R-08-132

Deep repository – engineered barrier systems

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Abstract

In order to examine the behaviour of water entering a section of tunnel that had recently been backfilled using a combination of bentonite pellets and compacted, smectitic clay blocks, a series of large-scale tests have been completed. These tests, done at a scale of approximately ½ that of an emplacement tunnel were completed in a mock-up constructed in the Buffer Laboratory at SKB's Äspö Hard Rock Laboratory. A total of 12 tests, undertaken under well-controlled conditions were completed, examining the effects of inflow rate, inflow location and time on assemblies of blocks and pellets.

Water was supplied to the assembly at rates ranging from 0.1 to 2.5 l/min and the time for water exit, the exit location, potential for erosion of backfill, the rate of water uptake and resistance of the assembly to water influx were all monitored for periods of 3 to 7 days. The testing time was selected to simulate a reasonable duration for unanticipated backfilling interruption. Longer durations were not necessary and risked both the stability of the system and the loss of the early-stage conditions through progression of swelling and homogenization.

Testing determined that initial water movement through backfill is largely controlled by the pellets. Water influx of up to 30 l/h at a single location was diverted by the pellets forming essentially horizontal flow channels (pipes) along the chamber wall – pellet interface. These piping features directed the majority of the incoming water around the backfill and towards the unconfined downstream face of the assembly. The time required for the water to exit the assembly was dependant on a combination of inflow rate and distance that it needed to travel. Water typically exited the face of the backfill at well-defined location(s) and once established, these features remained for the duration of the test. The exiting water typically carried only limited eroded material but could cause some disruption of the downstream face of the backfill as it flowed out of the assembly. Longer duration tests (7 days) or those with very long flow paths initially set close to the crown of the chamber show a tendency for the flow to shift to the uppermost regions of the backfilled chamber.

At point-source inflow rates exceeding approximately 30 l/h the risk of developing undesirable internal flowpaths or erosive flow through the pellet fill increased. At point inflow of 150 l/h, the system experienced extensive and ongoing erosion of the pellet-fill portion of the backfill near the downstream face. Despite disruption at the front face, the backfill did not undergo substantial internal damage during the 3 days of test operation.

The measured rate of piping feature advance indicates that in order to backfill at a rate of 8 m/day and avoid water influx from a previously backfilled volume entering the excavation at substantial rates, the total influx along a single discrete piping feature cannot be more rapid than about 0.5 l/min (30 l/h). This value is not necessarily conservative, as it does not take into account the stepwise nature of backfilling.

Sammanfattning

En serie storskaliga experiment har gjorts för att utreda funktionen hos vatten som strömmar in i ett tunnelavsnitt som just återfyllts med användning av staplar av kompakterad smektitlera kringfyllda av bentonitpellets. Experimenten, som utförts i halv skala jämfört med en deponeringstunnel i slutförvaret, genomfördes i ”Buffertlaboratoriet” i SKB:s Hard Rock Laboratory på Äspö. Totalt gjordes 12 experiment under väl kontrollerade förhållanden för att undersöka verkan på blockstaplar och pelletfyllning av inflödeshastighet, läge hos inflödespunkterna och tid efter inflödesstart.

Vatten tillfördes återfyllningen med en takt av 0.1 till 2.5 l/min och tiden och platsen för utströmning samt motståndet mot inströmning (tryckuppbyggnad) mättes liksom också tidsförloppet hos vattenupptagningen under 3 till 7 dagar. Försökstiden valdes med hänsyn till möjlig fördröjning av återfyllningsarbetet. Längre varaktighet var inte nödvändig och kunde riskera stabiliteten hos försöksanordningarna och ändring av försöksbetingelserna som följd av successiv svällning och homogenisering av återfyllningen.

Försöken visade att vattnets rörelse genom massan inledningsvis kontrollerades av pelletfyllningen. Inflöde av upp till 30 l/timme i enskilda punkter gav kanalströmning hos vattnet utmed kontakten mellan cellvägg och pellets. Dessa kanaler var orsakade av piping och ledde huvuddelen av vattnet runt återfyllningen till den fria framänden hos fyllningsmassan. Tiden för framträngning av vatten bestämdes av en kombination av inströmningshastighet och strömningslängd. Utströmningen ägde rum i enskilda, tydliga punkter som när de en gång utbildats fanns kvar under respektive försök. Det utströmmade vattnet innehöll endast små mängder eroderat material men kunde ge viss förändring där det lämnade fyllningen. Längre försökstider (7 dagar) eller försök innebärande långa flödesvägar gav en tendens till ändring av riktningen hos flödet mpt återfyllningens översta del.

Vid punktvis inflöde av mer än ca 30 l/timme ökade risken för utbildning av oönskade inre flödesvägar och erosivt flöde genom pelletfyllningen. Vid mer än 150 l/timme undergick systemet omfattande och fortskridande erosion av pelletfyllningen där utströmning skedde. Trots denna störning vid utflödet genomgick hela återfyllningen inga omfattande förändringar under 3 dagars försökstid.

Den uppmätta tiden för pipingbildning visar att inflödet från enskilda punkter inte får överskrida 0.5 l/min (30 l/timme) för att medge en återfyllningstakt av 8 m/dag. Detta inflöde är inte nödvändigtvis konservativt eftersom hänsyn inte är tagen till det stegvisa utförandet av återfyllningen.

Contents

1 Background

The sealing of a repository for used nuclear fuel requires the installation of backfill in the rooms, tunnels, shafts and other openings. This material has a number of functional requirements, including having the ability to take on water from the surrounding rock and subsequently swell to produce a material that is of adequately low permeability. It must also evolve such that there are no persistently open pathways for water flow once the repository is closed and local groundwater conditions are re-established. One of the emplacement room and access tunnel backfilling option being considered by SKB and Posiva is the installation of precompacted blocks of clay-based material into the majority of the tunnel volume and then use clay pellets or granules having a high swelling capacity to fill the spaces where blocks cannot be installed (space between blocks and tunnel walls/roof). These pellet or granules would also be installed on the tunnel floor to produce a level surface for subsequent block placement.

The installation of backfill composed of blocks and pellets has a number of potential challenges, particularly with regards to initial system stability under conditions of localized water influx. The presence of substantial water influx, especially when localized, makes placement of the backfilling materials difficult and in extreme cases such influx may cause localized erosion of the backfill and loss of mechanical stability. Given these issues it is important to gain an understanding of how water will move into (and through) the backfill in the period immediately following its installation. Of particular concern is a need to determine the time between material installation and when inflowing water can be expected to exit the face of the backfilled volume. This provides an indication of the time available between interruption of backfilling operations and water exiting the working face of the backfill where it may influence installation operations and material stability.

This study is a progression from smaller-scale tests done at Äspö during 2006 and 2007 /Dixon et al. 2008ab/. In those tests the manner in which water entered and was distributed within a volume of backfill installed into a chamber geometry similar to that proposed for tunnels and rooms in the KBS-3H concept was examined. They provided some important general behavioural patterns which if confirmed in tests done at scales closer-to or at tunnel dimensions indicate that it will not be possible to rely on the pellet fill to substantially delay water transport during the operational phase of backfilling. The tests described in this document are a substantial up-scaling (to ½ tunnel-dimension) of earlier tests and contain pellet filled gaps and emplaced densities that are representative of what might be installed in an emplacement tunnel of a KBS-3V-type repository.

2 Objectives

This study is intended to examine the water uptake and transport behaviour of a ½-scale KBS-3V emplacement tunnel mock-up that has been backfilled using precompacted and simulated backfill blocks and bentonite pellets. In these tests, the effect of varying water influx rate from a point source on the backfilled tunnel section is examined. Previous work done at smaller scale /Dixon et al. 2008ab, Sandén et al. 2008/ showed that most of the early hydraulically-important responses of the backfilled volume are likely controlled by the pellet fill. Rather than being able to take on a considerable volume of water before clay pellet swelling occurs, the clay pellets respond quite rapidly to the inflowing water. The result of this is rapid development of a low-permeability region of pellets immediately adjacent to the inflow point. With this comes the formation of preferential flow path(s) along the ”rock” – pellet contact. Water moves rapidly toward the front face of the system where it exits. At a distance of 0.6 m from the inflow point to the front face of the test cells, outflow typically took only hours to develop and then nearly the full volume of inflow is rapidly and effectively transported from the inflow point to the front face of the test. As a result of these earlier findings, the tests described in this report mainly focus on the pellet-fill component, with less importance attached to the block materials.

In a few cases in previous tests inflowing water was able to develop a flow path through the relatively loose pellets into the clay blocks, resulting in considerable erosion of the block materials /Dixon et al. 2008a/. This is a highly undesirable situation but may have been the result of the very small thickness of pellets installed in these tests (~ 0.1 m) which gave opportunity for inflowing water to reach the blocks before swelling of the pellets occurred and could thereby kept an open flow path. In the ½-Scale tests the width of the pellet filled region and density achieved during their installation are more representative of what is believed achievable in an emplacement tunnel. The time and manner in which water moved into and through the ½-Scale test can therefore be compared to the behaviour recorded at smaller scales and general behavioural models further developed.

While the ½-Scale tests are much closer to repository dimensions than previous simulations and tests, it should be remembered that these tests are not actual field-scale tests done in a natural rock environment so the results are still only indicative in nature. They can provide guidance for the preliminary planning of backfilling operations and to plan for full-scale demonstrations in an underground environment. The ½-Scale tests allow for evaluation of two point sources of water inflow (at different distances from the downstream face), as well as different inflow rates (inflows examined are 0.1, 0.25, 0.5, 1 and 2.5 L/min) on opposite sides of the simulated tunnel.

As these tests progressed it was determined that it was important to examine the influence of extreme inflow conditions on the stability of the backfill and how water would move through the system. In a repository environment additional factors, such as multiple or non-point sources of water supply, the presence of excavation damage in the surrounding, larger blocks and potentially a greater thickness of pellet fill will exist. All of these factors may result in a much more complex hydraulic behaviour than the carefully controlled boundary conditions of the ½-Scale test can provide. The ½-Scale tests allow for assessment of the effects of scale on water outflow from a backfilled section of tunnel. From this, better approaches of how to deal with exiting water at the working face of the tunnel backfill can be developed. Ultimately this information and the resultant technical approaches to deal with them will need to be tested under repository-like conditions.

There also exists a potential for unexpectedly large inflow (> 2.5 l/min) into already backfilled sections of the tunnels and the tests described in this report provide an initial description of what might occur in such situations. Specifically, Tests 9 and 10 examine such high-flow conditions, where 2.5 l/min was supplied at two locations at the rear of the ½-Scale test chamber. This simulated a situation where flow from regions further away from the working face had somehow combined into two discrete flow channels, each providing 2.5 l/min, along opposite sides of the tunnel but at different elevations (0.3 and 1.8 m). The manner in which the water supplied at these inflow points interacted with the backfill was examined in order to gain a clearer understanding of how water might move into a section of tunnel that has not yet been closed.

3 Materials used

3.1 General description of clay materials

Two clay materials were examined in the course of this study. Both contain a swelling clay mineral component and are being examined for potential use in backfilling. For ease of reference all three of these materials are distinguished from one another by use of their source or trade names. Much of the information contained below is reproduced from /Dixon et al. 2008a/ but for the purposes of completeness of reporting it is reproduced in this document. Details on the mineralogy, chemical characteristics and other key features of the clays used in this study can be found in Section 3.2.

3.1.1 Friedland clay

Friedland-clay is a smectitic clay from northeastern Germany that has a limited swelling capacity and is being considered as a potentially suitable backfilling material in a repository, provided it is precompacted to an adequate density. The raw material used for manufacture of these blocks is of much lower smectite content than the "bentonite" materials (reportedly approximately 45–50% of which 50% is montmorillonite and the remainder mixed layer clays of lower swelling capacity) and is generally referred to as a smectitic clay rather than bentonite. The mineralogy of the material has been studied by several researchers including, /Henning 1971, Pusch 1998, 2001, Carlson 2004, Karnland et al. 2006/. A summary of these data is provided in the report by /Dixon et al. 2008a/. The blocks shown in Figure 3-1 were manufactured in Sweden by Höganäs Bjuf using uniaxial compression.

3.1.2 Cebogel Clay

CEBOGEL QSE pellets are produced as short cylindrical rods by Cebo Holland BV. According to the producer of the pellets, the raw material is soda ash activated high-grade Ca-bentonite quarried by Silver & Baryte Mining Company S.A. from Isle of Milos, Greece. The mineralogy and chemistry of Milos bentonite has previously been studied e.g. in /Carlson 2004/ and /Karnland et al. 2006/. The mineralogy and chemistry of Cebogel pellets were investigated as a part of Posiva's Belake project concerning development of quality control for bentonite clays. The results of the project are reported in /Ahonen et al. 2008/. Further detail on the mineralogy and chemical properties of this material is also found in /Dixon et al. 2008a/.

The Cebogel pellets were used as a floor-levelling material, on which Friedland clay blocks were piled as well as to fill the space between the block assembly and steel walls of the ½-Scale chamber. The mass of pellet material varied from test to test, largely as a function of the

Friedlandand Clay Blocks Cebogel Pellets

Figure 3-1. *Clay Materials Used in ½-Scale Tests.*

packing efficiencies achieved in each test, but was measured for each test pair installed. The diameter of each pellet is 6.5 mm and their length is between 5 and 20 mm and can be seen in Figure 3-1. The producer reports that the bulk density achievable through pouring of pellets is approximately 1,100 kg/m³ and the dry density of the individual pellets is 1,810 kg/m³ with an as-produced gravimetric water content of 16%. The actual dry density of the poured pellet mass was calculated to be between 950 and 1,080 kg/m³ for the tests done in this study with an average of 1,000 kg/m³ at the start of testing and the gravimetric water content was measured to average 18.9%. The specifics for each test are presented in Chapter 6 of this report.

3.2 Basic geotechnical properties

The original raw material used in the manufacture of the clay blocks used in this study Friedland clay granular) had granule size between 0–1 mm and was sourced from Friedland Industrial Minerals (FIM) GmbH in Germany. This material was moisture conditioned and mechanically compacted (via uniaxial compression) to generate bricks. According to preliminary results /Johannesson 2008/ the test blocks produced in Bjuv brick factory in Sweden in July 2006 had water content of 6.3%, bulk density of 1,940 kg/m³, dry density of 1,820 kg/m³ and a degree of saturation of 33%.

The liquid limit of a sample of the Friedland-clay used in these blocks was 112 (%) and the swelling index (ml/g) was 4.3%. Based on preliminary results by /Johannesson 2008/, blocks of this density level should yield swelling pressure of approximately 1.5 MPa and have a hydraulic conductivity of 2×10^{-12} m/s.

The compacted Friedland clay blocks used in this test were 300 × 150 × 75 mm in dimension. The water content of the clay was approximately 6.3% during block compaction but the dry density achieved was only 1,800 kg/m³. The lower than desired density was the result of an inadequate compaction pressure being used during manufacturing, only approximately 7 MPa was applied, which was inadequate to achieve the previously specified 2,000 kg/m³ densities. Clay Technology AB had initially defined the block specifications to be: a water content 8.6% (saturation 62.2%), bulk density 2,200 kg/m³, dry density 2,000 kg/m³ and a void ratio of 0.385. On determination of the improper block density a review of the purposes of the smaller-scale tests described in /Dixon et al. 2008a/ as well as the ½-Scale tests was undertaken. It was decided that while these low-density blocks are not of an adequate density for use in an actual repository, for the purposes of tests where the main focus is on the pellet materials, the blocks could be used without compromising the results.

The index properties measurements (liquid limit (%) determined with fall-cone test and the swelling index (ml/g)) determined in Sweden and Finland are presented in Table 3-1 (Clay Technology AB and by /Ahonen et al. 2008/). This information is supplemented by results obtained in Canada that indicate a much lower liquid limit (using Casagrande method) than previously reported for the Friedland clay. The very substantial difference in these measurements cannot be explained by technique or operator and indicate that there is a material consistency issue that will need to be addressed in the future. For the purposes of these tests it is unlikely that variation in Friedland clay quality will substantially alter the results since the focus is on the pellet material surrounding it. The apparent uncertainty in the swelling clay content in at least some Friedland materials may mean that these blocks may be more susceptible to water erosion than originally anticipated. The lower swelling clay content will also make them more sensitive to changes in permeant salinity, although that is not a factor in this set of tests. More importantly, the clay blocks used in the study described in this report were manufactured to a lower density than is proposed for backfill blocks. This will mean that they are less mechanically sound, have a lower swelling capacity and are likely to be more vulnerable to erosion by flowing water. However, based on the results of previous studies done at a smaller scale /Dixon et al. 2008a/, the block materials were not expected to play a dominating role in the initial behaviour of the ½-Scale simulations.

For comparison purposes some of the geotechnical properties previously reported for MX-80 bentonite clay are also provided Table 3-1. These data provide a commonly recognized reference material, against which other clays can be compared.

Table 3-1. Liquid limit (%) and swelling index of clay materials used.

	MX-80	Cebogel	Friedland
Liquid limit (%)	524[++], 518[+]	576*; 575**	57[+]; 112[++]
Plasticity Index	483[+]	> 500	34[+] – 89
Swelling index (ml/1g)	20.8[++]	11.9*, 14**	4.3[++]

* Unpublished data from Clay Technology AB.

** /Ahonen et al. 2008/, value converted to ml/1g.

[+] unpublished data from AECL (2007).

[++] /Johannesson 2008/.

4 Test setup

4.1 General description of test setup

The 1/2 – Scale Tests were operated in a steel chamber constructed in the Buffer Laboratory at SKB's Äspö facility. The test chamber was constructed in a manner such that it's cross-section was nominally ½ that of an emplacement tunnel that would be present in a repository using the KBS-3V concept for in-floor canister installation. Figure 4-1 and Figure 4-2 provide a schematic layout of the ½-Scale chamber and photographs of it respectively. In Figure 4-1 the water inlet points are shown as blue coloured circles on the sketch.

Based on the dimensions provided in Figure 4-1, the cross-sectional area of the test chamber is nominally 7.1 m^2. The chamber length is 6 m but only 4 m was utilized for each assembly, as shown in Figure 4-3. The use of only 4 m of its length (volume of 28.8 m^3) was based on several factors. As there was a limited supply of block materials and if 4 or more test assemblies were to be constructed there would be an insufficient supply of clay blocks. Another reason for utilizing only 4 m of the chamber's length was decision, based on the results of previous, smaller-scale simulations /Dixon et al. 2008a/, to provide mechanical restraint to the downstream face, as shown in Figure 4-3. Additionally, the length of time needed before water exits the test should be at least in part determined by the distance it has to travel before it exits the chamber. Based on a review of the smaller scale tests done at Äspö during 2006/07 /Dixon et al. 2008a/, it was decided that extending the flow path length to more than 2.2 m (or 4-m for Test assemblies 5 and 6), from the 0.6-m-length of previous tests was unnecessary and that a system of 4-m total length would provide a suitable up-scaling to allow for evaluation of the role of path-length. The results of the smaller tests done at Äspö /Dixon et al. 2008a/ indicated that only a small proportion of the pellet fill would initially interact with the inflowing water. Previous tests also indicated that for most situations, the majority of backfill block – filled region was little influenced by the inflowing water at the earliest states of hydration. The type of backfill blocks (Friedland clay), utilized in the previous smaller-scale tests were only available in limited quantities and so there was a desire to use the materials available in the most judicious manner possible.

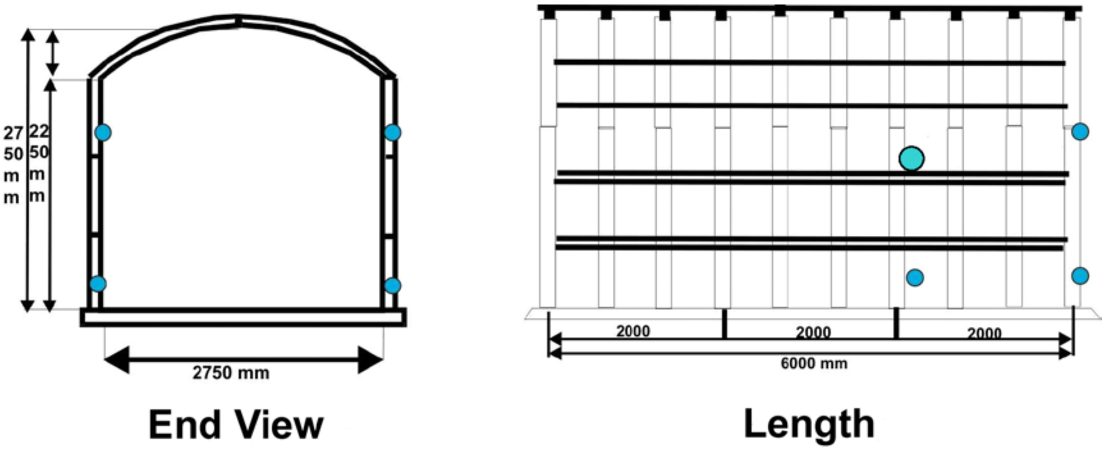


Figure 4-1. Schematic of ½-Scale Test Chamber.

Figure 4-2. *As-built ½-Scale test chamber.*

Figure 4-3. *Chamber and restraint system.*

The final 4 tests done in this study (Tests 9-12) differed in their installation. The pellet materials installed were placed with addition of water at the nozzle of the shotcrete hose. This allowed the pellets to be placed as a cohesive mass that did not require downstream mechanical support to keep them in place. It also allowed installation of a nearly vertical face of pellets at the downstream end. This installation technique also allowed for examination of the role of initial water content on the flow path location developed by the inflowing water.

The construction layout developed for the ½-Scale tests included, for the first installation of clay pellets to a thickness of 0.1 m on floor of the rearmost 4 m of the test chamber (Figure 4-4). On this base a large number of backfill-block sized boxes were installed, they were surrounded with heavy-gage plastic sheeting to prevent water penetration into the central volume. The plastic-encapsulated volume was then covered with a bentonite geotextile in order to simulate the type of contact that might be provided by dense clay backfill blocks (Figure 4-4). Beyond the geotextile layer a further layer of backfill blocks of the same type as were previously used in the smaller-scale backfill and pellet tests were installed (Figure 4-4). The limited thickness of backfill blocks were deemed to be sufficient based on the experiences of the previous smaller-scale tests where water penetration into the block-filled volume was typically very limited or only for the period at the start of testing. This construction thereby provided a reasonable simulation of a large mass of backfill blocks in a tunnel environment while minimizing the number blocks actually used.

A gap of 155 mm was intentionally left between the walls of the test chamber and the clay blocks to simulate the space that would not be able to be filled with block materials in an actual repository. Into this gap bentonite pellets were installed by pouring as the test was built from the floor up (Figure 4-5). The pellets also provided physical support to the clay blocks ensuring that they stayed as they were initially installed.

(a) Bentonite-Pellet Base *(b) Geotextile* *c) Plastic liner & filler blocks*

(d) Wooden Blocks with Plastic and Geotextile *(e) Completed Installation* *(f) Pellet fill along wall*

Figure 4-4. *Generic assembly process used in ½-Scale Tests.*

Supplying pellets to shotcrete machine *Blowing pellets into crown* *Final filling of crown region*

Figure 4-5. *Pellet installation into roof region of Assemblies 1 through 3.*

The uppermost (crown) region of the simulation was subsequently filled with clay pellets using the concrete emplacement technology known as shotcreting. Installation utilized air entrainment to move the pellets into the test chamber. It should be noted that due to the two techniques used in pellet installation, the density of the pellet-filled volumes was slightly different with higher density being achieved in the side regions. This is discussed in greater detail later in this report. A summary of the quantities of materials installed in each of the four test assemblies constructed in the course of this study is provided in Table 4-1.

The downstream face of the test assembly required vertical support to avoid potential slumping or collapse should the system destabilize in the course of testing. Restraint was provided in Tests 1–6 and 11–12 by a stiff steel grating and screen system (Figure 4-6). This structure served the same function as the restraint grid used in the smaller tests /Dixon et al. 2008a/.

The setup process described above was used for Assemblies 1 through 3 (Tests 1 through 6) and Assembly 6 (Tests 11–12). The setup of Assemblies 4 through 6 (Tests 7 through 12) differed considerably from previous ones in that the entire pellet fill was installed at the end of block assembly (Figure 4-7 and Figure 4-8) and there were no pellets installed on the chamber floor for Assemblies 4 and 5. The first six tests confirmed that water does not travel readily along the floor of the chamber, similar to what was observed in smaller-scale simulations /Dixon et al. 2008a/. This meant that the granular bed installed below those tests served no function in terms of controlling flow and so was not installed for Assemblies 4 and 5. The final assembly of this study (Tests 11–12) also had pellets installed so as to provide full comparability to Assembly 1 (identical inflow rates were supplied at 2.2 m rather than 4 m from the downstream face). Additionally, the last 6 tests did not have large volumes of blocks installed as they too were also found to play little role in movement of water. Tests 7, 9 and 11 (left side of assemblies) did not have a block component at all, only the pellet fill with the bentonite geotextile mat providing the hydraulic boundary between the centre of the chamber and the pellets. Tests 8, 10 and 12 had a 300 mm thickness of blocks installed between the pellets and the internal spacer of the assembly.

Figure 4-6. *Mesh and Restraint at Downstream Face in Tests 1 Through 6.*

Setup showing blocks on right side and geotextile-only on left side

Setup following clay pellet installation

Figure 4-7. *General layout of Assemblies 4, 5 and 6 (Tests 7 through 12) where pellets were installed in one operation.*

4.2 Supply and collection of water

Four water supply ports were installed in the ½-Scale test setup, two on each side of the chamber. For the purposes of simplifying descriptive terminology the following directional conventions have been adopted:

1. Downstream – the end of the test chamber which is open to atmosphere and free drainage of the system is allowed.
2. Upstream – the blind end of the test chamber where a steel wall exists to prevent any water escape or materials movement.
3. Left side – the side to the left of the centreline of the test chamber when viewed from the downstream face. This region represented odd numbered tests.
4. Right side – the side to the right of the centreline of the Assembly chamber when viewed from the downstream face. This region represented even numbered tests.

On each side of the chamber three inflow points are provided for water. The first is located 1.8 m from the upstream end of the chamber at an elevation of 1.5 m from the floor. The second and third were located at the rear (upstream) near the floor of the chamber at 0.3 and 1.8 m elevation, 0.07 m from the outside edge of the chamber wall).

Water was supplied to the test via constant-rate-of-flow pumps, each of which could be preset to supply different rates of water to the test. For the first 8 tests completed they operated at nominal supply rates of 0.1, 0.25, 0.5 or 1.0 l/min. At the lower end of the preset range the pumps were difficult to preset, resulting in flow rates slightly different than intended. The actual flow rates provided by the pumps could be and were measured in the course of each test and were found to be stable for the course of each test. The result was flow rates that deviated slightly from the predefined targets but this did not affect the results of the tests since actual rates were measured. Tests 9 and 10 were undertaken to examine more severe water inflow conditions (2.5 l/min via a single inflow location at the rear of the chamber. Test 9 was at 0.3 m elevation and Test 10 was at 1.8 m elevation, simulating a large flow path that has reached a recently installed section of backfill. In Tests 11 and 12, water was supplied at rates of 0.25 and 0.5 l/min at the rear of the chamber, once again at 0.3 and 1.8 m elevation respectively.

The resistance to inflow of water to the tests was monitored via pressure transducers installed at the inlet ports of the chamber (one at each inlet location). This allowed changes in water inflow resistance to be continuously monitored and since inflow resistance is known to correspond to the development of water transport channels these data provide valuable information on system performance.

The water used in testing was artificial Äspö water (1% TDS as equal mass proportions of NaCl and $CaCl_2$). It was prepared in large (1,000 Litre) holding tanks and the pumps then drew water as necessary to supply the tests (Figure 4-8, Figure 4-9).

During test operation the water (and eroded solids) exiting each side of the assembly was collected in a tray that was emptied into an outflow holding tank using a constantly operating pumping system (Figure 4-8). Each tank was equipped with a pressure sensor that allowed for continuous monitoring of the mass of water and sediment exiting. In this way inflow and outflow rates can be compared. Unfortunately, it proved impractical to separate out the solids and liquids components in the outflow tanks due to the large volumes involved. In the tests where erosion was substantial the removed material tended to swell and fill the outflow trays with a thick mass that could not be pumped into the holding tanks. This material also occupied too large a volume to be separately collected and measured. Additionally, at the lip of each of the outflow collection trays an electrical conductivity meter was installed. This allowed the time at which outflow began to be determined, even if it occurred during non-working hours.

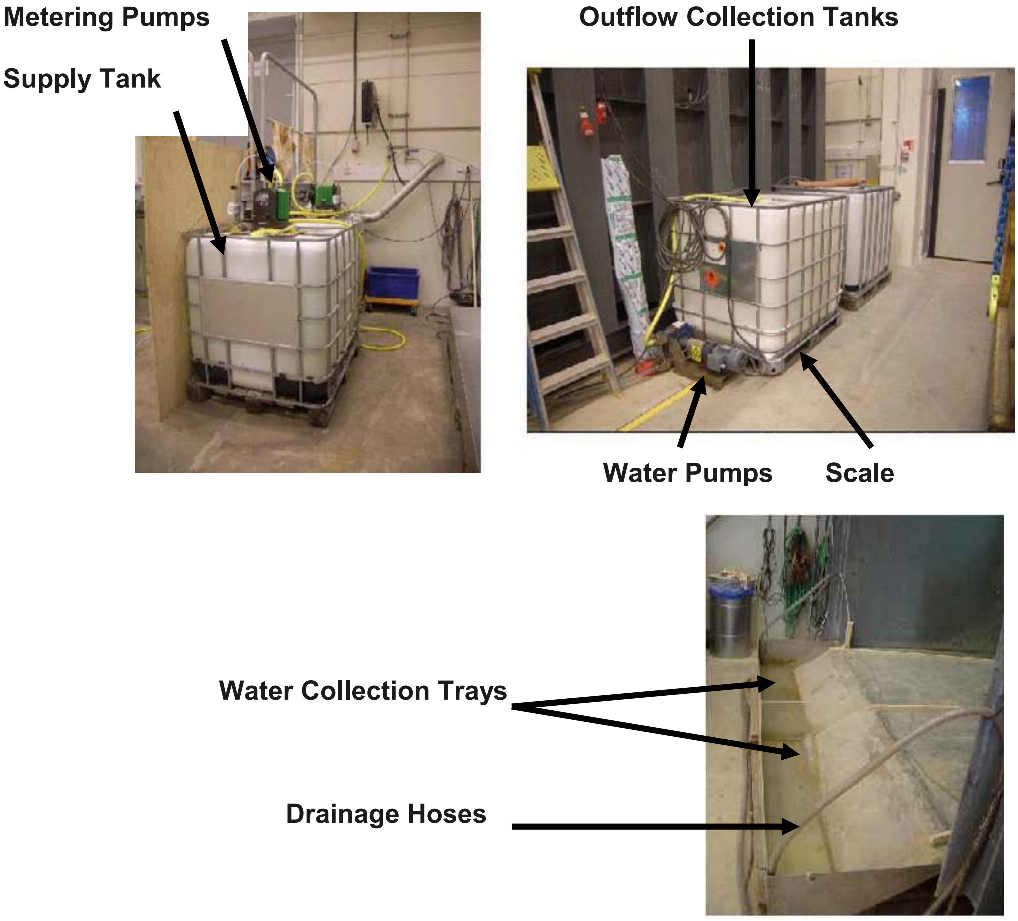


Figure 4-8. Photographs showing water supply and collection system.

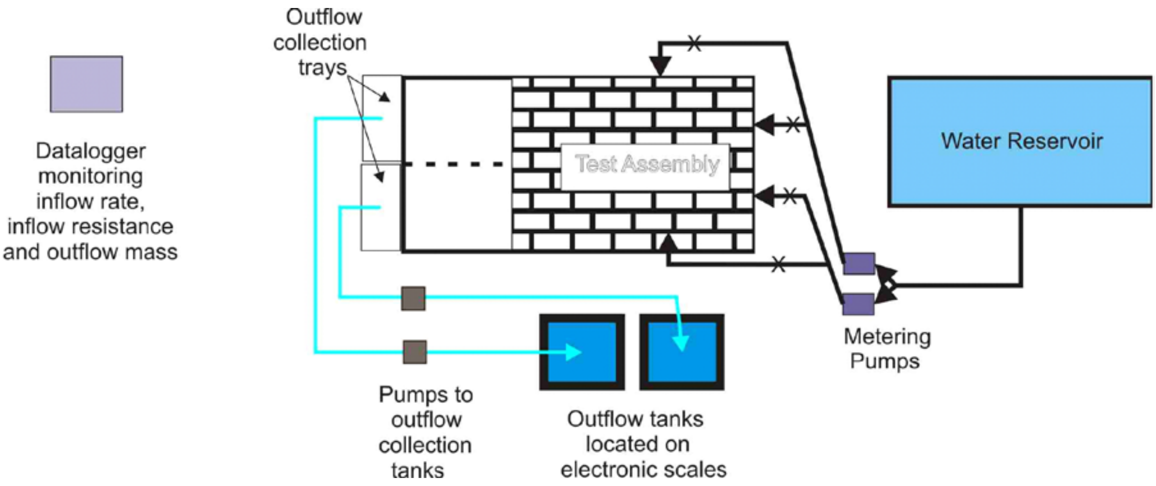


Figure 4-9. *Schematic showing water supply and collection system.*

4.3 Test plan

The ½-Scale Tests involved conduct of 6 paired sets of two tests each for a total of 12 sets of results. The smaller scale tests conducted previously at Äspö found that there was no hydraulic interaction between the two sides of a test setup where water was supplied to both sides independently or one side only. Hydraulic activity was confined to the side of the assembly it was supplied to (over the duration of the tests done (up to 5-days). As a result, the new ½-Scale tests were planned to take advantage of this and tests could be run separately and without interference with one-another. Each test was intended to operate for at least 5 days following initiation of water supply to the setup, but some variations occurred due to excessive erosion or decisions to operate for slightly longer periods. Water was supplied to each of the tests at one of the following rates (0.1, 0.25, 0.5 1.0 or 2.5 l/min). Table 4-1 provides a listing of the tests done and the numbers assigned to each.

Table 4-1. Tests done as part of ½-Scale simulations.

Test number	Inflow location* (m)	Inflow rate (litres/min)	Test duration (days)	Percolating fluid**	Side of ½-Scale mockup (Left/Right)
1	1.5 : 1.9	0.25	5	Äspö	Left
2	1.5 : 1.9	0.5	5	Äspö	Right
3	1.5 : 1.9	0.5	5	Äspö	Left
4	1.5 : 1.9	1.0	5	Äspö	Right
5	1.5 : 1.9	0.1	5	Äspö	Left
6	1.5 : 1.9	0.25	5	Äspö	Right
7	1.5 : 1.9	0.25	5	Äspö	Left
8	1.5 : 1.9	0.5	5	Äspö	Right
9	0.3 : 3.9	2.5	< 1***	Äspö	Left
10	1.8 : 3.9	2.5	3	Äspö	Right
11	1.8 : 3.9	0.25	7	Äspö	Left
12	0.3 : 3.9	0.50	7	Äspö	Right

* elevation from floor : distance from front face of assembly.

** Artificial Äspö water (1% TDS).

*** Water bypassed clay and entered core of restraint system, test terminated at 17.5 h.

4.4 Layout of tests

While the general setup described in Section 4.1 was used for all the tests conducted in the ½-Scale study there were some variations in the actual assembly and geometry used. Most of these changes related to the shape of the upper portion of the wooden box assembly and the associated clay blocks. These variations did not affect the comparability of the results obtained in ½-Scale Tests 1 through 6 as water did not enter the clay block region to any substantial extent and the wooden box filled regions did not see any water ingress. Tests 7 and 8 showed similar behaviour to the previous 6 tests with no substantive water flow being observed moving through either the clay block or geotextile portions respectively. Tests 9 and 10 were built in the same manner as Tests 7 and 8 but involved very high inflow (and outflow) rates and Test 9 experienced internal leakage that could not be corrected and was discontinued after only a few hours. Tests 11 and 12 were similar in construction to Tests 9 and 10 in that only the right-hand side of the assembly had a clay block component installed between the pellets and the central spacer.

The hydraulic behaviour of all of the tests were controlled the clay pellets, hence minor differences in assembly geometry was not a factor. What is important to know is the exact geometry of each test so that the volume into which the clay pellets were placed can be accurately estimated and the as-placed density of the pellet-filled region determined. The manner in which Assemblies 1, 2 and 3 (Tests 1-6) differed was primarily associated with their uppermost (step-like) portion where the wooden boxes, geotextile liner and clay blocks were assembled in slightly different manners. These tests had differing numbers of block layers installed, which slightly altered the volume into which pellets were subsequently installed. These variations are described in the detailed description of each assembly. They did not affect subsequent operation or behaviour of the tests as these regions were internal and did not see any water in the course of the test. Tests 7–8, 9–10 and 11–12 were much different in their construction and the severity of the flow conditions imposed on them. For the purposes of completeness of documentation, the layout of each setup is described below.

4.4.1 Assembly 1: Tests 1 and 2

The first test assembly of the ½-Scale test series was built to the geometry shown in Figure 4-3. The total length of the installed test was 3.95 m and the total chamber volume utilized in this assembly was 28.2 m^3. On the floor of the test chamber 1,221 kg of Cebogel pellets were installed, providing a thickness of 40 mm (rear of chamber) to 100 mm (front of test assembly). The chamber was tilted slightly so that the downstream face was 60 mm lower than the rear, simulating the expected conditions in an emplacement tunnel. The underlying pellet materials therefore occupied 0.77 m^3. A gap averaging 155 mm (±10) width was left between the blocks and the chamber wall and into this volume the Cebogel pellets were installed.

A total of 1,974 clay blocks each of 150 × 75 × 300-mm dimension occupying a total volume of approximately 6.8 m^3 (this assumes a 1 mm gap between each block) were installed around a core made using wooden boxes. The wooden boxes are 0.96 × 0.45 × 0.48-m dimension and occupied an estimated 16.3 m^3 of the test chamber's 28.8 m^3 volume. The geotextile lining between the blocks and the wooden boxes was nominally 10mm thick occupying a total of (0.26 m^3) of the chamber volume. Into the 155 mm wide gap along the sides of the assembly a total of 2,029 kg of pellet materials were installed, it was assumed that the amounts added were equal on each side.

Figure 4-10 shows the sequencing of the construction of Assembly 1. A detailed sketch and a photograph showing the details of the clay block assembly pattern in the uppermost portions are provided in Figure 4-11. It should be noted that the slight lateral offset of the side blocks is the result of the overlapping of the bentonite geotextile next to the boxes. This resulted in approximately a 10 mm thicker geotextile layer in the uppermost region. The method used to install the wooden boxes also resulted in a small gap (30mm) being left between the uppermost wooden boxes and the block assembly on each side, as shown in Figure 4-10. In order to deal with this, the volume was filled with pellet materials. Neither of these slight as-built variations from the initial design plan affected the behaviour of the system.

Gap between blocks and wall Top of block assembly Pellet fill along wall right side

Pellet fill along wall left side Block installation near crown Pellet filler at top of assembly

Blocks and geotextile at top of assembly

Figure 4-10. *Construction steps for Assembly 1 (Tests 1, 2).*

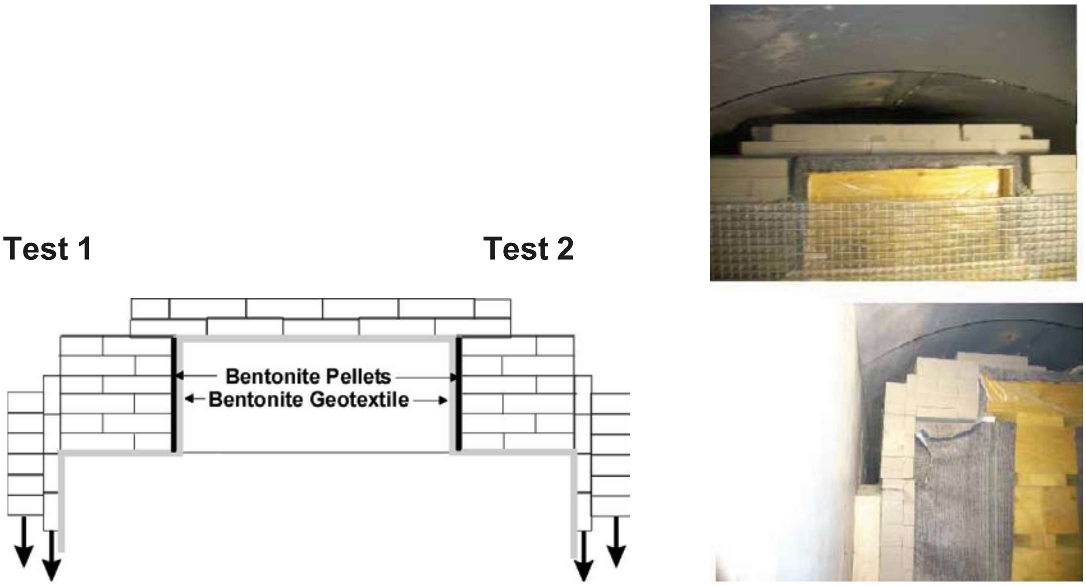


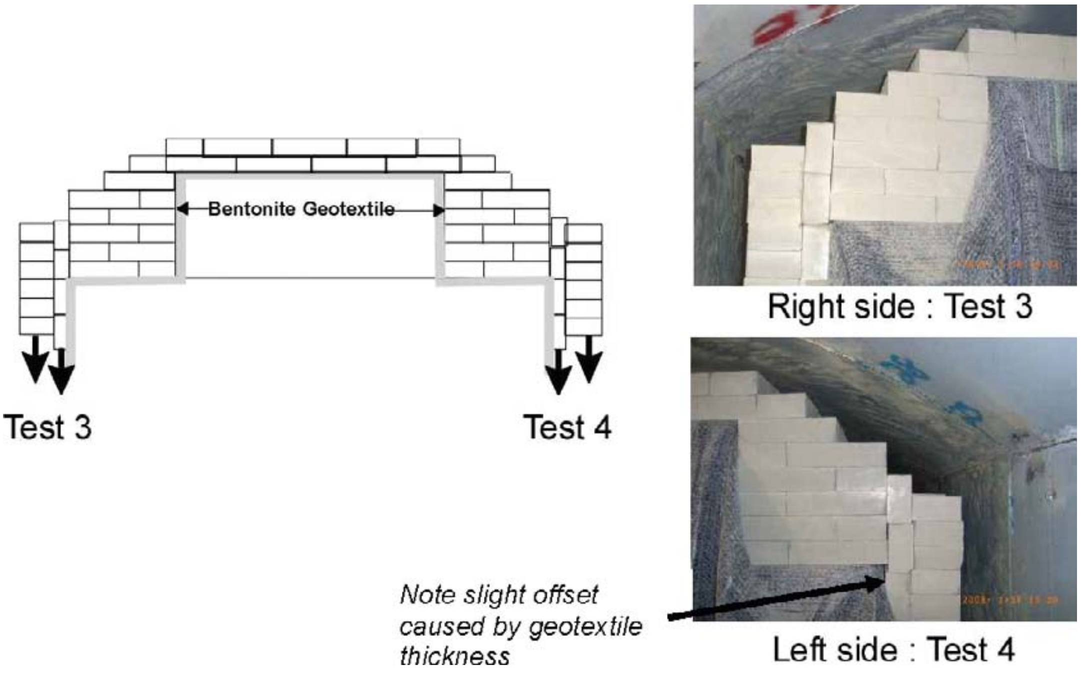
Figure 4-11. *Details of spacer and block assembly in upper portion of Assembly 1.*

Following installation of the blocks and filling of the gap between them and the steel wall with air-dry Cebogel pellets, the uppermost (crown) regions were filled with pellets using shotcreting equipment. Only enough water was provided to the nozzle of the sprayer to achieve dust control during placement (total of 2 l added). The water added was not sufficient to cause a discernible change in the water content of the pellets and did not affect subsequent water uptake by the system. The total amounts of materials installed in Tests 1 and 2 are provided in Table 4-2. The floor materials were mechanically compacted to a dry density of 1,360 kg/m^3 providing a firm base on which the blocks were assembled. The sides and upper crown materials were not mechanically compacted but were blown in using conventional shotcreting equipment, achieving an average dry density in the order of 1,080 kg/m^3. No separate measurements for the two sides were made and as the geometry was symmetric it was assumed that equal portions of pellets were installed in both sides.

4.4.2 Assembly 2: Tests 3 and 4

In this assembly a total of 1,740 clay blocks were installed around the wooden box core. A sketch and a photograph showing the details of the clay block assembly pattern are provided in Figure 4-12. Details related to water movement into and through Assembly 2 (Tests 3 and 4) are provided in Chapter 6 of this document. The blocks in the lower portion of the assembly were installed in the same manner as in Assembly 1 (two layers of blocks totalling 225 mm thickness between the geotextile liner and the gap where pellets were subsequently installed. The general sequencing of the construction of Assembly 2 was much the same as for Assembly 1 and can be seen in Figure 4-4.

Assembly 2 differed slightly from that of Assembly 1. Firstly, the base of the test chamber had a uniform 0.1 m thickness layer of pellets installed on it. The chamber was still slightly tilted towards the front, as it was in Assembly 1. This minor change in the layout did not affect any of the results observed as no water moved into or through this region. Figure 4-12 shows the layout of Assembly 1 and the slight change from the previous construction this did not affect the results observed because water did not move through the block materials. Finally, the manner in which the upper-most spacer was installed was altered so that there was no gap between the box-filled region and the clay blocks (filled with pellets in Assembly 1). Table 4-2 provides a summary of all the materials installed in Assembly 2.



Right side : Test 3

Left side : Test 4

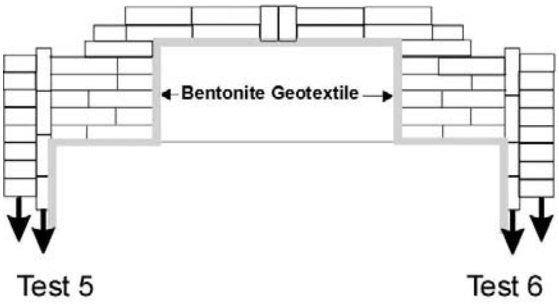
Figure 4-12. Details of block layout in crown of Assembly 2 (Tests 3, 4).

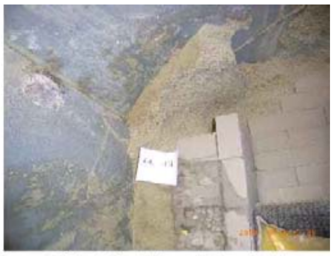
Assembly 2 had a total of 2,656 kg of Cebogel pellets installed into the lowermost 1.35 m of the block assembly, achieving an average as-placed dry density of approximately 930 kg/m^3. A total of 1,740 Friedland clay blocks were installed in Tests 3 and 4, equal numbers were used on each side. Knowing the total quantity of pellet materials (5,869 kg of dry mass (corrected for water present in placed materials)), installed along the sides and into the crown regions and the volume involved results in a calculated dry density of the pellet fill of 950 kg/m^3.

4.4.3 Assembly 3: Tests 5 and 6

A sketch and a photograph showing the details of the clay block assembly pattern are provided in Figure 4-13. Details related to water movement into and through Assembly 3 (Tests 5 and 6) are provided in Section. The blocks in the lower portion of the assembly were installed in the same manner as in Assemblies 1 and 2 (two layers of blocks totalling 225 mm thickness between the geotextile liner and the gap where pellets were subsequently installed. The chamber was still slightly tilted towards the front, as it was in previous setups. Although Assembly 3 had a slightly different block pattern than Assemblies 1 and 2, as shown in Figure 4-13, this did not discernibly affect the results observed because water did not move through the block materials to any substantial degree. Details related to water movement into and through Assembly 3 (Tests 5 and 6) are provided in Chapter 6 of this document.

Assembly 3 had a total of 6,108 kg of Cebogel pellets were installed into the sidewall and crown regions of Tests 5 and 6 (dry weight corrected for water present) resulting in an as-placed dry density of approximately 1,030 kg/m^3. A total of 1,740 blocks installed in it, the same as for Assembly 2. A summary of the materials installed is provided in Table 4-2.





Right side : Test 5

Left side : Test 6

Figure 4-13. Assembly 3 (Tests 5 and 6).

4.4.4 Assembly 4: Tests 7 and 8

Assembly 4 (Tests 7 and 8) differed in many ways from any of the previous tests done in the ½-Scale chamber. In this assembly there were no pellets installed on the floor of the chamber. The central portion of the chamber was empty with a wooden braced internal plywood formwork installed where the wooden boxes were previously used. The formwork had a plastic and geotextile lining put on its outside surface, as was done in all previous assemblies. No restraint was provided at the front of the assembly.

On the left side of the chamber (Test 7) there were no blocks installed, a 155 mm wide gap that went from floor to the crown region of the assembly was left after installing the central spacers. Previous tests showed limited water influx to the block layers and no ongoing flow through this region so they played little role in the movement of water through the test. The removal of the clay blocks provided a field test of just how important this component actually is in determining water movement into and through the clay pellet-filled region specifically and the backfill in general.

On the right side of the chamber (Test 8) a vertical wall of clay blocks was installed to thickness of 300 mm, slightly more than previously but this was required to keep the entire assembly stable until pellets were installed. There were no blocks installed on the top of the formwork at all since previous tests showed no tendency for substantial water movement upwards and the expectation that the dampened pellet mass would be less likely to allow vertical water migration. Figure 4-14 shows the test as it was assembled. A total of 6,858 kg of Cebogel pellet materials were installed into Assembly 4 (5,812 kg of dry material). The average dry density of the pellet fill installed in this test was 980 kg/m^3. A summary of the materials used in Assembly 4 and their as-placed density is provided in Table 4-2.

Before pellet placement **Following pellet placement**

Protective Plywood removed

Figure 4-14. *Assembly 4 (Tests 7 and 8).*

Table 4-2. Summary of Initial Conditions in ½-Scale Tests.

Test number	Volume of blocks (m^3)	Dry mass & volume of floor fill (kg : m^3)	Density of floor fill* (kg/m^3)	Dry mass & volume of pellet fill (Sides) (kg : m^3)	Dry density of side materials (kg/m^3)	Dry mass & volume of all pellet fill (sides & crown) (kg : m^3)	Average dry density of pellet fill (sides & crown) (kg/m^3)
1	6.82	1,035 : 0.76	1,360	1,720 : 1.76	980	6,565 : 6.07	1,080
2	6.82	1,035 : 0.76	1,360	1,720 : 1.76	980	6,565 : 6.07	1,080
3	6.01	NM : 1.09	NM	2,656 : 2.85[+]	930	5,869 : 6.17	950
4	6.01	NM : 1.09	NM	2,656 : 2.85[+]	930	5,869 : 6.17	950
5	6.01	NM : 1.09	NM	1,729 : 1.65	1,050	6,108 : 5.95	1,030
6	6.01	NM : 1.09	NM	1,729 : 1.65	1,050	6,108 : 5.95	1,030
7**	0	NA	NA	NM	NM	5,812 : 5.95	980
8***	2.64	NA	NA	NM	NM	5,812 : 5.95	980
9	0	NA	NA	NM	NM	5,383 : 5.45	988
10	2.5	NA	NA	NM	NM	5,383 : 5.45	988
11	0	NA	NA	NM	NM	5,365 : 5.45	984
12	2.5	NA	NA	NM	NM	5,365 : 5.45	984

* Manner in which masses and volumes were recorded precluded calculation of accurate density of certain portions of assemblies.

** No blocks or flooring materials used in this test

*** No flooring material used and only vertical lower portion of block fill installed

[+] Density is average for floor and sides of assembly to height of 1.45m from base of chamber.

On completion of the installation of the formwork and the clay blocks on the right side of Assembly 4 (Test 8), Cebogel pellets were installed using conventional shotcreting equipment. The manner in which these pellets were installed was different than were used in previous assemblies. The pellets were blown into the chamber, side gaps and crown in a single process. Pellets were prevented from rolling back out of the chamber by use of a small quantity of water (40 l for approximately 5,300 kg of dry pellets (< 1% water addition)), during the installation process. The water provided the pellets with a degree of adhesion that allowed them to more readily stay where they were placed. At the front face of the chamber the water addition was increased further, resulting in a tendency for the pellets to break down on impact with the face, forming a smooth, low porosity face. This allowed the pellets at the face to be installed as a nearly-vertical face. As can be seen in Figure 4-14 there was a shallow depth (~ 50–150 mm) on the front face that could not be filled with pellets using this technique. The force of the pellets contacting the materials already placed and lack of lateral constraint resulted in rebound of the pellets in this shallow depth. This did not seem to affect the remainder of the pellet fill and the face was left in this manner during the test, thereby simulating what might be present in an actual tunnel installation. Use of water-enriched pellet materials was also done as part of examining if the movement of water out of the pellet-filled region could be delayed or controlled by use of a wetter, gasket-like portion of pellets that could act to resist water movement. This wetter material also had the potential to force water to move in a different manner than was previously observed.

With the presence of a more water resistant downstream face on the pellet fill, two potential results were anticipated. The first was an increased potential for water to move into the block filled region, causing formation of internal flow paths similar to those observed in some of the smaller-scale tests described by /Dixon et al. 2008a/. The second was that the wet, lower permeability fill material might force water to move preferentially along the pellet-chamber wall contact, bypassing the internal volume almost completely. The geotextile portion on the left-side of this assembly removed any potential for water to move anywhere but through the pellets (or interfaces of pellets and steel wall or geotextile contact. The monitoring of the resistance to water inflow done in these tests will provide a means of comparing any differences in resistance to water movement induced by use of a "wetter" pellet material.

4.4.5 Assemblies 5 and 6: Tests 9 through 12

Assemblies 5 and 6 were built in exactly the same manner as for Assembly 4, differing only slightly in the quantity of pellets installed and number of blocks installed. Assembly 5 (Tests 9 and 10) was essentially the same as Assembly 4 with 155 mm thickness of pellet fill on the left side (Tests 9 and 11), a 0.3 m thick block section and 155 mm of pellets installed on the right side (Tests 10 and 12). The formwork had a plastic and geotextile lining put on its outside surface, as was done in all previous assemblies. No restraint was provided at the front of the assembly.

In these assemblies there were pellets installed on the floor of the chamber beneath the blocks and the central portion of the chamber was empty excepting for a wooden braced internal plywood formwork (Figure 4-15). In order to simulate the type of surface that exiting water would encounter in a backfilled tunnel, crushed bentonite (Minelco) was also installed as a 100 mm-thick layer on the floor at the downstream face in Assembly 5 (Figure 4-15). This simulated what might be encountered in a tunnel where flooring materials were installed prior to backfilling but backfilling operations had not progressed further. This material also retarded water movement into the base of the blocks or under the formwork. In Assembly 6 the Minelco granular materials was replaced by Cebogel pellets that were installed as a complete flooring material beneath the blocks.

Pellets Installed on Floor

Framework and Blocks

Blowing Wet Pellets at Downstream Face

Completed Assembly

Figure 4-15. *Assemblies 5 and 6 (Tests 9–12) and appearance at the start of operation (Assembly 6 shown).*

5 Documentation of tests

5.1 Test limitations

These tests focussed on the water uptake by and movement through the pellet-filled region of a simulated emplacement room backfill. The overall conditions present in the clay block – pellet assemblies were observed and changes in water content as the result of water uptake from a fixed rate-of-supply system that provided water to a point location at the perimeter of the ½-scale mock-up were measured. It should also be noted that these tests were generally of short duration (5 days of water supply), and were not intended to provide information on the longer-term behaviour of the system. It is the shorter-term performance of the backfill that water influx will most influence backfilling operations as many metres length of backfill are to be installed each day. The critical period associated with erosion, deformation and water transfer through the backfill will therefore be immediately after its installation.

5.2 Documentation prior to start of test

Prior to the conduct of each test a number of aspects were documented. These included the following:

- Measuring the dimensions of the blocks used to provide a “typical” reference block size.
- Measuring of the outer dimensions of the stack of blocks before the test began.
- Weighing of the mass of clay pellets used to fill the spaces between the blocks and the walls of the test cell.
- Photo-documentation of the test-set-up.

5.3 Documentation during test

In the course of this test a process of routine visual monitoring and water outflow measurements was followed. This documentation process usually included:

- Photo-documentation as required to record any obvious changes.
- Notes were taken to record observations made.
- Collection and measurement of water seepage/outflow volumes.
- Evaluation of erosive activity occurring during test.
- Monitoring of water inflow rate and resistance to water inflow.

5.4 Documentation at test termination and during dismantling

At the time of dismantling of the tests a number of records were made and samples taken, usually including:

- Photo-documentation and
- Careful notation of visual observations made prior to disassembly of test.

Photo documentation and notation of the conditions present in the ½-Scale tests were particularly important in the analysis of water movement patterns. It was noted in the first pair of tests that not only did water tend to move preferentially along the sidewall of the "tunnel", but these regions also experienced a greater degree of bentonite adhesion to the walls. The result of this was a visual record of the pathway taken by the water along the wall as it moved from its source to the downstream face. This allowed the tortuosity and actual pathways to be accurately recorded. These observations are provided in each of the test descriptions provided later in this report.

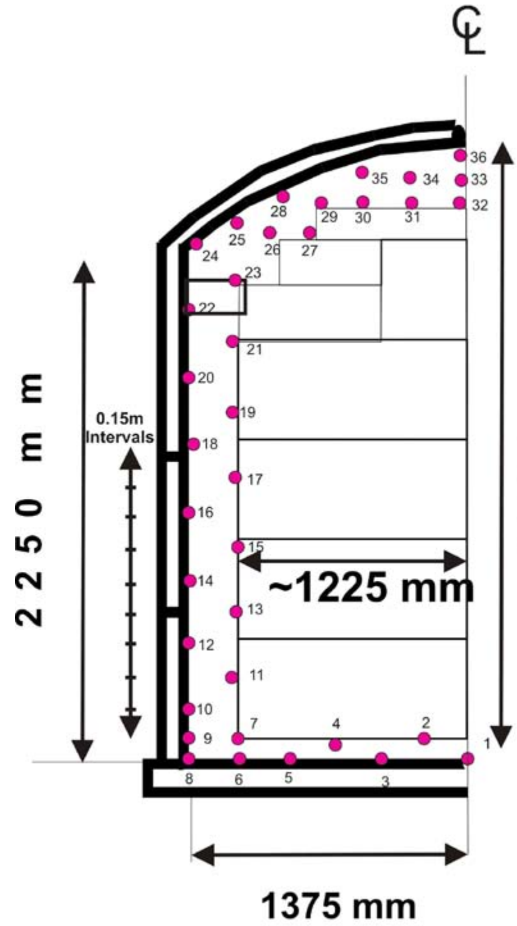
5.5 End of test sampling

The block geometries used in the conduct of the Baclo ½-Scale tests at Äspö during 2007–2008 are described in Section 3.2 but the specifics of the block material geometries played little role in the behaviour of the system. At the end of each test the restraint installed at the front face of the test chamber was removed and the general condition of the downstream face was noted and photographed.

On completion of initial examination of the end-of-test state of each test set-up, the pellet filled volume was sampled to water content determination. This sampling was done using a pre-defined sampling pattern that would allow for capturing of the basic water distribution in this volume. The sampling pattern developed for tests occupying the left-hand side of the chamber (odd numbered tests), is shown in Figure 5-1.

For tests occupying the right-hand side of the chamber (even numbered tests), the sampling plan was the same. The generic sampling plan called for sampling that would collect 36 individual samples at each of 0, 0.6, 1.2, 1.8, 2.4, 3.0, 3.6 and 4.0-m distances from the front face. These samples were recovered from approximately 20 mm distance from the chamber wall, or block/geotextile contacts so as to provide a uniform sampling protocol. In practice, full sets of samples were often not collected since water distribution tended to be quite localized. In tests where large volumes did not contain any additional water at the time of test completion samples were not recovered from these dry regions. They were noted as being dry and the samples recovered from the wet regions were numbered based on the template so that their location could be readily identified. Beyond the basic sampling pattern used, if there were particular locations not immediately on a preset sampling location then additional samples were taken and their location noted.

The data from water content analyses are provided in Appendix A and provide a quantifiable record of where the flow path for the water exiting these tests was and may have travelled over the course of the test. Tests 1, 2 and 11, 12 had these flow paths clearly traced in the course of dismantling but the other tests were not so clear regarding the path through the backfill.



Note measuring stick with pre-marked 150-mm sampling intervals. Sampled locations can be seen on photograph

Figure 5-1. *Sampling to determine distribution of water in pellet fill.*

6 Test results

This section provides a summary of the water uptake, movement and erosion that occurred within each of the 12 tests done as part of this study. Subsection 6.1 provides an abrieviated summary of the observations made during the operation of each test. Detailed observations made during test operation and dismantling are provided in Appendix A together with photographs illustrating the processes active during testing. These tests also involved sampling during disassembly in order to gain quantitative measures of water distribution, the results are tabulated in Appendix B. The manner in which the tests resisted water inflow is very instructive regarding how water may move in an actual tunnel and is discussed in Section 6.2. The removal of solids for each of these tests is also instructive regarding evolution of the sealing system as well as in developing an understanding of potentially disruptive processes. Erosion within these tests is discussed in Section 6.3.

6.1 General observations

Three of the assemblies (Tests 1–6), done as part of the ½-Scale test series involved installation of the pellet fill in two distinct phases. These six tests had the central block assembly installed in stages building upwards from the floor and the pellet fill along the sidewalls was installed stepwise as the blocks were installed (Figure 4-5). This approach provided the maximum lateral support to the block assemblies, precluding any physical instability developing that might threaten the assembly's integrity. This method also resulted in a relatively high as-placed pellet density to be achieved in the sidewall regions. The uppermost sections of blocks could not be installed in parallel with the pellets and as a result the pellet filling of this region occurred after block installation was completed. Air-dry clay pellets were blown into this region using a machine used to install cementitious materials (shotcrete/gunnite) shown in Figure 4-5.

The fourth and fifth assemblies (Tests 7 through 10 differed considerably from the first 6 tests in terms of their construction. They used a different internal support system than previous tests and a much lower number (or none) of block materials between the internal formwork and the steel wall of the test chamber. The pellet materials installed between the formwork and the steel chamber walls were also installed in a single operation with addition of small to moderate quantities of water during blowing, both for dust control and to provide a degree of adhesion to the individual pellets, especially at the front face of the assembly.

The final test assembly, Assembly 6 (Tests 11 and 12) differed from all the previous tests in that it had both a floor of Cebogel pellets installed as well as water input from the rear of the chamber. In terms of construction of this assembly, the physical dimensions and setup were essentially identical to that used in Assemblies 4 and 5.

A summary of conditions present in the chamber at the start of each was presented in Table 4-2 and the dry density of the pellets in the crown and side gap regions of all of the assemblies falls within a range of 950 and 1,080 kg/m^3. The use of a limited amount of water to facilitate pellet placement and reduce dust generated during placement in Assemblies 4 through 6 did not result in any discernible change in the dry density of the placed materials. Additionally, use of higher water addition at the downstream face allowed for installation of a stable, durable, nearly vertical wall of pellets without adversely affecting the density achieved. As a result, any changes in the water outflow location or pattern observed must be attributable to other parameters. Table 6-1 provides a general summary of the water inflow and resistance data for each test.

6.1.1 Assembly 1 : Tests 1 and 2: 0.25 and 0.5 l/min Inflow

The general layout of Tests 1 and 2 was provided in Figure 4-10. Test 1 was located on the left side of Assembly 1 and Test 2 occupied the right-hand side. These tests were provided with water at constant inflow rates of 0.25 and 0.5 l/min (15 and 30 l/hr) respectively, via small point sources of water located in the steel wall. The inflow points were located at 1.8 m from the rear of the chamber and 1.5 above the floor on each side. The water entering the pellet fill was allowed to move freely, with no restrictions beyond those induced by the test construction (no exit to rear of chamber).

Test 1: 0.25 l/min

Water first exited this test after approximately 16 hours into testing. Water initially exited the test at the block pellet interface at a slightly lower elevation than the water inlet (approximately 1 m). Within 48 hours the flow path appears to have stabilized to a single location along the wall – pellet contact at an elevation of approximately 2 m from the floor of the chamber, showing little erosive action (clear outflow).

At the end of 5 days (~ 120 hours of operation) the water supply to the test was discontinued and dismantling was initiated. Water entering the test tended to move laterally both forward and backwards along the chamber wall – pellet contact, developing a wetted band at or near the elevation of the inlet pipe. This is shown in the simplified schematic prepared as Figure 6-3. There was clearly very limited water inflow into the pellets or the block-filled region and little evidence of ongoing water movement into or through the blocks, as evidenced by the desiccation present on the blocks joint surfaces (result of discontinued supply of water to blocks). There was some evidence of short-term erosive flow along the block joints during the early stages of water inflow (Figure 6-2) but they were not a persistent feature as flow did not continue in this region and no substantial erosion occurred.

In addition to the visual monitoring (provided in Appendix A), water inflow rate, estimated outflow rate, and inflow resistance were recorded. The very stable inflow resistance readings (see Section 6.2) indicate that this test established a flow path early in its evolution. The setup of Tests 1 and 2 was such that it was not possible to collect the outflow of the two tests separately. As a result there is only an average outflow rate for the two tests available. At the end of 5 days of operation an average of 84% of the inflow that was immediately exiting the tests. These results are discussed in greater detail later in Section 6.2 and 6.3.

Test 2: 0.5 l/min

Water first exited Test 2 at approximately 12 hours into its operation. In the early outflow period the outflow was observed to be greatest along the pellet-block interface close to the floor of the assembly. This outflow point gradually moved higher up the face of the assembly and also gradually shifted towards the steel wall – pellet contact. This lateral movement of the flow path is attributed to the successive hydration of the pellets, inducing a greater and greater resistance to water movement through them. At 24 hours the flow path appears to have stabilized along the wall – pellet contact at an elevation only slightly lower than the inlet, showing little erosive action (clear outflow). This pattern of wetting is essentially the same as was described for Test 1. At the time of dismantling, water uptake and movement was limited to a horizontal band at or near the elevation of the inlet point. Wetting of the regions above the inlet elevation was beginning, but insufficient time had passed for this to progress very far.

Figure 6-1 shows the limited region where water uptake occurred and Figure 6-3 shows the pathways taken. As with Test 1, the lower regions (close to front face and at elevation of water inlet port), showed more extensive water influx with some limited early erosive activity during the period before the pellets had hydrated sufficiently to seal off water influx towards the core of the test (Figure 6-2). A detailed description of the evolution of this test, wetting patterns observed during dismantling and other events of interest are provided in Appendix A. Resistance to water inflow was essentially identical to that observed in Test 1 and is discussed in Section 6-2. Outflow rate and erosion from this test are discussed in Sections 6.2 and 6.3 respectively.

(a) Wet downstream face

(b) Dry material at crown and base of assembly, just in from front face

Figure 6-1. *Face of Test 1 and Test 2 at end of testing.*

Test 1

Test 2

(Note loose, dry pellet materials near floor and at crown of chamber)

Figure 6-2. *Water inflow along block joints at depth of water inflow in Tests 1 and 2. (wetting shows as dark areas on block edges).*

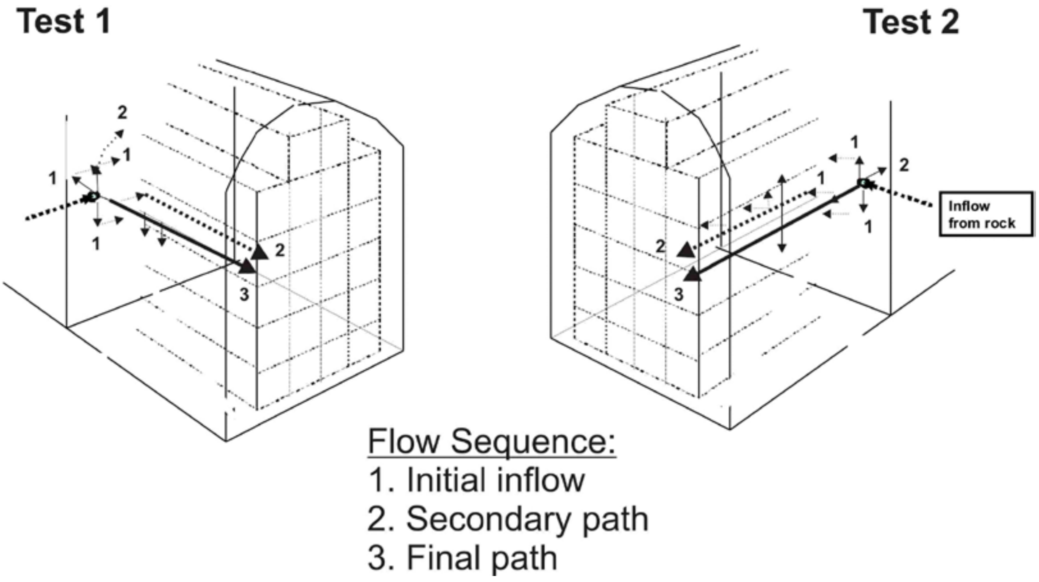


Figure 6-3. *Schematic showing water movement into and through Tests 1 and 2.*

6.1.2 Assembly 2: Tests 3 and 4: 0.5 and 1 l/min inflow

Test 3

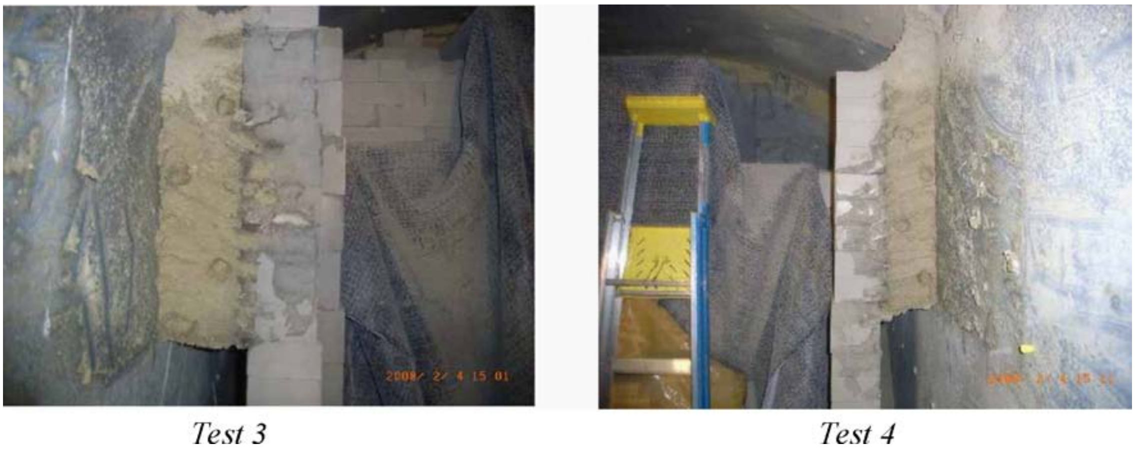
Test 3 was supplied with water at a rate of 0.5 l/min via a single port located 1.8 m from the rear of the chamber and 1.5 m above the floor. Outflow from the face of the assembly was observed after only 5 hours of operation, beginning at the pellet-block boundary part way up the assembly. The outflow point gradually shifted towards the pellet-chamber wall contact, in the same manner as was observed in Tests 1 and 2. Within 24 hours the flow path appears to have stabilized to a single location along the wall – pellet contact close to the elevation of the inlet port. There was little evidence of ongoing erosion along this pathway (clear outflow). There was only limited, early-stage water inflow into the block joints, as can be seen in Figure 6-4 and water tended to be limited in its distribution within the assembly (Figure 6-4). Figure 6-5 is a schematic drawing showing the water movement patterns interpreted from test operation and later dismantling.

The extent of wetting of the system show an even narrower band of wetting than was observed in Tests 1 and 2 (see Appendix A, B for details). It would appear that at this inflow rate there is only a limited capacity for water to move within the pellet fill and that water will be preferentially channelled towards the downstream face of the backfilled volume.

Like Assembly 1, there is no evidence of any hydraulic connection between the two sides of the chamber. Although equipped with independent water collection systems Tests 3 and 4 experienced cross flow from Test 3 to Test 4 at the downstream face of the assembly. This occurred as the result of water flowing along the steel mesh installed on the front face of the assembly. The outflow for Tests 3 and 4 could therefore only be measured as an accumulated total. At the end of testing the system was discharging 86% of its inflow and there was minimal resistance to its movement, as recorded in the outflow resistance plots. Details of water movement, resistance to inflow and erosion are provided in Sections 6.2 and 6.3.

Test 4

Test 4 had an inflow rate of 1 l/min, supplied at a single source 1.8 m distant from the rear of the chamber and an elevation of 1.5 m from its floor. Outflow from the downstream face occurred after only 2.5 hours of operation, beginning at the pellet-block boundary part way up the assembly. This outflow source moved towards the pellet-chamber wall contact with time, as was observed in Tests 1 and 2. Within 24 hours the flow path through the test appears to have stabilized at a single location along the wall – pellet contact, close to the elevation of the inlet



Test 3 Test 4

Figure 6-4. *Wetting near Inflow location in Tests 3 and 4. (Note very limited extent of wetting and dark areas where limited water movement inwards along block joints occurred).*

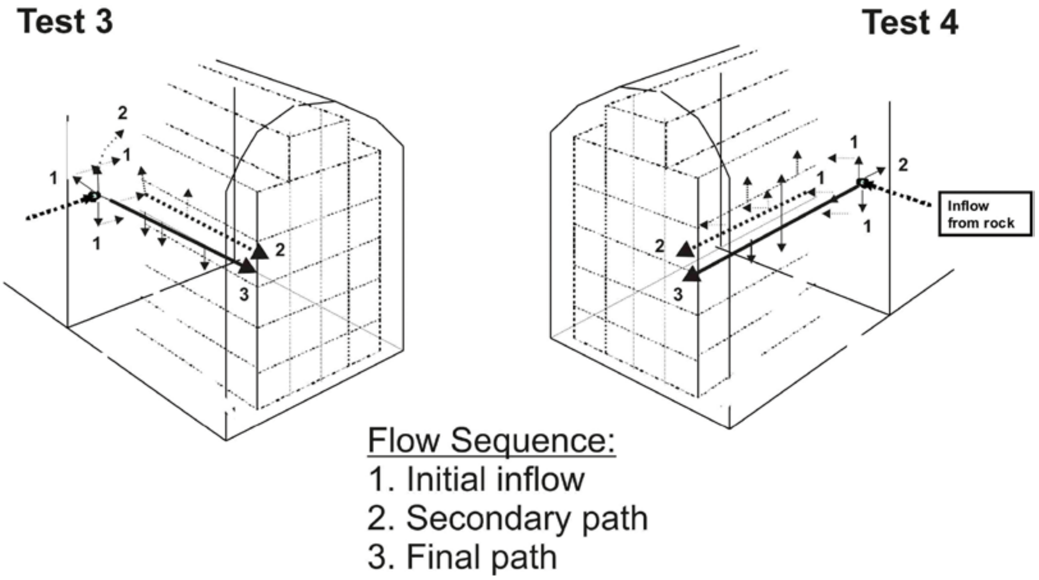


***Figure 6-5.** Schematic showing water movement into and through Tests 3 and 4.*

port. At the end of 5 days (~ 120 hours of operation) the water supply to the test was discontinued and it was disassembled and sampled to determine water uptake patterns (data is provided in Appendix B and photographs provided in Appendix A). From these data it was possible to confirm the qualitative conclusions developed through observations made during test operation and subsequent dismantling.

There was little evidence of ongoing erosion in this test (clear outflow). It can be seen in Figure 6-4 that there was only a narrow region saturated by the inflowing water and that only limited water movement into the block-filled region occurred in the earliest stages of the test. The high inflow rate resulted in water first moving into the pellet fill adjacent to the inlet port and then rapidly moved laterally along the chamber wall – pellet interface. Figure 6-5 provides a schematic showing the pattern of water movement in the course of testing.

There is no evidence of any hydraulic connection between the two sides of the chamber. Although equipped with independent water collection systems Tests 3 and 4 experienced cross-flow at the downstream face of the assembly. The outflow for these tests could therefore only be measured as an accumulated total. At the end of testing the system was discharging 86% of its total inflow and provided little in the way of inflow resistance. This hydraulic behaviour and erosion that occurred in this test are discussed in Section 6.2 and 6.3.

6.1.3 Assembly 3: Tests 5 and 6: 0.1 and 0.25 l/min inflow

Test 5

Test 5 was supplied with water at a rate of 0.1 l/min, at 1.8 m distant from the rear of the chamber and 1.5 m above the floor. This was the lowest inflow rate examined in this study and outflow was observed after approximately 24 hours of operation. Outflow began at the pellet-block boundary close to the point at which the vertical side walls met the curved roof region of the chamber. This exit point moved towards the pellet-chamber wall contact with time and by 48 hours the flow path appears to have stabilized to a single location along the wall – pellet contact at approximately the elevation of the inlet port. At the end of 5 days (~ 120 hours of operation) the water supply to the test was discontinued and dismantling began. The water content data is provided in Appendix B and from this information it is possible to quantitatively assess water uptake and flow paths. From these data it was possible to develop a general understanding of the flow path present and its evolution, provided as Figure 6-7.

Figure 6-6 shows that there was only limited water inflow into the block-filled region via the block joints and that is likely occurred for only a short time at the start of testing (partially dried wetting locations). There was a higher degree of water movement towards the rear of the chamber than was evident in previous tests with water tending to pool as a perched water table in the rear of the cell. Unlike previous tests, there is clear evidence of a developing hydraulic connection between the two sides of the chamber. There was no apparent fluid flow occurring between the two sides at the end of the test but wetting was clearly occurring along the crown of the chamber, likely from Test 6 (right side) towards the left (Test 5). This is discussed further in the discussion of Test 6 and in Appendix A.

There was little evidence of ongoing erosion along this pathway (clear outflow) although material was removed by water flowing down the face of the assembly. Test 5 and Test 6 were equipped with independent water collection systems that operated correctly. At the end of its operation Test 5 was discharging 77% of its inflow via the front face at an elevation of approximately 1.8 m. Details on the hydraulic behaviour of this test are provided in Section 6-2.

Figure 6-6. Wetting along crown of Assembly 3 (Tests 5, 6). (Note dry (empty regions along walls) and wetting (darker regions) along crown.

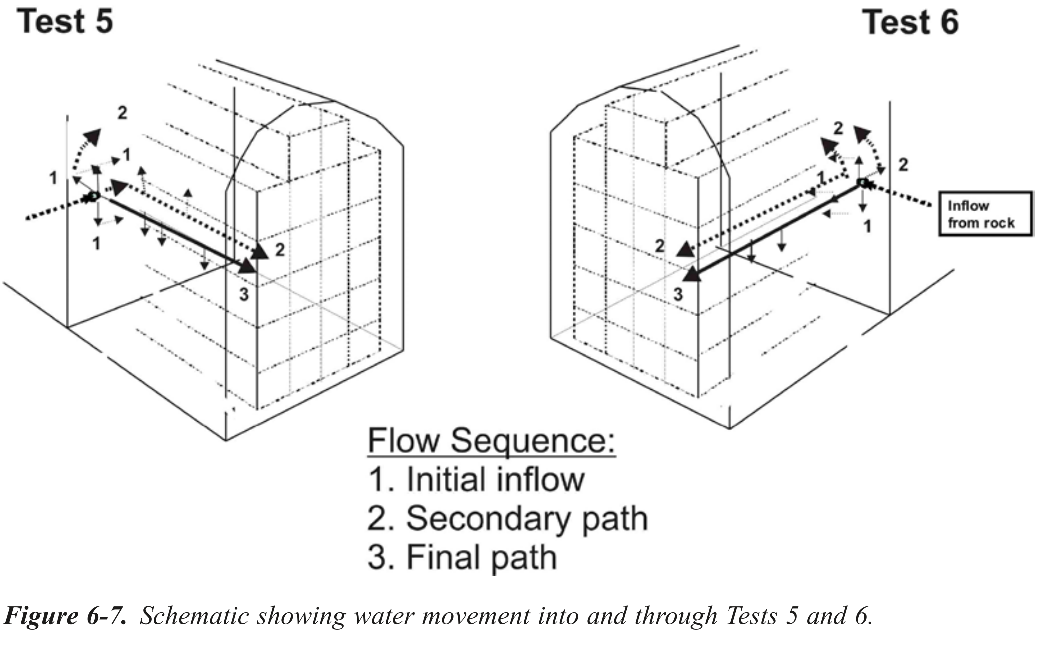


Figure 6-7. Schematic showing water movement into and through Tests 5 and 6.

Test 6

Test 6 operated at an inflow rate of 0.25 l/min at 1.8 m distance from the rear of the chamber, 1.5 m above the floor, for a total of 5 days. Outflow occurred after 21 hours of operation. The downstream face of the test showed the same pattern of water outflow (water exiting along steel wall-pellet interface at approximately the inflow port elevation) as was observed for most other tests.

At the end of its operation Test 6 had 76% of its inflow exiting the front face of the assembly via a single flow channel. Although a large volume this meant that Test 6 was supplying as much as 3.6 l/h to the still-dry portions of the assembly. Over the course of 5 days this represents 432 l of water retained within the assembly. Resistance to water inflow and erosion are discussed in detail in Section 6.2 and 6.3 respectively.

At the end of water inflow testing the assembly was dismantled and samples were recovered to quantitatively assess water distribution. The data collected are provided in Appendix B. In general, the water distribution pattern is similar to that observed in previous tests with one exception. There is a clear wetting process that has occurred in the pellet filling towards the rear of the chamber, particularly along the chamber roof and the pellet filling. There is a continuous layer of moistened pellets along the roof in the rearmost 1 to 2 m of the test and wetting upwards into the pellets in the lower crown region is occurring (Figure 6-6). The shape of this wetting feature indicates flow from the right-hand side (Test 6) towards the left (Test 5). This indicates that initially unconnected inflow locations may eventually merge into a single flow path. A schematic showing the interpreted water inflow and through-flow patterns in this test is provided as Figure 6-9. Further details of the water distribution and test evolution are provided in Appendix A.

6.1.4 Assembly 4: Tests 7 and 8: 0.25 and 0.5 l/min inflow

As noted previously, Tests 7 and 8 differed substantially in their construction from the previous tests of this study. They contained limited (or no) block materials, relying instead on the geotextile liner to prevent flow towards the core of the assembly. The focus of these tests was on the pellet filler materials, installed in a single process, much the same way as envisioned for application in an actual tunnel. The previous 6 tests provided strong evidence that the block fill component has minimal effect on the initial water movement through the simulated backfilled tunnel volume, thereby justifying reducing (or eliminating) that component of the assembly.

Test 7

Test 7 was supplied water at a constant rate of 0.25 l/min at 1.8 m distance from the rear of the chamber and at an elevation of 1.5 m from the floor. Outflow from the front of the assembly was detected at 28 h into its operation, beginning at the pellet-chamber wall contact approximately 0.8 m from the floor and continued from this location for the remainder of the test (Figure 6-8). There was no evidence of water movement along the pellet-geotextile contact at the downstream face during the test's operation.

Test 7 showed more uniform wetting than had been seen in previous tests, the downstream face was wet to an elevation of approximately 1.8 m. Wetting was somewhat less uniform but still extensive for the entire length of the assembly with a tendency towards reduced height of wetting towards the rear of the test. There was also limited movement of water upwards into the crown regions. These visual assessments were supported by the results obtained from physical samples recovered during test dismantling. Details of the water content distribution are provided in Appendix B and further information on and photographs of test is provided in Appendix A. Figure 6-9 provides a schematic showing the pattern of water uptake and movement.

This test showed inconsistent outflow rates, with water outflow oscillating for much of the first 2 days of outflow. This is perhaps evidence of internal channelling of water or more uniform movement of water into the pellet-filled region, rather than simple outflow from the established flow path. Detailed assessment of the water inflow behaviour based on inflow resistance is provided in Section 6.2 and erosive activity is discussed in Section 6.3.

Initial outflow from Test 8 (right) *End-of-test outflow locations*

Figure 6-8. *Front Face of Tests 7 and 8 at the start of outflow and end of testing.*

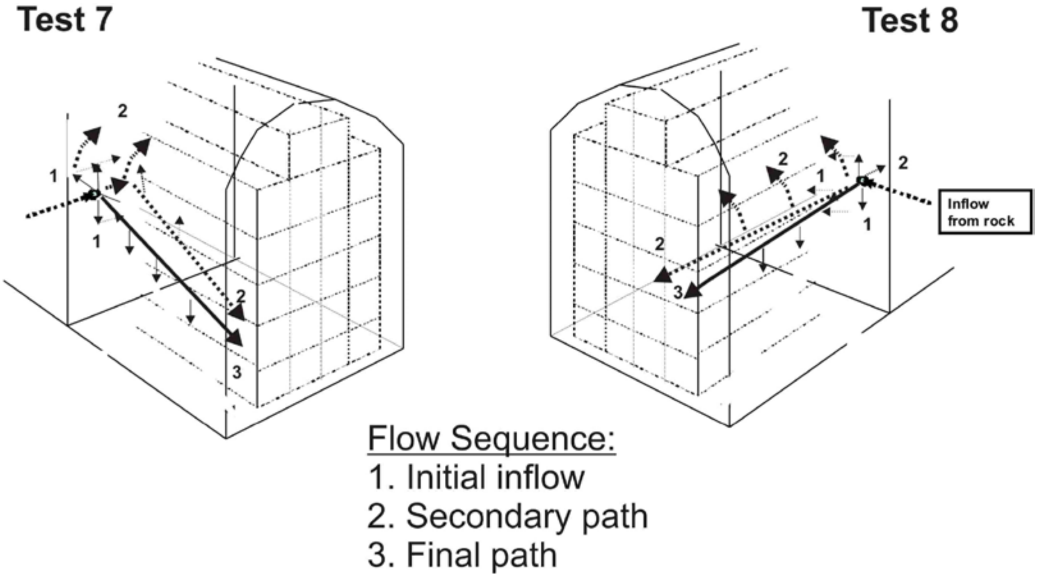


Figure 6-9. *Schematic showing water movement into and through Tests 7 and 8.*

Test 8

Test 8 was supplied water at 0.5 l/min at 1.8 m distance from the rear of the chamber and an elevation of 1.5 m from the floor. Outflow began at approximately 8.5 h into its operation, beginning at a single point, approximately 1.5 m from the floor of the chamber at the pellet-block contact and shifting to the pellet-chamber wall contact within a day (Figure 6-8). Although water was not actively flowing along the pellet-block interface, the persistence of a dark, wet contact indicates at least some moisture was continuing to reach this contact.

Wetting of the pellet fill in Test 8 was quite uniform in the lowermost 2 meters of the assembly, only the rearmost meter of the assembly exhibited limited water uptake, a feature commonly observed in other tests. There was essentially no movement of water into the crown regions of this test, despite the large quantities of water supplied to the system (0.5 l/min). Samples recovered during the dismantling of this test confirm this observation. The results of the water content tests are provided in Appendix B. Observations made in the course of the test and during its dismantling have been used to produce a schematic showing the likely water influx and through-flow patterns in this test (Figure 6-9).

Resistance to water inflow was monitored throughout the conduct of this test and the results are discussed in Section 6-2. There was also limited but discernible erosive activity, with the loss of a small quantity of pellet materials (determined by is lighter colour) over the course of the test. Much of the material that accumulated at the toe of the assembly was the result of water moving down the vertical face of the assembly and bentonite pellets swelling at the downstream face as can be seen in Figure 6-8. Erosion within this test is discussed in Section 6.3 and further photographs and text describing the evolution of this test are provided in Appendix A.

6.1.5 Assembly 5: Tests 9 and 10: 2.5 and 2.5 l/min inflow

As noted previously, Tests 7 through 10 differed substantially in their construction from the first 6 tests in this study. They contained limited (or no) block materials, relying instead on the geotextile liner to prevent flow towards the core of the assembly. They also had a 50 mm – thick layer of pellet materials installed on the floor of the chamber, on which the remainder of the test was constructed. The focus of these tests was on the pellet filler materials, installed in a single process, much in the same way as envisioned for application in an actual tunnel. The previous 6 tests provided strong evidence that the block fill component has minimal effect on the initial water movement through the simulated backfilled tunnel volume and so it could be safely excluded from these tests.

Test 9

Test 9 had water supplied at a rate of 2.5 l/min via an inlet port located at the rear of the chamber 0.3 m above the floor and 60 mm in from the sidewall. This test did not run for the planned duration due to development of an internal leakage path that exited on the floor of the assembly within the wooden framework. The result was water exiting the test without being forced to flow through the assembly to the downstream face. As a result, there was a risk to Test 10 and so water supply was discontinued after only 17.5 hours of operation.

Although this part of Assembly 5 was not operated beyond the first few hours, water was noted to be starting to exit the test in the lower pellet-filled region close to the floor of the chamber after approximately ½ hour of operation. This test was photographed and sampled for water content distribution and in the course of dismantling the assembly. The observations made during testing and the results of the post-test sampling are provided in Appendix A and B respectively. There were essentially only a few pockets of still-dry materials, largely in the rear surrounded by wet materials. Considerable portions of the materials installed on the floor were also still dry at the time of test termination. Overall, Test 9 showed that in a region where excessive water inflow is occurring, the majority of the pellet fill can wet quite quickly (with the possible exception of flooring materials). Water will also move rapidly through the backfill with the majority of flow occurring along the outer perimeter of the backfilled regions. Tests 9 and 10 also show that there may be a tendency for the backfilled tunnel to develop more than one flow path under conditions where there is very high water influx as well as causing extensive erosion of the backfill.

Unlike previous tests there is a clear hydraulic interaction between the two sides of Assembly 5. In the final two days of operation of Test 10, there was a clear wetting upwards in the assembly, with water moving along the pellet-chamber crown interface and then moving both forward in the assembly and as well as downward along the side of Test 9 (red-circled areas in Figure 6-10). Along the base of the test the degree of wetting is inconsistent, likely as this was the region where water first entered the test while water was being supplied to Test 9.

Although operated for only a few hours this test provided information, via inflow resistance monitoring, with regards to development of preferential flow channels. This is discussed in greater detail in Section 6-2. Also as a result of the short duration of the test, erosion measurements could not be collected, however visual monitoring during the initial stages of the test indicates the start of developing erosive flow path(s) (seen as material deposited at toe of assembly (Figure 6-10 left photo, bottom left corner). This is discussed in more detail in Section 6.3. "This test was photographed and sampled for water content distribution and in the course of dismantling the assembly. These results are provided in detail in Appendix A and B respectively. "

Test 10

Test 10 operated at a water inflow of 2.5 l/min from a point 1.8 m above the floor and 60 mm in from the chamber's sidewall (3.9 m distance from front face), for a period of 65 hours. This test had water outflow that started between 30–90 minutes after water was turned on. Initial outflow also occurred at approximately the same elevation as the inlet port. Figure 6-10 shows the downstream face of the test assembly at the time of first outflow and again at the end of testing.

Figure 6-11 shows the large quantity of material that was moved out of the assembly. Water moved out of the assembly through the pellet fill along the pellet-chamber wall interface via a small channel (approximately 5–10 mm in width) that extended at approximately the same elevation as the inflow location. The water exiting the front face was moving at a rate fast enough to erode and remove materials at the downstream face, resulting in an increasingly large hollow near the face of the backfill. After approximately 2 days of operation, this erosion resulted in the collapse of a considerable volume of pellet material that had been left suspended above the downstream face of the assembly (final photos in Figure 6-11).

The water moving through this assembly did not move uniformly through the pellet-filled material. Near the inflow location and for a distance extending at least 2 m along the test-length water was moving along the geotextile-block contact and causing considerable wetting and erosion of this region (Figure 6-12). At about 2 m distance the flow moved into the pellet filled region, locating at the pellet-chamber interface by the time it exited the front face. This is indicative of a system that was undergoing internal block erosion due to high water flow. This is discussed in greater detail in Section 6.3 and in Appendix A.

It was also evident that the inflowing water was moving upwards into the crown regions and that additional flow paths were developing along the uppermost pellet-block interface and also along the pellet-chamber roof interface (Figure 6-10 and 6-11). Sampling of the pellet-filled portions of the test during dismantling was done as for previous tests and allowed the visually-observed wetting patterns to be quantified. These data, provided in Appendix B confirm the patterns visually evident at the time of dismantling and were used in developing a water movement schematic for this test (provided as Figure 6-13).

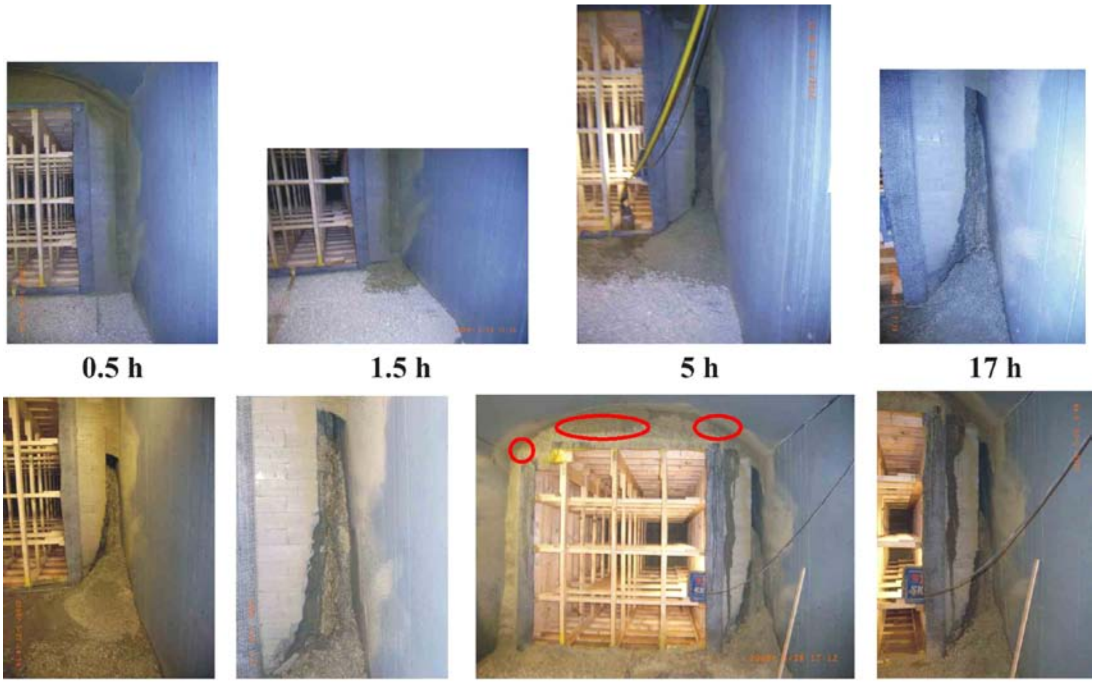
Test 9 *Test 10*

Start of Test

Test 9 *Test 10*

Prior to Test Termination

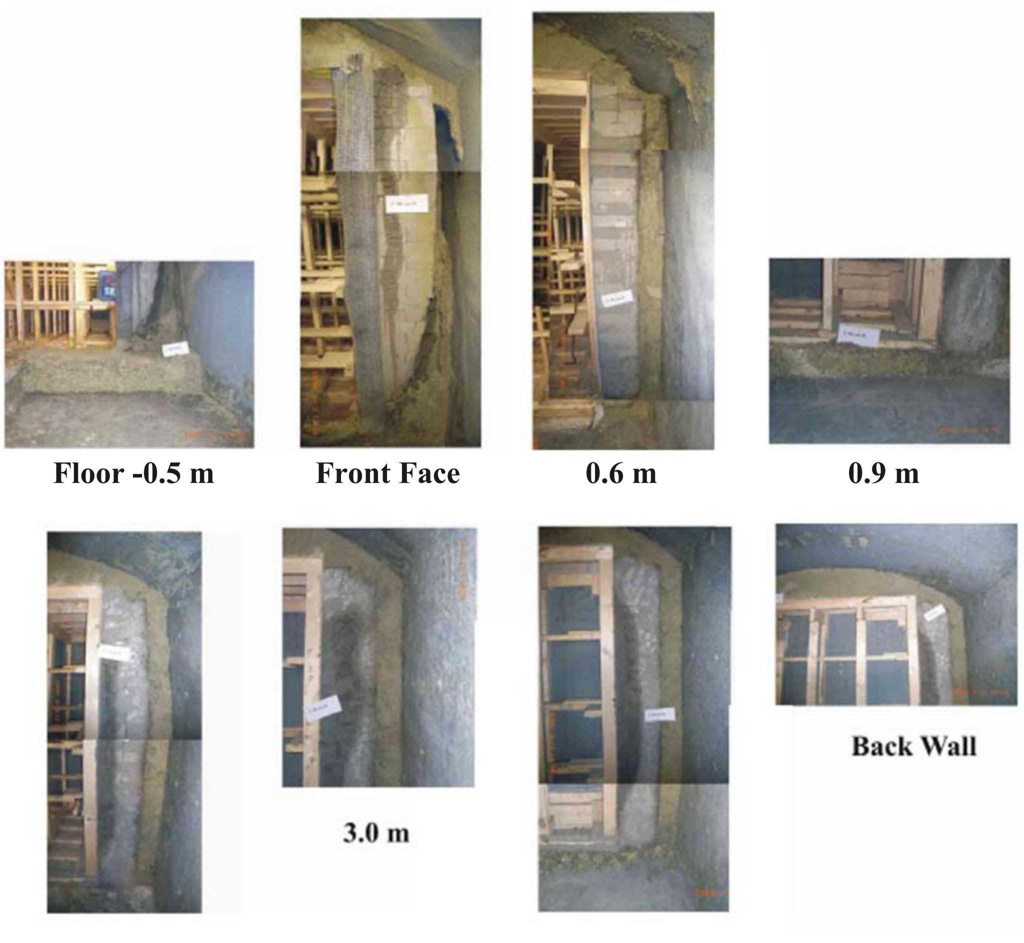
Figure 6-10. *Downstream face of Assembly 5 (Tests 9, 10).*



0.5 h 1.5 h 5 h 17 h

24.5 h 41.5 h 50 h 66 h

Figure 6-11. *Front face of Test 10 showing developing erosion of pellet materials.*



Floor -0.5 m Front Face 0.6 m 0.9 m

2.5 m 3.0 m 3.6 m Back Wall

Figure 6-12. *Profile through Test 10 showing wetting of blocks (Note wetting along geotextile-block contact in rear-most 2 m of test).*

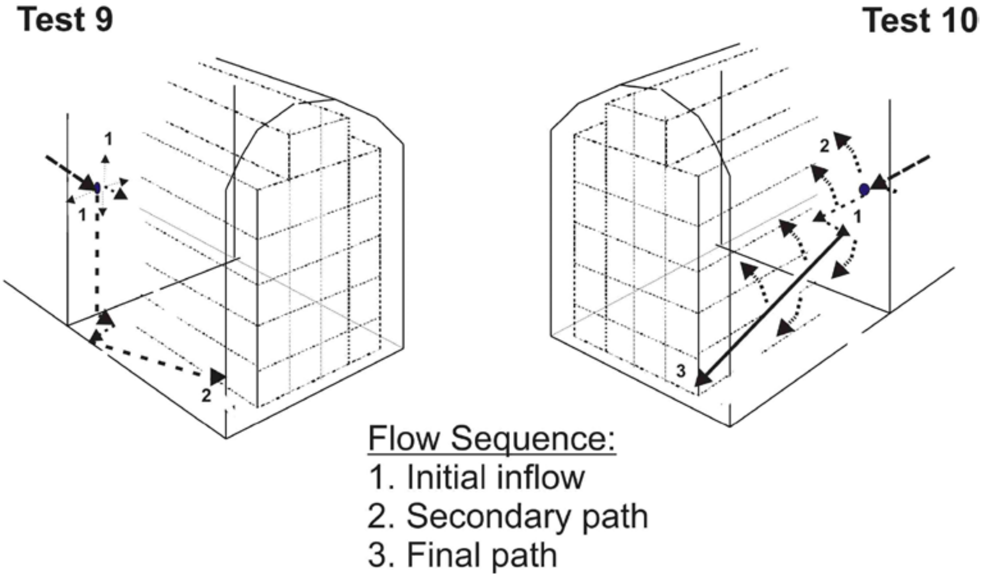


Figure 6-13. *Schematic showing water movement into and through Tests 9 and 10.*

In addition to the materials visible in Figure 6-11, there was considerable additional clay that was moved into the outflow containers. The water exiting Test 10 carried with it a substantial sediment load. The exiting water-sediment mixture contained a combination of block and pellet materials (as evidenced by their different colours and textures), indicating ongoing erosion of the entire backfill. The eroded materials also resulted in the redirection of a portion of the outflowing water, resulting in the flooding of the floor of the wood-framed central void in the Assembly. This water represents several hundreds of litres of outflow volume that was not captured by or recorded in the outflow measurements. Details of the outflow monitoring are provided in Section 6-2.

6.1.6 Assembly 6: Tests 11 and 12: 0.25 and 0.5 l/min inflow

Tests 11 and 12 were installed in a manner similar to that of Tests 9 and 10, with a wetter pellet material used on the downstream face to facilitate filling of the volume using blown pellets. The flooring pellets were extended beyond the front face of the assembly, simulating the conditions that might be expected to exist in an actual repository tunnel where pellets are used to level the floor and on which the clay blocks would be placed. In this assembly, a stiff-mesh was installed to support the front of the assembly, largely to reduce masking of wetting patterns due to water flow down the front of the assembly. Water was supplied at 1.8 and 0.3 m elevation from the rear of the chamber at inflow rates of 0.25 and 0.5 l/min respectively for a period of seven days, at the end of which time just prior to dismantling dyed water was supplied via the injection ports to trace the end-of-test flow path(s).

Test 11

Test 11 was provided with water at a rate of 0.25 l/min at the rear of the chamber, from a point 1.8 m above the floor and 60 mm in from the chamber's sidewall (4 m distance from front face), for a period of 7 days (168 h). This test had water outflow noted after approximately 20 hours of operation, exiting from a small region of the assembly in the upper region, slightly to the left of the centreline (Figure 6-14). This is the only test that showed actual outflow from the upper regions of the assembly.

Figure 6-14. *Assembly 6 (Tests 11 and 12) at the end of testing Test 12.*
(Note blue tracer exiting a crown of chamber).

It would appear that the inflow rate was sufficiently slow that the pellet-filled region was able to swell and seal off flow along the left side of the assembly. Associated with this point outflow, there was a dampened perimeter noted along the roof of the chamber on the left side of Assembly 6 (Test 11) but it did not produce any measurable liquid. This type of thin-film flow was not noted in any previous tests and is described in more detail in Appendix A. By 67 h into the test the flow along the crown of the chamber had localized sufficiently to be exiting the chamber at a single location. Between 67 h and the end of this test at 168 h, water moved along this pathway, falling to the floor of the chamber where it accumulated and subsequently flowed into the collection system. Test 11 was the only test to exhibit channelling along the crown of the test chamber, although Test 10 did show water movement into that region after two days of inflow at 2.5 l/min.

Dismantling of the test was done as per previous tests and the measured water contents through the assembly are provided in Appendix B. Visual examination during dismantling determined that there was essentially no water movement in the lower-most portions of the test with only the front face and rear-most regions having undergone any substantial wetting. Although water clearly moved into the crown regions of Test 11 and flowed forward and out of the assembly, there was only a limited degree of wetting in the pellet materials in this region (details are provided in Appendix A). The water flowing along the crown of the chamber was not moving readily into the pellet materials and wetting seems to have been limited to what the pellets could draw in as the result of their suction potential (see Chapter 7 for further discussion).

The water movement patterns developed through observation and measurements are provided in a schematic as Figure 6-15. Development of this schematic was greatly assisted by the pathway highlighted by the visual tracer injected at the end of testing (see Section 6.2 for discussion).

Test 11 had its resistance to water inflow monitored throughout its operation and showed behaviour consistent with a system that developed a low-resistance piping feature, through-which all but the water drawn into the pellets by suction forces would flow. This is discussed further in Sections 6.2 and Chapter 7.

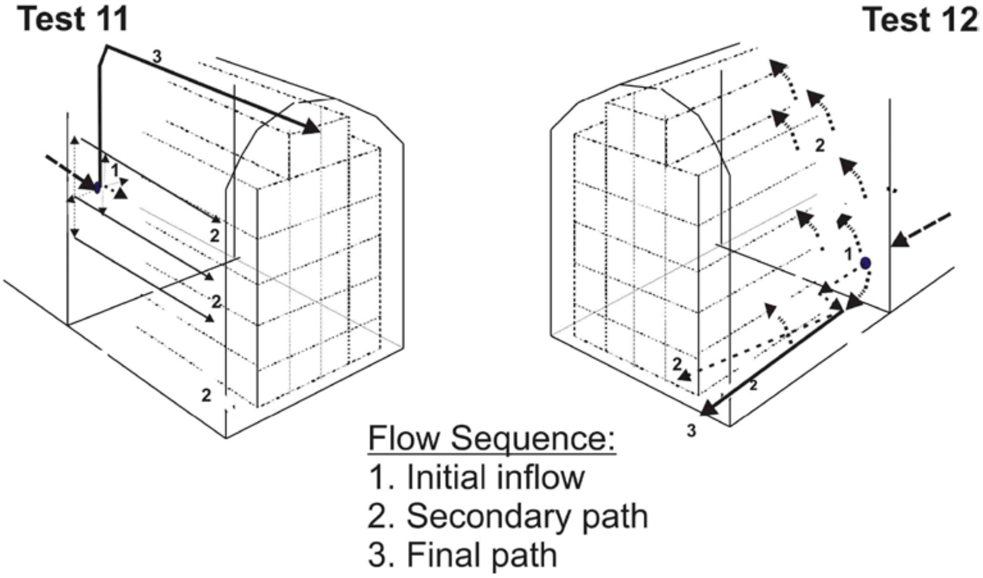


Figure 6-15. Schematic showing water movement into and through Tests 11 and 12.

Test 12

Test 12 operated at a water inflow of from the rear of the chamber, from a point approximately 0.3 m above the floor and 60 mm in from the chamber's sidewall (3.9 m distance from front face), for a period of 168 hours. This inlet location was therefore at or near the pellet-block contact.

This test had water outflow noted after approximately 24 hours of operation. Initially outflow was along the chamber – pellet contact as a damp film as can be seen in Figure 6-16 (circled in red). At 40 h, liquid water outflow was noted along the pellet – block contact at approximately 0.1 m elevation (red circled). This outflow location remained at this elevation for the remainder of the test, shifting towards the pellet-chamber wall contact by 67 h after which it did not move further. Details regarding the properties of this test and water content distribution measured during dismantling are provided in Appendix A.

Test 12 had a coloured dye (pink) added to the inflow water for the final 5 minutes of test operation in order to visually confirm the flow path through the test. The pink dye was a simple water-soluble ink that was strongly enough coloured to allow visual tracing of the flow path. The front face of the test at the time of tracer exit is shown in Figure 6-14, clearly showing a single flow path, located at the pellet-chamber wall contact was active at the end of test termination. Further discussion of water movement into and through the test is provided in Section 6.2 and 6.3.

The resistance to water inflow was monitored throughout this test and is discussed in Section 6-2. In general the test showed typically variable resistance to inflow for the first 2 days of operation and a relatively stable and less than peak resistance for the remainder of the test.

Figure 6-16. *Face of Test 12 showing damp surface exiting pellet fill.*

6.2 Inflow resistance and water uptake

6.2.1 Inflow resistance

The tests done in the ½-Scale chamber had resistance to water input monitored for the entire duration of each test. This resistance was defined as the backpressure present in the water at the point of inflow. These data provide valuable indirect measurement of the manner in which water moves into the pellet-filled mass and how progressive bentonite pellet saturation affects water movement. The evolution of inflow resistance also provides a measure of the timing and nature of channelled flow through the test.

It was previously observed in smaller-scale tests that development of preferential flow channels result in a decrease in flow resistance. Erosive channelling and piping typically result in unstable resistance (pressure fluctuations) as materials are moved and removed from vicinity of the flow path. This can sometimes be associated with changes in the inflow-outflow balance but most often is seen in as a dramatic change in the inflow resistance. Non-erosive channelling is typically associated with stable inflow resistance and a steady-state flow rate (stable inflow ~ outflow). The resistance to water inflow to the chamber for each of the twelve tests done in this study is summarized in Table 6-1 but more informative with regards to the initial water movement within each test than maximum and end-of-test resistance is examination of the resistance versus time for each test.

Figure 6-17 presents the inflow resistance data for the first 6 tests done in the half-scale chamber and Figure 6-18 provides data from the last 6 tests. The inflow resistance data shows the same generic patterns observed in previous smaller-scale tests. There was a fairly rapid development of resistance to inflow until the system is able to develop a preferential flow path to the front face of the chamber. The tests all showed occasions where these channelling events occurred and inflow resistance changed rapidly. The magnitude of resistance to inflow for all these tests was relatively low, never exceeding 100 kPa and typically in the order of 25 to 50 kPa. In two cases (Tests 3 and 7) the longer-term inflow resistance decreased to less than 20 kPa, indicative of an open, stable flow path.

Table 6-1. Inflow resistance observed and break-through time for water.

Test #	Inflow rate (l/min)	Distance inlet to outlet (m)	Testing time (hrs)	Time to first outflow (hrs) **	Highest resistance to inflow (kPa@hrs)	Inflow resistance at end of testing (kPa)	End-of-Test flow path location	End-of-Test outflow rate (%)
1	0.25	1.9	120.17	< 24* (12 h ?)	44 @ 110	44	sidewall	84[+]
2	0.5	1.9	120.17	< 24* (11 h?)	42 @ 110	42	sidewall	84[+]
3	0.5	1.9	116.85	5	42 @ 2.5	20	sidewall	87[++]
4	1.0	1.9	116.85	2.5	45 @ 24	25	sidewall	87[++]
5	0.1	1.9	109.75	24	62 @ 24	42	sidewall	77
6	0.25	1.9	109.75	21	55 @ 110	55	sidewall	76
7	0.25	1.9	108.5	28	43 @ 24	11	sidewall	72
8	0.5	1.9	108.5	8.5	47 @ 2.5	32	sidewall	90
9[***]	2.5	3.9	17.5	0.5	69 @ 1.5	35–40	NM	NM
10	2.5	3.9	65	0.5	81 @ 1.9	45	sidewall crown	84[+++]
11	0.25	3.9	168	20	72 @ 12.4	45	crown	94
12	0.5	3.9	168	24	98 @ 4	75	sidewall	83

NM Not measured, water supply discontinued after 17.5 hours.

* Outflow first noted, outflow detection system not installed in Assembly 1.

** Outflow time based on signal from conductivity meter located 2 m away from assembly face and as a result first outflow may have occurred several hours before signal triggered but flow was insufficient to reach outflow detection meter.

[***] Test developed severe leak past restraint system and was discontinued after 18.5 hours.

[+] Separate outflow collections systems not installed for Assembly 1.

[++] Mixing of outflow from two sides of Assembly 2 as result of seepage at downstream face, only overall flow quantity measurable could be made.

[+++] Large eroded sediment quantity made measurement of outflow difficult, actual amount likely higher.

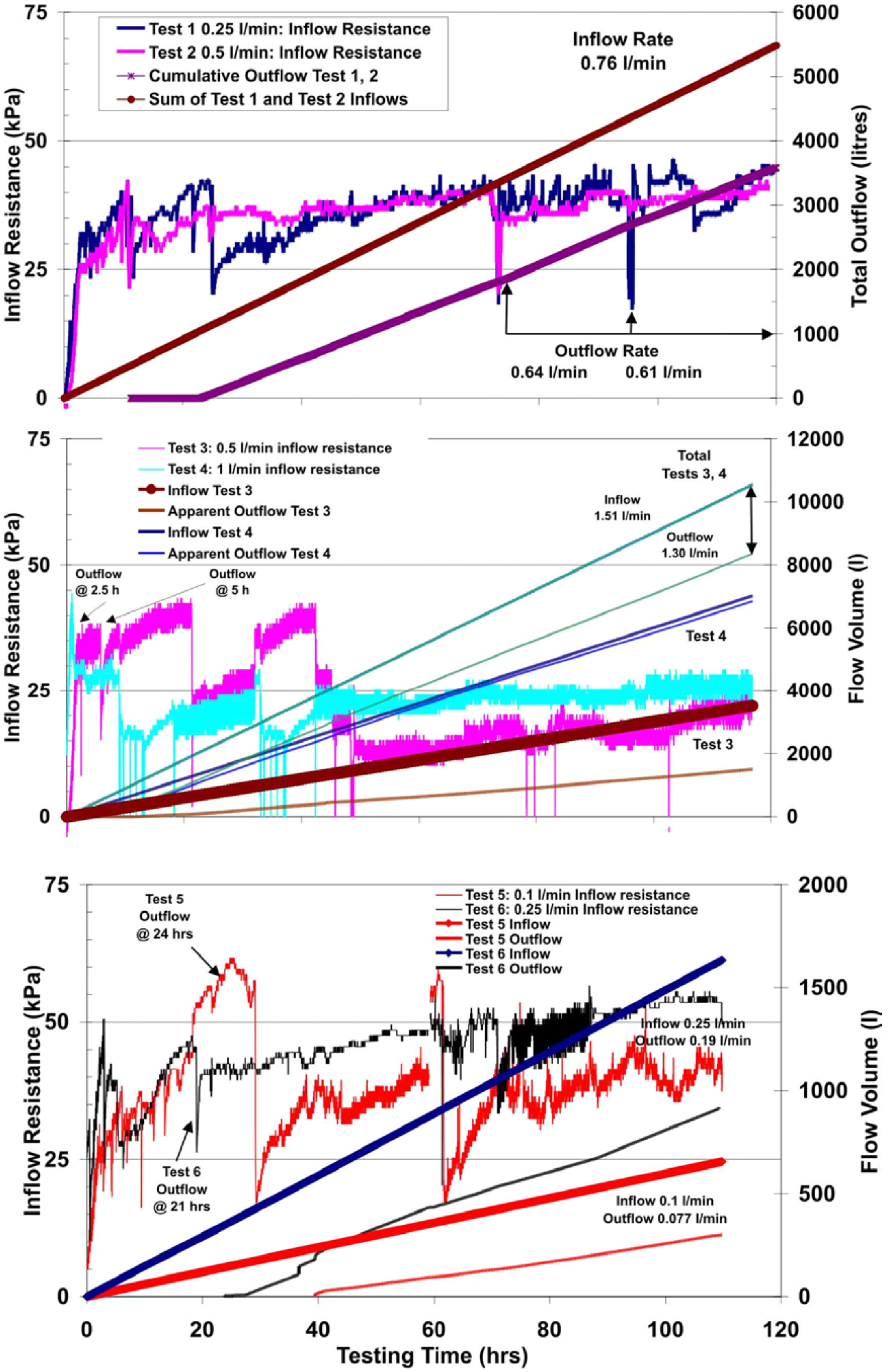


Figure 6-17. *Resistance to water inflow and inflow/outflow for Tests 1 through 6.*

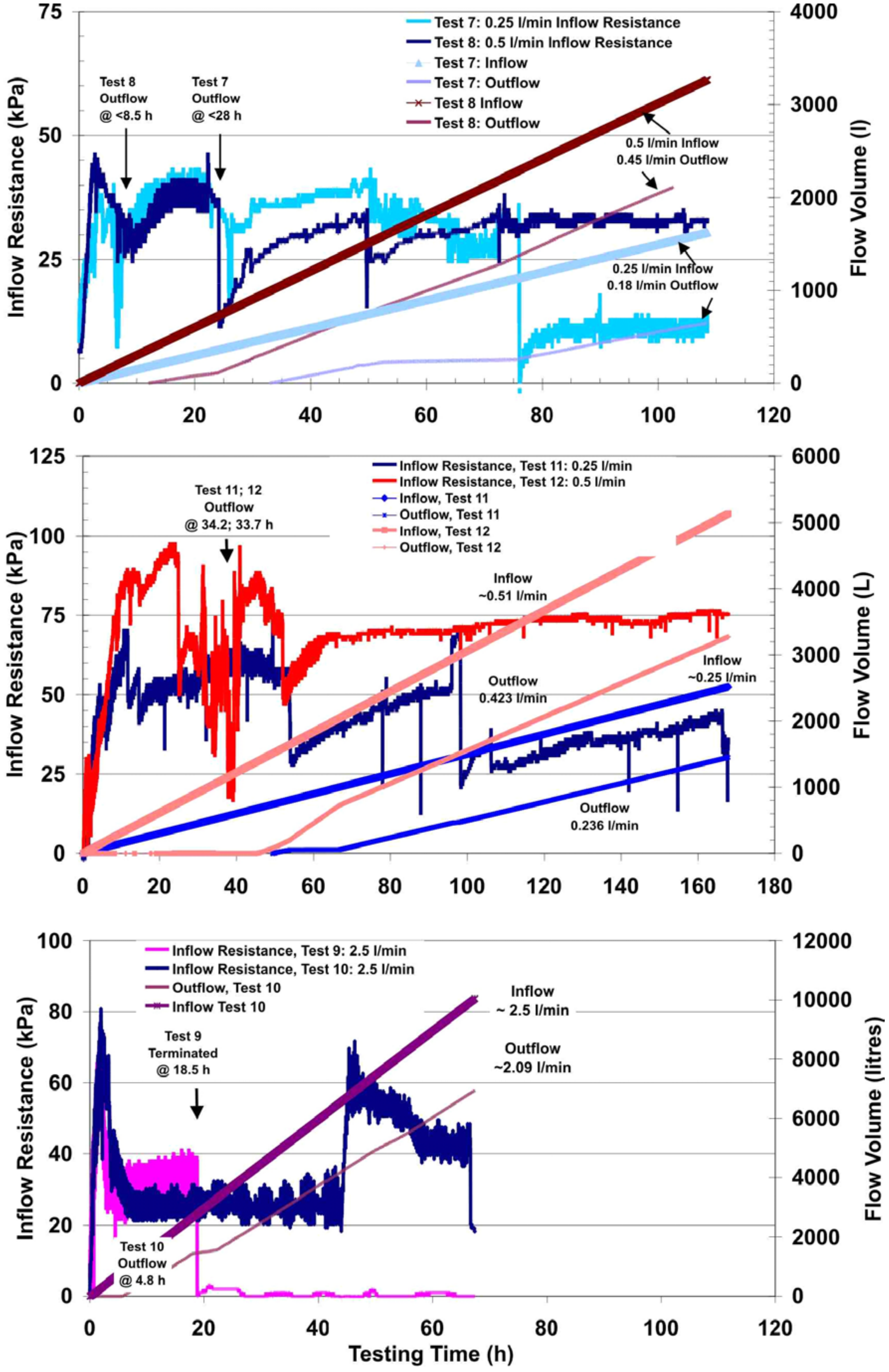


Figure 6-18. *Resistance to water inflow and inflow/outflow for Tests 7 through 12 (Tests 9-12 had water supplied at rear of chamber rather than at midpoint).*

As a first step in developing a conceptual model for water movement into and through a confined pellet fill it is necessary to look at the process as an interaction of processes that have different importance at different stages of system development. Evolution of the system will depend on a range of factors including both macro and microstructual factors including (individual pellet dry density and water content, as-placed pellet-fill density, fines content and mineralogical composition of the clay). Conceptually, the basic evolution of the system can be described as follows:

1. In the earliest stages, inflow will be controlled by the macro-structural features such as macroporosity and tortuosity. Thus the amount of initial water uptake can be greatly affected by rate water ingress, fines content (providing initial resistance to inflow). If water enters sufficiently rapidly and other factors are "favourable" then it has the potential to occupy a substantial portion of the macro-porosity before swelling begins.
2. Once water has entered the system, secondary processes such as mineralogy and associated processes such as suction of the individual pellets will begin to affect both water movement and water uptake.
3. Swelling of the pellets will reduce macro-porosity and begin to change the nature of water movement into the pellet-volume from an advection-dominated process to one dominated by suction from the as-yet unsaturated pellet mass.
4. The lower permeability of the volume occupied by the swelling clay results in increasing resistance being developed to further water inflow.
5. With this resistance and the heterogeneous nature of the pellet fill with respect to saturation, many changes in the pathway taken by the inflowing water will occur, resulting in oscillations in inflow resistance.
6. Depending once a sufficient volume is wet to provide a consistent resistance to flow, water will tend to move along the next-lower pathway (an interface).
7. The process of wetting and swelling adjacent to the source of water will ultimately result in a system where the path for water movement reaches the downstream face of the cell.
8. On reaching the downstream face hydraulic gradient will decrease due to loss of backpressure induced by low permeability clay, resulting in a decrease in inflow resistance.
9. Water movement will then be dominated by the channel developed.
10. Provided that inflow rate is low enough that turbulent flow is avoided the flow path will remain relatively stable and non-erosive.
11. For a period following the development of the hydrated zone around the flow path there will be further water uptake by the as-yet unsaturated clay further away from the source of free water. The quantity of ongoing water uptake will be rather small as it is driven by the suction gradient between the saturated region and the as-yet unsaturated regions.
12. Ultimately, on achieving saturation there will no longer be a demand for water from the perimeter regions and all water inflowing will move along the established flow channel, so long as there is unrestricted outflow at the downstream face.

The development of a basic conceptual model for system evolution aside, the basic conclusions that can be derived from the inflow resistance data are:

1. A pellet-block backfilling system cannot be relied on to substantially delay water movement to the front face of a backfilled section of tunnel, and
2. There is unlikely to be any substantial build-up of porewater pressure within the backfill during the period of backfilling.

This is important in two ways, firstly the water entering the tunnel will need to be dealt with within a short time of backfill placement (few hours to a few days) and secondly it is unlikely that there will be substantial deformation of the backfill as there will be no build-up of water or (air compressed by water influx). This provides additional confidence in the ability to install a mechanically stable backfill system although there is still a need to ensure that there is no opportunity for internal erosive pathways to develop. Test 10 demonstrated the potential risk to the backfilling system should very high, localized flow occur.

6.2.2 Outflow rate

The manner in which water moves into and through the test assemblies provides valuable information on the early evolution of a backfilled emplacement tunnel. The twelve tests done in the ½-Scale Chamber exhibited extremely consistent outflow behaviour. These tests showed a tendency towards development of preferential flow channels along their outer perimeter, with a general lack of substantial ongoing erosive behaviour at single-point of inflow rates of less than 0.5 to 1.0 l/min. At inflow rates exceeding this value there was a discernible change in the ability of the assembly to resist erosion induced by the water entering and flowing through a backfilled volume.

At inflow rates of less than 1 l/min these larger tests also did not show the type of ongoing internal erosion (of block materials) observed in smaller-scale tests /Dixon et al. 2008ab/. It may be that there is a minimum thickness of pellet materials needed to overcome disruptive initial water movement inwards to the clay-block-filled region, or that the previous tests did not have a sufficiently long path length to allow for water to migrate to the perimeter. It was evident in previous studies that the volume occupied by clay-blocks, are much more susceptible to channelling and erosive flow (particularly along joints between blocks), in the early hydration phases than the pellet-filled regions. As a result any means for designing or installing backfill that results in protection of the blocks during the period immediately following their installation is desirable.

For a point inflow rate in the order of 2.5 l/min at a distance of 2.2 m from the downstream face (Test 10), the backfilled volume proved unable to resist erosion and experienced considerable material loss as a result of water inflow. While the overall backfilling system did not experience physical disruption, the loss of pellet materials was substantial, resulting in a considerable reduction in the amount of material available to ultimately swell into that volume.

Figures 6-17 and 6-18 also present the inflow/outflow balances for those tests where it was possible to measure outflow. As was noted previously, Tests 1 through 4 did not have water collection systems installed that were capable of separating the flow from the two sides of the assemblies. As a result Assembly 1 (Tests 1-2) and Assembly 2 (Tests 3–4) can be considered as a simulation of full tunnel sections where there are water inlet points on either side of the tunnel. Water entering the tunnel moves independently from these two inlet points, staying on the side of the tunnel they initiated on and exit the face of the backfilled volume in two separate locations. The total quantity/rate of water exiting the tunnel section is measured to be 84% and 87% for Assemblies 1 and 2 respectively.

By the end of testing, water outflow from Tests 1 through 8, 11 and 12 was uniformly confined to the pellet-filled region and occurred via small pipe-like channels that formed along the pellet-chamber contact. These features resulted in only a small quantity of eroded material being removed from the test assemblies. Were such a situation encountered in a repository tunnel, it is possible that water outflow of this nature could be handled relatively easily via a collection system. Test 10 was operated at very high inflow rate, resulting in extensive erosive flow through the pellet-filled region and would likely prove difficult to control in an operational situation.

Tests 5 through 12 had their inflow-outflow behaviour measured separately so somewhat more analysis can be done on these one-point inflow tests. Tests 5 and 6 showed very consistent outflow behaviour with 76% and 77% respectively, although after 2–3 days of flow the rate of through-flow was still gradually increasing. Tests 7 and 8 behaved much the same way as the tests that had a substantial clay block component. At the end of those tests the rate of outflow was 72% and 90% respectively for Tests 7 and 8. The rates of outflow for these tests were comparable to the other tests with a discernible proportion of the incoming water (10–28%) still being taken up by the pellet fill. This and the presence of occasional changes in the inflow resistance indicate that both capillary-type gradual water uptake and channelling in drier regions are still ongoing in these systems. It is clear however that the majority of the water entering the system will rapidly move towards the downstream face of the backfill at a clearly defined outlet and that the proportion exiting will gradually increase with time.

The similarity of the water uptake and outflow behaviour of Tests 1 through 6 to those for Tests 7, 8, 11 and 12 is further evidence that the blocks initially play little role in the movement of water through the backfilled tunnel for moderate inflow rates (< 1 l/min localized inflow). Early flow is controlled by and passes through the pellet-filled region so long as there is sufficient thickness to prevent development of flow channels into and through the backfill clay blocks. Since the blocks did not affect the water movement through the tests, Tests 9 through 12 were constructed using limited block thickness or no blocks at all. A summary of the outflow data is provided in Table 6-1.

The rate of through-flow at the end of the tests was substantial in all tests (72–94%) and was generally in excess of 80%.There was no clear relationship between the proportions of exiting and inflow volume, which is indicative of the limited ability of the pellet fill to take on water once an initial region adjacent to the inlet points has saturated. High outflow rates are established within approximately 24 h of outflow starting and are generally associated with the outflow locations becoming established at the pellet-chamber wall contact. That the outflow does not equal inflow is indicative of ongoing water movement into the still dry pellet-filled portions of the chamber. This may be through gradual wetting of the pellet fill through capillary-type water uptake (not associated with discernible changes in inflow resistance), or else through discrete break-through type movement into dry pockets or along newly formed pathways into the backfill (seen as sudden decreases in inflow resistance).

Test 10 showed a different behaviour to previous tests, inflow to the chamber occurred at a greater distance (4 m) from the working face and simulated a situation where flow had concentrated into a single unrestricted flow channel of 2.5 l/min and then contacted a previously unaffected (dry) section of backfill. In this situation it was observed that the inflow first moved through the pellets as it would through a gravel-like material, exiting the setup very quickly. Once swelling of the material adjacent to the flow path began, the outflow location shifted towards the chamber wall at an elevation of approximately 1 m from the floor. The exiting water rapidly eroded the materials at this location and formed a large, open void, through which the water flowed as shown in Figure 6-19. The exiting sediment-loaded water tended to deposit the clay as an accumulation at the downstream toe of the backfill face and to clog the water collection trays installed to capture the exiting water (see Figure 6-29). The removed material continued to swell in these locations, resulting in reduction of the collection system's capacity and difficulty for the pumps to remove this water. This required physical removal of the saturated sediment on several occasions, with associated loss of outflow water. The outflow volume for Test 10 provided in Table 6-2 is therefore an underestimate of the volume exiting the system (it is likely that the actual outflow volume was several hundreds of litres more than was measured).

Figure 6-19. *Sediment accumulation in collection trays in Test 10.*

Table 6-2. Water retained by pellet fill.

Test	Inflow rate (l/min)	Test duration (hours)	Water retained by test (liters)	Initial air voids (pellets)** (liters)	Initial air voids (system) (litres)	Initial saturation of pellets (%)	End-of-Test pellet saturation (%)***	End-of-Test system saturation (%)
½*	0.25/0.5	120.17	2,208	2,400	3,610	34	94	80
¾*	0.5/1.0	116.85	2,153	2,900	3,740	28	81	72
5	0.1	109.75	359	1,280	2,850	31	51	49
6	0.25	109.75	698	1,280	2,850	31	69	61
7	0.25	108.5	< 928	1,360	1,360	29	< 77	< 77
8	0.5	108.5	< 945	1,360	1,830	29	< 79	< 68
9+	2.5	17.5	----	1,480	1,480	26	----	----
10++	2.5	65	< 2,901	1,480	1,930	26	~ 100	~ 100
11	0.25	168	1,068	1,480	1,480	26	79	79
12	0.5	168	1,764	1,480	1,930	26	~ 100	94

* Separate outflow collection not measured, total of 2 tests provided.

** Calculated based on as-built measurements.

*** Assumes no water uptake by blocks or geotextile.

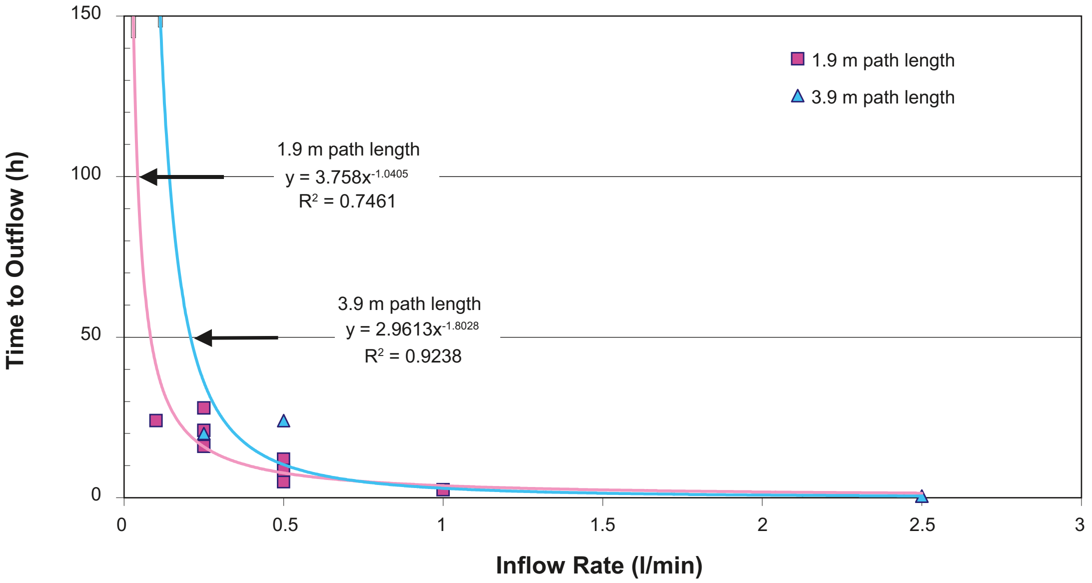
+ Test terminated at 17.5 hrs due to leak.

++ Actual water retained is lower, extensive swelling and erosion of clay resulted in considerable volume of water that did not enter collection system.

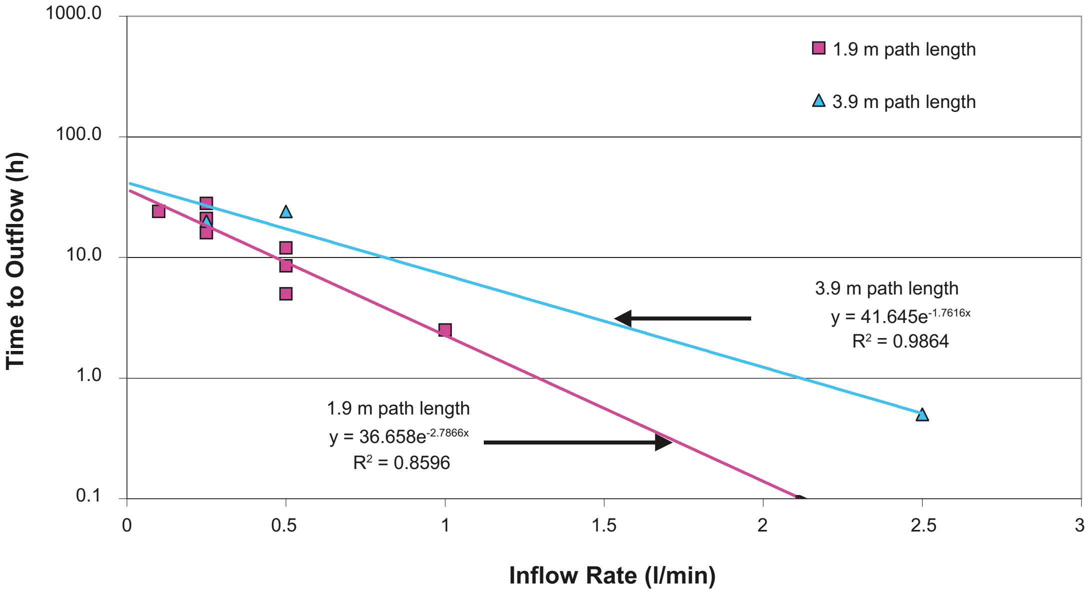
Tests 11 and 12 had water inlet points at the rear (3.9 m from face). Test 11 had the inlet located at an elevation of 1.8 m above the floor and approximately 60 mm in from the sidewall and supplied water at 0.25 l/min. The inlet for Test 12 was located at 0.3 m above the chamber floor and 60 mm from the sidewall and supplied water at 0.5 l/min. These tests were intended to simulate a situation where water was being supplied from different elevations and distances further from the downstream face of the backfilled volume than in previously completed tests done at the same inflow rate but a 1.9 m distance from the face (Tests 1, 6, 7 and Tests 2, 3, 8 respectively). Although there is only a limited body of data regarding inflow rate, flow path length and time to water discharge in the 1/2 – Scale Tests there are some trends evident.

The tests showed a longer time between start of inflow and initiation of outflow when the path length was increased (see Figure 6-20). This is not an unexpected result but in an ideal system it might be expected that a doubling of flow path length result in a doubling of the time to outflow, this was not the case in these tests. Similarly, a simple linear relationship between inflow rate and time to water discharge could be anticipated, but again while an increase in inflow rate resulted in a decrease in the time to outflow this relationship was not directly proportional. Factors such as density of the pellet fill, minor variations in the packing pattern of the pellets and inflow location all come into play in determining the time to outflow. Deviations from simple linear relationships in the flow rate – time to outflow and flow path length – time to outflow were particularly evident in the systems where the inflow rate was less than 0.5 l/min. It would seem that at lower inflow rates the effects of secondary factors such as texture and density play a greater role in determining outflow behaviour.

The results of similar, but smaller scale and shorter flow path tests done at Äspö /Dixon et al. 2008/ are consistent with those presented in Figure 6-20. These data will be discussed in greater detail in Chapter 7 of this report.



(a) Time to outflow from half-scale tests, linear plot.



(b) Time to outflow from Half-scale tests, log-linear plot.

Figure 6-20. *Relationship between time and outflow rate in Half-Scale tests.*

Viewed in context with the conceptual model for system evolution provided in Section 6-2, the outflow data indicate that the microstructurally-induced (suction) water uptake by the pellet-filled volume are a process that does not greatly affect system evolution in the early stages, unless the inflow to the pellet-fill are very low (< 0.05 l/min) at a single point. At such low inflow rates it would seem that much of the influx will be drawn into the pellet fill for a period of several days at least. Of course once the system has sufficiently saturated, water will tend to find a less resistant pathway to move along (rock-pellet contact).

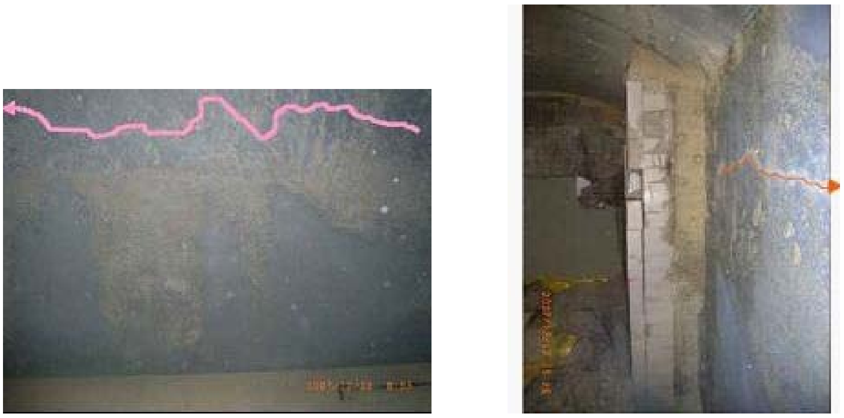
6.3 Erosion

As with previous, smaller-scale tests a key aspect in the conduct of the ½-Scale tests was monitoring of the amount of material eroded from these tests. In all cases where outflow occurred, there was some quantity of clay material removed. In general, the quantity of material removed by the water exiting the backfilled volume was quite small. Due to the large volumes of water passing through these tests and the tendency of this water to cause swelling of materials adjacent to the outflow locations it was not possible to get an actual measurement of the solids removed. It was possible to estimate the quantity in some cases based on the volume of materials deposited at the toe of the backfill wall. In cases where there were considerable quantities of materials removed it was not possible to do more than roughly estimate the mass removed. It should also be noted that these tests have been done using artifical boundry conditions (pellet-concrete or pellet-steel). These contacts are not necessarily representative of interactions that will occur in a rough rock contact, however it is likely that interface flow will dominate even the rock-pellet systems. Details of the erosion process and materials movement are provided below.

Most (8 of 11) of the ½-Scale tests lost in the order of 1 kg (or less), of clay material over the 3 to 7 days each operated. Often this material was removed as the result of exiting water flowing down the vertical face at the downstream face of the assembly rather than actually eroding materials from within the backfill. In this respect erosion was very similar to what was observed in smaller bench-scale and field simulations /Dixon et al. 2008ab, Sanden et al. 2008/. The majority of the material lost in the ½-Scale tests was bentonite fines, washed out of the pellet-filled volume or during initial formation of the piping features typically developed.

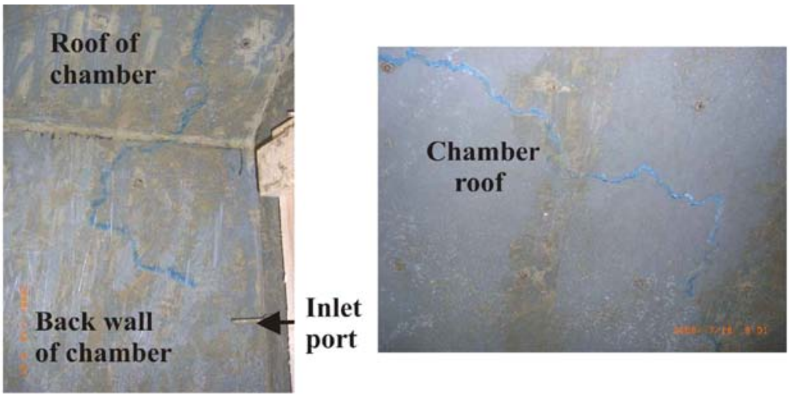
Once flow channels were established, the erosion rate dropped off to very low levels. These channels were discernible on some occasions during dismantling of the tests; they tended to be slightly tortuous features, which had a specific, very thin sediment deposit on the chamber walls (very fine materials that provided a traceable feature). Figure 6-21 and Figure 6-22 show the type of flow path observed during dismantling of Tests 1–2 and Tests 11–12 respectively.

The movement of water through the ½-Scale tests was typically forced through the pellet-filled volume, stabilizing at the chamber wall – pellet interface. In the first hours of testing, prior to this pathway being stabilized, there were several occasions where limited water flow along the pellet – clay block interface occurred, resulting in limited removal of clay from the surfaces of the blocks. There was also limited water penetration along block boundaries and in some cases very short-lived flow at those locations (as shown in Figure 6-22 and Figure 6-23). In all cases these flow paths closed up and water was not allowed to move along them, with a net result of only a few grams of materials being removed from the block surfaces. In none of the tests done as part of this study was there any evidence of extensive water penetration past the pellet fill or erosive activity similar to what was observed in the smaller-scale tests /Dixon et al. 2008a/.

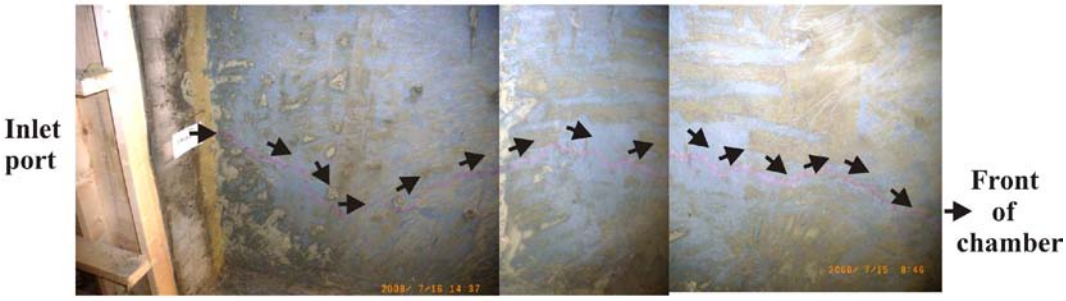


Test 1 Test 2

Figure 6-21. *Evidence of flow channels in Tests 1 and 2. (Pathway location traced with arrow showing direction of flow).*



(a) Test 11 showing flow path along back wall and roof of chamber



(b) Test 12 showing flow path along wall of chamber

Figure 6-22. *Tracer-highlighted flow paths on roof (Test 11) and side wall (Test 12). (actual dye tracks shown in photographs).*

Piping ***Piping*** ***Sheet Erosion: block face***

Figure 6-23a. *Short-term erosional features observed in block-filled regions.*

Eroded void at Geotextile - block contact 0.05 m from inlet

Erosion at pellet-block contact 0.9 m from rear of chamber

Small piping feature passing through block near geotextile contact at 0.9 m from rear of chamber

Figure 6-23b. *Piping features initially present along pellet-block interface in Test 12.*

Only 3 of 10 tests (7, 8, 12) done at inflow rate of less than 1 l/min, exhibited substantial (> 1 kg), amounts of material removal during their operation. The quantity of material eroded in those tests was still quite limited (estimated to be 2–3 kg). The material removed was predominantly fines that either exited the piping features along the chamber wall, or more importantly, materials that were picked up while the water flowed down the face of the backfill assembly. It was not possible to conduct direct measurements of the amount of sediment removed from these tests, the large volumes of water entering and leaving these tests made outflow accumulation, sediment decanting or other means of physically determining the sediment quantity impractical. Quantities based on visual examination were therefore the only means of estimating eroded clay amounts.

Test 10, operated at 2.5 l/min inflow for a period of 3 days, showed very high and ongoing erosion throughout its operation. Such an inflow rate was predicted to be unacceptable prior to its testing but the test was done anyway to provide information on what would happen under very high inflow conditions. As can be seen in Figure 6-24 water first exited between the chamber wall and the clay blocks, gradually eroded downwards as materials were removed and deposited as a sediment fan on the surface of the pellets initially present on the floor in front of the backfilled volume. Both clay pellets and block materials were removed in the course of the flow (dark and light eroded materials seen in Figure 6-19). Erosion is likely to depend on a) the amount of water flowing through a channel and b) the velocity of the flow (turbulent versus laminar flow). As a result a large, continuous channel was carved through the pellet-filled region. The outflow pipe and continued removal of large quantities of both bentonite and Friedland clay is indicative of a system where considerable ongoing erosion is occurring (Figure 6-24). This is an extremely undesirable situation as it means that large quantities of backfill materials are being physically relocated from already backfilled regions to the open tunnel. The result will be the development of a region of much reduced density (or a cavity). Such a situation would likely prove difficult to deal with in a repository situation and thereby a situation where 2.5 l/min is supplied to a localized area will be unsuitable with respect to backfill stability and would likely require some form of remediation.

1/2 h 1 h 4.5 h

17 h 19 h 21 h

25 h 51 h

Figure 6-24. *Ongoing erosion at inflow rate of 2.5 l/min.*

7 Comparison of half-scale and smaller-scale tests

7.1 Resistance to water movement through backfill

A key observation in the conduct of the ½-Scale tests was the very low resistance developed by the backfill material to incoming water. Water typically moved past the backfill with a driving pressure head of only a few tens of kPa. The development of a peak resistance is typically followed by a discernible drop in the resistance to water inflow as soon as a flow channel was established past the backfill.

The results obtained from the ½-Scale tests while consistent need to be assessed as to whether they are representative of what might be encountered in an actual tunnel. While there is no readily available data from field demonstrations of backfilling there is a body of data generated as part of the somewhat smaller Tube Tests done at Äspö as part of earlier Baclo studies /Dixon et al. 2008ab/. Those tests were done at considerably smaller scale than the ½-Scale tests and comparison of the results of these two studies will provide valuable indications regarding the effects of scale on the resistance of backfill to water influx.

The Tube Tests described by /Dixon et al. 2008ab/ involved installing clay blocks and pellet materials to occupy the upper half of a 2-m diameter concrete pipe for a length of 1.2-m. Water was supplied at the mid-height of the filled section or else at the floor of the test section at a location 0.6 m from the front face. These tests therefore were very comparable to the ½ Scale tests described in this report. The volume of the Tube Tests was approximately 1.9 m^3 and the ½-Scale occupied 19.7 m^3 so the ½-Scale tests represented a very substantial (10x) increase in the volume of the simulations. The Tube Tests typically had a minimum of 0.1 m of pellets installed between the cell wall and the clay blocks while the ½-Scale Tests had a minimum thickness of pellet fill of 0.15 m. Despite slight differences in the shape of the tests and block filling, the pellet fill in both these tests represented approximately 30% of the test volume (30% for ½-Scale and 29–32% for tube tests). This proportion is consistent with the anticipated range of pellet filling to be accomplished in an actual tunnel.

The data from the combined Tube- and ½-Scale Tests are presented in Figure 7-1. This data shows that there is no discernible change in the resistance to water flow as the result of slight changes in backfilling technique, increasing path length (1.9 or 3.9 m versus 0.6 m) or test dimension. Only in one test (at 0.5 l/min inflow for a path length of 3.9 m), did the ½-Scale Test show a resistance that was consistently higher than other tests (75 kPa versus 20–40 kPa), which while substantial is not really significant in terms of the ability of the system to resist throughflow.

These tests show that once the flow channels were established and water was bypassing the bulk of the backfilled volume, there was typically a decrease in flow resistance by a few 10's of kPa as can also be seen in Figure 7-2.

The peak, steady-state and decreases in flow resistance for the various tests and for the very different scales (Tube Test versus ½-Scale) were not discernibly different for the overlapping range of inflow rates examined (0.1 – 0.5 l/min). Based on these observations it can be concluded that there is little difference in the resistance to inflow developed at the scales examined in the Tube or ½-Scale tests. The consistent inflow resistance also indicates that there is little change in through-flow behaviour based on the length of tunnel backfilled prior to a break in backfilling operations. The findings of these studies can therefore likely be applied to a full-scale situation with only limited concerns regarding scale effects. These findings are also important in that they show that it is unlikely that there will be substantial pre-closure pressurization of the backfilled tunnel sections close to the working face prior to installation of tunnel or room plugs.

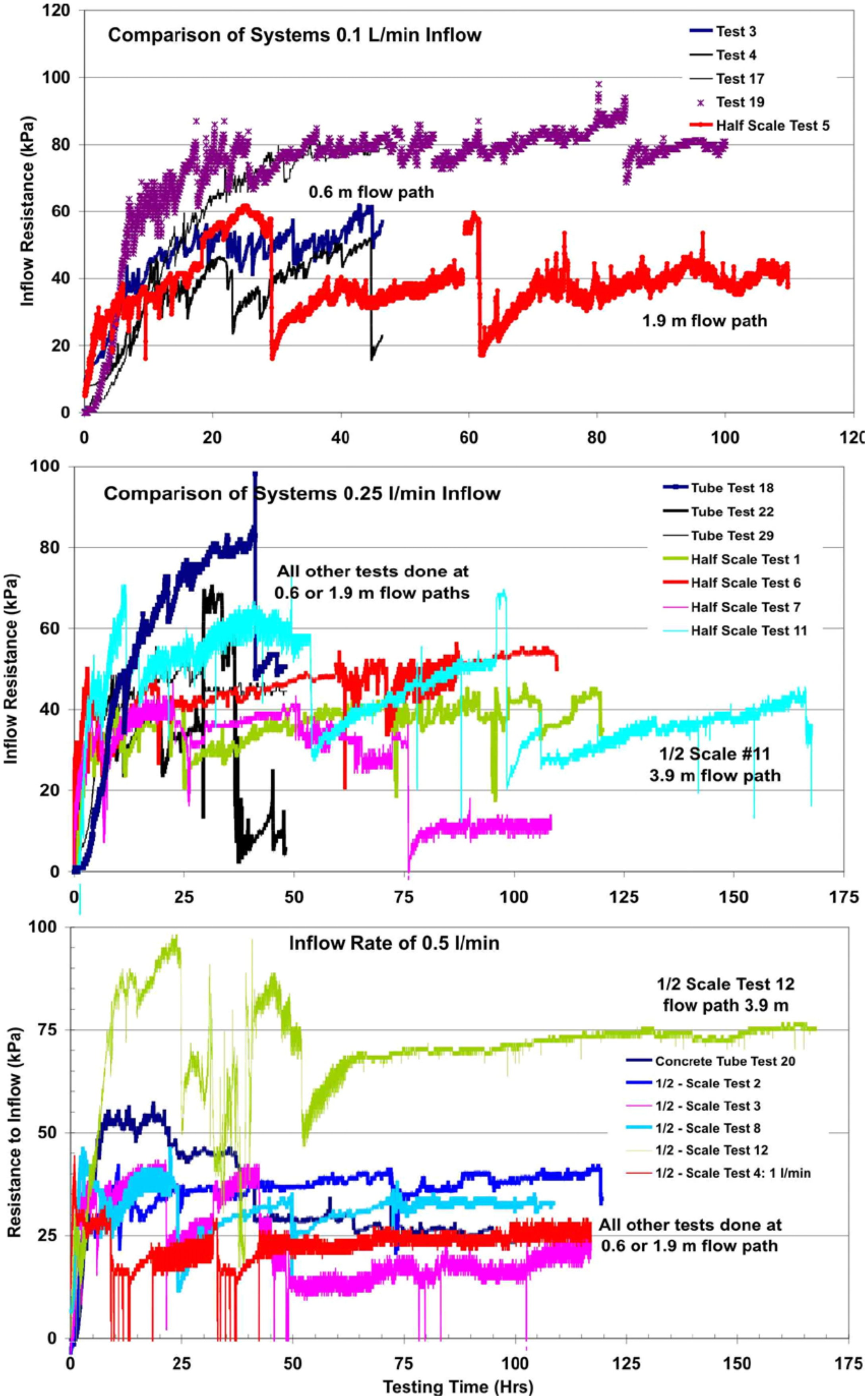


Figure 7-1. *Comparison of inflow resistance in Concrete Tube and ½-Scale tests.*

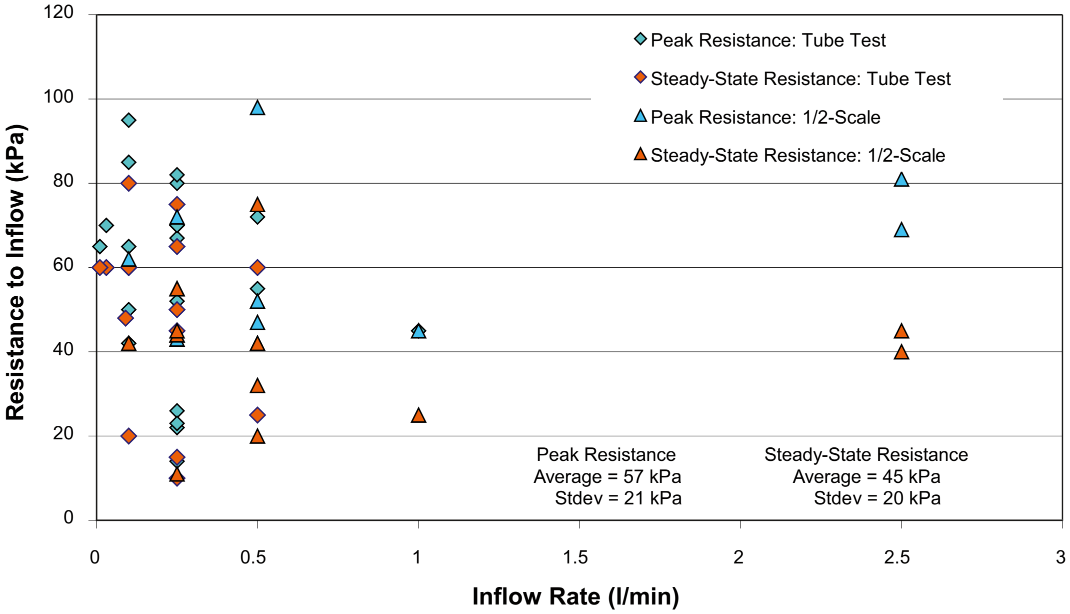


Figure 7-2. *Resistance to water inflow: comparison of ½-Scale and Pipe-Tests.*

7.2 Water outflow from backfill

Of primary importance in the evaluation of water movement into and through a backfilled volume is determining how long it will take water entering the backfilled volume to make its way to the front face of the backfill. This is of considerable importance in situations where there are scheduled (or unanticipated) stoppages in the backfilling process. If water entering at various times and rates along the tunnel is able to combine to form one or more discrete flows there is the potential for disruptive flow at the downstream face, or else the need to provide some means of collecting this outflow so that it does not adversely affect the downstream region of the tunnel (e.g. make the bentonite pellet/granulate flooring soft or unstable).

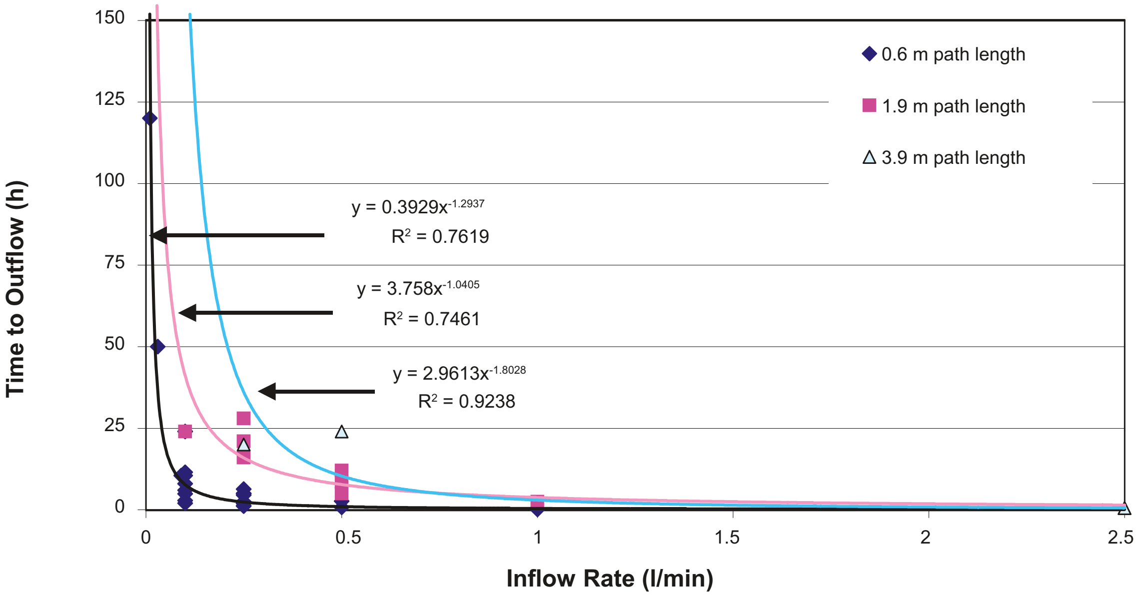
The ½ Scale Tests described in this report represent an up-scaling of the tunnel simulations from the tests previously reported by /Dixon et al. 2008ab/. In previous tests the flow path length was only 0.6 m as compared with the 1.9 and 3.9 m lengths of the ½-Scale Tests. The smaller-scale tests were also unable to operate at the inflow rates described in this report. What was noted in the smaller-scale tests was a general tendency for the water to preferentially move along the chamber-pellet boundary and to exit via a single (or very limited number) for discrete locations on that boundary. The flow that occurred along that interface also showed limited erosion of the pellets.

When the data presented in Figure 6-30 is compared to that generated by the larger number of tests previously completed at smaller-scale and for a shorter flow path the results shown in Figure 7-3 are obtained. In Figure 7-3(a) all of the data available are plotted and at inflow rates of less than 0.1 l/min the time to outflow increased exponentially with decreasing inflow rate. This is indicative of a system where very slow infiltration rate results in a greater proportion of absorption of water by the surrounding pellet materials. This results in a much-extended period before water makes its way to the front face of the assembly. However, if water is being supplied to the chamber at a single location, outflow will eventually occur prior to the system obtaining full water saturation and outflow will occur via small piping type feature(s).

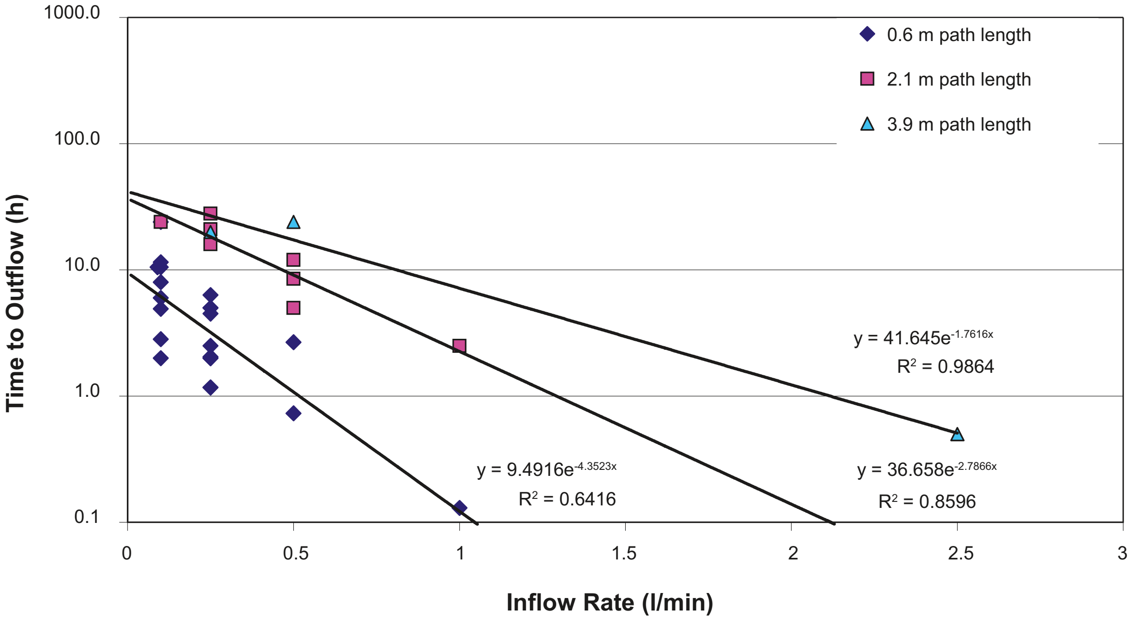
If the time for outflow development is examined for only those systems where inflow is via a discrete location at a rate of 0.1 l/min or higher, the relationship shown in Figure 7-3(b) is obtained. The time to start of outflow is clearly dependent on the both the distance from the inflow point and also the inflow rate although the limited body of data for longer flow paths makes the relationship somewhat difficult to quantify. These data are consistent with the conceptual model provided in Section 6.2.1.

Using the data generated in the ½-Scale Tests and the smaller-scale tests done previously, it is possible to generate an estimate of the time that will pass between backfilling past a discrete inflow point and water subsequently exiting the face of the backfill at some distance away. This is shown in Figure 7-4 and for most cases a linear extrapolation of the data seems appropriate. However, at low inflow rates (0.1 and 0.25 l/min), this relationship is better described using a second order polynomial fit. It should be noted that these numerical extrapolations, especially the polynomial fits, are only valid for flow paths to a maximum length of approximately 4 m and more data is needed before extending the presented relationships to longer flow paths.

The data provided in Figure 7-4 can be plotted in another manner that is perhaps more directly applicable to the tunnel backfilling process and design requirements for backfilling rate. If it is assumed that the data plotted in Figure 7-4 is representative of a steady-state water penetration process then the penetration rate of the piping features per day can be estimated for the range of water inflow rates examined in this study. From this it is possible to determine at what rate backfilling must continue in order to stay ahead of the water conductive features developed. It should be noted that such calculations are not necessarily conservative, as time progresses, length of tunnel backfilled and degree of water saturation in the backfilled tunnel increases, a higher proportion of the inflowing water will be trying to move downstream. In the tests conducted in this study this would represent a potential 20% increase in the rate of water supply to the piping feature (outflow in this study was ~ 80% of inflow).



(a) Inflow rate versus time to start of outflow (linear scale) for all tests.



(b) Inflow rate versus time to start of outflow (log – linear scale) where inflow > 0.1 l/min.

Figure 7-3. *Time required for water to exit backfilled volume at various inflow rates.*

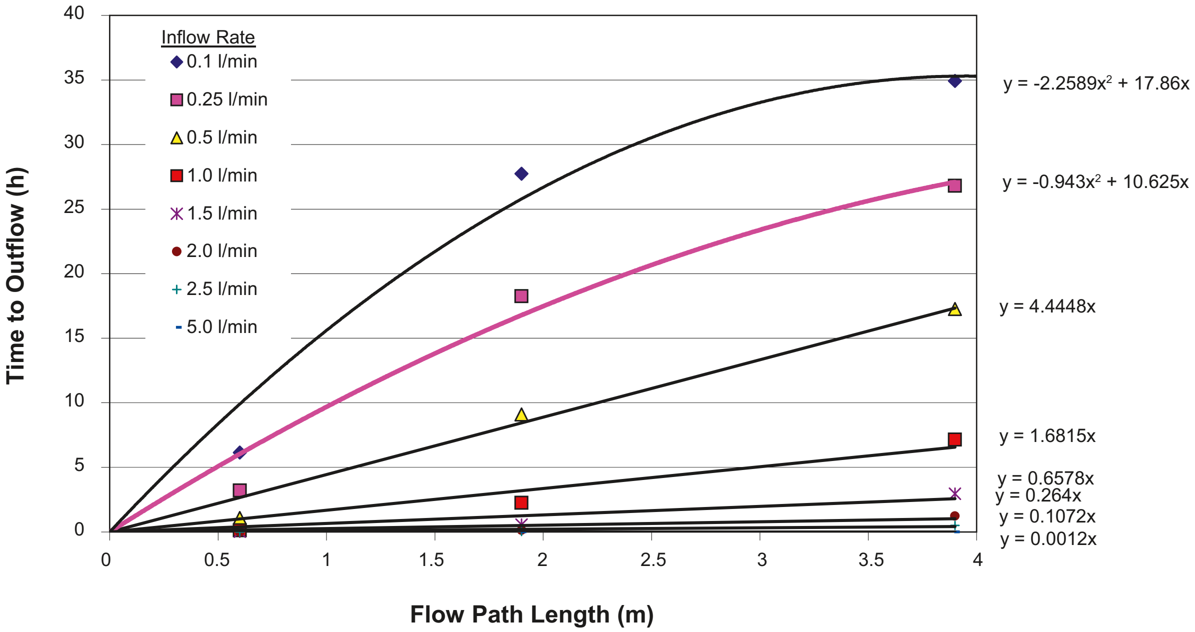


Figure 7-4. *Length of flow path and estimated time required for water outflow at inflow rates of 0.1 to 5.0 l/min.*

Figure 7-5 presents the results of estimation of the rate of water penetration via perimeter piping features in a recently backfilled section of tunnel. It indicates that if a backfilling rate of 6–8 m/day is desired that a single water conductive channel cannot carry more that approximately 0.5 l/min in order for the backfilling process to continue without potentially adverse interaction with inflowing water. At this backfilling rate, the piping feature will not be able to penetrate sufficiently rapidly to reach the working front of the backfill. It should be noted that this type of inflow rate calculation is of limited value as water influx is continuous and backfilling is a stepwise process. It also does not take into account interactions or interconnection of rock hydraulic features. It is more appropriate to develop means whereby most of the water entering the open excavation or entering via already backfilled volumes is dealt with via collection prior to installation of new volumes of backfill. Ideally this would include pre-backfilling treatment to at least temporarily reduce influx into the open excavations through means such as grouting or localized shotcreting.

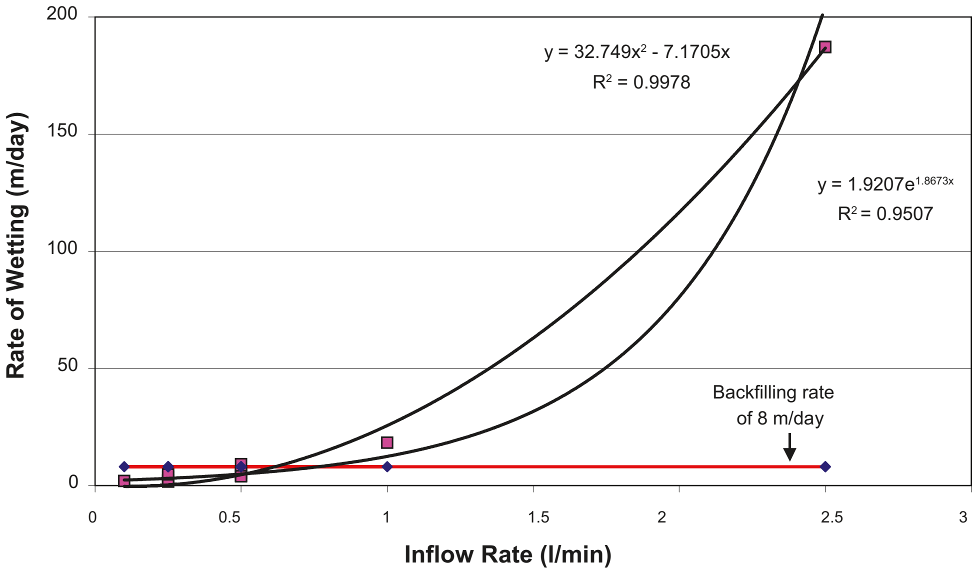


Figure 7-5. *Rate of water penetration through pellet backfill (m/day) at various inflow rates.*

8 Discussion and conclusions

Based on the current series of ½-Scale tests and supported by previous tests done at smaller scale, it would appear that water entering the tunnel via discrete fractures will predominantly move along the tunnel wall contact rather than moving towards the central areas of the backfilled tunnel. In general if the accumulated flow rate is kept below about 0.5 l/min at a single outflow point, or accumulated inflow totalling this quantity moving along a piping feature, the backfill can withstand a few days of interruption in the backfilling process before it begins to experience substantial degradation (development of piping features on wall or erosion of substantial quantities of pellet materials). This inflow rate is equivalent to approximately 30 l/h of combined inflow. If it were based on a homogeneous 100 m section of tunnel the average inflow into the tunnel would need to be 0.3 l/h (0.005 l/min) per m of tunnel length. It should be noted that these values assume that all the inflow sources somehow combine into a single hydraulic feature and that secondary processes (suction-driven water movement into unsaturated pellet-fill) are not active. While the tests done at lower inflow rate (< 0.1 l/min) were limited, 1 in ½-Scale Tests, there were 11 such in the Tube Tests reported on by /Dixon et al. 2008ab/. For accumulated inflow of less than 0.1 l/min the systems showed a markedly (exponentially), longer time until outflow occurred and a tendency towards higher degree of initial water uptake by the pellet materials before flow along the tunnel wall developed (see Figure 7-3). This means that in regions where the localized inflow is limited to < 0.1 l/min that there is a considerable time (several days) before the backfill is likely to begin seeping water. If the water inflow is via dispersed and unconnected features, the time until outflow development will be even longer.

It is likely that water inflow into the tunnels will be non-uniform and perhaps a mixture of dispersed seepage and point inflow from discrete cracks or fractures. In such an environment initially there is likely to be a combination of fairly uniform water uptake by the pellet fill and small connected or unconnected flow channels developed along the rock-pellet contact. If for conservative purposes, the point inflow points that produce 0.1 l/min or more were considered to join together as a single flow then an upper limit to inflow rate to a tunnel section can be developed. Based on the inflow studies done in the Tube and the ½-Scale Tests it would seem that a combined – single channel flow of 0.5 l/min is tolerable in a tunnel for a period of several days at least. If flow occurs along more than one of flow path the system is potentially able to withstand an even higher total through flow, provided that these flows do not combine. For example in Tests 3-4 the total inflow was 1.5 l/min via two inlet points. It is likely that these conditions are close to the limit for the system to withstand for more than a few days as 2.5 l/min (Test 10), was clearly not tolerable.

In general for a backfilled system where there is a suitably thick (~ 150 mm) pellet layer between the walls and the clay blocks there would seem to be an ability of the pellet fill and hence the overall backfilled volume to remain hydraulically/mechanically stable for a period of at least several days. Tests done previously in systems where the pellet fill was typically < 100 mm in thickness showed a vulnerability of the system to internal piping at point inflows of 0.25 l/min or more. In the ½-Scale Tests there were not the same disruptive erosional features developed but at inflows of > 0.5 l/min there was evidence of at least some internal piping occurring during the initial stages of water inflow. The potential does therefore exist for piping features to develop within the region of the tunnel backfilled with clay blocks.

Tests done where there was a supporting screen installed on the downstream face also tended to show a lower rate of material removal as the result of water exiting the mock-up. This was observed in both the Tube Tests /Dixon et al. 2008ab/ and these ½-Scale Tests. This is attributed to the exiting water being directed away from the face as it exited the system, reducing the potential for this fluid to flow down the unsupported blocks or pellet materials. Based on this it would seem that some form of temporary or removable support would be useful should backfilling operations be temporarily interrupted. This would reduce the ability of any exiting water to erode the front face of the backfill and would also facilitate collection of the outflow water before it could influence any flooring or other materials installed downstream of the already completed backfilling.

A similar situation regarding controlling where water will move was observed in those tests where a very wet pellet fill is placed at the downstream face of the assembly. This material is very impermeable and so is not a preferred flow path through the backfill. It will also tend to direct water away from the block fill materials and towards the chamber wall. Should this prove to be a consistent property of pellets installed “wet”, then it may be possible to install a relatively impermeable pellet layer around the more hydraulically–sensitive clay blocks and cause inflowing water to move preferentially along the chamber wall to locations where it could be more easily collected. Installation of pellets with some degree of water addition also has the advantage of reducing the potential for the crown regions to be of lower density, or to settle and form a gap between the pellets and the tunnel crown. Dampened pellets can be installed such that they can stand vertically, reducing slumping or the need to deal with the very low natural angle of repose for dry pellet materials and the potential for substantial variations in the density of the placed fill.

Summary

A series of water inflow tests were conducted in a chamber that was scaled to ½ that proposed for the emplacement rooms of the KBS-3V concept. These tests examined the effects of water influx from point sources simulating locations where hydraulically conductive fractures or joints intersected an emplacement tunnel. The manner in which water moved through a recently backfilled section of simulated tunnel was studied. Inflow rates of 0.1 to 2.5 l/min were examined, simulating a situation where all the water entering a backfilled tunnel were able to coalesce into a single flow path that subsequently contacted a short (1.9–3.9 m) section of backfill on the downstream end of the backfilled tunnel section. This allowed the manner in which water would move into and through the backfill to be evaluated and the potential for this water to physically disrupt (erode or destabilize) the backfill to be determined.

The general conclusions developed are based on controlled simulations where rate and location of inflow water are clearly defined and at point sources. This is likely a conservative situation relative to a tunnel environment, simulating highly conductive fractures supplying water to the tunnel. In the field it is likely that water influx will be non-uniform and a combination of very slow, almost indiscernible seepage and slow inflow through slightly conductive features. In practice it is also likely that highly conductive features will be remediated either during repository construction/operation or else immediately prior to backfilling. While such remediation will likely provide some assistance in the backfilling process it cannot be relied on to entirely deal with water influx into the tunnel. As a result it is important to develop as thorough an understanding of how water will move into and past backfill during the tunnel closure process.

A further series of mock-ups that examine multiple inlet points that more closely represent geologic features and the interaction between these inlet sources should be considered. With these tests some means of accurately measuring outflow rate and erosion at separate locations will be important to bettering the understanding of flow through and erosion of backfill. It will ultimately be necessary to move from the controlled conditions of the currently described and proposed additional tests to a field situation where the rock conditions are both variable and well characterized to evaluate backfill behaviour in the period immediately following its installation. Also of importance will be demonstrating the ability of backfilling operations to continue in an environment where water is entering the excavations during backfilling operations.

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Appendix A

Detailed description of individual tests and discussion of observed behaviour

A.1 Assembly 1 : Tests 1 and 2: 0.25 and 0.5 l/min Inflow

The general layout of Tests 1 and 2 was provided in Figure 4-10. Test 1 was located on the left side of Assembly 1 and Test 2 occupied the right-hand side. These tests were provided with water at constant inflow rates of 0.25 and 0.5 l/min (15 and 30 l/hr) respectively, via small point sources of water located in the steel wall. The inflow points were located at 1.8 m from the rear of the chamber and 1.5 above the floor on each side. The water entering the pellet fill was allowed to move freely, with no restrictions beyond those induced by the test construction (no exit to rear of chamber).

Test 1

Water first exited this test between 8 and 24 hours after start of inflow. The exact time was not recorded as it occurred during the night when there was no visual monitoring occurring. Based on the degree of water outflow observed at 24 hours it was estimated that the outflow likely began at about 16 hours. Water initially exited the test at the block pellet interface at a slightly lower elevation than the water inlet (approximately 1 m). In the early outflow period the location of the outflow location gradually moving upwards and towards the chamber wall. This is attributed to the successive vertical hydration of the pellets, inducing a greater and greater resistance to water movement through them. Within 48 hours the flow path appears to have stabilized to a single location along the wall – pellet contact at an elevation of approximately 2 m from the floor of the chamber, showing little erosive action (clear outflow). This test was carefully photographed in order to capture a visual record of the flow behaviour and location. Figure A-1 and Figure A-2 provide photo records of the water movement out of Test 1 and the wetting pattern evident during dismantling. Figure A-3 presents a view of the inside face of the blocks in the upper part of Test 1 (geotextile-block contact), illustrating the limited water inflow into the upper block-filled region.

There is little evidence of ongoing water movement through the block-filled region, as evidenced by the desiccation present on the blocks joint surfaces (result of discontinued supply of water to blocks). There was some evidence of short-term erosive flow along the block joints in the lower portions of the test during the early stages of water inflow (Figure A-4) but they did not appear to have been an ongoing feature as flow did not persist in this region and no substantial erosion occurred.

Test 1 **Test 2**

Just prior to disassembly: note water on floor of test chamber

Assembly immediately after restraint removed
Dark regions are wet clay blocks, note dry regions
near crown and bentonite on surface of lower blocks

Assembly immediately after restraint and first block layer removed
Wetting limited to block joints and very distinct areas of pellets
Remaining pellets still dry and loose

Figure A-1. *Downstream face of Test 1 and Test 2.*

Front face of Test 1 and Test 2 once surface layer removed

Front portion of Test 1 and Test 2 showing vertical wetting

Central portion of Test 1 and Test 2 showing dry crown region

Figure A-2. *Wetting patterns for Test 1 and Test 2.*

Figure A-3. *Movement of water along block joints near top of Test 1. (view from front (F) to back (B)).*

Test 1　　　　*Test 2*

(Note loose, dry pellet materials near floor and at crown of chamber)

Figure A-4. *Water inflow along block joints in assembly (front view) Tests 1 and 2.*

In general terms the following sequence of events appears to have occurred:

1. Water entered the pellet-filled regions and flowed downwards and towards the centre of test chamber in pellet-filled regions.
2. Water entered joints between the clay blocks in a somewhat random manner, moving inwards and downward as space was available between the blocks.
3. Pellet hydration progressed, making downwards and inwards movement more difficult,
4. Water began to "pool" at higher levels within the pellet fill.
5. Accumulating water flowed into still dry regions above, and adjacent to initial inflow location expanding the wetted areas.
6. Ongoing hydration began to force inflow to concentrate along the wall of the chamber and it moved both upwards into lower-density materials near crown of chamber or forward towards the front face of the assembly.
7. Water reached the front face of the assembly, generally exiting over a large region between the blocks and the chamber wall.
8. Some block materials were eroded out of the interface regions between the pellets and blocks as water sought to move out of system.
9. As hydration of pellets progressed further flow from chamber began to concentrate along the pellet-chamber contact.
10. A preferential flow path became established on the pellet-chamber wall contact, resulting in stable non-erosive flow past the chamber assembly.

The process described above could generally be said to be the same for all of the tests conducted in the 1/2 – Scale study, excepting Test 10 which had a very high inflow rate applied. There were some minor variations in the patterns observed and some evidence of short-lived erosive action along the clay block boundaries and interfaces. These were similar to the piping features observed in the smaller-scale tests completed at Äspö during 2006/2007 /Dixon et al. 2008a/, but did not evolve permanent, uncontrolled erosive pipes observed in those smaller-scale tests. There is an uncertainty as to whether this lack of progressive erosive activity is a function of the larger volume/thickness of pellet materials installed in the ½-Scale tests or if it was a result of the geotextile installed within 225 mm distance from the block – pellet contact.

In addition to the visual observations made during the test, there was a continuous set of water inflow rate, estimated outflow rate, and inflow resistance collected. These data indicate that there were only a few occasions where there were changes in inflow resistance (sudden decrease), and these were generally small. The very stable inflow resistance readings indicate that this test established a flow path early in its evolution and that whatever water was not being taken into the remainder of the pellet system could move towards the front face of the test. The setup of tests 1 and 2 was such that it was not possible to collect the outflow of the two tests separately. As a result there is only an average outflow rate for the two tests available. At the end of 5 days of operation an average of 84% of the inflow that was immediately exiting the tests. The remaining 16% seems to have been continuing to progressively wet the pellet-filled regions in the uppermost portions of the test as can be seen in Figures A-1 through A-4. Wetting seemed to be preferentially occurring along the steel-pellet interface and be gradual in nature (fairly uniform and not intense wetting). These results are discussed in greater detail in Section 6.2. At the end of 5 days of flow through the test there also does not seem to be any hydraulic connection between the two sides of the assembly (Tests 1 and 2) allowing them to be independently assessed.

At the end of 5 days (~ 120 hours of operation) the water supply to the test was discontinued and dismantling was initiated. Careful note was taken of the outflow location and sampling of the pellet materials was done in the manner described in Section 5-2. For efficiency of sampling and analysis, only those locations where a change in water content had occurred were sampled and these data are provided in Appendix B. From these data it was possible to quantitatively confirm the patterns of water uptake and movement developed from the visual examination of the test during and after its operation. Examining the data provided in Appendix B shows a consistent horizontal band of wetting of the pellet-filled region In Test 1 this is generally centred on sampling locations 15–23, with the wettest locations at the chamber wall – pellet interface at, or very-near sampling location 18. This zone and location 18 is at or slightly higher than that of the inflow location (located at centre of assembly). The front face of the test is so heavily influenced by the exiting water and subsequent swelling and water uptake that this pattern is somewhat masked but the observed location of the water outflow is consistent with the observations. Water entering the test at a location halfway along the assemblies length also tended to move towards the rear of the chamber in a similar manner, developing a wetted band at or near the elevation of the inlet pipe.

Test 2

Water first exited Test 2 at some point between 8 and 24 hours of operation and based on the amount of outflow observed at 24 hours it was estimated that outflow began at approximately 12 hr. In the early outflow period the location of the outflow was observed to be greatest along the pellet-block interface and gradually moved higher up the face of the assembly. This was as a result of the lower regions gradually hydrating and sealing the pellet filling. With time the outflow location also gradually shifted towards the steel wall – pellet contact and tended to move slightly upwards. This lateral movement of the flow path is attributed to the successive hydration of the pellets, inducing a greater and greater resistance to water movement through them. Within 24 hours the flow path appears to have stabilized to a single location along the wall – pellet contact, showing little erosive action (clear outflow). This pattern of wetting is essentially the same as was described for Test 1. As with Test 1, this test was carefully photographed in order to capture a visual record of the flow behaviour and location.

At the end of 5 days (~ 120 hours of operation) the water supply to Assembly 1 was discontinued and dismantling was initiated. Careful note was taken of the outflow location and sampling of the pellet materials was done in the manner described in Section 5-2. For efficiency of sampling and analysis, only those locations where a change in water content had occurred were sampled and the data is provided in Appendix B. From these data it was possible to develop a general understanding of the flow path present and its evolution.

The water distribution at the end of this test, provided in Appendix B show a water uptake pattern very similar to that observed in Test 1. Most of the wetting occurred in the region where samples 15 through 23 were recovered. The wettest region along the length of the test was at the area where samples 18–20 were recovered, at the pellet-chamber wall contact, consistent with the location of the observed flow paths and exit elevation of the test. Water uptake and movement was limited to a horizontal band at or near the elevation of the inlet point. At the time of dismantling, the water was clearly beginning to wet those regions above the inlet elevation but insufficient time had passed for this to progress very far.

Figures A-1 and A-2 shown the patterns of water movement out of Test 2 and the wetting patterns observed during dismantling. Figure A-5 shows the wetting pattern in the uppermost block filled region of Test 2. This shows the same pattern as was evident in Test 1, a relatively random pattern of limited water inflow into the blocks with no ongoing flow was found. As with Test 1, the lower regions (close to distance from front face and elevation of water inlet port), showed more extensive water influx into both the pellet fill and the blocks with some limited early erosive activity during the period before the pellets had hydrated sufficiently to seal off water influx towards the core of the test. Hydration of the pellet filled regions was also notably incomplete, only a limited portion of the pellet fill had actually hydrated after 5 days of water inflow and this tended to be in the regions about 1 m above the floor and extending upwards towards the crown of the chamber. Water seems to have initially moved generally downwards (with gravity) and in some regions briefly penetrated along the block joints. Relatively quickly the pellets hydrated and sealed off essentially the entire test. This forced water to move along the path of lest resistance, generally along the pellet-outside wall contact moving either towards the front face of the assembly or upwards towards the crown regions, showing little tendency to move into the block filled core of the test.

Figure A-5. Movement of water along block joints near top of Test 2. (Photomosaic view from rear (left) to front (right) along the block-geotextile boundary).

A.2 Assembly 2: Tests 3 and 4

Test 3

Test 3 was supplied with water at a rate of 0.5 l/min via a single port located 1.8 m from the rear of the chamber and 1.5 m above the floor. Outflow from the face of the assembly was observed after only 5 hours of operation, beginning at the pellet-block boundary part way up the assembly. The outflow point gradually shifted towards the pellet-chamber wall contact, in the same manner as was observed in Tests 1 and 2. This is once again attributed to ongoing hydration and swelling of the pellet materials, inducing a greater and greater resistance to water movement through them towards the clay blocks. Within 24 hours the flow path appears to have stabilized to a single location along the wall – pellet contact close to the elevation of the inlet port. There was little evidence of ongoing erosion along this pathway (clear outflow). This test was carefully photographed in order to capture a visual record of the flow behaviour and location. Figure A-6 and Figure A-7 provide photographic records of the water movement within Test 3 and the wetting pattern evident at the time of dismantling. It can be seen that there was only limited water inflow into the block-filled region via their joints, although it would appear that somewhat more occurred in the regions closest to the inlet point as can be seen in Figure A-6. This figure also indicates that there was a higher degree of water movement towards the rear of the chamber than was evident in previous tests. Water is also tending to pool in the rear of the cell and hydration higher in the assembly is evident.

Like Assembly 1, there is no evidence of any hydraulic connection between the two sides of the chamber. Although equipped with independent water collection systems Tests 3 and 4 experienced cross flow from Test 3 to Test 4 at the downstream face of the assembly. This occurred as the result of water flowing along the steel mesh installed on the front face of the assembly. The outflow for Tests 3 and 4 could therefore only be measured as an accumulated total. At the end of testing the system was discharging 86% of its inflow and there was minimal resistance to its movement, as recorded in the outflow resistance plots.

At the end of 5 days (~ 120 hours of operation) the water supply to the test was discontinued and dismantling was initiated. Careful note was taken of the outflow location and sampling of the pellet materials was done in the manner described in Section 5-2. For efficiency of sampling and analysis, only those locations where a change in water content had occurred were sampled and the data is provided in Appendix B. From these data it was possible to develop a general understanding of the flow path present and its evolution.

Near (~0.4m) front *Central* *Near rear*

Figure A-6. *Test 3 showing water movement along block joints and incomplete wetting of pellets.*

The water uptake measurements obtained by sampling the pellets, show an even narrower band of wetting than was observed in Tests 1 and 2, generally restricted to sampling regions 16–21 with the wettest regions at or near location 20 at the chamber-pellet contact. It would appear that at this inflow rate there is only a limited capacity for water to move outwards from the inflow point and that water will be preferentially channelled towards the downstream face of the backfilled volume.

Test 4

Test 4 had an inflow rate of 1 l/min, supplied at a single source 1.8 m distant from the rear of the chamber and an elevation of 1.5 m from its floor. Like all the other tests it operated for 5 days before being dismantled. Outflow from the downstream face occurred after only 2.5 hours of operation. It began at the pellet-block boundary part way up the assembly but moved towards the pellet-chamber wall contact, in the same manner as was observed in Tests 1, 2 and 3. This is once again attributed to ongoing hydration and swelling of the pellet materials, inducing a greater and greater resistance to water movement through them towards the clay blocks.

Within 24 hours the flow path through the test appears to have stabilized at a single location along the wall – pellet contact, close to the elevation of the inlet port. There was little evidence of ongoing erosion along this pathway (clear outflow). This test was carefully photographed in order to capture a visual record of the flow behaviour and location. Figure A-7 and Figure A-8 provide photographic records of the water distribution in Test 4. It can be seen that there was only limited water inflow into the block-filled region via their joints, although it would appear that somewhat more occurred in the regions closest to the inlet point, as can be seen in Figure A-8.

Water also seems to have persisted in entering only a small region of the pellet fill adjacent to the inlet port and then rapidly move laterally into the pellets. The result is a greater degree of wetting upstream and downstream of the inlet point, as can be seen by comparing the profiles in Figures A-7 and A-8. This is likely a result of the very high inflow rate at this location.

At the end of 5 days (~ 120 hours of operation) the water supply to the test was discontinued and dismantling was initiated. Careful note was taken of the outflow location and sampling of the pellet materials was done in the manner described in Section 5-2. For efficiency of sampling and analysis, only those locations where a change in water content had occurred were sampled and the data is provided in Appendix B. From these data it was possible to confirm the qualitative conclusions developed through observations made during test operation and subsequent dismantling.

The water distribution data show the same pattern of limited vertical movement of water following entry into the pellet fill of Test 4. The wettest materials are at sampling locations 18-20 at the chamber wall – pellet contact. There may be a slight trend towards move water movement towards the floor of the assembly but the magnitude of this change in behaviour is small, water is still moved at, or near, the inflow elevation to the downstream face of the backfill.

There is no evidence of any hydraulic connection between the two sides of the chamber. Although equipped with independent water collection systems Tests 3 and 4 experienced cross-flow at the downstream face of the assembly. This occurred as the result of water flowing along the steel mesh installed on the front face of the assembly. The outflow for these tests could therefore only be measured as an accumulated total. At the end of testing the system was discharging 86% of its total inflow and provided little in the way of inflow resistance.

Test 3 Test 4

(Note dry regions below and above inflow elevation)

Figure A-7. *Wetting near inflow location in Tests 3 and 4.*

near centre near rear

(Note dry pellets above and below inflow elevation)

Figure A-8. *Test 4, showing water movement along block joints and incomplete wetting of pellets.*

A.3 Assembly 3: Tests 5 and 6

Test 5

Test 5 was supplied with water at a rate of 0.1 l/min, at 1.8 m distant from the rear of the chamber and 1.5 m above the floor. This was the lowest inflow rate examined in this study and outflow was observed after approximately 24 hours of operation. Outflow began at the pellet-block boundary close to the point at which the vertical side walls met the curved roof region of the chamber. This exit point moved towards the pellet-chamber wall contact with time. This pattern was observed in most of the other tests done in the course of this study. Within 48 hours the flow path appears to have stabilized to a single location along the wall – pellet contact close at approximately the elevation of the inlet port (Figure A-9). There was little evidence of ongoing erosion along this pathway (clear outflow) although material was removed by water flowing down the face of the assembly. This test was carefully photographed in order to capture a visual record of the flow behaviour and location. Figure A-10 provides a photographic record of the areas that saw water inflow in the course of the test. It can be seen that there was only limited water inflow into the block-filled region via the block joints and that is likely occurred for only a short time at the start of testing (partially dried wetting locations). As was the case with all the tests done in this study it would appear that somewhat more flow into the block-filled volume occurred near the inlet point (Figure A-10). This figure also indicates that there was a higher degree of water movement towards the rear of the chamber than was evident in previous tests with water tending to pool in the rear of the cell. It would also seem that the wetting extended to a higher elevation than has been observed in the other tests done up until this time.

Unlike Tests 1-4, in Tests 5 and 6 there is clear evidence of a developing hydraulic connection between the two sides of the chamber. There was no apparent free fluid flow occurring between the two sides at the end of the test but wetting was clearly occurring along the crown of the chamber, likely from Test 6 (right side) towards the left (Test 5). This is discussed further in the discussion of Test 6. Test 5 and Test 6 were equipped with independent water collection systems that operated correctly. At the end of its operation Test 5 was discharging 77% of its inflow via the front face at an elevation of approximately 1.8 m.

Test 5 *Test 6*

Figure A-9. *Front Face of Assembly 3 (Tests 5, 6) showing wet regions.*

Front *1.2 m* *1.85 m* *3.3 m*

Test 5

Front *1.2 m* *1.85 m* *2.45 m* *3.3 m*

Test 6

Figure A-10. *Excavation profiles for Test 5 and Test 6. (note: incomplete wetting of pellets and movement of water into upper rear part of tests).*

At the end of 5 days (~ 120 hours of operation) the water supply to the test was discontinued and dismantling began. Careful note was taken of the outflow location and sampling of the pellet materials was done in the manner described in Section 5-2 with only those locations where a change in water content had occurred being sampled. From these data it was possible to develop a general understanding of the flow path present and its evolution. The data is provided in Appendix B and it from this information it is possible to quantitatively assess the degree of water distribution and where channelling was occurring.

Measurements of water distribution in Test 5 shows a water distribution not dissimilar to the other tests and which are consistent with the visual observations (Figure A-10). The region closest to the inlet port (sampling location 18 in Figure 5-1) were the wettest and a relatively narrow band of wetting extending at about the same elevation as the inlet port towards the downstream face of the assembly. The water also spread to the rear from the inlet with an apparent tendency to move upwards in the pellet mass rather than towards the floor. At the rear- and upper-most region of this test there is an apparent localized wetting at the crown, perhaps the result of tiny piping features or water moving along narrow channels along the chamber wall – pellet interface.

Test 6

Test 6 operated at an inflow rate of 0.25 l/min at 1.8 m distance from the rear of the chamber, 1.5 m above the floor, for a total of 5 days. Outflow occurred after 21 hours of operation. The downstream face of the test showed the same pattern of water outflow (along steel wall at approximately the inflow port elevation) as was observed for most other tests (Figure A-9). The distribution of water within the pellet fill at various depths in Test 6 is presented in Figure A-10.

In general the water distribution pattern is similar to that observed in previous tests with one exception. There is a clear wetting process that has occurred in the pellet filling towards the rear of the chamber, particularly along the chamber roof and the pellet filling. There is a continuous layer of moistened pellets along the roof in the rearmost 1 to 2 m of the test. Additionally in Figure A-10 at 2.85 m depth, there is a wetting front extending upwards into the pellets in the lower crown region. The shape of this wetting feature indicates flow from the right-hand side (Test 6) towards the left (Test 5). Figure A-11 shows this even more clearly with a much greater volume of dampened pellets on the right side of the crown region than is visible on the left, again supporting the conclusion that flow was moving from right to left. This type of feature indicates that within 5 days water not exiting the assembly via the flow channels developed early in the test has begun to wet towards the crown of the assembly and also to move towards areas of lower degree of wetting (lower inflow rate). This indicates that it is quite possible that initially unconnected inflow locations may eventually merge into a single flow path and that water is moving a considerable distance from its inflow point, despite most of the inflow volume being channelled towards the downstream face of the backfill. At the end of operation Test 6 has 76% of its inflow exiting the front face of the assembly. Although a large volume this meant that Test 6 was supplying as much as 3.6 l/h to the still-dry portions of the assembly. Over the course of 5 days this represents 432 l of water retained within the assembly.

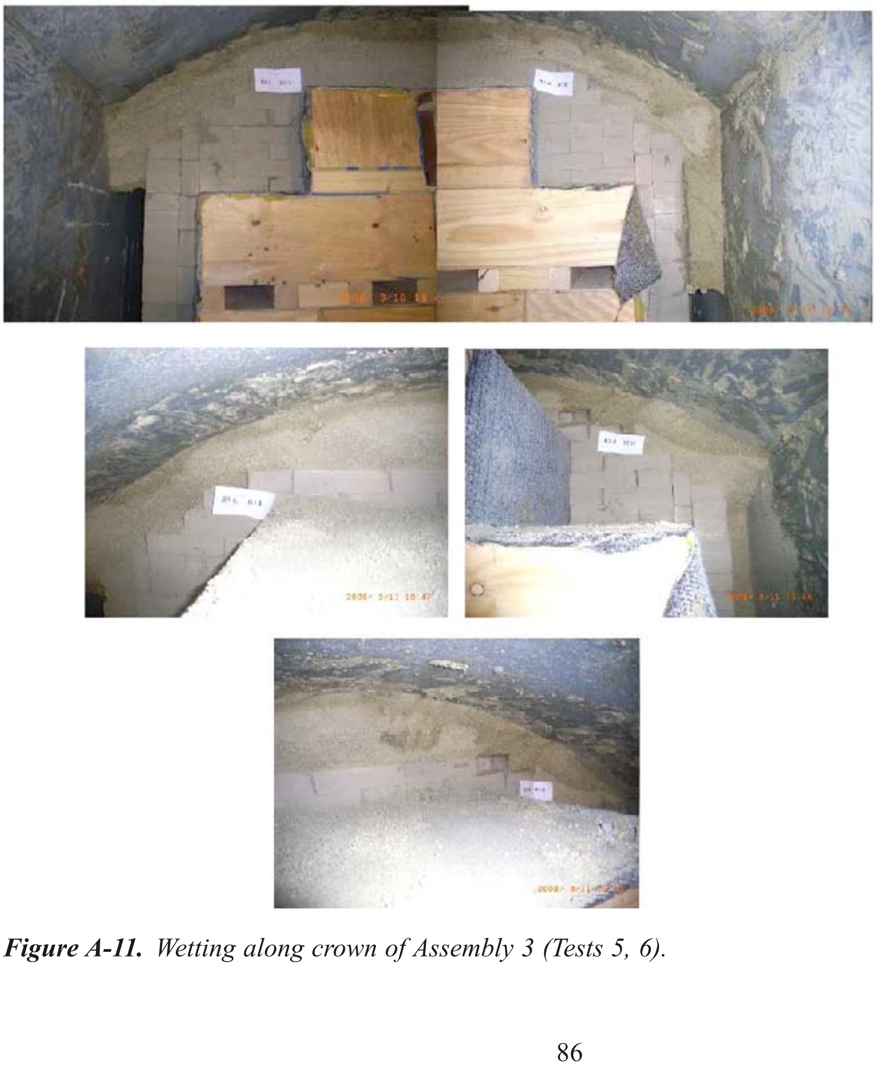


Figure A-11. *Wetting along crown of Assembly 3 (Tests 5, 6).*

A.4 Assembly 4: Tests 7 and 8

As noted previously, Tests 7 and 8 differed substantially in their construction from the previous tests of this study. They contained limited (or no) block materials, relying instead on the geotextile liner to prevent flow towards the core of the assembly. The focus of these tests was on the pellet filler materials installed in a single process, much in the same way as envisioned for application in an actual tunnel. The previous 6 tests provided strong evidence that the block fill component has minimal effect on the initial water movement through the simulated backfilled tunnel volume.

Figure A-12 shows the front face of Assembly at the start of outflow from Test 8 and at the end of testing, just prior to disassembly. It can be seen that there was very little change in the front face following almost 5 days of water influx (0.25 l/min left side, 0.5 l/min right side). These tests did not run for their full planned time as a mechanical failure in the pumping system resulted in loss of water supply approximately 12 hours before the tests were scheduled to end. Given the stability of the flow rates, flow resistances and lack of deformation in the front face of these tests, loss of 12 hours of testing time was not deemed to have affected the results obtained. Figure A-12 clearly shows the high mechanical stability of the system after 5 days of water supply to the pellets. Outflow from Test 7 was always at pellet-chamber wall contact. Test 8 initially began to show water outflow at pellet-block contact, visually evident by dark, wet region in Figure A-12. The outflow location subsequently moved to the chamber wall within 12 hrs of flow starting. Figure A-12 also shows how little material was removed by the exiting water.

As was done with all tests in this study, the assembly was sampled during dismantling in order to develop a quantitative sense of the water uptake patterns and magnitude. The data generated by this sampling is provided in Appendix B. From these data it was possible to develop a general understanding of the flow path present and its evolution.

Initial outflow from Test 8 (right)

End-of-test outflow locations

Figure A-12. Front face of Tests 7 and 8 at the start of outflow and end of testing.

Test 7

Test 7 was supplied water at a constant rate of 0.25 l/min at 1.8 m distance from the rear of the chamber and at an elevation of 1.5 m from the floor. Outflow from the front of the assembly was detected at 28 h into its operation, beginning at the pellet-chamber wall contact approximately 0.8 m from the floor and continued from this location for the remaining duration of the test (approximately 3.5 days longer). There was no evidence of water movement along the pellet-geotextile contact at the downstream face during the test's operation. This test showed somewhat inconsistent outflow rates with water outflow oscillating for much of the first 2 days of outflow. This is perhaps evidence of internal channelling of water or more uniform movement of water into the pellet-filled region, rather than simple outflow from the established flow path.

Figure A-13 shows the front face of Test 7 in the course of water inflow and the outflow elevation can be seen as the coarser textured lower portion. This texturing was caused by the water exiting the test and flowing down the face of the pellet fill, causing swelling of this region. Figure A-14 shows the appearance of the pellet-filled region in the course of dismantling this test. The downstream face was quite uniformly wet to an elevation of approximately 2 m as can be seen in Figure A-14a. Wetting was somewhat less uniform but still extensive for the entire length of the assembly with a tendency towards reduced height of wetting towards the rear of the test (Figure A-14b).

Sampling of the assembly at the completion of the test to determine the water distribution was done as for all the tests in this study. Provided in Appendix B, the water content results show a wetting pattern that was somewhat different than those previously completed. Water apparently moved downwards from the inlet point tending to have wet all the way down to the floor of the chamber. There is limited movement of water upwards into the crown regions and generally a fairly uniform wetting pattern along the walls. This may have been more the result of the leakage path developed along the floor that allowed the water to move preferentially downwards although similar water uptake was observed in other tests (e.g. Test 8).

Figure A-13. *Water outflow from Test 7 at various times.*

Downstream face ~0.15 m ~ 0.5 m ~ 1 m ~1.5 m

(a) Wetting patterns observed at various distances from front face of Test 7

~0.5 – 1.5 m ~1.5 – 2.5 m ~2.5– 3.5 m ~3.5 – 4 m

(b) Wetting of pellet fill along walls of chamber following removal of dry pellets

Figure A-14. *Test 7: Wetting of pellet-filled region.*

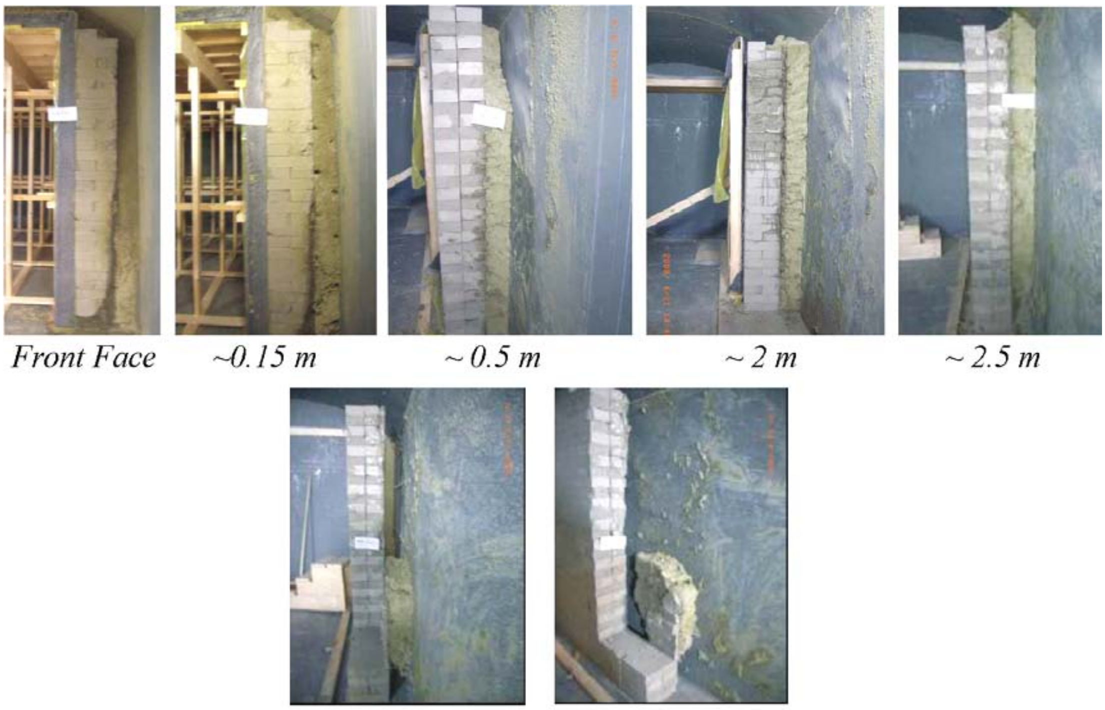
Test 8

Test 8 was supplied water at 0.5 l/min at 1.8 m distance from the rear of the chamber and an elevation of 1.5 m from the floor. Outflow began at approximately 8.5 h into its operation, determined using the conductivity sensor. This sensor was used to detect water movement into the outflow collection system. Outflow from Test 8 began at a single point, approximately 1.5 m from the floor of the chamber at the pellet-block contact and shifted to the pellet-chamber wall contact within a day. There was limited but discernible erosive activity during those 4 days, with the loss of a small quantity of pellet materials (determined by is lighter colour). Much of the material that accumulated at the toe of the assembly was the result of water moving down the vertical face of the assembly and bentonite pellets swelling at the downstream face (see Figure A-12 and Figure A-15).

The wetting of the pellet fill in Test 8 was quite uniform in the lowermost 2 meters of the assembly, as can be seen in Figure A-16 and also in the water content measurements provided in Appendix B. Only the rearmost meter of the assembly exhibited limited water uptake, a feature commonly observed in other tests. There was essentially no movement of water into the crown regions of this test, despite the large quantities of water supplied to the system (0.5 l/min). An additional feature observed in Test 8 was the penetration of water along a vertical joint in the clay block assembly, shown in Figure A-17.

28 h 70 h 97 h 108 h

Figure A-15. Water outflow during operation of Test 8.



Front Face ~0.15 m ~ 0.5 m ~ 2 m ~ 2.5 m

~ 3 m ~ 3.5 m

Figure A-16. Wetting of clay pellets along length of Test 8.

Figure A-17. Evidence of early seepage through block assembly in Test 8.

The type of vertical joint shown in Figure A-17 was present in only one location in this assembly, close to the inflow port of this test. While not significant with respect to the overall evolution of this test, it highlights the importance of block orientation and the need to avoid uninterrupted flow paths where possible. Beyond this feature it would appear that there was movement of the water along the block-pellet boundary in the early stages of this test. This interface would have provided limited resistance at the start of the test and would be the least tortuous pathway along the length of the test. This explains the initial water outflow at the block-geotextile boundary as can be seen in Figure A-16. As the pellet filled region between the water inlet location and the blocks hydrated, resistance to water movement to the block-pellet interface increased and shortly into the test water would have begun moving along the next-least resistant pathway (the chamber wall – pellet interface), for the remainder of the test. This would be consistent with the shifting of the outflow location from the block-pellet contact to the chamber-pellet boundary as seen in Figure A-16.

A.5 Assembly 5: Tests 9 and 10

As noted previously, Tests 7 through 10 differed substantially in their construction from the first 6 tests in this study. They contained limited (or no) block materials, relying instead on the geotextile liner to prevent flow towards the core of the assembly. The focus of these tests was on the pellet filler materials installed in a single process, much in the same way as envisioned for application in an actual tunnel. The previous 6 tests provided strong evidence that the block fill component has minimal effect on the initial water movement through the simulated backfilled tunnel volume and so it could be safely excluded from the assemblies.

Figure A-18 shows the front face of Assembly 5 at the start of testing and on completion, just prior to disassembly. It can be seen that there was extensive erosion of material from the pellet-filled volume of Test 10 and subsequent deposition of that material as an outflow fan at the face and also in the collection system located beyond that location. Test 9 shows little evidence of outflow, due to the discontinuation of water supply to the left side of the Assembly after only 17 hours of operation. The crown region on the left side (Test 9) did however show considerable evidence of wetting after 2 days of water supply to Test 10 (right side, circled in Figure A-18), as a result of water migration within the assembly.

Start of Test *Prior to Test Termination*

Figure A-18. *Downstream face of Assembly 5 (Tests 9, 10).*

Test 9

Test 9 had water supplied at a rate of 2.5 l/min via an inlet port located at the rear of the chamber 0.3 m above the floor and 60 mm in from the sidewall. This test did not run for the planned duration due to development of an internal leakage path that exited on the floor of the assembly within the wooden framework. The result was water exiting the test without being forced to flow through the assembly to the downstream face. As a result, there was a risk to Test 10 since water standing on the floor could potentially enter the block-pellet assembly on the right-hand side of the system. This leak was detected 15 hours into the test's operation and could not be corrected. As a result, water supply was discontinued after only 17.5 hours of operation. Although this part of Assembly 5 was not operated beyond the first few hours, water was noted to be exiting the test in the lower pellet-filled region close to the floor of the chamber after approximately ½ hour of operation. This test was also sampled for water content distribution and photographed in the course of dismantling the assembly. Unlike previous tests there is a clear hydraulic interaction between the two sides of Assembly 5. In the final two days of operation of Test 10, there was a clear wetting upwards in the assembly, with water moving along the pellet-chamber crown interface and then moving both forward in the assembly and down along the side of Test 9 as can be seen in the red-circled areas in Figure A-19.

The distribution of water within Test 9 at the end of testing is shown in Figure A-20. It should also be noted that water entering Assembly 5 was also collecting on the floor of the wooden-framed volume of the assembly. This water likely originates on the floor of Test 10 where the eroded material acted as a dam, diverting water into the core of the assembly rather than allowing it to flow freely to the outflow collection area (see Figure A-18). Figure A-19 clearly shows the wetting induced by water supplied to Test 10; the crown region is essentially fully wet for the entire length of the assembly, as is the rear-most portion of the test. Similarly, the uppermost region of pellets between the formwork and the chamber wall showed extensive wetting for the length of the assembly while immediately below that region was a large volume of dry pellet materials. Along the base of the test the degree of wetting is inconsistent, likely as this was the region where water first entered the test while water was being supplied to Test 9. The pellets below the formwork showed only limited water uptake excepting at the downstream face, where water could be drawn in from the water standing on the surface of the pellets or the wooden floor of the formwork.

(a) Test 9 at beginning of water inflow and at time of dismantling (note water standing on floor of wooden framed volume)

Figure A-19. *Appearance and water distribution in Test 9.*

(b) Wetting within Test 9

Figure A-20. *Appearance and water distribution in Test 9.*

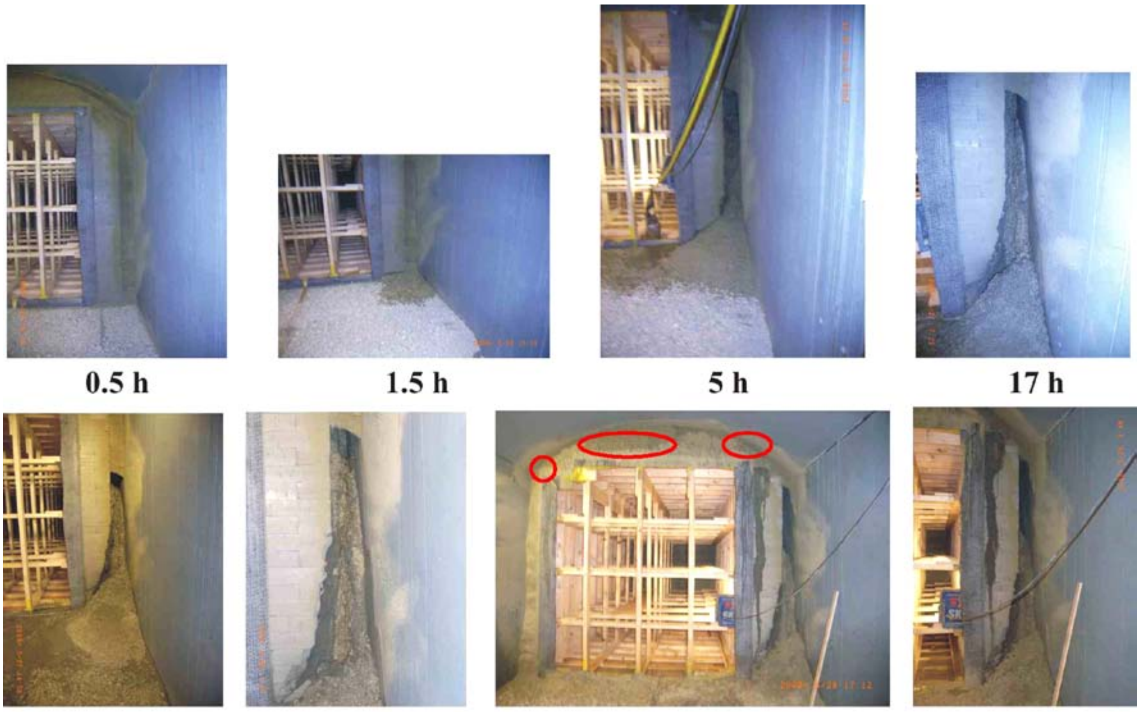
The results of the sampling of this test are provided in Appendix B and show quantitatively what was visually evident during dismantling. The region at and forward of the inlet point underwent extensive wetting with considerable water movement into the crown regions. Overall there were only a few pockets of still-dry materials, largely in the rear surrounded by wet materials. Considerable portions of the materials installed on the floor were also still dry at the time of test termination.

Overall, Test 9 showed that in a region where excessive water inflow is occurring, the majority of the pellet fill can wet quite quickly (with the possible exception of flooring materials). Water will also move rapidly through the backfill with the majority of flow occurring along the outer perimeter of the backfilled regions. Tests 9 and 10 also show that there may be a tendency for the backfilled tunnel to develop more than one flow path under conditions where there is very high water influx as well as causing extensive erosion of the backfill.

Test 10

Test 10 operated at a water inflow of 2.5 l/min from a point 1.8 m above the floor and 60 mm in from the chamber's sidewall (4 m distance from front face), for a period of 65 hours. This test had water outflow to the collection system noted at 4.8 hours of operation. This outflow time was not however the time at which water began to exit the backfill itself since it took considerable time to flow from the downstream face, across the pellet materials and into the outflow tray. Figure A-21 clearly shows that water began to exit the assembly between 30 minutes and 90 minutes after water was turned on. Initial outflow also occurred at approximately the same elevation as the inlet port. Figure A-18 shows the downstream face of the test assembly at the time of first outflow and again at the end of testing. Figure A-21 shows the large quantity of material that was moved out of the assembly in the course of the test as well as the large channel cut through the pellet and backfill materials (circled in red). Water moved through the pellet fill along the pellet-chamber wall interface via a small channel (approximately 5–10 mm in width) that extended at approximately the same elevation as the inflow location. The water exiting the front face was moving at a rate fast enough to erode and remove materials at the downstream face, resulting in an increasingly large hollow near the face of the backfill.

After approximately 2 days of operation, this erosion resulted in the collapse of a considerable volume of pellet material that had been left suspended above the downstream face of the assembly (final photos in Figure A-21). It was also evident that the inflowing water was moving upwards into the crown regions and that additional flow paths were developing along the uppermost pellet-block interface and also along the pellet-chamber roof interface.



0.5 h 1.5 h 5 h 17 h

24.5 h 41.5 h 50 h 66 h

Figure A-21. Front face of Test 10 showing erosion of pellet materials.

In addition to the materials visible in Figure A-21, there was considerable additional clay that was moved into the outflow containers. The water exiting Test 10 carried with it a substantial sediment load. The exiting water-sediment mixture contained a combination of block and pellet materials (as evidenced by their different colours and textures), indicating ongoing erosion of the entire backfill. The eroded materials also resulted in the redirection of a portion of the outflowing water, resulting in the flooding of the floor of the wood-framed central void in the Assembly. This water represents several hundreds of litres of outflow volume that was not captured by or recorded in the outflow measurements.

Figure A-22(a) provides a photographic record of the profile through Test 10 as it was stepwise dismantled. It is evident from this figure that water entering the chamber resulted in two transportation paths being developed in Test 10.

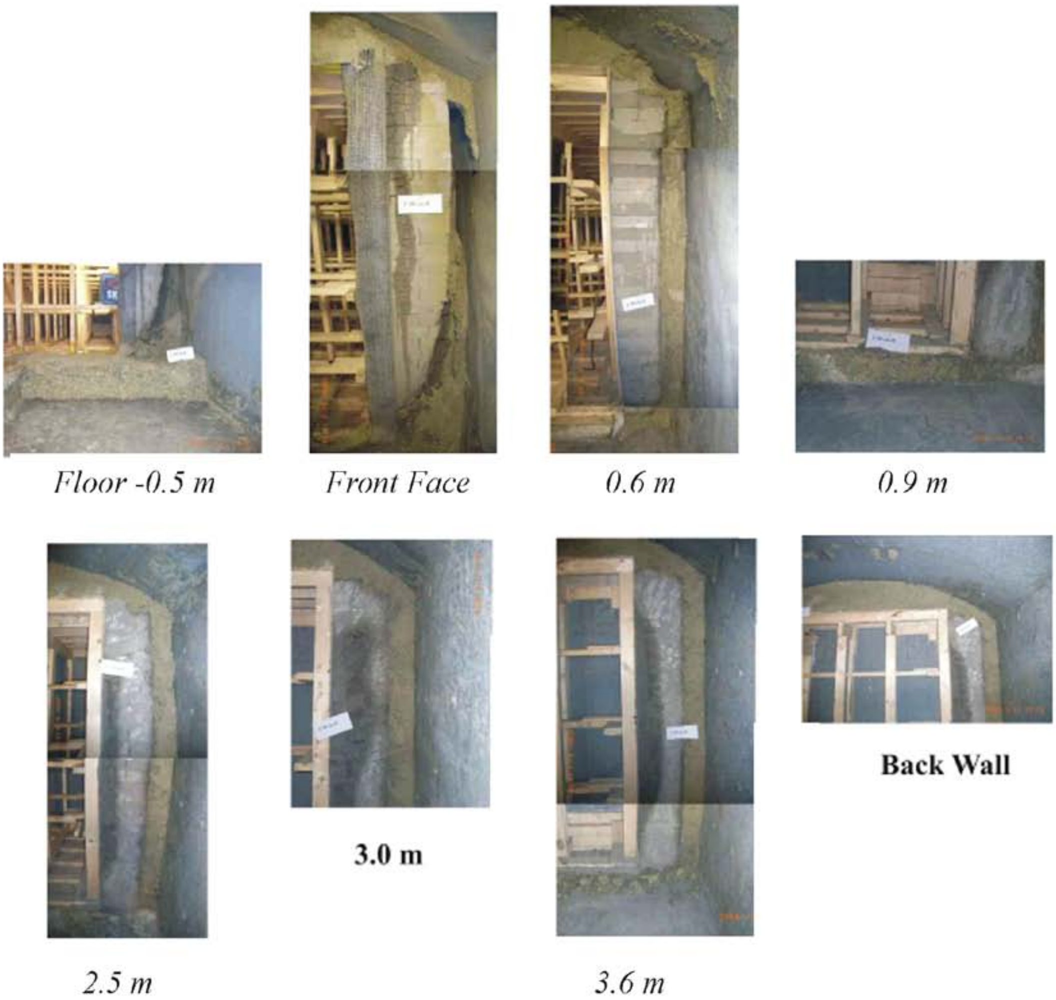
- The first was along the clay block – geotextile boundary extending from the rear of the chamber forward to within 0.9 m of the front face (see Figure A-21), but did not reach the front of the backfill. The block – geotextile region experienced considerable water flow through it and at the rearmost portion of the clay blocks there is evidence of considerable material removal. The water seems to have crossed through the clay blocks at a point approximately 3 m distance from the front face (0.9 m from rear of chamber) and at an elevation of approximately 2.2 m. This is evidenced by the broadening of the wetted clay block region shown in Figure A-22a as well as a clear termination of flow along this interface (Figure A-22b). This connection will have allowed water to move along the chamber wall – pellet contact forward to the downstream face as well as upwards towards the crown of the chamber and along the clay block – pellet contact at the top of the assembly. Figure A-21 and Figure A-22 both show the presence of backfill block materials in the eroded materials. The flow path along the geotextile-block boundary shown in Figure A-23 indicates that if the central volume were occupied with block materials that there is a possibility that there would be excessive erosion within the internal portions of the backfill, as seen in previous smaller-scale tests /Dixon et al. 2008a/.

- The second and ultimately the most important pathway was through the pellet fill (eventually eroding a considerable volume). The flow path that resulted in this erosion of pellets and blocks could be clearly traced through the length of the test assembly but for most of its length it was only a small piping feature. The material removed by this flow extended approximately 0.5 m into the pellet-filled volume and represents an ongoing erosive process that would continue so long as water entered the system. There was also evidence of erosion near the inlet point, the result of the large volumes of water entering a single point.

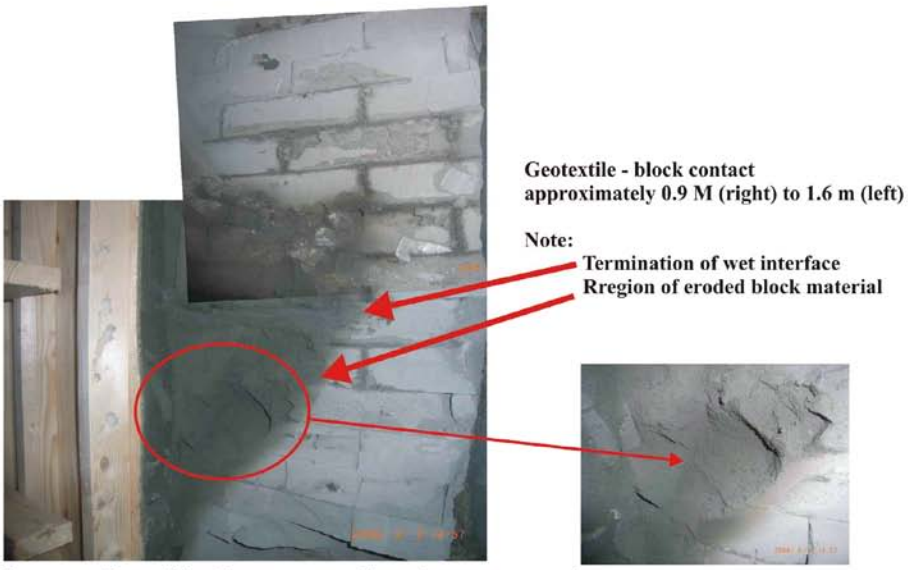
Sampling of the pellet-filled portions of the test during dismantling was done as shown in Figure 5-1. This sampling allows the visually-observed wetting patterns to be quantified. These data, provided in Appendix B confirm the patterns visually evident at the time of dismantling.

A.6 Assembly 6: Tests 11 and 12

Tests 11 and 12 were installed in a manner similar to that used in Tests 7 through 10 with a wetter pellet material used on the downstream face to facilitate filling of the volume using blown pellets. In this assembly there were several differences from previous simulations, firstly the entire chamber had a 50 mm thick layer of pellets installed on it. On top of this layer the remainder of the assembly was constructed, with no blocks installed on the left side (Test 11) and a 0.3 m thick block assembly installed on the right side (Test 12). The pellets simulated the conditions that might be expected to exist in an actual repository tunnel where pellets are used to level the floor and on which the clay blocks would be placed. Water was supplied at 1.8 and 0.3 m elevation from the rear of the chamber at inflow rates of 0.25 and 0.5 l/min respectively for a period of seven days, at the end of which time it was dismantled and sampled as per previous tests. Figure A-24 shows the construction and the front face of this assembly prior to the start of wetting. Figure A-25 shows the assembly at the time of test completion, with outflow locations clearly shown using coloured dyes (blue for Test 11 and pink for Test 12).


Floor -0.5 m
Front Face
0.6 m
0.9 m
2.5 m
3.0 m
3.6 m
Back Wall

(a). Profile through Test 10 at time of dismantling.



(b) Geotextile – Block contact showing extent of water movement

Figure A-22. *Photomosaic showing wetting and erosion in Test 10.*

Pellets Installed on Floor Framework and Blocks

Blowing in Pellets Completed Assembly

Figure A-23. *Assembly 6 (Tests 11 and 12) and appearance at the start of operation. (Note pellet flooring installed below and in front of assembly).*

Figure A-24. *Assembly 6 (Tests 11 and 12) at the end of testing.*

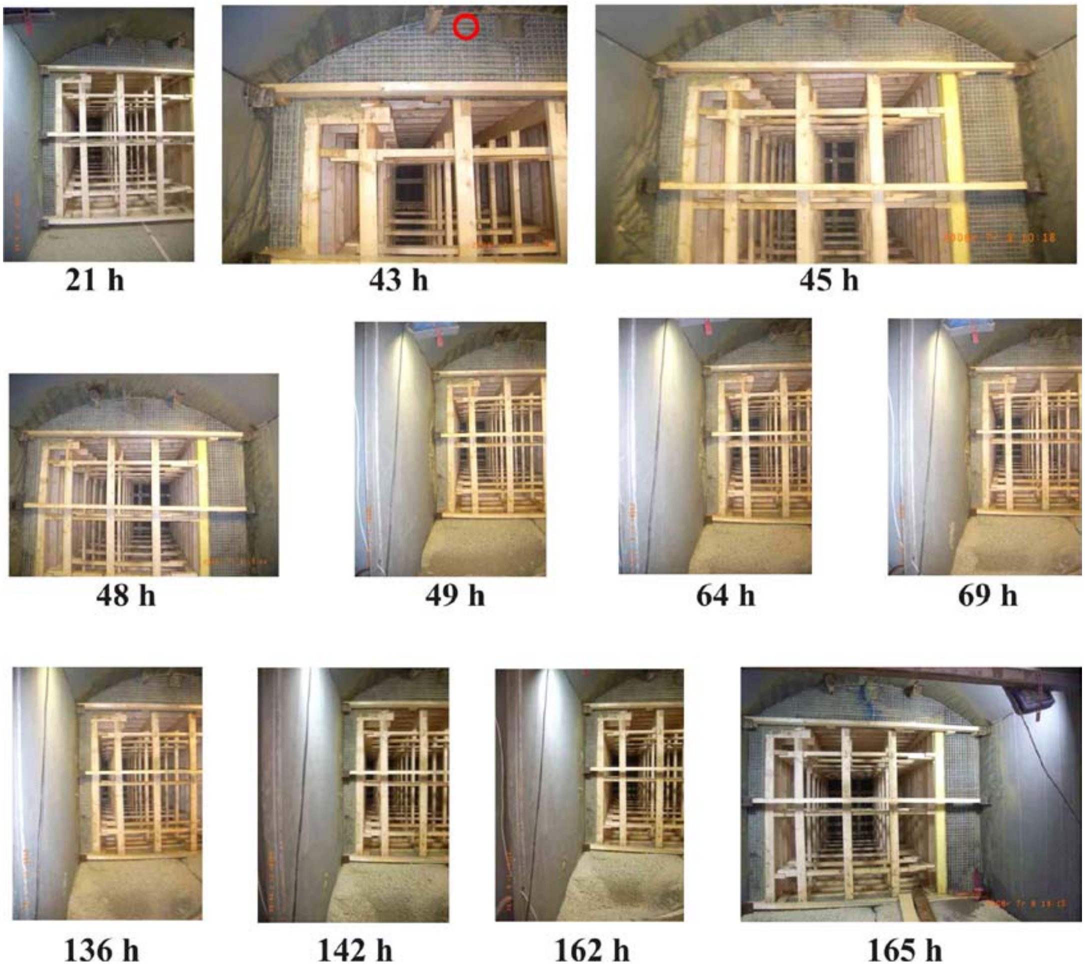

21 h 43 h 45 h 48 h 49 h 64 h 69 h 136 h 142 h 162 h 165 h

__Figure A-25.__ Downstream face of Test 11 during water inflow testing.

Tests 11 and 12 were the only tests where a dye was added to the inflowing water during the final 5 minutes of testing. Test 11 had a strong blue dye, composed of water-soluble writing ink that strongly sorbed onto any surfaces it contacted. The result was a clear visual record of the flow path present at the end of the test (Figure A-25). There was no evidence water having moved outside the single flow channel during the period when the coloured water was used.

The water exiting the crown of Assembly 6 did not carry with it a discernible sediment load. This is consistent with the other tests done at similar inflow rates during this study and indicates that incoming water is being effectively channelled past the backfill along one pathway. On completion of water percolation, the test was dismantled and water distribution within it was determined. Figure A-26 shows the water distribution throughout the test.

As was done with all tests in this study, the assembly was sampled during dismantling in order to develop a quantitative sense of the water uptake patterns and magnitude. The data generated by this sampling is provided in Appendix B.

Test 11

Test 11 was provided with water at the rear of the chamber, from a point 1.8 m above the floor and 60 mm in from the chamber's sidewall (4 m distance from front face), for a period of 168 hours. This test had water outflow noted after approximately 20 hours of operation, exiting as a flow from a small region of the assembly in the upper region, slightly to the left of the centreline (shown in Figure A-25 as a red circled region at 43 h). This is the only test that showed initial outflow from the upper regions of the assembly.

0.6 m beyond face

Front face

0.6 m

0.6 - 0.9 m
Side wall

1.2 m

2.4 m

3.0 m

3.0 - 3.6 m
Side wall

3.6 m

3.85 m

Figure A-26. *Water distribution within Test 1.*

It would appear that the inflow rate was sufficiently slow that the pellet-filled region was able to swell and seal off flow along the left side of the assembly. Associated with this point outflow, there was a film-like flow of water noted exiting along the roof of the chamber on the left side of Assembly 6 (Test 11). This type of thin-film flow was not noted in any previous tests and can be seen in Figure A-25 (43 h photo) and persisted from 20 h through to approximately 67 h into the test. At approximately 67 h into the test the flow along the crown of the chamber had localized sufficiently to be exiting the chamber at a single location. Between 67 h and the end of this test at 168 h, water moved along this pathway, pouring from the clay pellets and falling to the floor of the chamber where it accumulated and subsequently flowed into the collection system. Test 11 was the only test to exhibit channelling along the crown of the test chamber, although Test 10 did show water movement into that region after two days of inflow at 2.5 l/min. Flow along the roof is not unexpected as the crown region likely contains the lowest density of pellet fill and any settlement after their installation will likely leave a small gap along which water could move with little difficulty.

The pellets in front of Test 11 were only wet to a shallow depth as a result of water exiting the assembly, there was no evidence of water movement below the system. The front face appeared to be uniformly wet but this extended only about 0.6 m into the test, at which depth wetting began to be essentially limited to the crown regions with only limited water uptake along the chamber wall – pellet contacts as can be seen in Figure A-27. The lower regions of

2 h 20 h 24 h 25 h

43 h 48 h 50 h 67 h

Figure A-27. *Face of Test 12 at various times during water infiltration.*

Test 11 remained dry for the distance 0.6 m to 3.6 m with gradually increasing depth of wetting as the rear of the chamber was approached. Additionally, in spite of the preferential flow of water along the crown of Assembly 6, there was only a limited degree of wetting in the pellet materials in this region (see red circled areas in Figure A-27). There was a considerable depth of pellets between the interior spacer and the flow path that showed little or no water uptake. The water flowing along the crown of the chamber was not moving readily into the pellet materials below it once the region around the pathway was saturated.

Test 12

Test 12 operated at a water inflow of from the rear of the chamber, from a point 0.3 m above the floor and 60 mm in from the chamber's sidewall (4 m distance from front face), for a period of 168 hours. This test had water outflow noted after approximately 24 hours of operation. Initially outflow was along the chamber – pellet contact as a dampening film as can be seen in Figure A-28 at 24 hours (circled in red). It is not clear if this wetting was actually as the result of water supplied to Test 12 at 0.3 m from the floor or if it was overflow from Test 11 with its 1.8-m elevation inflow port. It is likely that this initial seepage was the result of crossover from Test 11 given the need for water in Test 12 to have climbed vertically within the pellet fill in order to supply this region. Additionally, at 40 h, liquid water outflow was noted along the pellet – block contact at approximately 0.1 m elevation (red circled). This outflow location remained at this elevation for the remainder of the test, shifting towards the pellet-chamber wall contact by 67 h (red circled) after which it did not move further.

Pellets at front face **Front face** **0.6 m**

1.2 m *1.8 m* *2.4 m* *3.0 m*

3.6 m **3.85 m**

Figure A-28. *Water distribution in Test 12.*

Test 12, like Test 11 also had a coloured dye (pink) added to the inflow water for the final 5 minutes of test operation in order to visually confirm the flow path through the test. The pink dye was a simple water soluble red ink that allowed the path taken to be seen. The front face of the test at the time of tracer exit is shown in Figure A-27 and clearly shows that there was only a single flow path active at the time of test termination and that it was located at the pellet-chamber wall contact.

Figure A-28 shows the water distribution through Test 12 at the end of 7 days of water percolation. This figure clearly shows the extensive wetting of the pellet-filled volume as well as the considerable wetting of the block materials, particularly in the rear-most region of the assembly. Much of the block wetting can be attributed to the geotextile – block interface, along which considerable flow obviously occurred in the initial stages of the test. Of note is the clearly wetter (darker) region between 3.0 m and the rear of the assembly. This would indicate that there was a preferential flow path along that region. There is no clear flow path between 3.0 m and the front face of the assembly where it exited via a very small channel. This is likely due to water moving along a very small pipe that did not influence the surrounding materials to a discernible extent.

Appendix B

Water content data from ½-Scale tests

BACLO 1/2-Scale Tests: Front Face of Assembly

Gravimetric Water Content Measurements (%)
Note: Blank cells respresent locations where the pellet water content was unchanged

Front	Assembly 1		Assembly 2		Assembly 3		Assembly 4		Assembly 5		Assembly 6	
3.9 m	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
Sample #	3.9 m	3.9 m	3.6 m	3.6 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m
	0.25 l/min	0.5 l/min	0.5 l/min	1 l/min	0.1 l/min	0.25 l/min	0.25 l/min	0.5 l/min	2.5 l/min	2.5 l/min	0.25 l/min	0.5 l/min
1	56.2				NI	NI	NI	NI	68.2	62.6	68.7	61.0
2	163.8	187.1			NI	NI	NI	NI	53.3	60.6	69.3	78.1
3	63.4	81.5	55.1		NI	NI	NI	NI	52.2	59.4	62.0	47.8
4	268.9	179.6	80.6		NI	NI	NI	NI	55.8	60.9	66.2	53.1
5	165.9	78.4	122.2	42.0	110.7	72.6	NI	NI	59.8	58.8	63.4	40.8
6	64.0	59.7		41.4	80.5	90.5	161.1	93.5	72.2	61.3	50.5	46.3
7	113.2	104.7		51.9			63.9	96.5	64.4	99.4	42.4	64.1
8	72.9	71.9					222.4	142.8	64.8	63.4	51.5	50.8
9	106.7	126.7		48.9		74.2	124.2	140.7	63.1	62.7	66.2	79.4
10		106.4				90.8	113.4	133.5	30.9	78.0	88.4	88.1
11		104.8		36.4		92.5	42.5	181.4	34.1	80.3	90.4	91.0
12		103.5		32.1		103.7	28.2	123.4	24.2	90.9	139.6	49.1
13	96.1	91.2		56.9		99.2	65.0	93.3	22.9	NR	49.9	79.1
14	101.9	91.7	58.2	56.2		95.3	33.6	49.4	23.8	NR	73.9	33.2
15	113.7	142.0		61.6		91.4	25.0	68.1	21.1	NR	63.9	79.5
16	95.5	85.0	57.7	62.9	77.5	74.5	31.1	59.9	23.0	NR	56.1	37.6
17	82.6	76.2	67.6	69.5	72.0	86.3	21.7	31.7	24.2	NR	40.3	43.9
18	78.5	77.6	71.3	78.0	79.0	100.0	25.9	35.2	23.3	NR	45.0	44.4
19	75.6	73.0	67.5	73.6	73.1	63.9	19.6	21.1	22.0	NR	48.4	49.9
20	73.0	75.4	68.4	81.7	89.5	78.3	23.3	32.9	24.3	NR	57.2	43.0
21	70.0	72.9	38.7	69.4	80.2	73.8	18.4	22.8	60.8	NR	48.1	49.2
22	74.1	87.1		47.7	85.2	72.6	22.5	22.6	25.1	NR	59.6	64.0
23	61.1	107.5				69.8	24.2	23.6	71.0	NR	49.9	60.1
24	74.9	84.7				86.4	22.1	30.3	27.5	NR	63.0	57.0
25	65.1	86.5				65.4	21.2	27.4	25.4	NR	45.3	60.9
26	19.2	81.3					22.5	21.1	199.8	112.5	35.2	75.7
27	18.6	62.0					20.9	23.1	131.9	181.1	47.0	81.4
28	19.9	83.7					22.3	27.7	115.0		48.7	36.6
29	46.4	83.5					30.4	21.7	176.1	172.8	55.3	68.3
30		19.1					30.9	18.8	112.5	183.5	58.1	74.1
31		19.0					26.0	20.5	99.1	162.7	63.8	70.1
32		19.7					25.9	22.6	106.9	165.1	62.9	74.3
33							25.4	25.6	76.6		88.9	58.8
34							25.1	28.8	22.8		85.3	83.8
35							26.4	23.1	65.2		60.3	73.4
36							25.4	21.2	43.7		60.5	61.2

NI - not installed, no pellets in this location
NR - samples not recoverable, e.g. material eroded away
NS - not sampled or sample lost

BACLO 1/2-Scale Tests: 3.3 m from Rear of Assembly (0.6 m from Front Face)

Gravimetric Water Content Measurements (%)
Note: Blank cells respresent locations where the pellet water content was unchanged

3.3 m	**Assembly 1**		**Assembly 2**		**Assembly 3**		**Assembly 4**		**Assembly 5**		**Assembly 6**	
Sample #	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**	**Test 10**	**Test 11**	**Test 12**
	3.9 m	**3.9 m**	**3.6 m**	**3.6 m**	**3.9 m**	**3.9 m**	**3.9 m**	**3.9 m**	**3.9 m**	**3.9 m**	**3.9 m**	**3.9 m**
	0.25 l/min	**0.5 l/min**	**0.5 l/min**	**1 l/min**	**0.1 l/min**	**0.25 l/min**	**0.25 l/min**	**0.5 l/min**	**2.5 l/min**	**2.5 l/min**	**0.25 l/min**	**0.5 l/min**
1	17.8				NI	NI	NI	NI	58.3	76.3		
2					NI	NI	NI	NI	46.3	52.5		
3					NI	NI	NI	NI	58.1	53.9		
4					NI	NI	NI	NI	45.3	48.4		
5	39.2	44.9			NI	NI	NI	NI	49.9	19.8		49.2
6	24.0						74.3	61.1	52.4	49.3		
7							72.4	60.2	77.2	63.2		
8							81.4	74.9	56.5	53.8		61.0
9							89.7	75.6	74.9	65.1		44.1
10							92.8	75.5	66.4	72.0		84.8
11							72.6	44.3	51.3	64.1		61.1
12				38.9			94.6	92.2		78.4		93.4
13				55.2			70.4	65.5		56.7		60.6
14				62.8			73.1	100.9		56.0		82.1
15	23.8	48.9	wet	58.3			45.2	52.7		55.3		61.6
16	78.1	69.5	58.3	66.4			42.3	74.1		48.1		94.4
17	42.8	44.5	60.8	56.8	71.8	64.5		62.7		53.6		58.7
18	80.4	77.5	84.0	93.3	99.9	107.4		76.7		56.9		70.8
19	40.7	63.2	68.8	70.6	66.3	68.7		35.8		68.1		60.0
20	68.8	82.7	69.0	81.8	75.1					51.3		68.5
21	38.3	47.2	63.9	68.4	65.1	52.5				134.6	51.6	56.3
22	20.8	30.9		70.7	85.8	75.7				72.9	61.6	66.5
23		20.5			61.0	46.4			23.6	110.9	58.6	58.3
24	57.4									66.1	67.6	67.0
25									39.6	36.9	68.3	75.3
26									26.0	28.4	61.1	58.2
27									47.1	54.3	64.2	61.6
28						89.0			38.8	49.8	81.7	79.9
29									53.4	56.0	55.4	52.8
30									56.0	58.6		47.4
31									44.8	57.9	52.6	49.0
32									53.1	59.6	44.9	40.3
33									56.3	61.7	49.4	52.5
34									22.2	65.5	52.9	54.9
35									73.7	65.8	80.0	109.6
36									75.6		65.9	102.2

NI - not installed, no pellets in this location
NR - samples not recoverable, e.g. material eroded away
NS - not sampled or sample lost

BACLO 1/2-Scale Tests: 2.7 m from Rear of Assembly (1.2 m from Front Face)

Gravimetric Water Content Measurements (%)
Note: Blank cells respresent locations where the pellet water content was unchanged

F3	Assembly 1		Assembly 2		Assembly 3		Assembly 4		Assembly 5		Assembly 6	
2.7 m	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
	3.9 m	3.9 m	3.6 m	3.6 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m
Sample #	0.25 l/min	0.5 l/min	0.5 l/min	1 l/min	0.1 l/min	0.25 l/min	0.25 l/min	0.5 l/min	2.5 l/min	2.5 l/min	0.25 l/min	0.5 l/min
1							NI	NI	53.7	59.0		
2							NI	NI	17.3	24.1		
3							NI	NI	39.8	27.4		
4					53.0		NI	NI	19.1	25.4		
5							NI	NI	21.7	42.2		
6							71.5	53.1	50.1	51.1		
7							70.4	36.4	57.5	67.5		
8							97.7	68.1	46.8	58.8		44.8
9			45.7				105.0	75.1	61.9	48.3		43.9
10			53.7				120.5	74.9	75.5	76.3		73.4
11			48.3	34.4			69.4	62.3	71.9	44.6		64.9
12			71.6	39.1			111.8	73.7	71.6	75.8		91.2
13			62.8	58.4			64.4	64.9	50.3	37.9		63.3
14			71.3	62.8		40.3	86.1	96.3		75.3		101.9
15	61.2	59.7	70.6	62.6	43.5	60.5	69.7	61.0		42.3		56.2
16	50.3	63.7	66.5	67.5	63.9	70.0	99.3	106.1		49.2		85.2
17	56.5	76.5	65.4	59.1	51.2	63.1	68.7	61.6		44.2		63.1
18	71.8	66.1	89.5	71.0	87.6	101.0	63.6	82.4		57.2		79.7
19	67.9	74.0	93.5	64.0	55.7	60.8	46.7	56.3		52.7		58.2
20	69.9	61.7	85.6	78.7	46.0	75.2		68.7		47.1		49.4
21	54.8	54.5	77.9	63.4	28.6	36.4		42.3		62.1		57.7
22	38.7	50.6	60.6			74.0		53.4	36.7	72.6		57.2
23	48.4		61.7			42.0		46.7	32.5	45.2		63.0
24									63.3	69.8	59.0	70.9
25									50.6	63.1	75.7	53.5
26									21.2	50.0	59.3	61.4
27									60.2	45.8	75.6	64.9
28									71.7	72.4	96.7	78.7
29									53.9	40.8	58.6	76.7
30									57.1	40.8	46.5	63.2
31									59.0	60.0		46.4
32									61.0	59.7		
33									57.7	57.9	28.9	
34									61.0	43.5	23.3	53.4
35									80.2	61.4	103.5	94.7
36									71.2	78.3	88.3	90.5

NI - not installed, no pellets in this location
NR - samples not recoverable, e.g. material eroded away
NS - not sampled or sample lost

BACLO 1/2-Scale Tests: 2.1 m from Rear of Assembly (~Centre of Assembly)

Gravimetric Water Content Measurements (%)
Note: Blank cells respresent locations where the pellet water content was unchanged

Center	Assembly 1		Assembly 2		Assembly 3		Assembly 4		Assembly 5		Assembly 6	
2.1 m	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
	3.9 m	3.9 m	3.6 m	3.6 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m
Sample #	0.25 l/min	0.5 l/min	0.5 l/min	1 l/min	0.1 l/min	0.25 l/min	0.25 l/min	0.5 l/min	2.5 l/min	2.5 l/min	0.25 l/min	0.5 l/min
1					NI	NI	NI	NI		52.5		
2					NI	NI	NI	NI		40.5		
3					NI	NI	NI	NI		46.0		
4					NI	NI	NI	NI	76.3	48.3		
5					NI	NI	NI	NI	74.4	55.1		34.3
6							57.3		73.7	46.1		39.4
7							67.5		50.6	43.0		50.1
8							54.2			40.9		48.7
9							72.9			34.6		79.5
10							100.4			60.7		101.9
11							68.4	34.2		72.4		62.8
12							113.6	43.0		62.3		105.0
13							61.8	56.1		73.7		52.4
14	39.7					46.7	136.4	76.4		65.3		113.0
15				38.0		45.1	77.5	59.5		67.9		56.9
16	58.6	54.9		64.6	44.9	68.8	123.5	88.7		56.4		93.3
17	49.8	68.2		59.2	43.7	65.5	62.7	60.1		64.9		53.6
18	84.1	146.1	81.4	76.2	107.4	88.1	94.6	108.6		63.9		56.4
19	55.3	66.5	68.2	58.6	66.9	61.2	64.9	68.5		61.2		41.9
20	66.5	78.1	76.5		87.8	122.6	63.9	93.4		57.7		55.1
21	57.3	61.0	61.4	56.7	54.2	65.1	48.1	59.2		53.5		35.1
22	53.2	57.2	35.6	52.0	55.2	76.0		76.1		56.4	40.0	62.6
23	49.1	43.4	51.6		37.4	57.1		49.1	55.1	61.5	51.4	29.6
24					51.9	61.9		70.0	75.3	63.2	75.3	78.2
25					52.1	37.5		57.9	68.7	49.2	79.4	87.7
26						53.1			35.8	33.0	56.6	36.7
27									51.8	40.8	51.9	40.7
28					61.0	46.3			67.2	51.3	86.0	88.3
29									49.9	47.3	64.6	67.6
30									35.1	49.1	52.8	25.9
31									24.2	51.5	27.0	59.5
32									47.5	49.4	31.7	29.5
33									38.8	43.9	49.0	48.8
34									45.8	51.1	27.9	45.6
35									79.4	59.5	107.0	105.4
36						100.1			72.2	62.7	94.1	86.1

NI - not installed, no pellets in this location
NR - samples not recoverable, e.g. material eroded away
NS - not sampled or sample lost

BACLO 1/2-Scale Tests: 1.5 m from Rear of Assembly (2.4 m from Front Face)

Gravimetric Water Content Measurements (%)
Note: Blank cells respresent locations where the pellet water content was unchanged

B1	Assembly 1		Assembly 2		Assembly 3		Assembly 4		Assembly 5		Assembly 6	
1.5 m	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
	3.9 m	3.9 m	3.6 m	3.6 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m
Sample #	0.25 l/min	0.5 l/min	0.5 l/min	1 l/min	0.1 l/min	0.25 l/min	0.25 l/min	0.5 l/min	2.5 l/min	2.5 l/min	0.25 l/min	0.5 l/min
1					NI	NI	NI	NI				
2					NI	NI	NI	NI	30.9			
3					NI	NI	NI	NI				
4					NI	NI	NI	NI		10.0		
5					NI	NI	NI	NI		138.5		
6							66.6			47.4		
7							37.1		43.8	83.7		
8							66.6		48.5	6.4		
9							95.4		79.6	216.0		49.3
10		24.2					101.8		50.7	87.1		77.1
11		42.6					39.4		73.0	-41.3		66.4
12		65.7					99.5		71.2	54.3		96.7
13		24.5					69.3		70.8	82.0		70.4
14	54.1	60.2			71.8		111.1		71.7	86.3		82.9
15		33.9			61.1		68.6		68.7	-8.1		61.2
16	51.0	61.7			76.1		96.0	62.0	65.6	96.0		76.7
17	46.6	66.4			62.4		67.3	37.0	43.3	80.7		57.7
18	67.9	111.5	59.1	65.3	53.2	82.5	86.0	59.4		50.8		68.2
19	63.3	68.3	62.5	50.7	41.8	93.3	59.4	45.9		-50.5		64.9
20	65.6	104.5	67.5	60.5	38.6	84.8	49.0	72.6	47.8	35.8	44.3	65.9
21	45.0	72.0	58.3	55.2	63.0	56.0		60.8	53.5	43.6	56.0	47.7
22	67.3	74.7		37.5	34.8	89.0		56.4	51.8	141.5	52.2	56.5
23	57.8	68.6							59.7	96.5	60.9	53.4
24		51.0							70.3	13.3	67.8	59.3
25		41.1							70.1	122.9	77.4	55.0
26	58.5								62.4	105.5	66.6	55.3
27									41.1	108.2	57.5	61.3
28					67.9	134.5			72.5	-22.6	91.1	55.3
29					85.4	38.8			44.3	52.6	109.4	64.3
30									44.6	56.4	39.0	69.6
31									46.6	141.9	24.6	63.2
32									41.3	26.7	60.6	77.6
33									49.9	14.6	49.4	50.6
34					43.9	44.1			49.2	139.2	41.5	59.5
35					76.6	85.1			69.3	61.8	64.0	86.9
36					96.0	128.8			60.6	114.6	56.4	103.0

NI - not installed, no pellets in this location
NR - samples not recoverable, e.g. material eroded away
NS - not sampled or sample lost

BACLO 1/2-Scale Tests: 0.9 m from Rear of Assembly (3.0 m from Front Face)

Gravimetric Water Content Measurements (%)
Note: Blank cells respresent locations where the pellet water content was unchanged

B2	Assembly 1		Assembly 2		Assembly 3		Assembly 4		Assembly 5		Assembly 6	
0.9 m	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
	3.9 m	3.9 m	3.6 m	3.6 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m
Sample #	0.25 l/min	0.5 l/min	0.5 l/min	1 l/min	0.1 l/min	0.25 l/min	0.25 l/min	0.5 l/min	2.5 l/min	2.5 l/min	0.25 l/min	0.5 l/min
1			NS	NS	NI	NI	NI	NI		43.7		
2			NS	NS	NI	NI	NI	NI		39.6		
3			NS	NS	NI	NI	NI	NI		49.7		
4			NS	NS	NI	NI	NI	NI		55.1		
5			NS	NS	NI	NI	NI	NI	17.4	45.6		
6			NS	NS			70.5		22.3	19.8		
7			NS	NS			76.0		47.6	30.0		
8			NS	NS			68.2		20.2	22.0		
9			NS	NS			104.1		45.1	42.8		45.1
10			NS	NS			97.8		61.9	73.3		72.8
11			NS	NS			69.4		69.6	56.1		66.7
12			NS	NS			98.5		63.2	75.1		89.8
13			NS	NS			68.0		67.6	52.1		64.1
14			NS	NS			73.2		71.1	75.1		94.2
15		36.4	NS	NS			60.9		73.1	45.7	60.5	70.0
16		46.8	NS	NS			62.9		76.9	67.4	66.1	117.4
17		49.4	NS	NS		50.1	58.4		73.0	55.3	61.4	69.2
18	68.0	82.3	NS	NS		75.5	63.9		60.9	68.8	69.8	72.4
19	64.5	67.0	NS	NS		64.7	64.5		67.5	53.0	57.4	55.8
20	71.4	90.4	NS	NS		100.7	63.0		58.9	58.2	64.6	63.7
21	42.6	60.1	NS	NS		28.5			64.2	34.8	62.1	56.4
22	46.9	38.7	NS	NS	32.9	47.4			56.2	61.8	70.2	58.8
23		57.8	NS	NS	57.5	45.6			55.9	49.4	57.8	56.6
24	36.8	25.5	NS	NS					66.7	56.7	66.9	55.5
25		65.3	NS	NS	90.3	136.8			63.0	58.9	67.6	69.8
26			NS	NS					28.0	53.0	52.2	56.4
27			NS	NS					38.7	32.0	29.3	50.5
28			NS	NS	72.8	98.7			65.4	61.8	72.7	57.9
29			NS	NS					26.4	46.4	59.4	52.5
30			NS	NS					25.5	40.5	34.0	60.3
31			NS	NS					25.5	33.7	43.4	51.7
32			NS	NS					34.8	31.0	62.1	62.9
33			NS	NS					56.7	57.2	56.7	57.1
34			NS	NS					54.2	57.1	64.2	53.2
35			NS	NS	68.5				72.9	72.6	81.3	75.8
36			NS	NS	95.4				70.5	76.6	79.1	72.1

NI - not installed, no pellets in this location
NR - samples not recoverable, e.g. material eroded away
NS - not sampled or sample lost

BACLO 1/2-Scale Tests: 0.3 m from Rear of Assembly (3.6 m from Front Face)

Gravimetric Water Content Measurements (%)
Note: Blank cells respresent locations where the pellet water content was unchanged

B3		Assembly 1			Assembly 2			Assembly 3			Assembly 4			Assembly 5			Assembly 6	
0.3 m		Test 1	Test 2		Test 3	Test 4		Test 5	Test 6		Test 7	Test 8		Test 9	Test 10		Test 11	Test 12
		3.9 m	3.9 m		3.6 m	3.6 m		3.9 m	3.9 m		3.9 m	3.9 m		3.9 m	3.9 m		3.9 m	3.9 m
Sample #		0.25 l/min	0.5 l/min		0.5 l/min	1 l/min		0.1 l/min	0.25 l/min		0.25 l/min	0.5 l/min		2.5 l/min	2.5 l/min		0.25 l/min	0.5 l/min
1					NS	NS		NI	NI		NI	NI			53.5			
2					NS	NS		NI	NI		NI	NI			54.4			
3					NS	NS		NI	NI		NI	NI			54.4			
4					NS	NS		NI	NI		NI	NI		30.5	55.6			
5					NS	NS		NI	NI		NI	NI		30.2	51.1			
6					NS	NS					60.6			45.6	50.2			
7					NS	NS					68.8			50.2	50.3			
8		57.5			NS	NS					47.4				53.2			
9		60.5			NS	NS					70.2			57.6	55.9			52.4
10		35.3	35.7		NS	NS					84.0			46.0	70.1			66.1
11		60.5	44.0		NS	NS					75.5			53.6	41.3			59.3
12		52.6	51.2		NS	NS					84.3			42.5	72.8			68.1
13		58.9	53.1		NS	NS					72.3			53.8	35.7			66.1
14		64.5	62.0		NS	NS					69.3			42.6	70.1			75.8
15		62.9	57.5		NS	NS					68.1			60.1	40.2			65.7
16		62.2	61.7		NS	NS					62.3			58.9	60.3			73.1
17		68.4	56.7		NS	NS					54.8			68.1	32.7			68.6
18		73.8	64.2		NS	NS					45.7			79.3	56.9		61.3	67.0
19		91.3	59.4		NS	NS								78.8	37.7		64.0	62.3
20		66.2	105.3		NS	NS								68.7	59.3		65.6	67.6
21		64.4	69.8		NS	NS								66.6	35.1		80.9	62.9
22		35.3	77.0		NS	NS								53.0	66.9		60.7	62.7
23			54.1		NS	NS								60.5	52.3		80.1	57.4
24			49.4		NS	NS		49.3						54.7	61.9		73.8	61.5
25					NS	NS		55.2	23.3					64.9	66.8		83.3	64.0
26			55.8		NS	NS			34.7					43.9	49.3		78.5	56.5
27					NS	NS								32.8	50.6		51.5	49.6
28					NS	NS		74.7	64.0					67.3	66.3		35.2	60.7
29					NS	NS								54.8	52.9		73.2	54.3
30					NS	NS								46.8	49.1		35.0	51.0
31					NS	NS								36.4	46.6		26.6	49.8
32					NS	NS								43.8	40.8		32.2	41.3
33					NS	NS			41.4					51.9	51.5		37.3	61.5
34					NS	NS			40.2					36.5	55.4		56.1	64.0
35					NS	NS		54.8	109.1					58.9	76.8		70.1	64.0
36					NS	NS		42.8	83.4					66.7	73.4		75.0	66.9

NI - not installed, no pellets in this location
NR - samples not recoverable, e.g. material eroded away
NS - not sampled or sample lost

BACLO 1/2-Scale Tests: 0.05 - 0.1 m from Rear of Assembly (3.8 - 3.85 m from Front Face)

Gravimetric Water Content Measurements (%)
Note: Blank cells respresent locations where the pellet water content was unchanged

5B	Assembly 1		Assembly 2		Assembly 3		Assembly 4		Assembly 5		Assembly 6	
0.05-0.1 m	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
	3.9 m	3.9 m	3.6 m	3.6 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m	3.9 m
Sample #	0.25 l/min	0.5 l/min	0.5 l/min	1 l/min	0.1 l/min	0.25 l/min	0.25 l/min	0.5 l/min	2.5 l/min	2.5 l/min	0.25 l/min	0.5 l/min
1	NS	NS	NS	NS	NI	NI	NI	NI		54.7		
2	NS	NS	NS	NS	NI	NI	NI	NI		54.6		
3	NS	NS	NS	NS	NI	NI	NI	NI		55.9		
4	NS	NS	NS	NS	NI	NI	NI	NI		55.8		
5	NS	NS	NS	NS	NI	NI	NI	NI	45.2	53.3		
6	NS	NS	NS	NS	NS	NS	68.6		46.3	50.3		
7	NS	NS	NS	NS	NS	NS	61.2		49.8	48.7		
8	NS	NS	NS	NS	NS	NS	47.9		43.5	57.5		
9	NS	NS	NS	NS	NS	NS	53.8		71.1	67.2		42.5
10	NS	NS	NS	NS	NS	NS	51.4		51.0	68.9		56.2
11	NS	NS	NS	NS	NS	NS	51.7		57.9	61.1		55.0
12	NS	NS	NS	NS	NS	NS	66.2		53.1	61.2		55.7
13	NS	NS	NS	NS	NS	NS	69.5		59.5	54.5		56.4
14	NS	NS	NS	NS	NS	NS	66.4		42.8	49.5		63.9
15	NS	NS	NS	NS	NS	NS	62.1		57.1	50.0		65.3
16	NS	NS	NS	NS	NS	NS	51.0		51.2	71.1		65.6
17	NS	NS	NS	NS	NS	NS	37.9		74.0	41.9	52.9	69.9
18	NS	NS	NS	NS	NS	NS			59.6	47.2	35.2	64.9
19	NS	NS	NS	NS	NS	NS			76.0	42.6	58.1	72.5
20	NS	NS	NS	NS	NS	NS			73.4	52.6	72.1	64.1
21	NS	NS	NS	NS	NS	NS			76.5	64.7	65.3	72.3
22	NS	NS	NS	NS	NS	NS			54.9	62.9	66.7	64.3
23	NS	NS	NS	NS	NS	NS			59.1	63.7	73.4	187.3
24	NS	NS	NS	NS	NS	NS			59.9	66.0	77.8	64.4
25	NS	NS	NS	NS	NS	NS			61.8	57.3	85.8	63.7
26	NS	NS	NS	NS	NS	NS			48.7	56.3	57.7	91.0
27	NS	NS	NS	NS	NS	NS			61.1	54.2	62.2	142.2
28	NS	NS	NS	NS	NS	NS			61.3	59.8	52.6	64.7
29	NS	NS	NS	NS	NS	NS			53.0	49.5	27.3	60.2
30	NS	NS	NS	NS	NS	NS			58.3	57.6	27.1	58.6
31	NS	NS	NS	NS	NS	NS			56.7	57.4	26.9	44.2
32	NS	NS	NS	NS	NS	NS			47.5	45.1	32.2	24.5
33	NS	NS	NS	NS	NS	NS			62.4	51.6	49.8	30.3
34	NS	NS	NS	NS	NS	NS			58.9	50.3	47.1	51.3
35	NS	NS	NS	NS	NS	NS			64.0	55.6	60.6	69.3
36	NS	NS	NS	NS	NS	NS			59.2	51.7	71.7	64.1

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