filling leading out from the deposition hole to the tunnel.
- Numerous measurements of water flowing in channels in bentonite pellets or on the surface of bentonite blocks show that the discharging water contains bentonite collected on the way through the channels due to erosion. Water flowing in channels out from the deposition hole will thus transport bentonite from the deposition hole into the backfill.

5.3.2 Installation, water filling and water saturation periods

Installation of the engineered barriers and the subsequent water saturation can be divided into three different periods:

1. **Installation period**: Refers to the engineering work and includes the time until the tunnel has been backfilled and the plug is built and functions both hydraulically and mechanically.
2. **Water filling period**: Refers to the water filling of open spaces and includes the time after installation until the pellets filling in both the deposition holes and the tunnel is filled with water.
3. **Water saturation period**: Refers to the wetting of the buffer and backfill bentonite blocks and includes the time after installation until both the deposition holes and the tunnel have been completely water saturated.

These periods partly overlap each other. The water saturation period starts at the same time as the water filling period and both periods start during the installation period. The reason for the subdivision in these periods is that they concern different processes of the initial phase of the repository lifetime.

5.3.3 Critical processes caused by water inflow and criteria for allowable deleterious effects

General

Water inflow that affects the buffer material starts directly after removal of the buffer protection. However, since there is a radial slot between the bottom plate and the rock that extends about 0.1 m below the surface of the bottom plate, all water entering the hole before the pellets is placed is presumed to be collected in the slot so no free water will come in contact with the bentonite blocks.

When the pellets have been placed the inflowing water fills up the pellets filled slot in a way that depends on the water inflow rate, see Chapter 3. Tests made indicate that water flows downwards and fills up the pellets filling like a sand filling (or a bathtub) at water inflow rates larger than 0.1 l/min. At lower inflow rates the water filling is incomplete and at filling rates lower than 0.01 l/min the water flow will not fill up the entire slot but instead be sucked upwards and flow out from the deposition hole and there will still remain a large volume of unfilled pellets left in the hole. However, this behaviour seems to depend on the type of pellets used and on the homogeneity of the pellets filling. Complete understanding and models that allow full prediction of the water transport are not available but the water will start affecting the buffer blocks as soon as the water filling has started.

Upwards swelling of buffer blocks

When water enters the pellets it comes in contact with the blocks, which means that the bentonite blocks starts to suck water and swell. Since there is a period of up to four days until the backfill is placed and thus full weight from the backfill is applied there may be upwards swelling of the bentonite blocks that is not included in the buffer/backfill interaction modelled in SR-Site.

This process have been investigated, see Chapter 3, but the effects are not completely understood. If the heave takes place locally (let us assume that only one block of 0.5 m height is affected) a heave of one cm will yield the following loss in density:

Initial average void ratio: $e = 0.78$ (corresponding to $\rho = 2{,}000$ kg/m^3 at saturation)

1 cm expansion in 50 cm length yields the following increase in void ratio:

$\Delta e = (1+e)\cdot\Delta V/V = 1.78\cdot 0.02 = 0.036$

Resulting void ratio will thus be $e = 0.816$, which yields resulting density after saturation

$\rho = 1{,}980$ kg/m^3

With these assumption the average density will thus decrease from 2,000 kg/m^3 to 1,980 kg/m^3 over the deposition hole length 0.5 m. This seems to be acceptable and 1 cm will be used as criterion of allowable upwards swelling before completed installation of the backfill.

Erosion of buffer out from the deposition hole

Erosion of bentonite has been measured in many types of tests and an erosion model has been suggested (see Section 6.5) but where the erosion takes place is not known. It is probable that the eroded material is lost along the entire water flow channel according to some distribution and not in one point. However, due to lack of knowledge we will make the conservative assumption that all eroded material is taken from the inflow point at the rock surface.

When the water flow has been stopped and the erosion is finished the bentonite will swell and fill up the empty space but with a remaining inhomogeneity due to internal friction in the bentonite. This healing has been investigated with finite element modelling /Börgesson and Hernelind 2006/. One case that was investigated was the case that 130 kg bentonite had been lost in a half sphere. This is a severe case with an empty hole with all bentonite lost in a half sphere reaching with a radius 26 cm from the rock surface. Figure 5-2 shows the modelled healing of the hole plotted as contour lines of the swelling pressure at different times.

The results show that the homogenisation is far from complete and there is a strongly remaining reduced swelling pressure. However, there is enough bentonite to produce a swelling pressure higher than 1 MPa at two third of the distance between the rock and the canister. Since this case is probably conservative and since there still remains an acceptable swelling pressure the criterion of acceptable loss of bentonite from a deposition hole is suggested to be 100 kg.

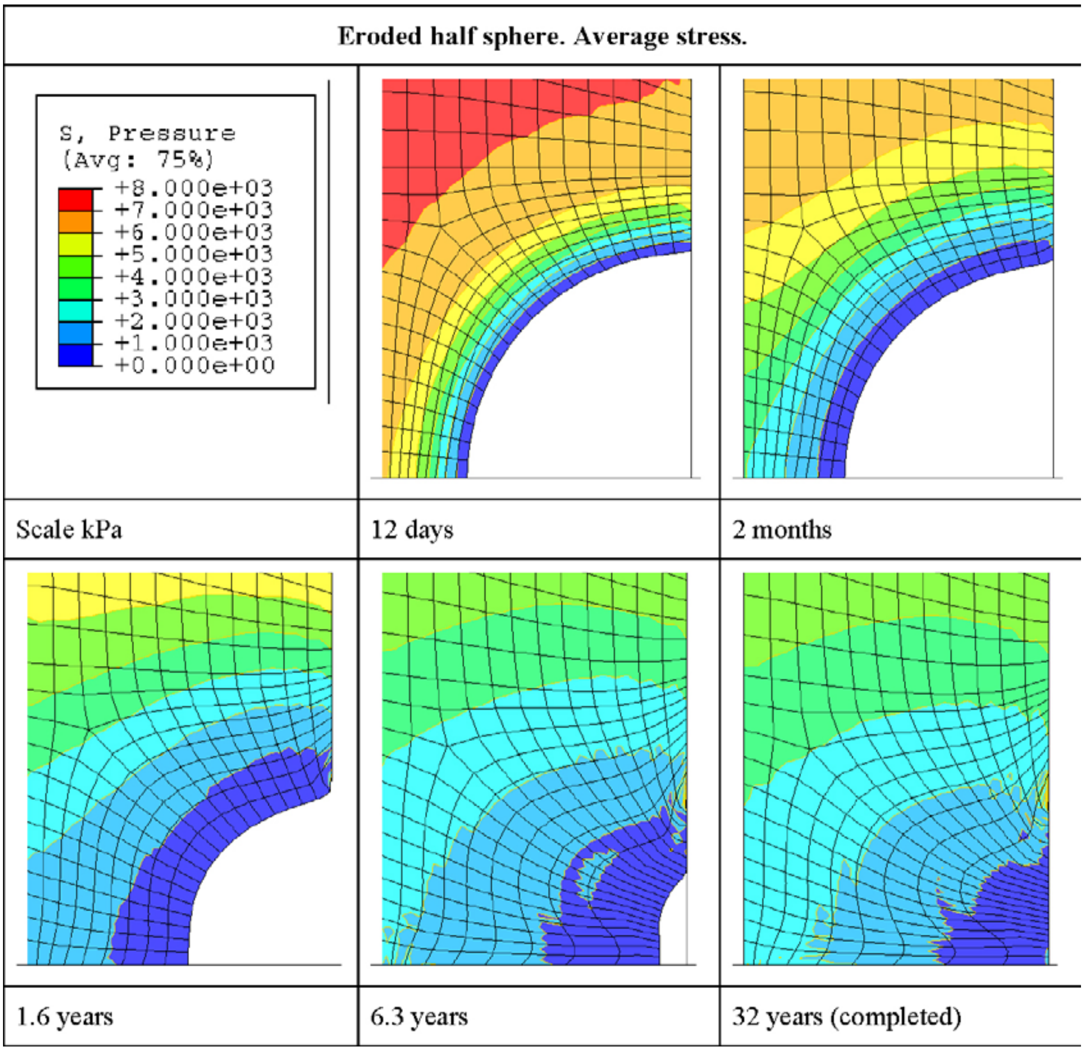

Figure 5-2. *Healing of an eroded half sphere. The left boundary represents the canister and the right boundary represents the rock surface. The swelling pressure (kPa) is plotted at different times. Water is supplied from only the hole.*

5.4 Upwards swelling of bentonite blocks caused by water inflow during the installation period

5.4.1 General

Upwards swelling of bentonite blocks have been observed both in field tests and in laboratory tests in different scales. Those observations are described in Section 5.4.2.

At the water inflow rate 0.1 l/min, with inflow located in one point, the water is likely to fill up the deposition hole from below. Since the empty pore volume of the deposition hole available for inflowing water is about 1.1 m^3 it will take 7–8 days to fill the buffer pellets. In four days about half the hole will thus be filled.

At the water inflow rate 1.0 l/min with inflow located in one point it takes only about 18 hours to fill the hole. Since water outflow from the deposition hole is undesired before completed backfilling the inflow 1 l/min. can thus not be accepted merely on this reason.

As concluded in sub-section 5.3.3 the allowable heave during the installation period before the backfill is placed is 1 cm.

5.4.2 Observed effects of water inflow

In the Canister Retrieval Test a heave of the buffer blocks of about 2 cm could be observed /Johannesson 2009/. The heave was caused by a waiting time of a couple of days that passed from the moment that water was artificially filled into the pellets slot until the moment that the plug above the deposition hole was placed and worked properly.

Laboratory tests for studying this process have been performed in two scales.. In the scale about 1:6 (diameter scaled 1:4 but slot scaled 1:1) a steel tube with the diameter 40 cm and height 60 cm was filled with bentonite blocks of LOT type with the diameter 30 cm. The remaining slot with the width 5 cm was filled with pellets. A copper tube was also installed in the central hole. Figure 5-3 shows a vertical cross section of the test setup and two photos (the tests are described in detail in Chapter 3).

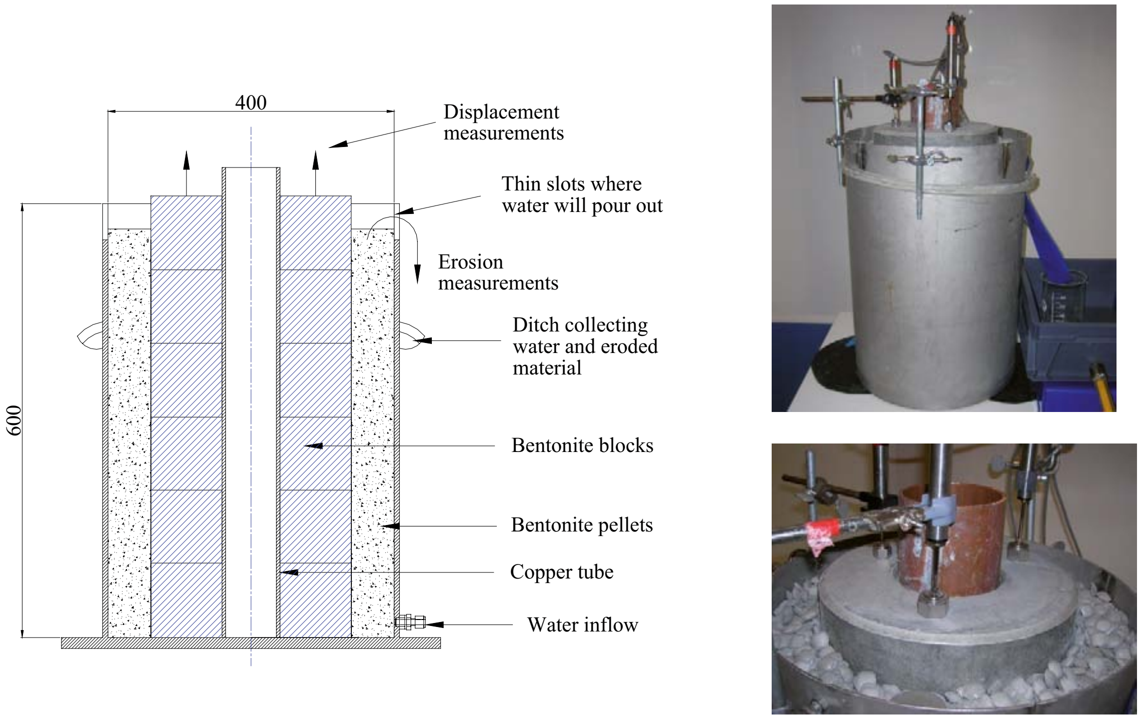

Figure 5-3. *Test setup and pictures of the equipment used for testing the effect of water inflow during the installation period.*

Tests with water inflow rates varying between 0.1 l/min and 0.0001 l/min were performed. The water inflow was located close to the bottom of the simulated deposition hole. The upwards movements of the block surface and the pellets surface was continually measured in three points each. One test with double height and one test with a load applied on the bentonite block surface were also made in order to study influence of these variables.

All tests resulted in significant heave of the bentonite blocks. After finished tests (1 week to three months) the equipment was dismantled and the bentonite carefully examined. The following important observations were done:

- The heave of the block pile was caused by cracking of the blocks due to local swelling at the block surface that led to dilating fractures inside the blocks.
- No swelling caused by water entering the joints between the blocks was observed. The original horizontal joints between the blocks were still intact.
- At water inflow rates 0.01 l/min and lower only parts of the pellets filled slot was water filled. Instead the water had moved upwards along the wall and at very low inflow rate only a small vertical column of pellets was wetted.

Figure 5-4 shows results from measured upwards displacement of the upper block.

Figure 5-4 shows that the displacement can be significant even within four days after start. If the test with Cebogel is excluded (not relevant due to water overflow) the resulting heave after four days is between 1.5 and 30 mm. There is an obvious influence of water inflow rate but the heave is far from proportional to the inflow rate. Even the low inflow rates 0.00125 and 0.0001 l/min provoke swelling. The reason that very low inflow also causes swelling is that water does not fill from the bottom but moves upwards, which means that all the bentonite blocks are affected although only partially.

Although the slot width is the same as in the deposition hole the total volume of the pellets filled slot is only a fraction of the actual volume. This scale effect must be considered when evaluating the results.

Tests have also been done in a test setup with full diameter and one meter height using two full bentonite blocks /Åberg 2009/. The inflow rates 0.1 and 0.01 l/min were used in these tests. The measured heave at those tests after four days was about 40% of the measured heave in the smaller scale.

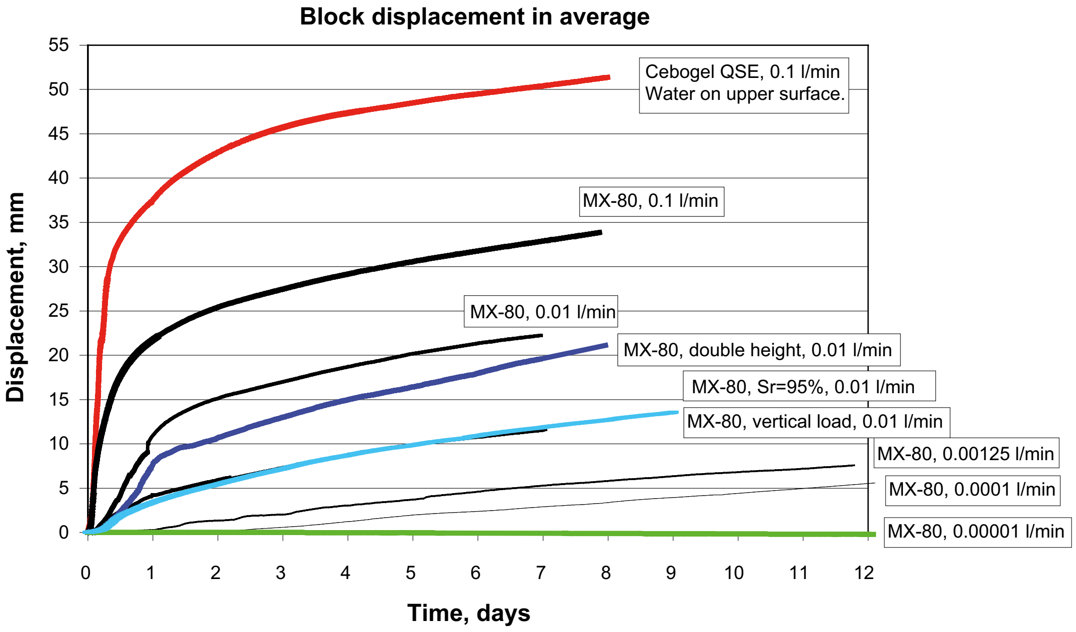

***Figure 5-4.** Measured upwards displacement in different tests. The legends show the water inflow rates applied and some alternative test conditions used.*

5.4.3 Allowable inflow

The results from the measurements of upwards swelling of bentonite blocks indicate that the heave is affected by

- Inflow rate.
- Surcharge load.
- Original water content in the blocks.
- Scale and geometry.

A preliminary conclusion of these tests is that an inflow of 0.1 l/min does not result in a heave larger than 1 cm in a deposition hole and that larger observed heave in the laboratory tests is caused by scale and surcharge load effects. It is thus concluded that 0.1 l/min can be accepted as an upper limit of water inflow into a deposition hole when the heave during the installation period before backfilling is considered.

This conclusion needs to be verified by tests in full scale.

5.5 Piping and erosion during the water filling period

5.5.1 General

The two basic premises for the second process that limits the allowable water inflow are as follows:

1. Since water inflow cannot be stopped, but piping always occurs with channel formation and subsequent erosion of bentonite in the channel, water inflow and erosion will continue until the empty space in the pellets fillings in the deposition holes and in the tunnel is water filled.
2. As a maximum 100 kg of bentonite is allowed to be lost in one point in the deposition hole.

Erosion will thus continue during the entire water filling period and this erosion may not bring more than 100 kg of dry bentonite out from the deposition hole.

In order to be able to estimate the amount of eroded material the erosion rate and the time or the water volume needed to fill the tunnel with water must be known.

5.5.2 Erosion model

A large number of erosion tests have been performed. Figure 5-5 shows some tests results with accumulated eroded mass plotted as a function of accumulated water flow in a double logarithmic diagram. All data is limited by two straight lines with the inclination corresponding to $\alpha = 0.65$.

An erosion model described by Equation 5-1 has been suggested /Sandén et al. 2008b/.

$$m_s = \beta \times (m_w)^{\alpha} \qquad (5\text{-}1)$$

where

m_s= accumulated mass of eroded bentonite (g)

m_w= accumulated mass of eroding water (g)

$\beta = 0.02–2.0$ = parameter defined by the level of erosion at a certain accumulated water flow

$\alpha = 0.65$ = parameter defined by the inclination of the straight line relation

$\alpha = 0.65$ yields a rather strong decrease in erosion rate with time and accumulated water flow. Constant erosion rate corresponding to $\alpha = 1.0$ is also illustrated in the figure.

α seems not very much affected by the test material or conditions and is according to the measurements a constant with the value 0.65.

β must be measured and seems mainly dependant on the material type, the salt content, the water ratio, the pellet grain size distribution and the geometry.

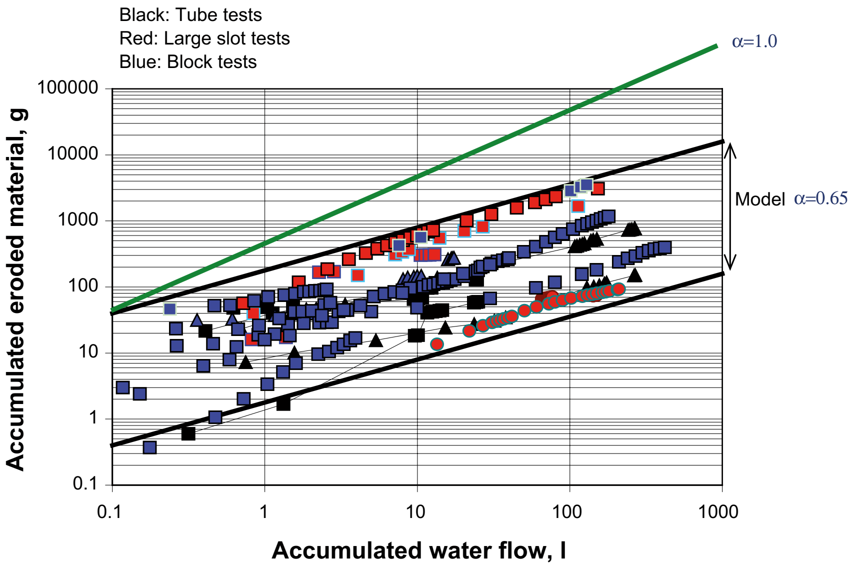

Figure 5-5. *All erosion results plotted in one diagram. The lower boundary line corresponds to $\beta = 0.02$ and the upper $\beta = 2.0$. The inclination corresponding to $\alpha = 0.65$ is motivated in the figure. $\alpha = 1.0$ (corresponding to constant erosion rate) is also illustrated.*

There is thus according to the model no influence of flow rate on the total amount of eroded material at a specified accumulated flow volume.

The new test series that have been performed see Chapter 3 and 4, simulating the erosion in a deposition hole that mainly takes place in vertical direction in pellets filling. Figure 5-2 shows results of those tests compiled in the same diagram together with the proposed model.

Figure 5-6 shows that the new measurements are embraced by the model and that it seems as the model can be further specified for the case of vertical flow in a pellets filling. All measurements fall inside a lower limit that is characterised by the values

$\beta = 0.02–0.2$

i.e. 10 times lower upper limit than the original model.

The long term test described in Chapter 4 was performed in order to verify the extrapolation of the relation illustrated in the figure, which is needed for the modelling.

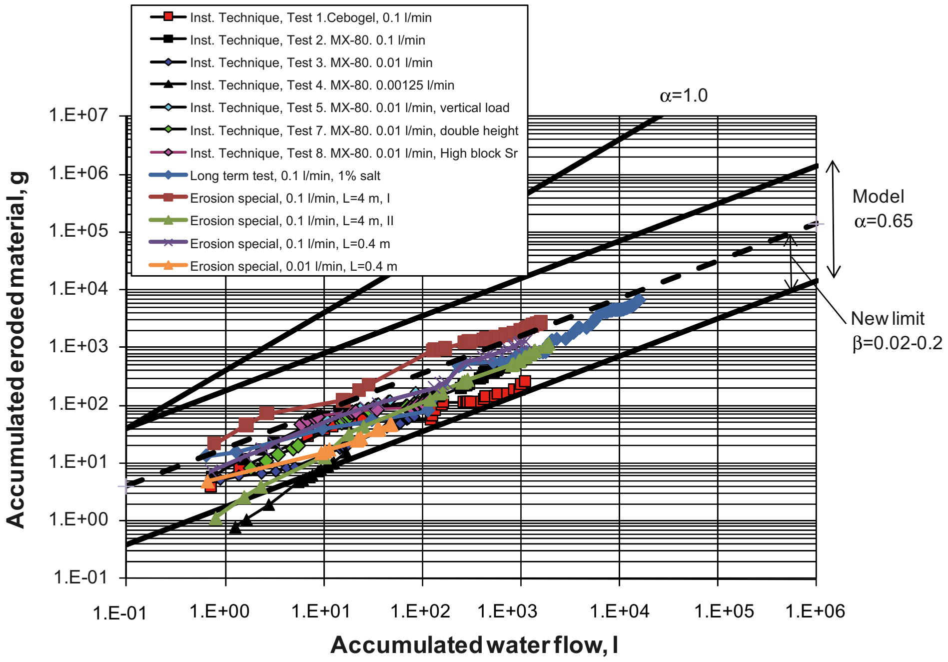

Figure 5-6. *New tests made with vertical flow in pellets filling and suggested revision of the model.*

5.5.3 Allowable inflow rate in a deposition hole

The erosion model can be used to study the effect of water flowing from a deposition hole out to the tunnel.

A total volume of about 1,250 $m^3 = 1.25 \cdot 10^9$ g water is expected to flow into the tunnel before it is filled with water and sealed including possible leakage through the plug. If all water comes from one deposition hole the eroding mass of bentonite will according to Equation 5-1 and $\beta = 0.02–0.2$ be

$m_s = \beta \cdot (1.25 \cdot 10^9)^{0.65}$ g = 16.4–164 kg bentonite,

which is more than 100 kg that is proposed to be the allowable limit of local loss of bentonite from one inflow point.

Equation 5-1 can be reformulated to yield the inflow that corresponds to a certain mass of eroded material:

$$m_w = \left(\frac{m_s}{\beta} \right)^{\frac{1}{\alpha}} \qquad (5\text{-}2)$$

m_s = 100 kg yields that the total water volume that may flow from the deposition hole to the tunnel is 586 m^3 or 47% of the total volume available.

However, since the limits of the β-value found for vertical erosion needs to be further verified it is conservatively proposed that the old limits ($0.02 < \beta < 2$) are used, which yields the volume 17 m^3 or 1.4% of the total volume. If further tests confirm the finding that $0.02 < \beta < 0.2$ for vertical flow the critical total volume of inflowing water can be increased considerably.

The limit is thus set so that when the available space in the pellets in both the tunnel and the deposition holes is filled with water only 1.4% of the water may come from any deposition hole, which is equivalent to that the inflow rate into the deposition hole may only be 1.4% of the total inflow rate.

5.6 Processes during the water saturation period

When the pore space in the pellets filling in the tunnel and the deposition hole has been filled with water the water pressure will start to increase and a water pressure gradient along the plug will be formed. Since the plug is presumed to be water tight there will be no more water flow in the channels in the pellets filling. Instead the channels will be partly sealed by swelling of the pellets although the low density does not yield a very good healing.

With time water will be absorbed from the pellets filling by the bentonite blocks in both the deposition holes and the tunnel. The pellets filling will be compressed by swelling blocks and the channels further healed. However, there are still water missing for complete saturation of the backfill and the buffer. About 450 m^3 water is missing in the backfill until full saturation, which constitutes about 25% of the total water volume required to saturate the backfill (450 m^3 + 1,300 m^3 = 1,750 m^3).

There is thus not much empty space left in the backfill after the water filling period. Since the hydraulic conductivity of the backfill blocks is very low and the water transport paths rather long it will take decades until the backfill is water saturated /Åkesson et al. 2010/. The water inflow into the tunnel will under those circumstances be very small and water pressure in the rock high, almost corresponding to hydrostatic.

Thus the deposition holes that have high water inflow rates will be water saturated well in advance of the backfill which means that there is a very small risk of continuing water flow from the deposition holes to the backfill after the water filling period. The conclusion is that there are no restrictions in hydraulic conditions of the deposition holes during the water saturation period after finished water filling.

6 Conclusions and comments

6.1 General

The tests described in this report were made in order to study the processes that will occur both during installation of buffer and canister but also during the time until the macro voids in the tunnel backfill have been filled with water. With the performed tests as a basis a number of scenario descriptions have been done. This chapter summarizes the main conclusions from the tests and scenario descriptions.

6.2 The effect of water inflow into a deposition hole

6.2.1 General

Tests have been performed in a test equipment simulating a deposition hole in scale 1:6 (the diameter was scaled 1:6 but the width of the pellets slot was in full scale). In addition to these tests, full scale tests (the diameter was full scale but the height was set to 1 meter) have been performed at Äspö HRL /Åberg 2009/.

The issue with erosion of bentonite has been investigated earlier. In order to increase the understanding some complementary tests have been performed investigating the specific issues how the erosion rate is influenced by the flow length as well as the time dependence.

6.2.2 Heaving

The results from the laboratory tests yielded the following conclusions:

- The heave depends mainly on the fact that the buffer blocks are cracking due to the high relative humidity in the water filled pellet filling.
- The influence of inflow rate is very clear; higher flow rates result in larger heave of the buffer blocks. This depends on the fact that the number of affected blocks is higher when the water flow rate is higher.
- Also with very small water inflow rates (0.00001 l/min) a displacement of the blocks could be measured due to local wetting along a pipe in the pellets as described in section 6.2.3. The rate of the movements was however very low.
- The movements decrease when an overload (other blocks or backfill) is applied at the top.
- Buffer blocks manufactured with high initial water content are more resistant against the wetting and the movements are smaller.

6.2.3 Wetting behavior of pellets

During dismantling of the laboratory tests it was noticed that the wetting behavior of the pellet fillings differed at the different inflow rates. The following influence of inflow rate could be seen:

- 0.1 l/min: The water filling starts from the bottom and all voids between pellets (macro voids) will be filled with water.
- 0.01 l/min. The water ascends along one side without affecting the opposite side. Only parts of the pellets filling will be wetted.
- 0.001 l/min. Only a very small part of the filling is wetted. The water flows upwards in a small channel only affecting the pellets close to the channel.

This difference in behavior for different water flow rates has an impact on the time until water can be expected to reach the top of the deposition hole. In a full scale deposition hole, where canister, buffer and pellets are installed, water that has reached the top will not leak out like in the performed tests, but will stay on the surface and affect the top of the uppermost block which then can swell freely. This effect limits the time until the backfilling above the deposition hole must be finished. With an inflow rate of 0.1 l/min the calculated time for water to reach the top surface is 7 days, since the pellet filling will be water filled from the bottom at that inflow rate (the volume of the macro voids in the pellet filling is about 1 m^3 and with this rate, the wetting behavior will lead to a complete filling of the available voids).

6.2.4 Erosion

The results from the erosion measurements can be summarized as follows:

- All results from the erosion measurements are well between the limits of the erosion model.
- Erosion rate in vertical direction i.e. in a deposition hole seems to be lower than in horizontal direction. The influence of gravity can be one explanation for this behaviour.
- The influence of test length on the erosion rate is still not known. The results are not conclusive and more tests are probably necessary. However, there does not seem to be a proportional relation between test length and erosion rate.
- The decrease in erosion rate by time characterized by the constant $\alpha = 0.65$, continued also in the long term test (four months). This is an important factor in order to understand and calculate the loss or redistribution of material, during the installation phase.
- Piping channels are formed and they seem to stabilize by time i.e. all water is flowing in one channel.
- The fine material in a channel is washed out and there is a residue left with coarse grains.
- There is a principal problem that occurs at some parameter combinations. In the test tubes (plexiglas tubes with an inner diameter of 100 mm) and in the larger long term test equipment (d = 600 mm) arches were formed which sealed the flow channels. This sealing led to separation between pellets in a section. After a short time the water pressure could act on the whole cross section area and push the pellets column forward. This phenomenon is believed to be controlled by factors such as grain size distribution, size of the available voids and the geometry of the confinement. The phenomenon is not believed to appear in a full scale deposition hole, but needs to be further studied.

6.3 Scenario descriptions

The processes related to water inflow into a deposition hole that may lead to unacceptable reduction in buffer density during the installation and water saturation phases have been analyzed. There are mainly two processes that may be detrimental to the buffer. One of them occurs during installation before the backfill has been placed on top of the deposition hole. The inflowing water will cause a heave of the buffer blocks, which may cause unacceptably decrease in density of the buffer material around the canister. The other process is erosion that will take place when water flows out from the deposition hole into the tunnel in channels formed in the pellets filling.

The criterion for acceptable heave of the buffer blocks has been set to one cm based on the reasoning in section 5.3.3 and the maximum allowable water inflow rate that causes such a heave within four days has been found to be 0.1 l/min. These conclusions should be confirmed in full scale.

The criterion for acceptable loss of bentonite in one spot in a deposition hole has been settled to 100 kg and the allowable inflow rate that limits the amount of eroded material from the deposition hole until the tunnel is filled with water has been found to be 1.4% of the total inflow rate into the entire tunnel.

The maximum allowable inflow into a deposition tunnel (on installation reasons) has earlier been settled to 10 l/min, which means that the second process of erosion overrules the first one since 1.4% of 10 l/min corresponds to 0.14 l/min. However, if ongoing measurements verify the suggested revision of the model the limit may be increased considerably.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Börgesson L, Hernelind J, 2006. Consequences of loss or missing bentonite in a deposition hole. A theoretical study. SKB TR-06-13, Svensk Kärnbränslehantering AB.

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Åkesson M, Kristensson O, Börgesson L, 2010. THM modelling of buffer, backfill and other system components. TR-10-11, Svensk Kärnbränslehantering AB.

Appendices

Appendix 1

Installation technique, Test 1

Layout: MX-80 block, Cebogel pellets in slot, water inflow: 0.1 l/min

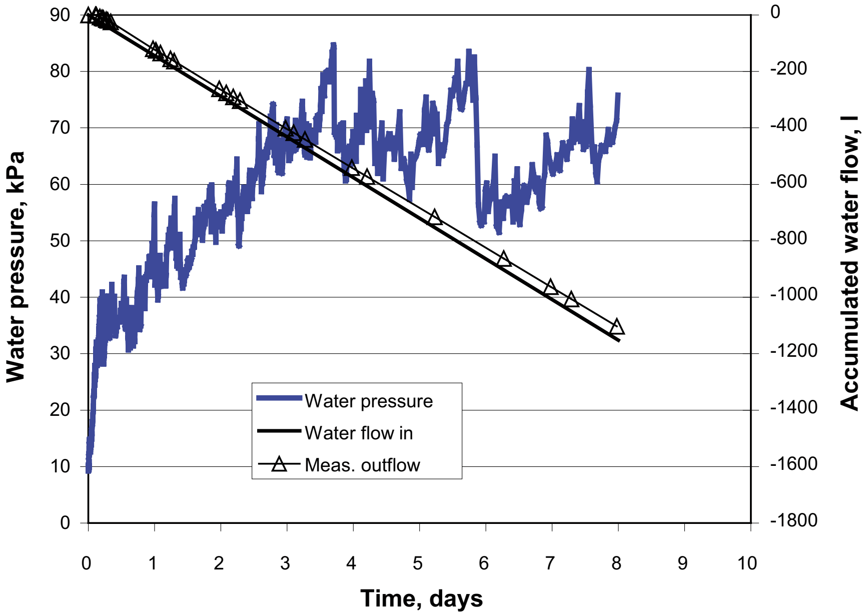

Figure A1-1. The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.

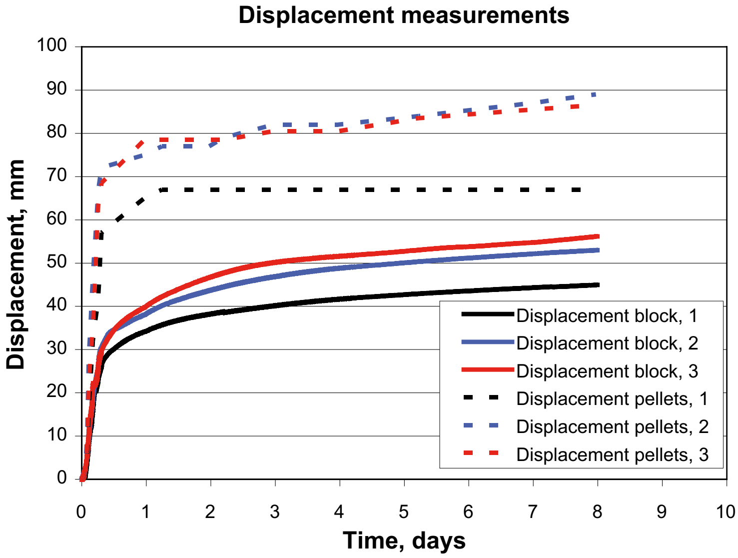

Figure A1-2. Displacement of block and pellets filling plotted vs. time.

Figure A1-3. Photo showing the upper surface of the test just before test start.

Figure A1-4. Photo showing the upper surface of the test after 24 hours. Water have poured out on the block surface and the bentonite have swollen.

Appendix 2

Installation technique, Test 2

Layout: MX-80 block, MX-80 pellets in slot, water inflow: 0.1 l/min

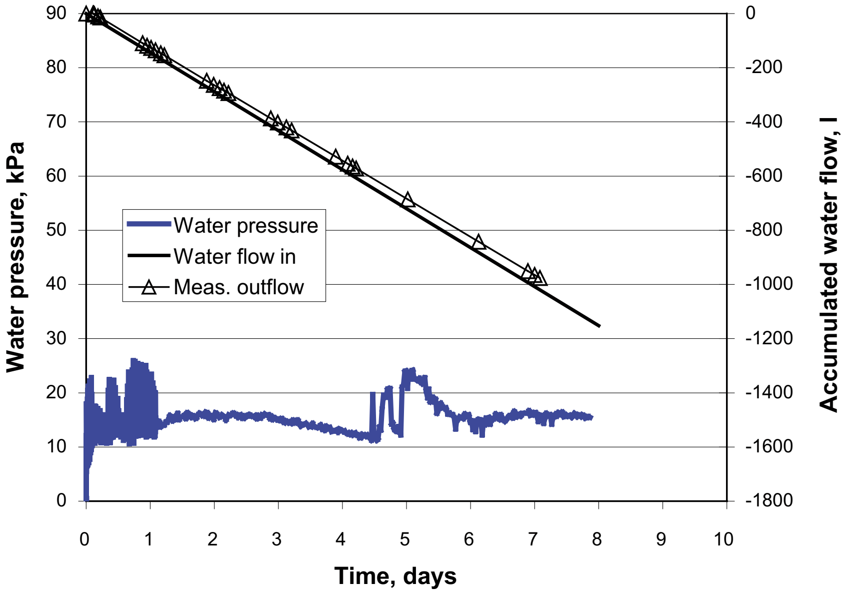

Figure A2-1. The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.

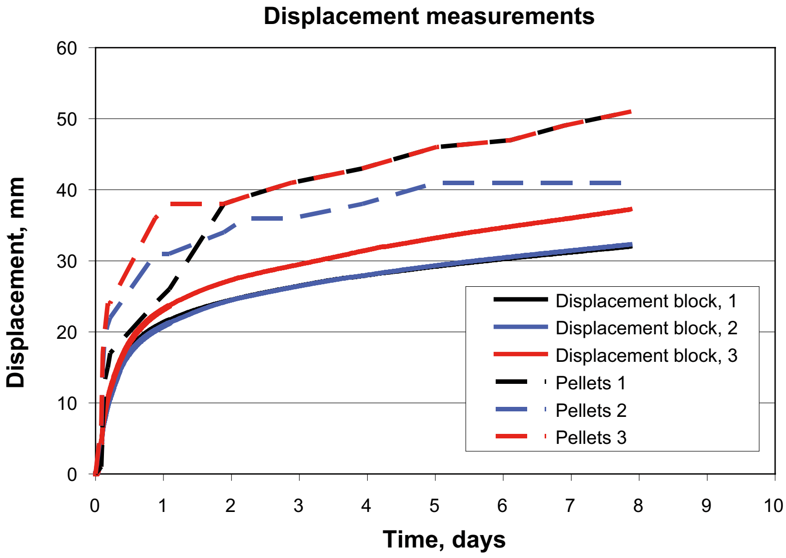

***Figure A2-2.** Displacement of block and pellets filling plotted vs. time.*

__Figure A2-3.__ Photo taken during excavation. The surface between the blocks is still dry but the pellets are completely wetted.

__Figure A2-4.__ Photo taken during excavation. The large cracks in the blocks are very clear.

Appendix 3

Installation technique, Test 3

Layout: MX-80 block, MX-80 pellets in slot, water inflow: 0.01 l/min

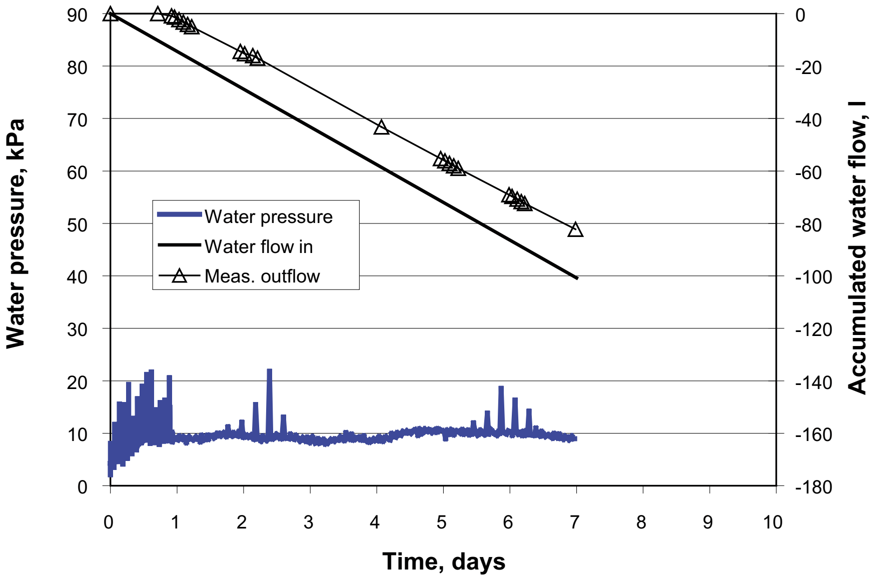

Figure A3-1. The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.

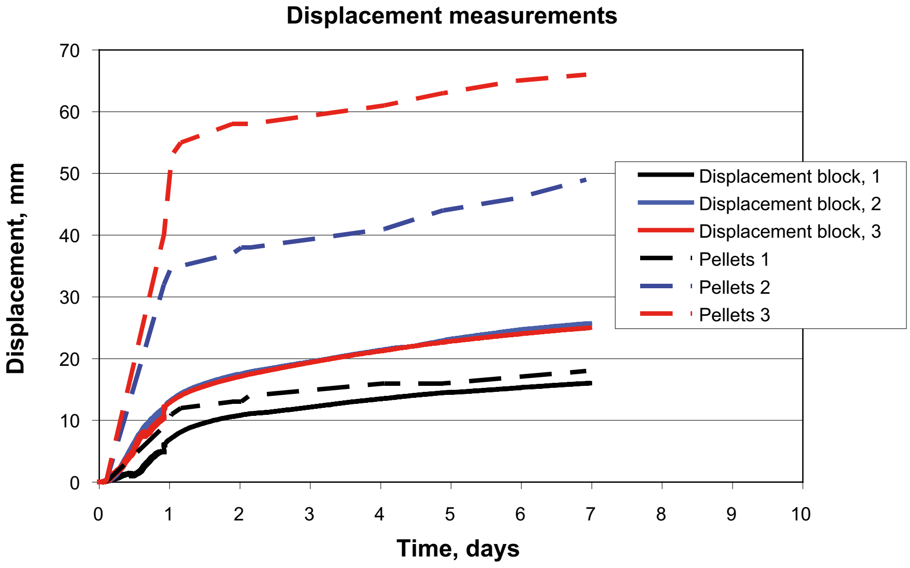

Figure A3-2. Displacement of block and pellets filling plotted vs. time.

Figure A3-3. Photo taken during excavation. The surface between the blocks is still dry and it is only parts of the pellets filled slot that is wetted.

Figure A3-4. Photo taken during excavation. The large cracks in the blocks are very clear.

Appendix 4

Installation technique, Test 4

Layout: MX-80 block, MX-80 pellets in slot, water inflow: 0.001251 l/min

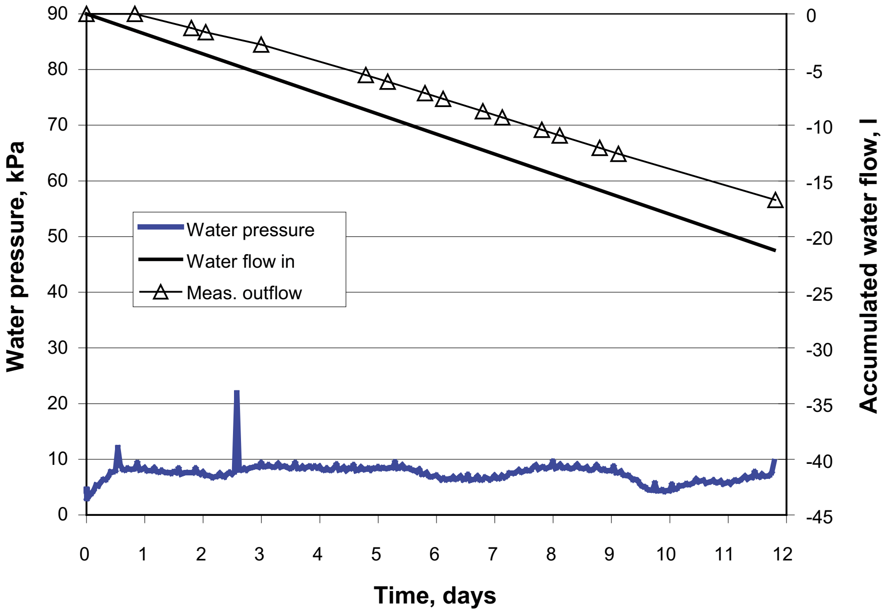

Figure A4-1. The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.

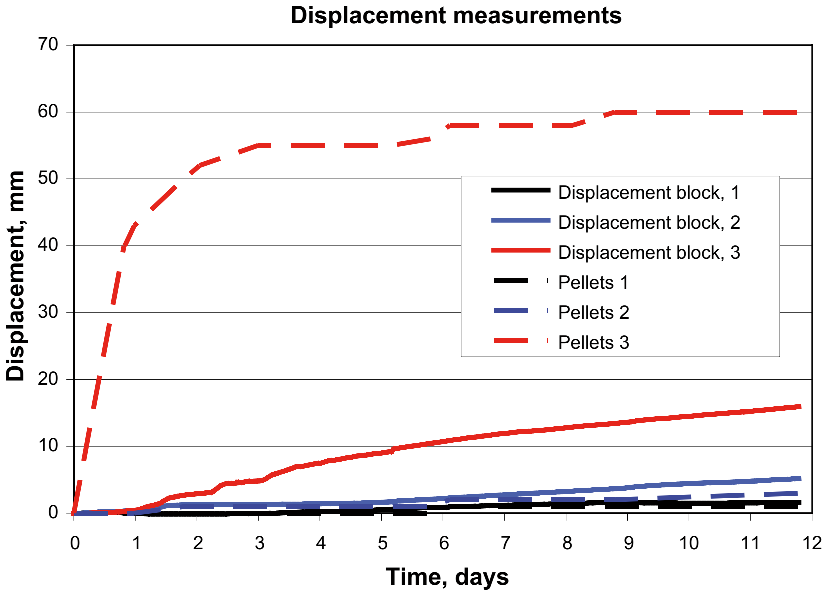

Figure A4-2. Displacement of block and pellets filling plotted vs. time.

Figure A4-3. Photo taken just before terminating of the test. The upper block and pellets are strongly influenced by the water flow.

Figure A4-4. Photo taken during excavation. The water have been flowing from the inflow point up along the wall, only influencing a small part of the pellet filling.

Installation technique, Test 5

Layout: MX-80 block, MX-80 pellets in slot, water inflow: 0.01 l/min, vertical load

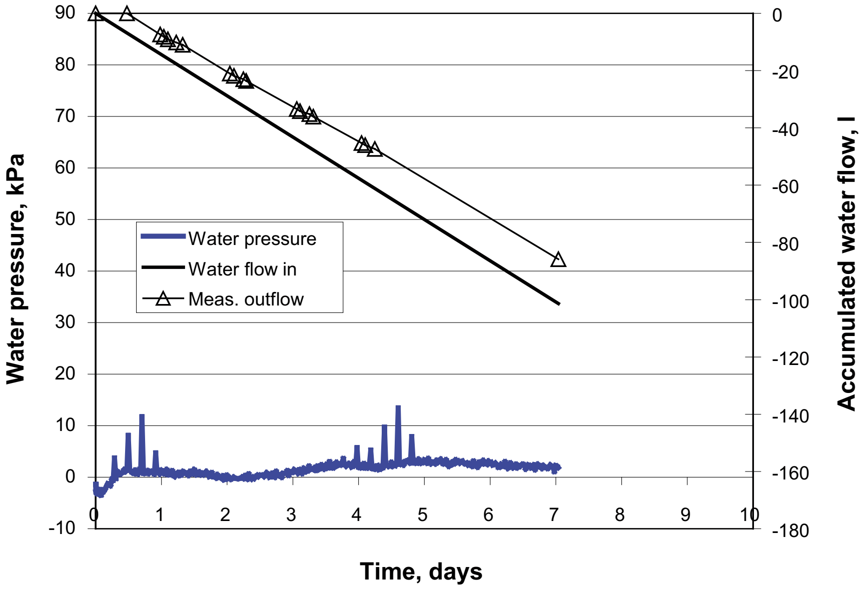

Figure A5-1. The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.

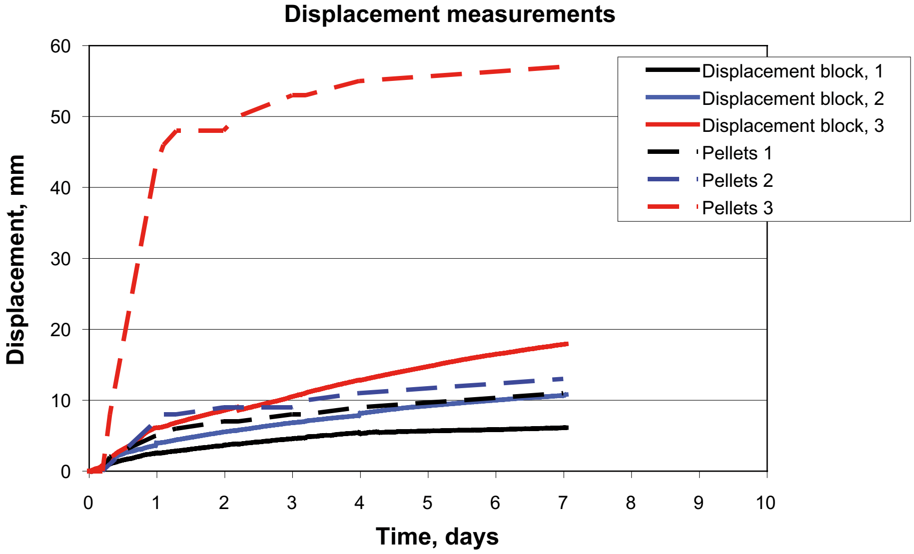

Figure A5-2. Displacement of block and pellets filling plotted vs. time.

Figure A5-3. *Overview of the test layout. Weights are placed on yhe top of the bentonite blocks simulating an overload of 40 kPa.*

Figure A5-4. *Photo taken during excavation. The pellet filling is only partly wetted. There are large cracks in the blocks, mainly on the half closest to the wetted pellets.*

Installation technique, Test 6

Layout: MX-80 block, MX-80 pellets in slot, water inflow: 0.0001 l/min

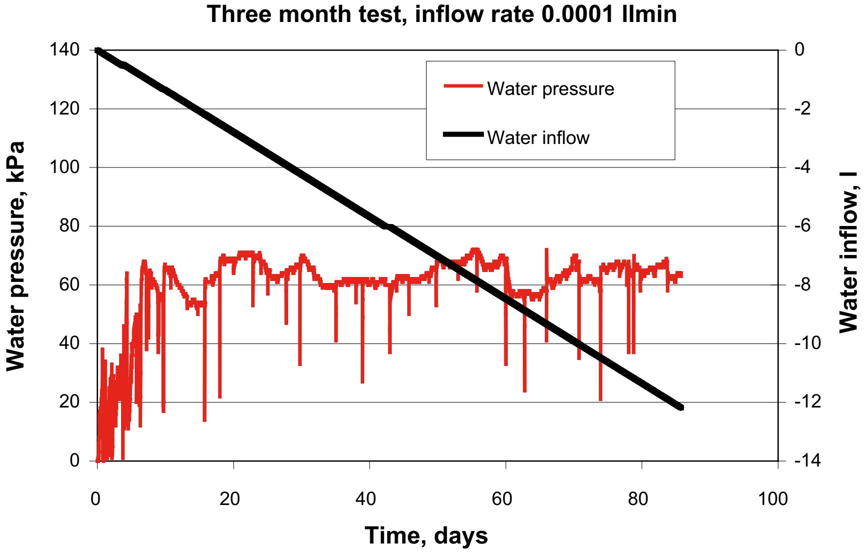

Figure A6-1. The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.

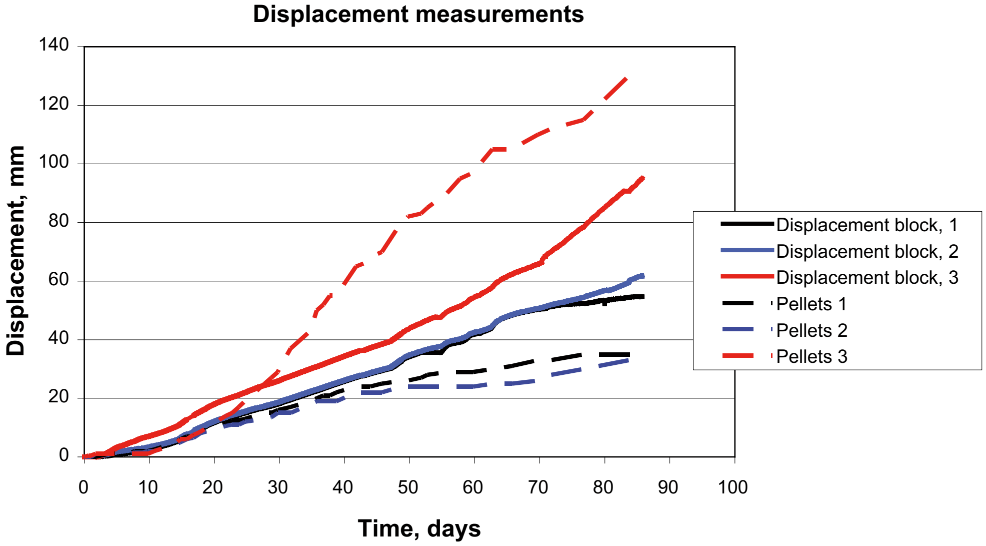

Figure A6-2. Displacement of block and pellets filling plotted vs. time.

Figure A6-3. *After three months test has the uppermost block tilted strongly.*

Figure A6-4. *Photo taken during excavation. The large cracks in the blocks are very clear. Only parts of the pellet filling is wetted.*

Appendix 7

Installation technique, Test 7

Layout: MX-80 block, MX-80 pellets in slot, water inflow: 0.01 l/min, double height

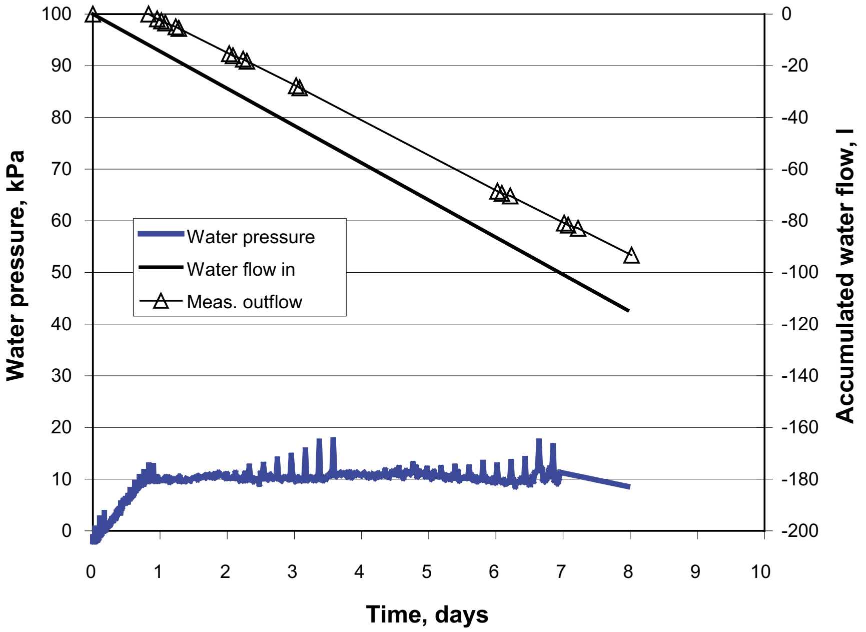

Figure A7-1. *The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.*

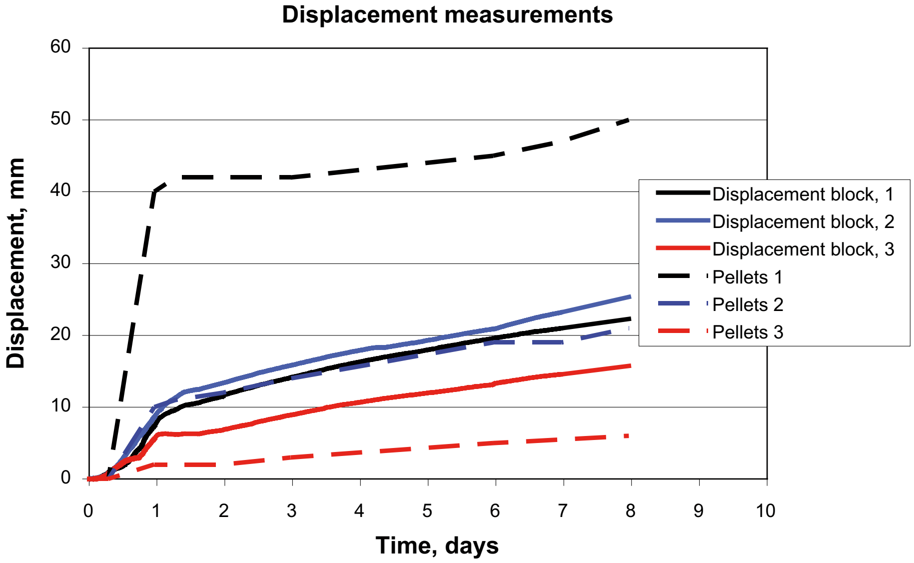

Figure A7-2. *Displacement of block and pellets filling plotted vs. time.*

Figure A7-3. Photo showing the test layout of test 7. To the right in the picture can test 6 be seen.

Figure A7-4. Photo taken during excavation. The large cracks in the blocks are very clear.

Appendix 8

Installation technique, Test 8

Layout: MX-80 block, MX-80 pellets in slot, water inflow: 0.01 l/min, w block = 24%

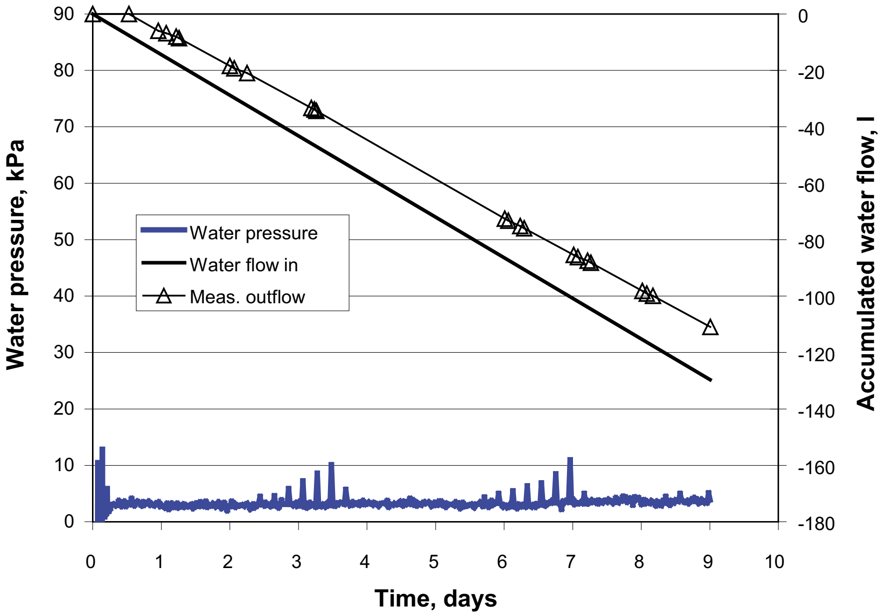

Figure A8-1. The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.

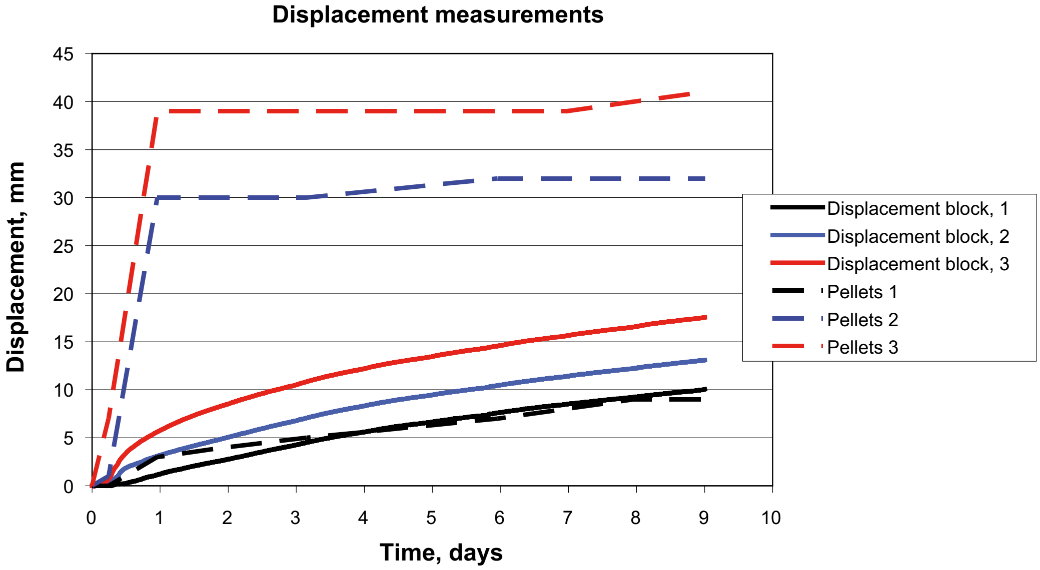

Figure A8-2. Displacement of block and pellets filling plotted vs. time.

Figure A8-3. *Photo taken during excavation. The pellets filling is only partly wetted. The blocks are almost unaffected of the water and major cracks can be seen.*

Figure A8-4. *Photo taken during excavation. The movements of the blocks have been made by the pellets which have "grabbed" the block surface.*

Appendix 9

Installation technique, Test 9

Layout: MX-80 block, MX-80 pellets in slot, water inflow: 0.00001 l/min

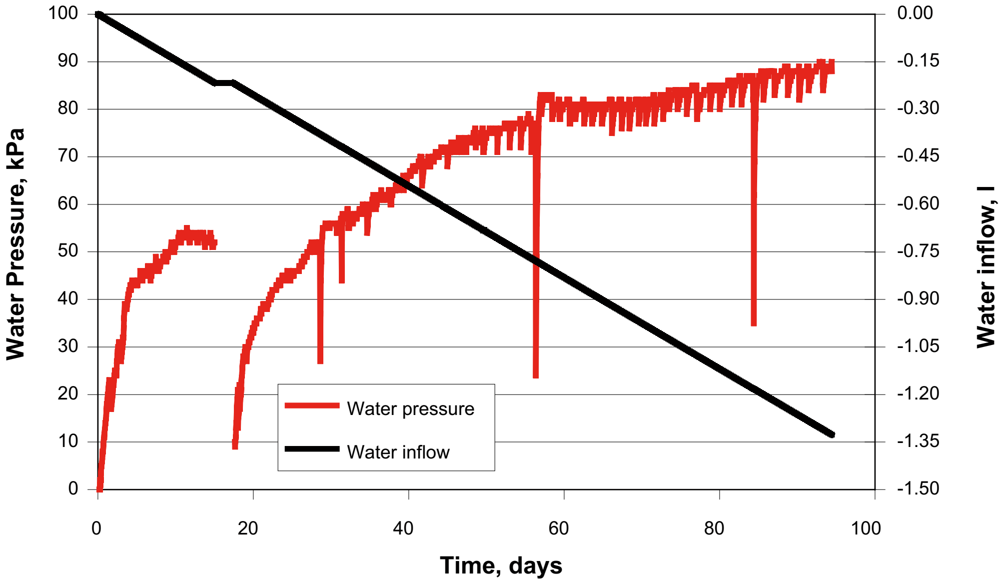

Figure A9-1. *The applied water inflow, the measured flow out from the test and the measured water pressure plotted vs. time.*

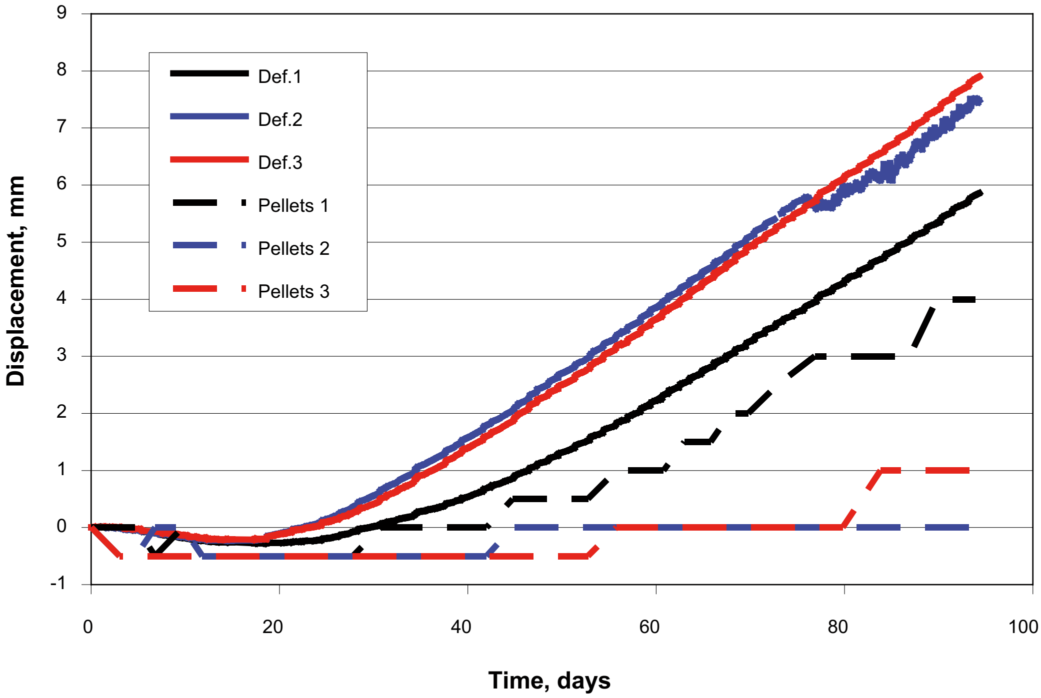

Figure A9-2. *Displacement of block and pellets filling plotted vs. time.*

Figure A9-3. *The second block from the bottom. One part is affected of water and has swollen 4–5 mm (block thickness). The block has cracked opposite the water inlet.*

Figure A9-4. *Picture showing the bottom block. Only a small part of the pellets are affected of the water. The block has cracked diametrically.*

Appendix 10

Pellets erosion, Test 1. Flow rate: 0.01 l/min, flow length: 0.4 m

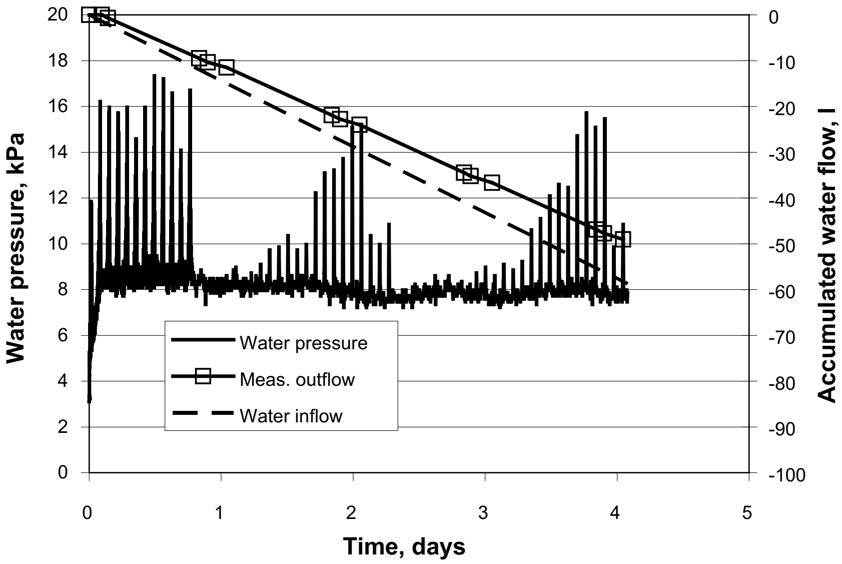

Figure A10-1. *Water pressure, water inflow and measured outflow plotted vs. time.*

Figure A10-2. *The water is flowing in a channel.*

Appendix 11

Pellets erosion, Test 2. Flow rate: 0.01 l/min, flow length: 4 m

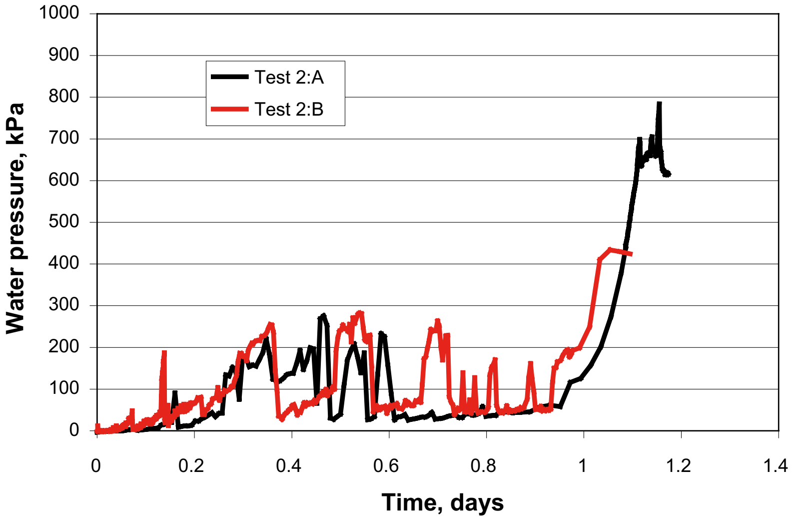

***Figure A11-1.** Counter pressure build up during the tests plotted vs. time.*

***Figure A11-2.** The bentonite separates and the water pressure can act on the whole cross section area, pushing the bentonite upwards.*

Appendix 12

Pellets erosion, Test 3. Flow rate: 0.1 l/min, flow length: 0.4 m

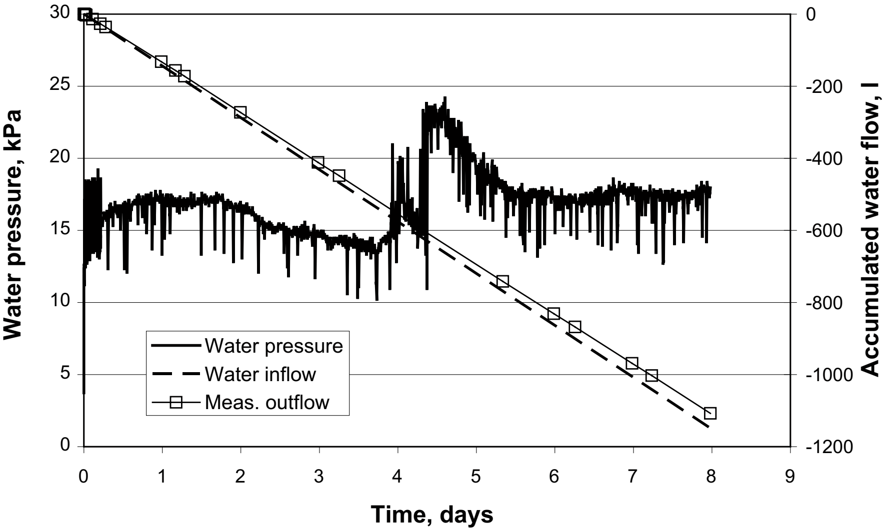

Figure A12-1. Water pressure, water inflow and measured outflow plotted vs. time.

Figure A12-2. In the beginning of the test it is possible to see how material is transported in the channel formed by the flowing water.

Appendix 13

Pellets erosion, Test 4. Flow rate: 0.1 l/min, flow length: 4 m

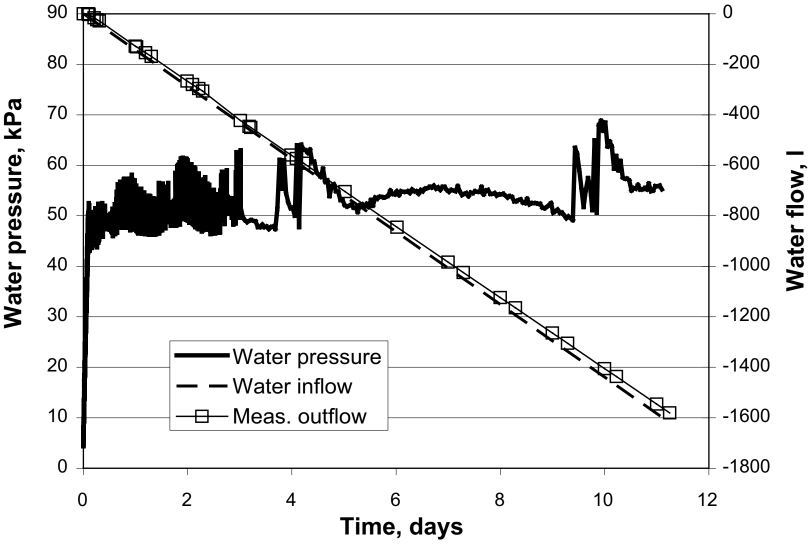

Figure A13-1. Water pressure, water inflow and measured outflow plotted vs. time.

Figure A13-2.

Appendix 14

Pellets erosion, Test 5. Flow rate: 0.1 l/min, flow length: 4 m

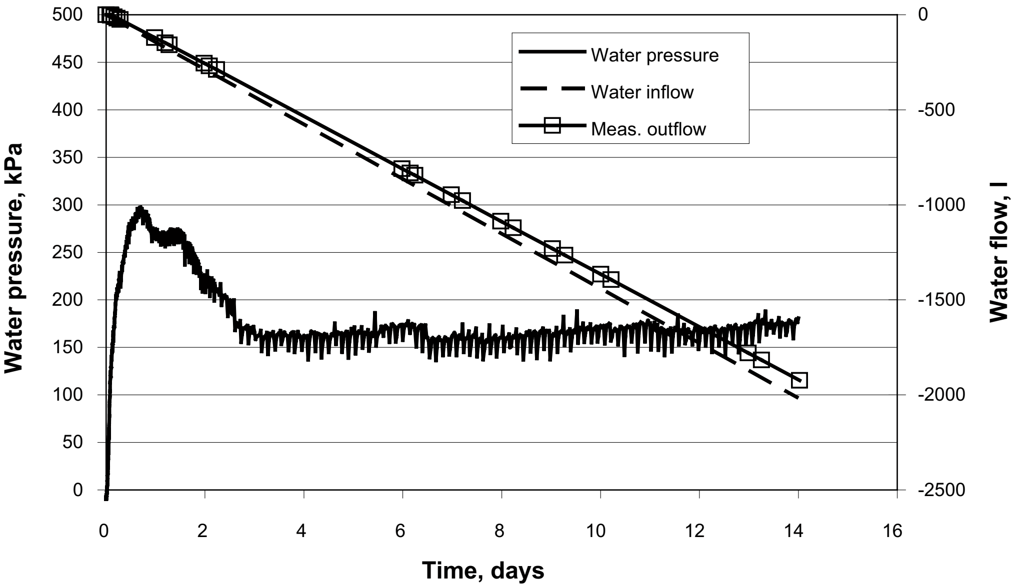

Figure A14-1. Water pressure, water inflow and measured outflow plotted vs. time.