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Conceptual and mathematical models of water storage and spreading

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Abstract

This report describes the development of a conceptual and a mathematical model of water storage and spreading of water in pellets fillings during backfill installation. Different backfill designs and installation sequences were considered in this work, as well as different water handling methods, e.g. geotextiles, water storage sections and drainage boreholes.

The conceptual model were based on experimental data from a large number of tests. From artificial slot tests different wetting patterns were identified for different ranges in water inflow rate, and these patterns were used for the definition of a conceptual model. Results from steel-tunnel tests (i.e. test performed in half-scale at Äspö HRL) were evaluated as the time of the first outflow from a 6 m tunnel section for a specific inflow rate, and this data was used to define tentative flow rate limits, either with or without the use of geotextiles at inflow points.

The objective of the mathematical model was to calculate the available time for specific deposition tunnels and for specific water inflow scenarios, and to analyse if there is a risk that inflowing water can catch up with the backfill front. The water transport was represented as progressing water fronts from multiple water inlets in a tunnel, for essentially any combination of inlet positions and flow rates. The partial water-filling of the pellets-filled sections was represented with a flow rate depend a general definition which could enable an evaluation of features which are specific for SKB and Posiva, respectively, such as tunnel section area and backfilling rate.

Sammanfattning

Denna rapport beskriver framtagandet av en konceptuell och matematisk modell av hur vatten lagras och sprider sig i en pelletsfyllning i samband med installationen av återfyllning. Olika design på återfyllningar och installationssekvenser har undersökts i detta arbete såväl som olika metoder för att hantera vatteninflöde till exempel geotextil, vattenlagringssektioner och dränerande borrhål.

Den konceptuella modellen bygger på data från ett stort antal laboratorieförsök. Försök med en konstgjord pelletsfylld spalt har resulterat i att olika bevätningsmönster har kunnat identifieras för olika vatteninflöde och dessa mönster har sedan använts för att definiera en konceptuell modell. Resultaten från ståltunnelförsöken (det vill säga tester som utförts i halvskala vid Äspö HRL) har använts för att bestämma tiden till första utflödet från en 6 m lång tunnel sektion för ett specifikt vatteninflöde och denna data har sedan använts för att uppskatta maximala acceptabla inflöden till en 6 m sektion, antingen med eller utan geotextil monterat vid inflödespunkterna.

Syftet med den matematiska modellen har varit att kunna beräkna den tillgängliga tiden för en specifik deponeringstunnel med specifika inflöden och att kunna analysera om det finns en risk för att det inflödande vattnet kommer att hinna ikapp återfyllningsfronten. Vattentransporten i pelletsfyllningen har representerats av framåtskridande vattenfronter från ett antal inflödespunkter i en deponeringstunnel, för i princip alla kombinationer av inflödespositioner och flödeshastigheter. För en partiell vattenuppfyllning av pelletsfyllda sektioner har en funktion som är beroende av inflödeshastigheten använts. Denna funktion har tagits fram med hjälp av de resultat som erhållits från ståltunnelförsöken. Modellen har avsiktligt getts en allmänt hållen definition vilket gör det möjligt att utvärdera egenskaper som är specifika för både SKB och Posiva som till exempel olika tvärsnittsareor på deponeringstunnlarna samt olika hastighet på installationen av återfyllning.

Contents

1 Introduction

SKB and Posiva develop and test different designs of the KBS-3 concept for a final repository of spent nuclear waste. The work has been going on for several years in order to develop methods for backfilling, sealing and closure of a future repository.

The reference design considered by both SKB and Posiva for backfilling of deposition tunnels includes emplacement of pre-compacted blocks in the tunnel and bentonite pellets that fill up the space between the blocks and the tunnel walls, Figure 1-1. Pellets will also be placed on the tunnel floor in order to even out the rough rock surface and by that provide a suitable surface on which the backfill blocks can be piled. The installation of such a backfill system includes advanced technical solutions for automation of block manufacturing, block transports, piling of blocks, emplacement of pellets etc.

One of the main problems identified is how the water inflow to the tunnels should be handled during emplacement. Depending on flow rates and how the inflow points are distributed in the tunnels the inflowing water may affect the stability of the backfill installation and also cause erosion of the backfill. Both the Forsmark site in Sweden and the Olkiluoto site in Finland are assessed to be rather dry, but preliminary studies show that approximately 25–30 % of the planned deposition tunnels will have an inflow of more than 5 l/min and in some tunnels the inflows can be more than 30 liters per minute (Joyce et al. 2013, Hartley et al. 2010).

Since it is desirable that no deposition tunnels should be abandoned, it has been necessary to develop methods and techniques to handle these expected water inflows. The deposition tunnels in the current reference design have an inclination upward, towards tunnel face, of 1 degree to enable drainage of inflowing water away from the backfilling works as long as possible.

The modelled inflow rates are considered to largely be handled by storing the inflowing water in the pellet filling and optionally also use geotextile fastened on the rock surface, to distribute the inflowing water over a larger area. A considerably large amount of tests have been made in different scales during the last ten years in order to study the water storing properties in a pellet filling. The achieved results have been used to create a conceptual model for how water is stored in pellets for different water inflow rates. With this knowledge it also has been possible to create a model in order to calculate the position of the water front in relation to the backfill front for different inflow scenarios. This is assessed to be an important tool when planning the backfilling process of a deposition tunnel.

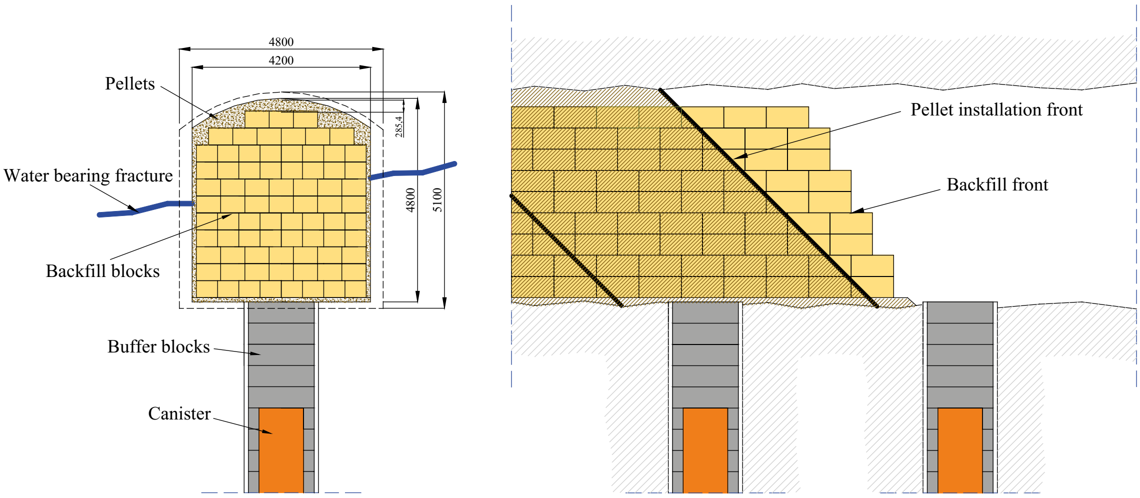


__Figure 1-1.__ Schematic drawing showing the reference design for backfill considered by SKB. The reference design for backfill considered by Posiva is similar and the only differences are in principle the size of the deposition tunnels and the choice of raw material used for blocks and pellets.

The work presented in this report has been performed within the SKB-Posiva project KBP1011 "Water handling during backfill installation". A schematic illustration of the outline of the report is shown in Figure 1-2. A compilation of results from different tests setups in presented in Chapter 2. A conceptual model for different wetting patterns at different flow rates is presented in Chapter 3, and this is used together with different test results and scaling techniques to produce a synthesis of different tests results. Descriptions of the present backfill design and planned installation sequences are presented in Chapter 4. A description of different water handling methods is presented in Chapter 5 together with a table with proposed inflow limits for different methods. Finally, a mathematical model of storage and spreading of water in the pellets filling of the backfill is presented in Chapter 6.

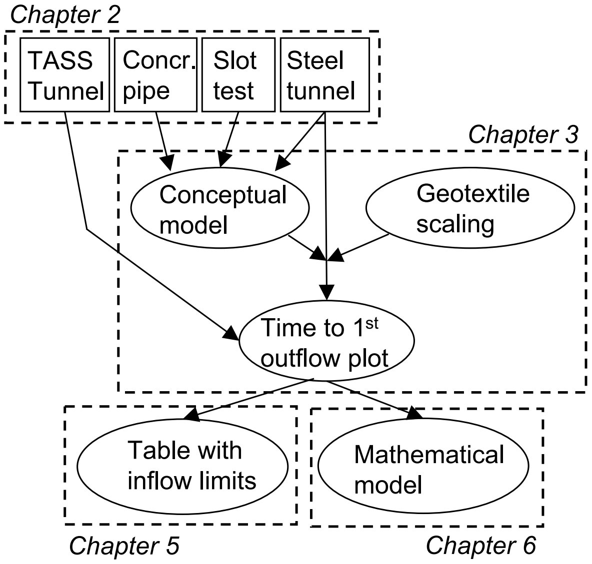


Figure 1-2. *A schematic illustration of the outline of the report and the evaluation of experimental data from different tests (TASS tunnel, concrete pipe, slot tests and steel tunnel test), via the conceptual model and different scaling techniques, to a synthesis of different test results (time to 1^{st} outflow plot). This is in turn used as input to a table with inflow limits for different methods, and a mathematical model of storage and spreading of water in the pellets filling.*

2 Compilation of results from different test setups

2.1 General

Tests have been performed in different scales and with different types of test equipment, during the last ten years, with the main objective to investigate different processes that may occur during installation of backfill material in a deposition tunnel, such as erosion of bentonite and how inflowing water is stored or flowing in a pellet filled gap. The tests have mainly been performed using bentonite pellets manufactured by extrusion, since this pellets type have been found to be superior regarding water storing properties (Andersson and Sandén 2012). This chapter provides a compilation of results from the tests. The presented test results origin both from old tests but also from new test series performed to further increase the understanding especially regarding the issue how the presence of fines affects the storing of inflowing water in a pellet filling. For every test, the basic test information and the determined water storage capacity is provided in tables together with an assessment of the wetting behaviour and the resulting wetting pattern. This data has later been used to update the conceptual model describing how water is stored depending on the flow rate of the inflowing water, see Chapter 3.

The following tests and investigations have been included in this compilation of results:

1. Concrete pipe tests. Tests performed in scale 1/12. The tests are reported in Dixon et al. (2008a).
2. Artificial slot tests. Tests have been performed in a number of different test series. The tests are reported in Sandén et al. (2008), Andersson and Sandén (2012) and Posiva SKB (2017).
3. Steel tunnel tests. Tests performed in scale ½. The tests are reported in Dixon et al. (2008b), Koskinen and Sandén (2014) and in Posiva SKB (2017).
4. Full scale test in TASS tunnel. This test is reported in Johnsson and Sandén (2013).

Only tests that are assessed to be of relevance for the water storing issue have been further investigated and included in this report.

2.2 Pellet

2.2.1 Material description

The pellet properties are essential for the test results. The majority of tests that have been performed with the objective to study water storage in a pellet filling have been made using either Asha pellets or Cebogel pellets. The Asha pellets have been manufactured at Äspö HRL while the Cebogel pellet is a commercial product. Asha pellets are of main interest for SKB and Cebogel pellets are of main interest for Posiva. Some single tests have earlier been made with other pellets types but the results from these tests have not been used in this report. The materials can be described according to the following:

1. **Asha NW BFL-L.** This bentonite is produced by Ashapura Minechem Co. The bentonite is quarried in the Kutch area on the northwest coast of India. The bentonite is sodium dominated with a montmorillonite content of about 70 %. The pellets made of this material have been manufactured at Äspö HRL (batches were delivered to SKB 2010 and 2012).
2. **Cebogel QSE**. This is a commercial bentonite product. The bentonite is an activated sodium bentonite originating from the island Milos, Greece. Typical value of the montmorillonite content is 80 %. This pellets type has been used in many different large scale tests at Äspö HRL.

2.2.2 Requirements

The pellet properties influences the water storage capacity. In the tests presented in this report the pellet have had a water content between 12 and 20 % and the dry density of the individual pellets have been between 1 810–2 000 kg/m^3, see e.g. Dixon et al. (2008a, b) and Andersson and Sandén (2012). If the water content is too high, then water will pass through voids between the pellets more easily which means that the storage capacity is decreased. Besides the basic material requirements it is judged that these figures regarding water content and density should serve as a guideline for the requirements on the pellet properties.

2.3 Concrete pipe tests

These tests were performed at Äspö HRL and are reported in Dixon et al. (2008a). The tests were performed in scale 1/12. A concrete pipe with the diameter 2 m and the length 1.2 m was used in order to simulate the deposition tunnel, Figure 2-1. Only the upper part of the pipe was used for the test. Blocks made of Friedland clay were piled inside the tube and bentonite pellets were used to fill up the empty spaces. The test duration varied between 5 and 120 hours and the water inflow rates between 0.01 and 1 l/min.

In total twenty-nine tests were performed in this equipment. Eighteen of these are assessed to be of interest for the issue with water storing in a pellet filling. Eleven tests were excluded since they were either performed as start-up tests with no pellets in the gaps, performed with a different material (Minelco bentonite) or that leakage through the test equipment had occurred during test duration. As mentioned, all these tests were performed using Friedland blocks, but it has been judged that the block quality only have had a minor impact on the test results. A compilation of the results from all tests of interest is provided in Table 2-1.

The table also shows evaluated water storage data such as time to first outflow and the amount of water stored before outflow occurred. The earlier suggested conceptual model describing water storage behaviour in a pellet filling (Sandén and Börgesson 2014) is based on the development of different wetting pattern around the inflow point for different water inflow rates. The presented by Dixon et al. (2008a) was evaluated and compiled in Table 2-1,

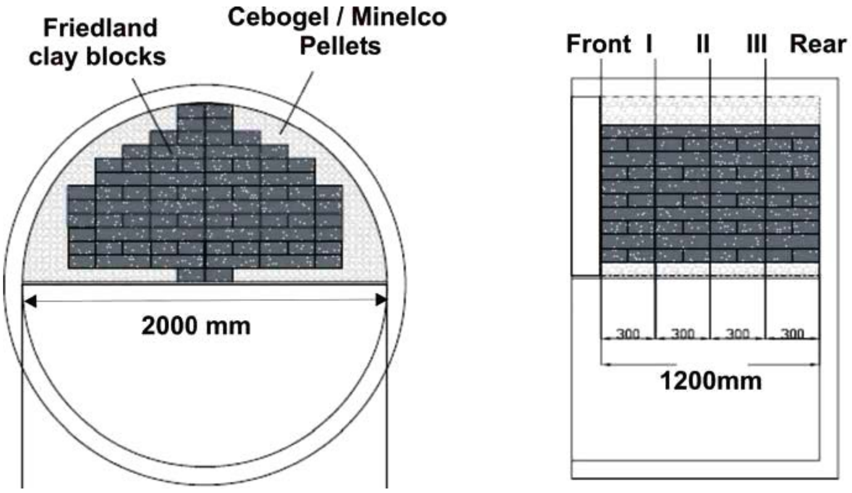


Figure 2-1. Schematic showing the 1/12 scale tests (Dixon et al. 2008a).

Table 2-1. Compilation of test results from the tests performed in a concrete tube at Äspö HRL (Dixon et al. 2008a).

Data from different tests with pellets (6 mm extruded)									**Water storage, test data**				
Bentonite	**Report**	**Test equipment**	**w ini**	**Fines removed**	**Water salinity**	**Water flow rate**	**Geotextile**	**Remark**	**Wetting behaviour**	**First outflow**	**Storage before outflow**	**Storage before outflow**	**Remark**
Origin/ batch no.			**%**	**Yes/No**	**%**	**l/min**	**Yes/No**		**Up/Down/Symmetric**	**h**	**litre**	**%**	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	1	No	Test 5	Downwards	0.13	7,8	4	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.25	No	Test 6	Symmetric/Downwards	2	30	15	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.01	No	Test 7	Symmetric/Upwards	NA	NA	NA	No leakage during test time
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.03	No	Test 8	Symmetric/Upwards	50	90	45	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.1	No	Test 9	Symmetrical	15	90	45	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.25	No	Test 10	Symmetric/Downwards	2	30	15	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.1	No	Test 11	Symmetrical	11.5	69	35	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.25	No	Test 12	Symmetric/Downwards	2.5	37,5	19	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.5	No	Test 13	Symmetric/Downwards	0.75	22,5	11	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.25	No	Test 14	Symmetric/Downwards	5	75	38	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.1	No	Test 15	Symmetrical	6	36	18	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.25	No	Test 16	Symmetric/Downwards	6.33	94,95	48	Long term test. Wetting continues after the first
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.1	No	Test 17	Symmetrical	2.8	16,8	8	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.25	No	Test 18	Symmetric/Downwards	1.1	16,5	8	Long term test. Wetting continues after the first
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.1	No	Test 19	Symmetrical	5	30	15	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.5	No	Test 20	Symmetric/Downwards	2.33	69,9	35	
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.1	No	Test 23	NA	2	12	6	Inflow points in floor
Cebogel	SKB R-08-134	Concrete pipe	18.9	No	0.5 %	0.5	No	Test 24	NA	0.05	1.5	1	Inflow points in floor

2.4 Artificial slot tests

The water storing capacity and forming of piping channels in bentonite pellets have also been investigated with so called large slot tests. The artificial slot simulates a part of the pellet filled space between rock and backfill blocks. Tests have been performed in two different test equipments:

- Large slot test equipment (denoted CT type and designed at Clay Technology AB). This test equipment was developed within the BACLO project, Figure 2-2. The dimensions of the artificial slot are 2 × 1 × 0.1m. The walls are made of Plexiglas which facilitates the test evaluation.
- Large slot test equipment (denoted B+Tech type and designed at B+Tech Oy). The dimensions of the artificial slot are 2 × 1 × 0.25 m, Figure 2-3. The walls are made of Plexiglas which facilitates the test evaluation. The construction is made so that it is possible to turn the slot into horizontal position which facilitates sampling and cleaning after test termination.

2.4.1 Tests at Clay Technology 2006–2010

These tests were made with the smaller (CT type) test equipment. The slot was filled with pellets from the open end and a constant water flow was applied on the side of the slot, see the tube inlet on the photo in Figure 2-2. The inflow point is positioned 0.5 m from the bottom and 0.3 m from the closed end of the slot. The water pressure required to keep a constant inflow rate was measured and the amount of eroded material determined. The wetting behaviour of the pellet filling could be studied from the outside.

A compilation of the test results is provided in Table 2-2. Three tests were performed using Cebogel pellets (Sandén et al. 2008). Three different inflow rates were tested; 0.01, 0.1 and 1 l/min. In the test with the lowest inflow rate, no outflow occurred during test time (54 h). In the test performed with an inflow rate of 0.1 l/min, the pellet filling was completely filled with water (macro voids between pellets) before any outflow occurred. In the test with the largest inflow rate, 1.0 l/min, the first outflow occurred after 20 minutes. The pellet filling continued, however, also after this to store some of the inflowing water.

Two tests were performed using Asha pellets (Sandén et al. 2012). Two different inflow rates were used, 0.25 and 0.5 l/min. These tests were a part of the pellet optimization work performed within the project "System design of backfill".

Figure 2-2. *Picture showing the test equipment designed at Clay Technology AB. The slot is open on the short side to the right. A constant inflow can be applied at the mid height, see tube connection in photo.*

Figure 2-3. *Photo showing the further developed large slot test equipment (B+tech Oy.*

2.4.2 Tests at Clay Technology 2015

A new test series was performed within the project KBP1011, Water handling during backfilling (Sandén and Jensen 2016). These tests were performed with the larger (B+Tech type) test equipment. The main aim with this test series was to investigate the influence of fines present in the pellet filling.

A compilation of the test results is provided in Table 2-3. In total ten tests were performed using Asha pellets. The inflow rates varied between 0.1 and 1 l/min. The tests were running until water started to flow over the top of the test equipment.

All tests were performed using sieved pellet i.e. all fines were removed before installation, but in five of the tests, fines were placed in layers in the pellet filling, a scenario that had been observed to occur during pellet filling. Important results from the test series was e.g. recommendations that all pellets should be sieved before installation and also that the installation equipment should be set so that the amount of fines created during the installation process should be minimized. These layers were not taken into account in the evaluation of the wetting behaviour of these tests

Similar tests were also performed using Cebogel pellets. Unfortunately, the properties of the delivered pellets were inadequate; the water content was very high (24–25 %) and the dry density of the individual pellet was very low (in average 1 612 kg/m3). These figures should be compared to the recommended, Section 2.2.2, that are based on experiences from the earlier tests described in this report. The inadequate properties resulted in a completely different water storage behaviour and the results from these tests are therefore not presented in this report. The detailed results from these tests are presented in Sandén and Jensen (2016).

Table 2-2. Compilation of data from tests performed in the slot test equipment (CT type).

Data from different tests with pellets (6 mm extruded)								Water storage, test data				
Bentonite	**Report**	**Test equipment**	**w ini**	**Fines removed**	**Water salinity**	**Water flow rate**	**Remark**	**Wetting behaviour**	**First outflow**	**Storage before outflow**	**Storage before outflow**	**Remark**
Origin/batch no.			**%**	**Yes/No**	**%**	**l/min**		**Up/Down/Sym.**	**h**	**litre**	**%**	
Cebogel 2007/2008	SKB R-08-135	Slot (CT)	18,9	No	1 %	0,01		Symmetric	NA	NA	NA	All water was stored in the pellet filling
Cebogel 2007/2008	SKB R-08-135	Slot (CT)	18,9	No	1 %	0,1		Symmetric	11	66	118	Stores more than 100 % depending on swelling
Cebogel 2007/2008	SKB R-08-135	Slot (CT)	18,9	No	1 %	1		Initially downwards, but storing continues despite leakage	0,33	20	36	First outflow after 20 min, but the water storing continues.
Asha 2010	SKB R-12-18	Slot (CT)	18,7	No	1 %	0,25		Upwards/Symmetric	2,6	39	70	
Asha 2010	SKB R-12-18	Slot (CT)	18,7	No	1 %	0,5		Downwards/Symmet ric	2	60	107	

Table 2-3. Compilation of data from tests performed in the slot test equipment (B+tech type).

Data from different tests with pellets (6 mm extruded)								Water storage, test data				
Bentonite	**Report**	**Test equipment**	**w ini**	**Fines removed**	**Water salinity**	**Water flow rate**	**Remark**	**Wetting behaviour**	**First outflow**	**Storage before outflow**	**Storage before outflow**	**Remark**
Origin/batch no.			**%**	**Yes/No**	**%**	**l/min**		**Up/Down/Sym.**	**h**	**litre**	**%**	
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,1		Sym./Upwards	6,5	39	17	
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,25		Sym./Upwards	2,33	34,95	16	
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,5		Symmetric	2,3	69	31	
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,75		Symmetric	1,75	78,75	35	
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	1		Symmetric	1,85	111	49	
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,1	Fines in layers	Sym./Upwards	NA	NA	NA	No consideration has been given to the layers
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,25	Fines in layers	Sym./Upwards	NA	NA	NA	No consideration has been given to the layers
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,5	Fines in layers	Symmetric	NA	NA	NA	No consideration has been given to the layers
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,75	Fines in layers	Symmetric	NA	NA	NA	No consideration has been given to the layers
Asha	SKB PM	Slot (B+tech)	16	Yes	1 %	0,5	Geotextile	Symmetric	NA	NA	NA	

2.5 Steel tunnel tests

The steel tunnel tests have been performed in approximately half scale at Äspö HRL. The test equipment consists of a steel tunnel with a width of 2.75 m, a height of 2.75 m and a length of 6 m, Figure 2-4. The equipment is designed so that it is possible to apply water flow at different points and with different flow rates.

Tests have been performed in the steel tunnel at three different times within different projects:

1. 2008. Twelve tests were performed. The objectives of the tests were to investigate erosion and water uptake of backfill. The test results are reported in Dixon et al. (2008b). An additional evaluation of the wetting behaviour was performed within the framework of the current project and is provided in Appendices 1–6 and in Table 2-4. The graphs are based on data provided in the report.
2. 2012. Three tests were performed. The main objective was to investigate if geotextiles could be used to distribute water inflow over a larger area and by that increase the water storage of the pellet filling. The test results are reported in Koskinen and Sandén (2014).
3. 2015. Five tests have been performed within the project KBP1011. The main objectives were to continue the investigation of geotextiles as a water distributor and also to investigate the influence of removal of fines present in the pellet filling before installation. The test results are reported in Posiva SKB (2017).

2.5.1 Steel tunnel tests performed 2008

A compilation of the test results is provided in Table 2-4. All tests were performed using Cebogel pellets. The water inflow rate varied between 0.1 to 2.5 l/min. A major difference compared to the later test series was that every test setup included two tests i.e. one at each side of the steel tunnel. This means that the available pellet volume was half compared to later tests.

The two first tests did not include any sensor to detect the first water outflow and since the uncertainty was large it was decided to not use the results from these tests. In the last four tests, Test 9–12, the inflow point was moved backwards to the tunnel start and the results from these tests are also assessed to be difficult to use in order to study the wetting behaviour.

This was the first test series performed in this large scale, and the results have been very useful in order to study the water storage capacity of a pellet filling and by that the available time before water will reach the backfill front.

2.5.2 Steel tunnel tests performed 2012

Three tests were performed during 2012. A compilation of the test results is provided in Table 2-5. The tests were performed using Asha pellets and the water inflow rate varied between 0.25 to 0.5 l/min. The main objective with these tests was to study the effect of using geotextile to distribute the inflowing water and by that increase the water storage capacity of the pellet filling.

Important results on the function of geotextiles could be obtained from these test series although some uncertainties remained e.g. regarding the influence of fines in the pellet filling.

2.5.3 Steel tunnel tests performed 2015

Five tests were performed during 2015. A compilation of the test results is provided in Table 2-5. The tests were performed using Asha pellets and the water inflow rate varied between 0.25 to 1 l/min. The main objectives with these tests was to study the influence of using sieved pellets i.e. all fines were removed before installation but also the effect of geotextile as a water distributor. The test series also included one test, simulating an extreme case with an inflow rate of 1.0 l/min.

In addition to the achieved data regarding water storage capacity, the last test also included a pre-test of equipment supposed to be used as temporary drainage during the backfill installation process. The method includes that water is led from the geotextile into a special built vessel and then further out through a drainage tube. The design also includes that the drainage tube will be retrieved after usage while the vessel has to be left in the backfill.

Important results on the function of geotextiles could also be obtained from these test series and resulted in new useful data regarding water storage in a pellet filling.

Table 2-4. Compilation of data from the steel tunnel tests performed by Dixon et al. (2008b).

Data from different tests with pellets (6 mm extruded)									Water storage, test data				
Bentonite	**Report**	**Test equipment**	**w ini**	**Fines removed**	**Water salinity**	**Water flow rate**	**Geotextile**	**Remark**	**Wetting behaviour**	**First outflow**	**Storage before outflow**	**Storage before outflow**	**Remark**
Origin/batch no.			**%**	**Yes/No**	**%**	**l/min**	**Yes/No**			**h**	**litre**	**%**	
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	0.5	No	Test 3	Symmetric	5	150	11.1	
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	1	No	Test 4	Symmetric / Downwards	2.5	150	11.1	
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	0.1	No	Test 5	Symmetric / Upwards	24	144	10.7	
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	0.25	No	Test 6	Symmetric / Upwards	21	315	23.3	
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	0.25	No	Test 7	Symmetric / Downwards	28	420	31.1	
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	0.5	No	Test 8	Symmetric / Downwards	8.5	255	18.9	
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	2.5	No	Test 9	NA	0.5	75	5.6	Inflow point moved backwards. Long term tests.
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	2.5	No	Test 10	NA	0.5	75	5.6	Inflow point moved backwards. Long term tests.
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	0.25	No	Test 11	NA	20	300	22.2	Inflow point moved backwards. Long term tests.
Cebogel	SKB R-08-132	Steel tunnel	16	No	1 %	0.5	No	Test 12	NA	24	720	53.3	Inflow point moved backwards. Long term tests.

Table 2-5. Compilation of data from the steel tunnel tests performed during 2012 and 2015 (Koskinen and Sandén 2014, Posiva SKB 2017).

Data from different tests with pellets (6 mm extruded)									Water storage, test data				
Bentonite	**Report**	**Test equipment**	**w ini**	**Fines removed**	**Water salinity**	**Water flow rate**	**Geotextile**	**Remark**	**Wetting behaviour**	**First outflow**	**Storage before outflow**	**Storage before outflow**	**Remark**
Origin/batch no.			**%**	**Yes/No**	**%**	**l/min**	**Yes/No**		**Up/Down/Symmetric**	**h**	**litre**	**%**	
Asha 2010	SKB R-14-10	Steel tunnel	18.7	No	1 %	0.25	No	Test 1 (Reference)	Upwards/Symmetric	30.4	460	18.4	Reference test whithout geotextile
Asha 2010	SKB R-14-10	Steel tunnel	18.7	No	1 %	0.25	Yes	Test 2 (Geotextile)	Upwards from inflow point, along filter.Symmetric	39.5	588	23.5	
Asha 2010	SKB R-14-10	Steel tunnel	18.7	Yes	1 %	0.5	Yes	Test 3 (Geotextile)	Symmetric around filter, downwards at filter ends	53.3	1 600	64.0	
Asha 2012	SPR-05	Steel tunnel	16	Yes	1 %	0.25	No	Test 1 (Reference)	Symmetrically around inflow point	35	525	23.7	Reference test whithout geotextile
Asha 2012	SPR-05	Steel tunnel	16	Yes	1 %	0.18/0.25	Yes	Test 2 (Geotextile)	Symmetrically around inflow point and geotextile	132	1 762	79.5	Small leakage from steel tunnel. Inflow rate adjusted, 0.18/0.25 l/min.
Asha 2012	SPR-05	Steel tunnel	16	Yes	1 %	0.5	Yes	Test 3 (Geotextile)	Symmetrically around inflow point and geotextile	32	960	43.3	Somewhat early leakage depending on low backfill block quality.
Asha 2012	SPR-05	Steel tunnel	16	Yes	1 %	0.5	Yes	Test 4 (Geotextile)	Symmetrically around inflow point and geotextile	38	1 140	50.5	Repitition of test 3.
Asha 2012	SPR-05	Steel tunnel	16	Yes	1 %	1	Yes	Test 5 (Geotextile)	Symmetrically around inflow point and geotextile	7	420	18.6	This test included a pre- test of equipment for temporary drainage.

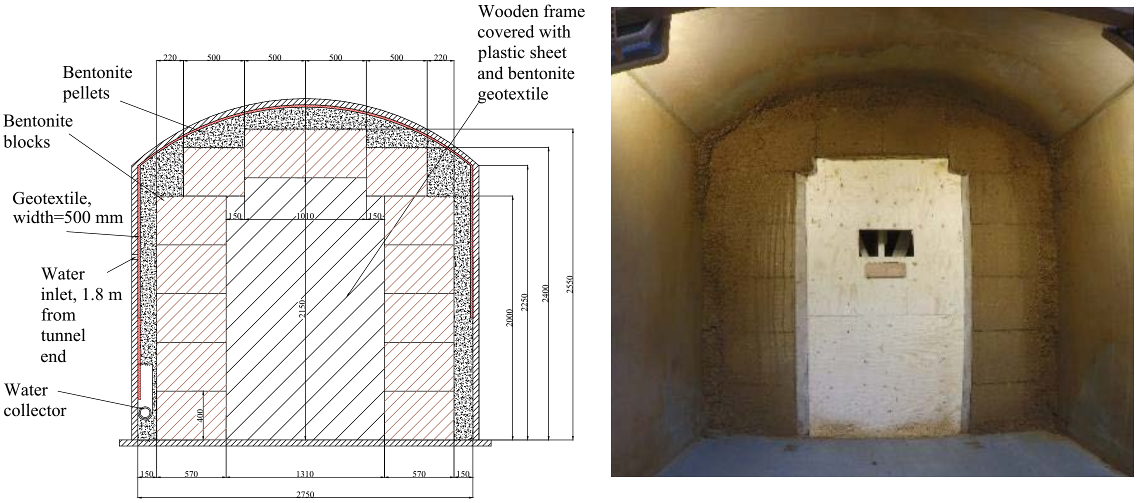


Figure 2-4. Steel tunnel equipment used in the half scale tests. The drawing and photo show the test setup used in the last test performed within KBP1011.

2.6 Full scale test in TASS tunnel at Äspö HRL

The test description in this chapter is entirely taken from Sandén and Börgesson (2014).

2.6.1 Test layout

The test is described in detail in Johnsson and Sandén (2013). The aim with this test was to investigate how a pellet filling can handle a rather high water inflow, 0.5 l/min, during installation of backfill. In order to simulate a fracture zone, geotextile was used as a distributor of water led in to the test site in a tube. One of the most important measurements in this test was to determine the time between start of backfill installation until the water reaches the front face of the backfill.

The test was performed in the TASS-tunnel at Äspö HRL. The test setup consisted of a central mould made of steel and wood, simulating a block stack, see drawings in Figure 2-5 and Figure 2-7; and photos in Figure 2-6. The outer surface of the mould was covered with plastic and a bentonite mat in order to prevent water leakage to the inside of the mould. The test length was 5.5 meters.

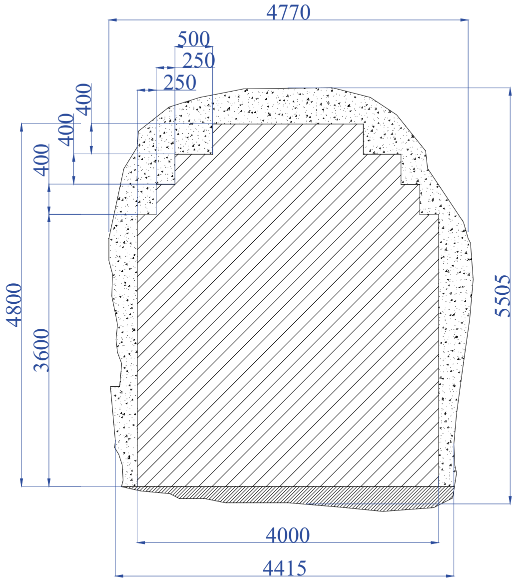


Figure 2-5. Schematic drawing showing the dimensions of the central mould and the approximate dimensions of the tunnel (Johnsson and Sandén 2013).

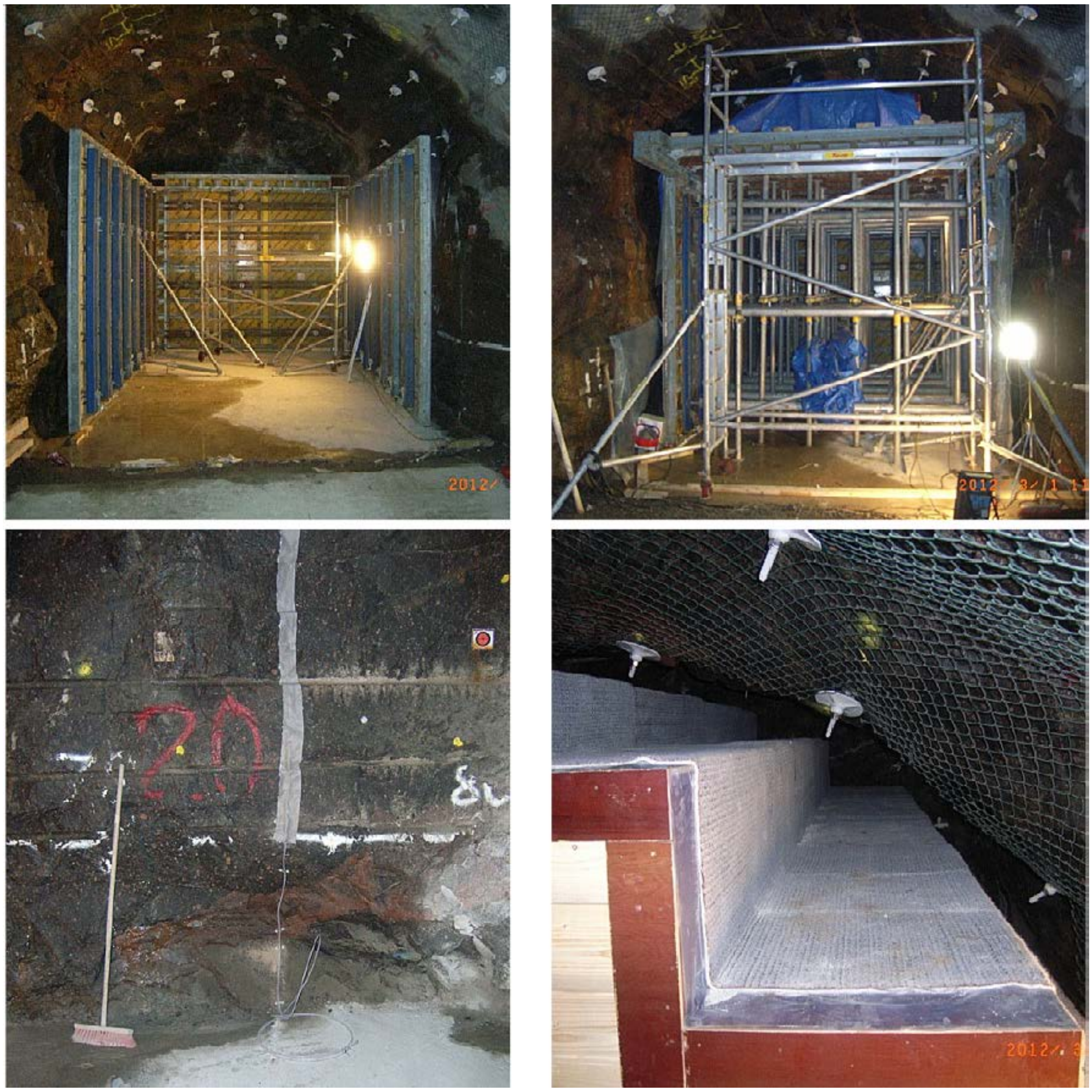


Figure 2-6. *Photos from the preparatory work. Upper left and right: Installation of the mould simulating a stack of backfill blocks. Lower left: An artificial water bearing "fracture" (geotextile) was installed four meters from the front. The "fracture" started one meter from the floor and went all way to the other side. Lower right: Photo showing the crown of the mould. The mould was covered with plastic and a bentonite mat in order to prevent leakage (Johnsson and Sandén 2013).*

An artificial water inflow was installed four meter from the front, see photo in Figure 2-6. A geotextile stripe was placed over the point inflow. The geotextile started about one meter above the floorand went up to the roof and down on the wall, ending one meter from the floor.

In order to end the installation as a vertical standing wall made of pellet, water was added at the nozzle positioned at the end of the tube coming from the shotcrete equipment. In total 882 liters of water was added.

2.6.2 Test results

The aim with this test was to study the behaviour of a pellet filling when exposed to a high water inflow from a water bearing fracture. The results can, however, be used as a reference regarding the function of geotextile as a distributor of inflowing water.

The following observations and conclusions were made:

- In total 33 715 kg of pellets was installed. In the pellet filling there are about 45 % macro voids (empty voids between the individual pellets) where water can be stored. This means that theoretically about 15 m^3 of water could be stored in the pellet filling. In total more than 12 m^3 of water was injected during the test. Taken into account that there was an outflow of water that started after about 118 hours, the water storing has been in total approx. 8.5 m^3, see Figure 2-8. This means that about 56 % of the pellet filling should be wetted which is rather close to the results obtained from the sampling.
- This full scale test has shown that the water storing continues also after the first breakthrough of water at the front, see Figure 2-8.
- The water storing has mainly taken place at the walls leaving the crown almost dry, except for the areas close to the geotextile stripe. This probably depends partly on gravimetrical effects i.e. the water flows downward in the geotextile.
- It was not possible to trace the outflow to a certain point. The outflow seemed, however, to mainly come from the right side of the test (the same side as where the water was injected.
- The wetted pellet wall ending up the installation has probably also contributed to the large water storing of this test. Water flowing from the inside will probably turn and again flow inwards against dryer parts when reaching the wet pellet wall which is much tighter than the un-wetted pellet filling.

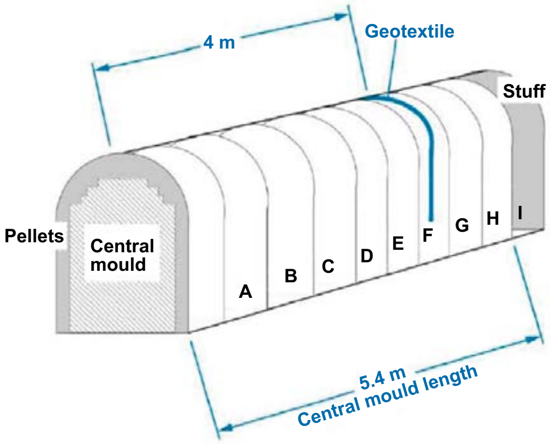


Figure 2-7. *Schematic drawing showing an overview of the TASS test layout.*

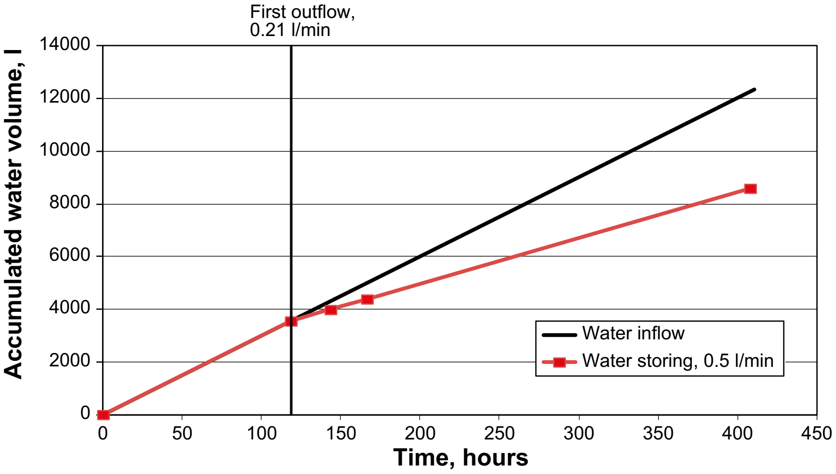


Figure 2-8. *The accumulated water inflow and water storing plotted versus time. After about 118 hours water starts to flow out but about 60 percent of the inflowing water continues to be stored in the pellet filling (Johnsson and Sandén 2013).*

2.7 Comments and conclusions

2.7.1 General

The results from the tests described in this report have clearly shown that inflowing water from the rock surface largely will be stored in the pellet filling. An evaluation of the results have been made regarding the following properties:

- Wetting pattern and water storage capacity. The wetting pattern for a point inflow as a function of the inflow rate is important since it ultimately will determine how much water that can be stored in the pellet filling before outflow occurs (when the water front reaches the backfill front). The water storage capacity evaluated from the different test types, depends on the design of the used test equipment or scale of the performed tests, and the achieved data can be used in order to study the behaviour and to estimate the water storage capacity for the full scale.
- Geotextile. A number of tests have included geotextile to distribute the inflowing water over a larger area and an obvious conclusion is that the water storing capacity increases with this method.

2.7.2 Wetting pattern and water storage capacity

The water storing capacity of a backfill pellet filling is mainly depending on the pellet properties and of the applied water inflow rate. Different water inflow rates results in different wetting pattern and the time to first outflow will vary depending on how much water that is stored before the wetting front reaches the backfill front. In the performed tests, the size and shape of the test equipment influences the results, but it is assessed that the wetting pattern and its flow dependence can be studied in different scales.

The photos provided in Figure 2-9 shows three examples of different wetting patterns; "Symmetrical/Upwards wetting", "Symmetrical wetting" and "Downwards wetting". The photos are taken from the tests performed at Clay Technology with the B+Tech type test equipment described in Section 2.4.

An assessment of the resulting wetting pattern or wetting behaviour has been done for all tests listed in Chapter 2. The graph provided in Figure 2-10 shows the results from the assessments as a function of the inflow rate. The wetting behaviour has been divided into five different scenarios. As shown in the graph, there is a large variation in results, but a number of clear trends can be identified:

- Upwards wetting. The wetting proceeds mainly upwards from the inflow point. This behaviour has mainly been seen in other pellets types (compacted pellets) when exposed for inflow rates < 0.1 l/min (Sandén and Börgesson 2010).
- Symmetrical/Upwards wetting. The wetting proceeds as a combination of upwards from the inflow point and symmetrically from the inflow point. The behaviour has mainly been seen when the pellet filling has been exposed for low and medium high inflow rates, approximately 0–0.25 l/min.
- Symmetrical wetting. The wetting proceeds almost symmetrically around the inflow point. The behaviour has mainly been seen when the pellet filling has been exposed for low and medium high inflow rates, approximately 0–0.5 l/min.
- Symmetrical/Downwards wetting. The wetting proceeds as a combination of downwards from the inflow point and symmetrically from the inflow point. The behaviour has mainly been seen when the pellet filling has been exposed for low and medium high inflow rates, approximately 0.2–1.0 l/min.
- Downwards wetting. The wetting proceeds mainly downwards from the inflow point. The behaviour has mainly been seen in pellet fillings when exposed for inflow rates between 0.6–1.0 l/min or when pellets with adequate properties have been used in the tests.

From the results in the graph provided in Figure 2-10, it seems that if the Asha pellets (red dots) are more prone to symmetric/upwards wetting while the Cebogel pellets (green dots) are more prone to symmetric/downwards wetting. The results from the steel tunnel tests performed with Cebogel pellets (green squares) seems, however, to be more similar to the results achieved from the steel tunnel tests performed with Asha pellets. This depends probably on the fact that the Cebogel pellets used in these tests had a lower water content, 16 %, and thus had a higher affinity to take up water, while the Cebogel pellets used in the other tests have had a water content of 19–20 % (see also the suggested requirements on pellets properties in Section 2.2.2).

Figure 2-9. *Upper: Photo showing an example of "Symmetric/Upwards"wetting. Middle: Photo showing an example of "Symmetric" wetting. Lower: Photo showing an example of "Downward" wetting.*

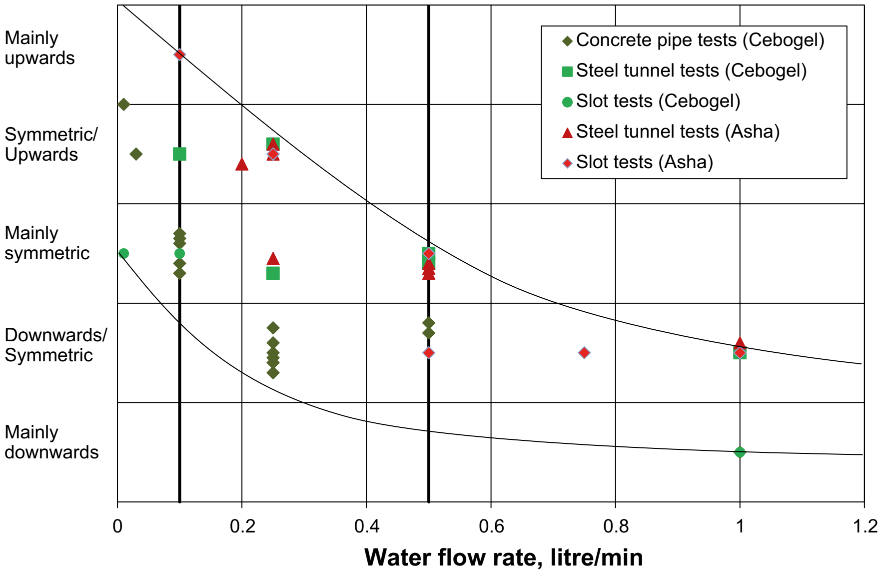


Figure 2-10. *Graph showing the wetting pattern assessed from the results from the tests presented in Chapter 2 plotted versus flow rates. The data points were spread in vertical direction for each category, in order to improve the clarity of the graph.*

The worst behaviour from a water storage point of view, is if all inflowing water flows downwards in the pellet filling and then along the floor out to the backfill front, see the lower photo in Figure 2-6. The wetting behaviour that should be pursued is a symmetrical wetting around the inflow point. With this wetting pattern the amount of stored water in the pellet filling can be very large. The upwards wetting only seems to occur at very low inflow rates which means that this will not anyway be a problem to handle.

The graph provided in Figure 2-11 shows the amount of water stored before outflow occurs plotted versus different inflow rates for the different test types. For the individual test type (different colors) it could be noted, in most cases, that the water storage capacity seems to decrease somewhat for the higher inflow rates i.e. above 0.5 l/min, but also in this graph, the spread in results is large.

2.7.3 Influence of geotextile on the water storage capacity

The main idea by using geotextiles is to distribute inflowing water from the rock surface over a larger pellet area and by that increase the water storage capacity and delay the water breakthrough at the backfill front.

The influence of using geotextile to increase the water storage capacity of a pellet filling has mainly been investigated in the steel tunnel test equipment. In addition, one full scale test was performed in the TASS tunnel at Äspö where a geotextile stripe, with a width about 10 cm, was used to simulate a water bearing fracture. The main objective with this test was not to test geotextile as a water distributor but the results are of course interesting also for this purpose.

An important difference between the test series is that the tests performed during 2008, included two tests in each test setup i.e. the steel tunnel was divided in the middle and inflows were applied on both sides. However, as mentioned earlier, no geotextile was used in these tests meaning that the wetting from an inflow point in general only affected the side wall and in some tests also partly the crown, see contour plots provided in Appendices 1–6. It has therefore been judged that these tests can be used as reference tests in order to determine the effect of using geotextile.

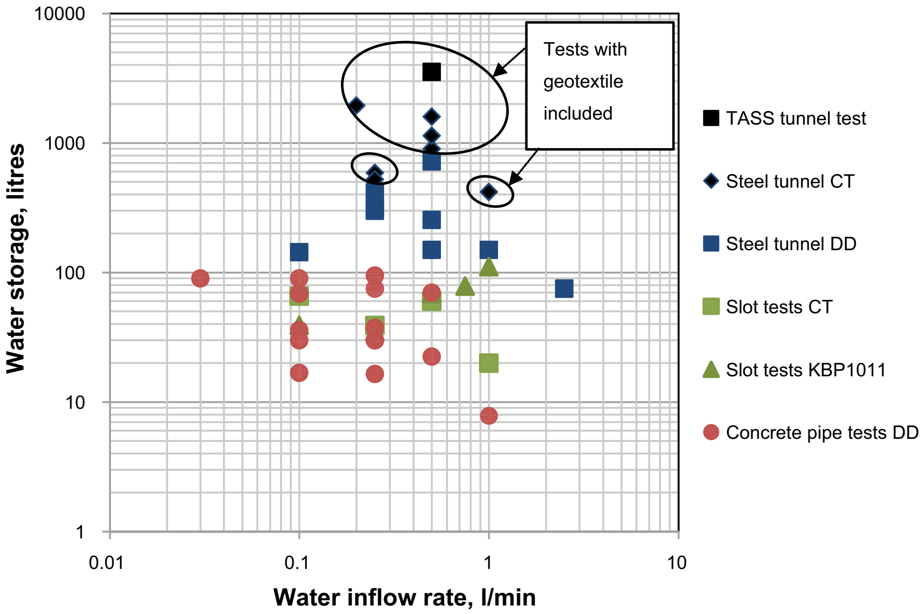


Figure 2-11. Graph showing the amount of water stored before outflow as a function of the inflow rate. The results are presented for the different test types presented earlier in this chapter.

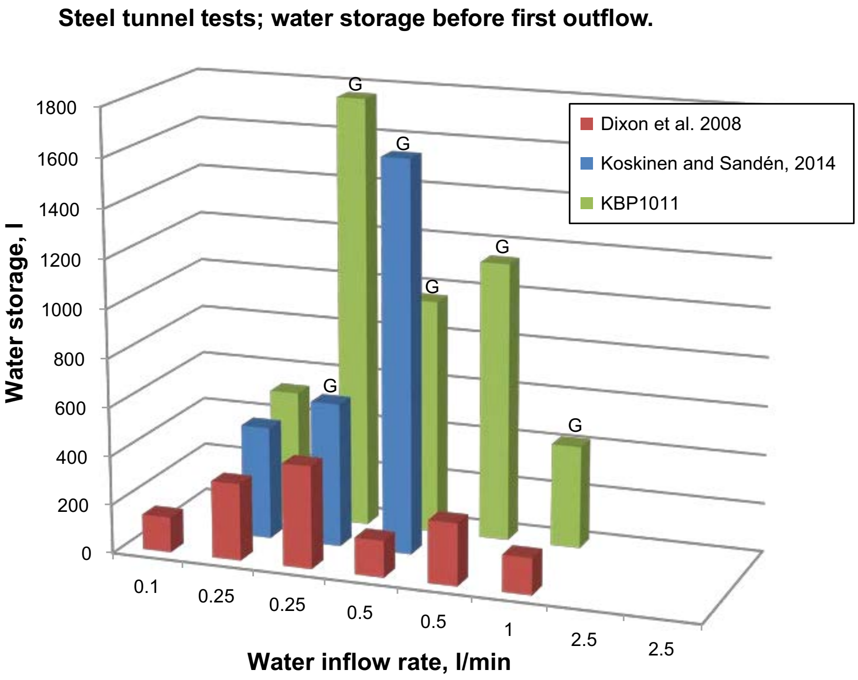


***Figure 2-12.** Graph showing the determined water storage in a pellet filling installed in the steel tunnel test equipment plotted versus water inflow rate. The bars with a "G" at the top indicates tests performed with geotextile.*

In order to study the effect of using geotextile to increase the water storage capacity, the results from all steel tunnel tests regarding water storage capacity before the first outflow occur, are presented in Figure 2-12 as a bar graph. The bars with a "G" on the top indicates that geotextile has been included in the test setup. As shown in the graph, there is an obvious effect of using geotextile to increase the water storage capacity. The effect seems, however, to vary a lot depending on flow rate and probably also somewhat in a random manner:

- **Inflow rate 0.25 l/min**. Two tests were performed during 2008 (no geotextile) and in addition two reference tests without geotextile were performed 2012 and 2015 respectively. The time to first water breakthrough was 21 and 28 hours respectively for the two tests performed 2008. The time to first breakthrough was 30 and 35 hours respectively for the tests performed 2012 and 2015. These figures should be compared with the times achieved when also using geotextile in the test setup; 39.5 hours for the test from 2012 and 132 hours for the test from 2015. The variation in results have been large at these rather low inflow rates, especially the result from the test that was performed 2012 (39.5 hours to first outflow) is assessed to be somewhat strange. One explanation could be that the pellets in this test series were not sieved before use and this may have influenced the results in a negative way (later tests, presented by Posiva SKB (2017), have shown that fines have a tendency to end up in layers in the pellet filling during installation, hindering the wetting process to continue in that direction).
- **Inflow rate 0.5 l/min**. Two tests were performed during 2008 (no geotextile). The time to first water breakthrough was 5 and 8.5 hours respectively for these tests. These figures should be compared with the times achieved when also using geotextile in the test setup; 53.3 hours for the test from 2012 and 32 and 38 hours respectively for the two tests from 2015. The variation in results is large also for this flow rate but although somewhat more consistent.
- **Inflow rate 1.0 l/min**. One test was performed during 2008 with this rather high inflow rate and with no geotextile. The time to first water breakthrough was 2.5 hours for this test. This figure should be compared with the times achieved when also using geotextile in the test setup; 7 hours for the test from 2015.

As described above, there is an obvious effect of using geotextile to increase the water storage capacity (see Figure 2-13).

Figure 2-13. *Photo showing a cross section (close to the installed geotextile) of the pellet filling at the top of the tunnel in Test 5. It is obvious that the inflowing water has followed the geotextile up over the crown and down on the other side of the tunnel (inflow side to the left in the photo). However, as shown in the photo, there is a remaining dry layer of pellets close to the block stack.*

2.7.4 Inflow behaviour in the steel tunnel tests

The graph provided in Figure 2-14 shows the results from the steel tunnel tests performed within three different projects (see description in Chapter 2). The test layout have been similar for these three test series even if there are some differences that probably have influenced the results somewhat:

1. The steel tunnel tests from 2008, were performed using Cebogel pellets while Asha pellets were used in the other two test series.
2. An important difference between the test series is that the tests performed during 2008, included two tests in each test setup i.e. the steel tunnel was divided in the middle and inflows were applied on both sides. However, as mentioned earlier, no geotextile was used in these tests meaning that the wetting from an inflow point on the side wall, in general only affected the side wall and in some tests also partly the crown.

The green triangular dots show the results from the tests performed with Cebogel pellets (no geotextile was used in this test series). These tests should be compared with the two tests performed with Asha pellets (red diamonds), that also were performed without any geotextile. As shown in the graph there is a certain spread in results but also a clear trend that the time to first outflow decrease with increased inflow rate. It seems, however, as if the water storage capacity of the Cebogel pellets is lower than of the Asha pellets.

The black dots (diamonds) show the results from the tests performed with Asha pellets and geotextile. There is basically one of the geotextile tests that deviates from the other and that is the test performed with an inflow rate of 0.25 l/min. This test (from 2012) resulted in a first outflow after 39 hours which was considered early. One explanation could be that the pellets in this test series were not sieved before use and this may have influenced the results in a negative way (later tests have shown that fines have a tendency to end up in layers in the pellet filling during installation, hindering the wetting process to continue in that direction, see Posiva SKB 2017).

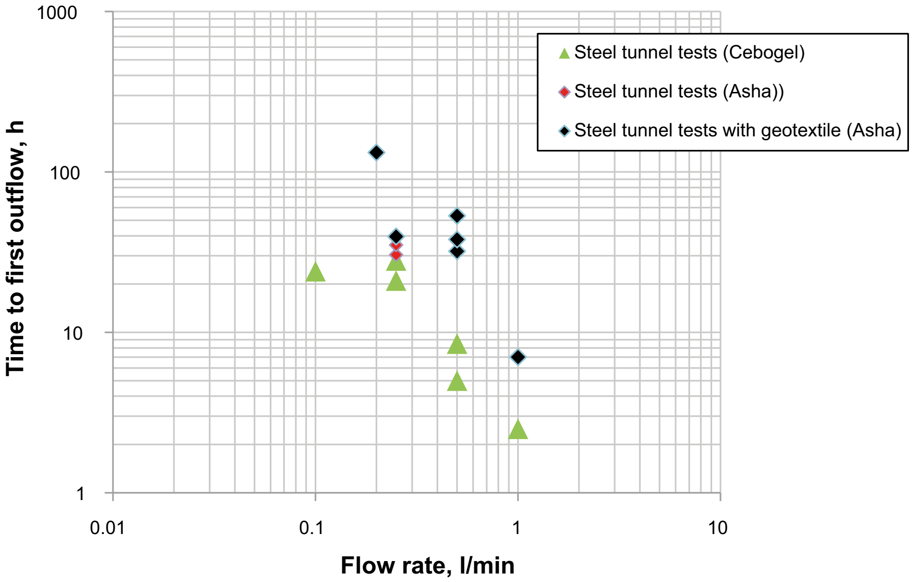


Figure 2-14. *The time to first outflow plotted versus flow rate for the tests performed in the steel tunnel. The black line shows the conceptual model for water storage in the steel tunnel and the dotted line shows the conceptual model increased with a factor three depending on the use of geotextile.*

3 Updated conceptual model

3.1 General

As a basis for the calculations regarding available time before inflowing water reaches the backfill front face, a simplified conceptual model is suggested. The model is based on results from the laboratory tests and the scale tests described in Chapter 2.

Besides the investigations made within the projects “System design of backfill” and “Water handling during backfill installation”, tests including bentonite pellets have also been performed within other projects e.g. the EVA project (Börgesson et al. 2015). It is, however, important to note that the pellets used in the EVA project were manufactured with the roller compaction method while the Asha and Cebogel pellets investigated in this report were manufactured by extrusion. Tests performed within the project System design of backfill (see Andersson and Sandén 2012), showed that there is a very clear difference in behaviour between these two pellets types regarding water storing capacity and that extruded pellets with a diameter of 6 mm are superior regarding the water storing capacity.

A conceptual model describing water transports in a pellet filling has earlier been suggested in Sandén and Börgesson (2014). The model described in this chapter is largely the same as previously. The only change is that it is now advised to remove fines from the pellets.

The conceptual model suggested in this chapter deals with the wetting behaviour of a 6 meter long backfill section and how long time it will take for the water to reach the backfill front i.e. the beginning of next 6 meter section. The wetting behaviour of a 300 meter long deposition tunnel, taking into account the position of a number of water bearing fracture zones with different inflow rates and how they may interfere with each other during the installation process, is discussed further in Chapter 5.

3.2 Assumptions

From the results of the tests described in this report and from laboratory tests made in the EVA project (Börgesson et al. 2015), a general view of how water is transported in a pellet filling surrounding the backfill can be applied, although the behaviour is somewhat irregular and not always repeatable.

1. The pellet fill cannot stop and seal the water inflow into the tunnel.
2. Internal piping will occur in the pellet filling until all macro voids in the pellet filling are filled with water or if a channel flow from the inflow point to the backfill front should arise.
3. Water will flow in or pipe between the macro voids between the pellets. Below a certain threshold everything will be stored adjacent to the inflow point, while above the threshold some part of the flow can escape. This threshold depends on the flow rate but also on the material, the shape of the pellets and thereby the shape and size of the macro voids, the ability to suck up water (density and water content of the pellets) and if there are fines present.
4. The pellet filling will not become homogeneous wetted in the beginning. Partly a shell close to the rock wall, or geotextile, will be wetted leaving drier parts close to the block stack.,
5. The influence of the inflowing water on backfill blocks is small in the short term period required for the normal backfill installation.
6. When the pellets get access to water they will start to swell which will affect the volume of the closest macro voids. There will be an increased resistance to water flow in these voids filled with gel, which means that the water will choose another flow path.
7. Once water has entered the free surface (backfill face), water will only flow through one or a few channels out of the pellets and very little water will flow into the un-wetted parts (This is a conservative assumption though it has been noticed that the water storing in dry parts continues although a breakthrough has occurred).

3.3 Conceptual model of inflow behaviour for six mm extruded pellets made of Cebogel or Asha

Evaluation of the results from all tests performed with pellets where a water inflow has been applied, see Chapter 2, have resulted in an assumption of four different wetting scenarios of the pellet filling that can occur, Figure 3-1. Depending on the water inflow rate different scenarios will occur. In the scenarios described in Figure 3-1, it has been considered that water is flowing into the pellet filled gap from a point inflow, situated on the wall in the middle of a six meter long backfill section. The different wetting behaviours, result in different available volume (macro voids between the individual pellets) for water storing, before water will reach the backfill front. This means that for a certain water inflow rate the available volume for water storing is known and this makes it possible to calculate the time to the first outflow from a 6 meter long section (or a steel tunnel test). In a full scale installation, where new 6 meter sections are installed every 24 hours (according to the present SKB installation sequence) it is of course important that the installation proceeds faster than the wetting front rate.

The limitations of the calculations are large since there are significant simplifications included e.g. the position of the inflow point at the middle of one wall and an even thickness of the pellet layer. In reality the inflow point locations could be anywhere and the thickness of the pellet layer will vary between 100 and 400 mm (250 mm is used in the calculations). The calculations give, however, an indication of available time before outflow for different inflow rates.

3.3.1 Scaling of test results to full scale conditions

The test results, from steel-tunnels and the TASS tunnel, were scaled to full-scale conditions. This was performed by multiplication of the experimental time to first outflow value (t) with a specific ratio (r):

$$t_{fullscale} = t_{test} \cdot r \tag{3-1}$$

The value of the ratio was estimated in different ways for different test conditions. Some of these were based on flow patterns, especially the water-filled volumes at the first outflow (Figure 3-1). The volume for triangular wetting (V_T) was calculated as:

$$V_T = \frac{B \cdot h}{2} \cdot l \cdot \phi \tag{3-2}$$

where B is the base of the triangle, h is the height, l is the thickness and ϕ is the accessible porosity. The corresponding volume for the symmetrical wetting (V_S) was calculated as:

$$V_S = \pi \cdot \left(\frac{D}{2}\right)^2 \cdot l \cdot \phi \cdot \frac{2}{3} \tag{3-3}$$

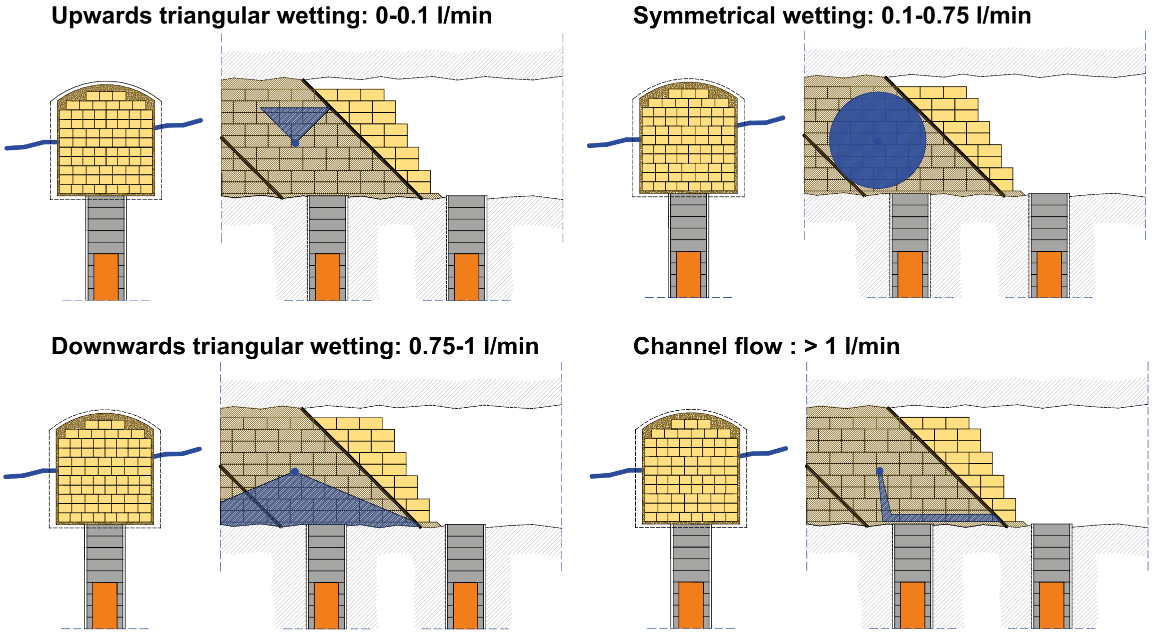
where D is the diameter of the disc. The factor of 2/3 was introduced due to the fact that the observed water storage patterns are not perfectly round. Dimensions for specific geometries and conditions are defined and quantified in Table 3-1.

Water volumes were used for two of the scaling ratios. For symmetrical wetting in steel tunnel test (without geotextile), the ratio r_S was given as the ratio of volumes (V_S) for full-scale and steel-tunnel geometries, respectively:

$$r_S = \frac{V_{S,FullScale}}{V_{S,Steeltunnel}} = \left(\frac{D_F}{D_S}\right)^2 \frac{l_F}{l_S} \tag{3-4}$$

This gives the r_S value of 1.63. The corresponding ratio for triangular downward wetting r_D was given as the ratio of volumes (V_T) for full-scale and steel-tunnel geometries, respectively:

$$r_D = \frac{V_{T,Down,FullScale}}{V_{T,Down,Steeltunnel}} = \frac{B_{DF}}{B_{DS}} \frac{h_{DF}}{h_{DS}} \frac{l_F}{l_S} \tag{3-5}$$


Upwards triangular wetting: 0-0.1 l/min

Symmetrical wetting: 0.1-0.75 l/min

Downwards triangular wetting: 0.75-1 l/min

Channel flow : > 1 l/min

Figure 3-1. *Schematic drawing showing the different wetting behaviour identified for different water inflow rates.*

This gives the r_D value of 5.79. The r_S and r_D ratios were used for results from steel-tunnels tests without any geotextile. The former was used for flow rates below 0.75 l/min and the latter for flow rates above (see green and red symbols in Figure 3-2). For tests results from steel tunnel test (with geotextile), the ratio r_G was given as the ratio of the lengths of the geotextiles (G) and the tunnel length (L) for full-scale (F) and steel-tunnel (S) geometries, respectively:

$$r_G = \frac{G_F}{G_S}\frac{L_F}{L_S} \tag{3-6}$$

This gives the r_G value of 3. This was used for results from all steel-tunnel tests with geotextile (see black diamonds in Figure 3-2). Finally, for results from the TASS tunnel test, the ratio r_T was given as the ratio of the tunnel length (L) for full-scale (F) and TASS tunnel (T) geometries, respectively:

$$r_T = \frac{L_F}{L_T} \tag{3-7}$$

This gives the r_T value of 1.11. This was used for results from the TASS tunnel test with geotextile (see black circle in Figure 3-2).

Relations between time to first outflow and flowrates, as implied by the conceptual model, were included as lines together with the scaled test results in Figure 3-2. These functions were generally defined as the ratio between the water-filled volumes at first inflow and the flowrate (q). All used dimension are defined and quantified in Table 3-1.

For triangular upward wetting (i.e. for flowrates 0.01–0.1 l/min) the time to first outflow (t_U) is derived as:

$$t_U(q) = \frac{V_{T,Up.Fullscale}}{q} = \frac{1}{q}\frac{B_U \cdot h_U}{2} \cdot l_F \cdot \phi \tag{3-8}$$

For symmetrical wetting (i.e. for flowrates 0.1–0.75 l/min) the time to first outflow (t_S) is derived as:

$$t_S(q) = \frac{V_{S,Fullscale}}{q} = \frac{1}{q} \cdot \left(\frac{D_F}{2}\right)^2 \cdot l_F \cdot \phi \cdot \frac{2}{3} \tag{3-9}$$

Finally, for triangular downward wetting (i.e. for flowrates 0.75–1 l/min) the time to first outflow (t_D) is derived as:

$$t_D(q) = \frac{V_{T,Down.Fullscale}}{q} = \frac{1}{q}\frac{B_{DF} \cdot h_{DF}}{2} \cdot l_F \cdot \phi \tag{3-10}$$

Table 3-1. Quantification of dimensions in test and full-scale geometries.

Quantity		Value
Width upward full-scale	B_U	3 m
Height upward full-scale	h_U	1.5 m
Width downward full-scale	B_{DF}	10 m
Height downward full-scale	h_{DF}	2.4 m
Width downward steel-tunnel	B_{DS}	4 m
Height downward steel-tunnel	h_{DS}	1.5 m
Diameter full-scale	D_F	4.2 m
Diameter steel-tunnel	D_S	4 m
Thickness full-scale	l_F	0.15 m
Thickness steel-tunnel	l_S	0.1 m
Porosity	ϕ	0.45 (–)
Length full-scale	L_F	6 m
Length steel-tunnel	L_S	4 m
Length TASS tunnel	L_T	5.4 m
Geotextile length full-scale	G_F	11 m
Geotextile length steel-tunnel	G_S	5.5 m

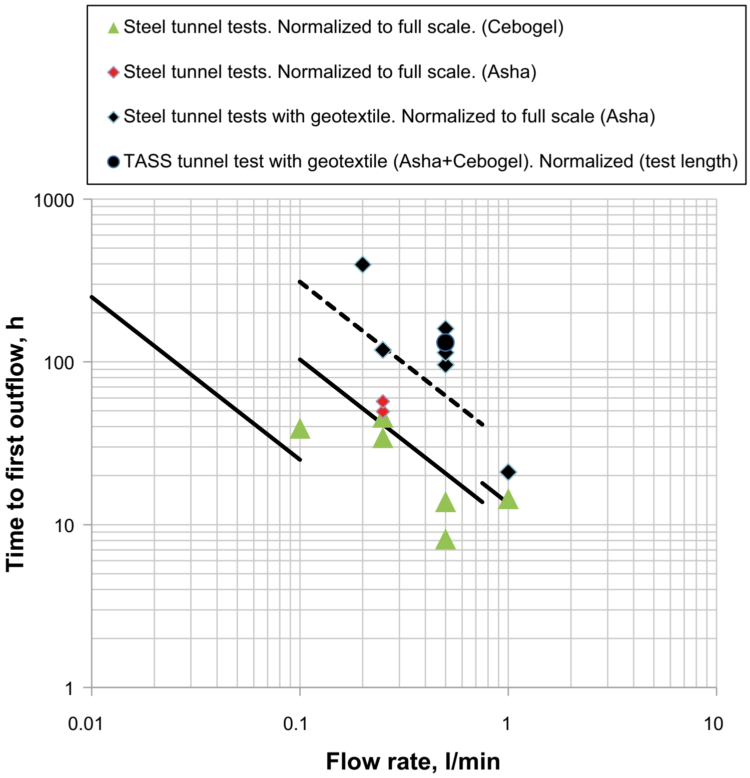


Figure 3-2. The time to first outflow plotted versus flow rate for the steel tunnels. The results (i.e. the data) have been normalized to full scale. The black lines show the conceptual model for water storage in a 6 meter section and the dotted line shows the conceptual model for water storing when using geotextile.

3.4 Comments and conclusions

The results from different test types performed during the last ten years have been used to develop a simple conceptual model describing how inflowing water is stored in the pellet filling during backfill installation. The most important tests are those performed in half scale in the steel tunnel test equipment at Äspö. The results from these test has been used to calculate the available time in full scale, until water starts to flow from one section to another, for a given inflow point position.

The results shows that the water storage in a pure pellet filling is enough in order to handle inflow rates up to < 0.25 l/min i.e. the time to first outflow takes more than 24 hours. When the inflow is 0.25 l/min or higher it will be necessary to use geotextile in order to distribute the inflowing water over a larger area and by that earn some extra time before water will reach the backfill front. All experimental data supports the notion that the use of geotextile will increase the water storage capacity. The water storage capacity seems to increase with at least a factor 3. This means that for an inflow rate of 0.5 l/min, the time to first outflow from the section will be about 60 hours. With an inflow rate of 1.0 l/min, the time to first outflow will be about 20 hours which will be on the limit. It is therefore recommended to also use temporary drainage equipment for inflow rates between 0.5 and 1 l/min.

It is thus judged that geotextile, possibly in combination with e.g. temporary drainage equipment, can be used for inflow rates up to 1 l/min. At higher inflow rates there will be a risk of local piping through the pellet filling out to the front.

3.4.1 Additional comments

The results from the steel tunnel tests clearly show that the water storage capacity of the pellet filling increases when using geotextile to distribute the inflowing water. In all steel tunnel tests, a wall built of wetted pellet, has been used as a delimiter of the test volume. The wall has certainly affected the results and it is thus not possible to explain the increased water storage capacity with the geotextile only.

The scaling of the results from the steel tunnel tests to a full scale deposition tunnel (SKB) is described in detail in this chapter. Basically the scaling is based on calculations of available pellet volume, different wetting patterns and the length of the test setup. In the tests including geotextile, the length of the geotextile has been used together with the length of the test setup to calculate the water storage capacity in full scale. Additional full-scale tests would be required in order to reduce the uncertainties inherent in these scaling calculations.

The scaling of the steel tunnel results to full scale deposition tunnels has only been made for a SKB deposition tunnel in this chapter. Adoption to Posiva deposition tunnels are addressed in the development of a mathematical model describing water storage and spreading, see Chapter 6.

It is not known how the wetting proceeds from one installed backfill section to another. The use of geotextile distributes the inflow over a larger area locally but it is possible that the distributed water flow eventually will gather and accumulate to a more concentrated flow. A possible way to handle this uncertainty could be to install geotextiles at a number of positions in a deposition tunnel regardless if there are water inflow or not. Water flowing from backfilled sections can be expected to be distributed again when reaching a new filter section.

4 Description of the present backfill design and the planned installation sequence (SKB and Posiva)

4.1 General

SKB and Posiva has a similar design of the backfill even if there are differences regarding tunnel dimensions, block stack pattern, the amount of pellets and which bentonite raw material that is planned to be used. The most important difference that is strongly influencing the water storage capacity over time is, however, the differences in installation sequences. This chapter includes a brief description of the present backfill designs and the assumed installation sequences.

4.2 Backfill design

The present reference designs for backfilling of deposition tunnels considered by SKB and Posiva are provided in Figure 4-1 and Figure 4-2 respectively. Bentonite pellets are placed on the tunnel floor to even out the rough surface. Backfill blocks are then piled on the pellets bed, filling up the main part of the deposition tunnel. After installation of a certain length of blocks, pellets will be blown in to fill up the gap between blocks and rock walls. As soon as the first pellets are installed, inflowing water will start to fill up the macro voids in the pellet filling. The inflowing water will largely be stored in the pellet filling. The water storing capacity depends on the water inflow rate, the pellets properties and the total available pellet volume. The position of the water front in the filling will change continuously and water from different water bearing fracture zones will over time interact with each other. Besides knowledge regarding the water storage capacity of the pellet filling, the rate of the backfill installation process is a very important factor in order to calculate the position of the water front in relation to the backfill front.

There are some differences in the decided deposition tunnel dimensions. The SKB tunnel is somewhat larger than the two tunnels considered by Posiva. The reason for having two different tunnels is that the length of the fuel is different between Olkiluoto and Loviisa, so the different tunnel sizes is due to an optimization.

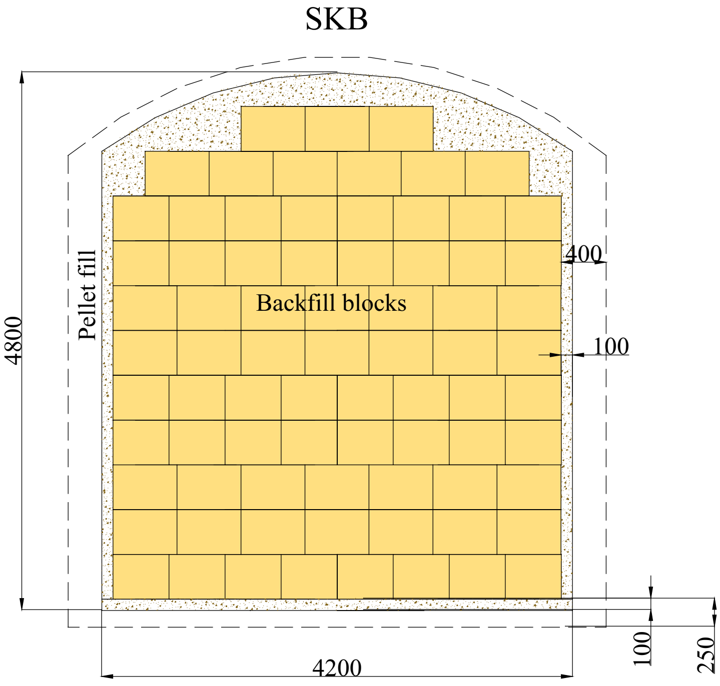


Figure 4-1. Schematic showing SKB's design of a backfilled deposition tunnel.

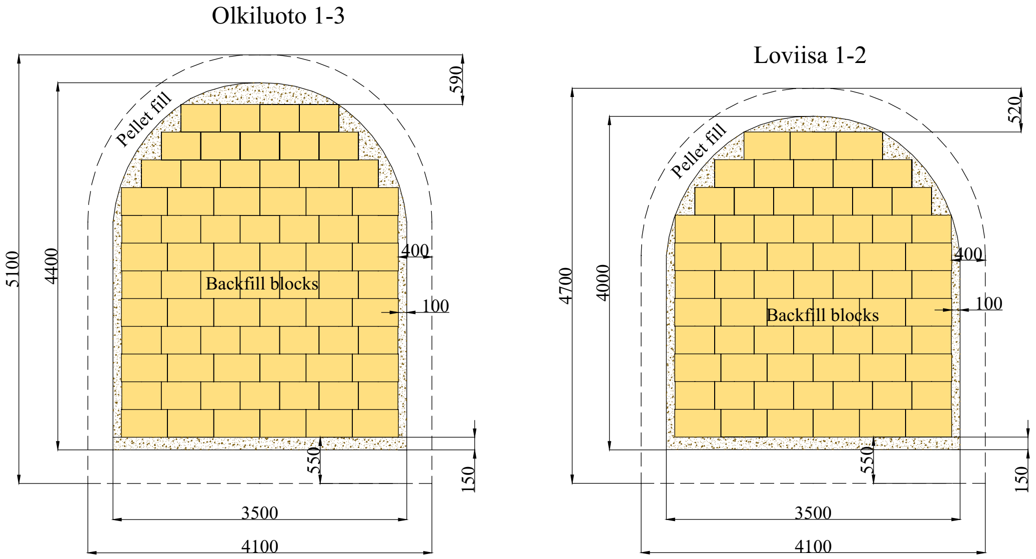


Figure 4-2. Schematic showing Posiva's design of a backfilled deposition tunnel.

A compilation of data regarding thickness of pellet layers at floor, walls and ceiling for the different tunnel types is provided in Table 4-1. The estimated total pellet volume per meter deposition tunnel is also given in the table

Table 4-1. Compilation of data regarding thickness of pellet layers and the total pellet volume in a backfilled section.

SKB tunnel **Pellet filling data**		**Min**	**Max**	**Average**
Total pellet volume/m (average)	m^3	2.4	6.0	4.2
Thickness of layers				
Floor	mm	100	250	175
Walls	mm	100	400	250
Ceiling (midpoint)	mm	300	450	375
Posiva, Olkiluoto **Pellet filling data**		**Min**	**Max**	**Average**
Total pellet volume/m (average)	m^3	1.3	4.6	2.9
Thickness of layers				
Floor	mm	150	550	350
Walls	mm	100	400	250
Ceiling (midpoint)	mm	290	590	440
Posiva, Loviisa **Pellet filling data**		**Min**	**Max**	**Average**
Total pellet volume/m (average)	m^3	1.0	4.1	2.6
Thickness of layers				
Floor	mm	150	550	350
Walls	mm	100	400	250
Ceiling (midpoint)	mm	220	520	370

4.3 Backfill installation sequence, SKB

The installation sequence for a deposition tunnel that has been suggested by SKB includes that canisters and buffer blocks are installed in all deposition holes before the installation of backfill starts. Thereafter the installation of backfill is made as one continuous operation. The backfill installation rate is estimated to 6 m tunnel in 24 hours including possible preparatory work. The total time for backfilling a 300 m long tunnel is thus 50 days (considering continuous campaign with 3 shifts per day and working on weekends).

4.4 Backfill installation sequence, Posiva

The backfill sequence suggested by Posiva is quite different compared to SKB. Instead of installing all buffer and canisters in a deposition tunnel as one continuous operation, the installation will be made in 40 m long sections, including four deposition holes (Keto et al. 2013). The installation time of canister and buffer for four deposition holes is estimated to four days. This operation is then followed of two days of preparatory work such as removal of temporary infrastructure. The following backfilling of 40 m deposition tunnel is estimated to 8 days (5 m/day). The planned sequence includes thus that the backfill installation process must stop for six days after every 40 m. The total installation time is thus estimated to 14 days for a 40 m long section and approximately 100 days for a 300 m long tunnel with 26 deposition holes. If the installation is made as a continuous campaign (3 shifts per day, working on weekends) a tunnel will be backfilled within 3–4 months.

4.5 Comments

The most important differences between SKB's and Posiva's planned backfill installation strategies that are affecting the water handling are:

1. Differences in tunnel size and thereby available pellet volume for water storage.
2. Backfill installation rate. (SKB has assumed 6 m in 24 hours and Posiva 5 m in 24 hours).
3. Installation sequence. SKB has assumed a continuous backfill installation of a deposition tunnel while Posiva has assumed that the backfilling is made in 40-metere long sections with temporary stops of 6 days for installation of buffer, canister and preparatory work of the next 40 meter long section.

These three differences listed above are all assumed to make it more difficult to handle the inflowing water when using the installation sequence suggested by Posiva.

5 Description of water handling methods

5.1 General

According to present knowledge, the water inflow into deposition tunnels can largely be handled by just letting the inflowing water be stored in pellet filling, see Chapter 2 and 3. This method is estimated to be enough in approximately 55 % of the deposition tunnels (Sandén and Börgesson 2014). In 15 % of the tunnels some minor additional methods must be added such as installation of geotextile on the rock wall in order to distribute a point inflow over a larger area or installation of a temporary drainage. The inflow into remaining 30 % of the deposition tunnels must be handled by e.g. installation of specially built water storage sections or by drilling of drainage boreholes to an adjacent tunnel.

A first investigation of possible water handling methods was made within the project System design of backfill (Sandén and Börgesson 2014). The methods has then been further investigated and in some cases also tested (geotextile, temporary drainage and artificial wetting) within the current project KBP1011. The performed investigations are reported in a number of internal PM and in Method descriptions. A public report, describing the project results, will also be written.

A brief description of the different water handling methods and for what water inflow rates they are planned to be used is provided in this chapter. In addition to the methods listed in this chapter there are also some other methods that still are in an early phase of development e.g. local freezing of a fracture zone.

5.2 Water handling methods

5.2.1 Water storage in pellet filling

The inflowing water is stored in the pellet filling that is surrounding the block stack. This is the main method for water storage and it is expected to be enough in the main part of the deposition tunnels. This method has been tested in a large number of tests in different scales. The method is suitable for inflow rates up to 0.5 l/min in a 6 m section (SKB).

5.2.2 Geotextile

Geotextile mounted on the rock surface distributes inflowing water over a larger area and increases the water storing capacity of a pellet filling. The method has been tested in a large number of large scale tests. The method is suitable for inflow rates between 0.25 and 1 l/min.

It is not known how the wetting proceeds from one installed backfill section to another. The use of geotextile distributes the inflow over a larger area locally but it is possible that the distributed water flow eventually will gather and accumulate to a more concentrated flow. A possible way to handle this uncertainty could be to install geotextiles at a number of positions in a deposition tunnel regardless if there are water inflow or not. Water flowing from backfilled sections can be expected to be distributed again when reaching a new filter section.

5.2.3 Temporary drainage

This method has been developed with the purpose to delay the inflowing water from hitting the pellet filling. With a temporary drainage from a section with high inflow rate, the backfill installation process can continue 2–4 days before the inflowing water is starting to influence the pellet filling. This method has been tested in conjunction with the steel tunnel tests at Äspö HRL. The method is suitable for inflow rates between 0.5 and 1 l/min.

5.2.4 Artificial wetting

After installation of a certain length of the pellet filling, the outermost pellet layer is artificially wetted with water. This is made by adding some water in the nozzle when blowing the pellets into the gap between backfill blocks and rock. The wetted pellet layer has a certain strength and is much tighter than the dry pellet filling inside. The idea with this method is that water flowing from the inside of the pellet filling towards the front, will reach the wetted pellet "wall" which is much tighter than the rest of the pellet filling, and the water will therefore turn around and flow inwards against the dry parts of the filling. Investigations regarding artificial wetting of pellet layers are still ongoing.

5.2.5 Water storage section, WSS

The idea is that a section of a tunnel will be used to store inflowing water from a fractured zone. Delimiters consisting of concrete beam walls are constructed and the volume between the walls is filled with a permeable filling. The inflowing water is stored in the macro voids of the filling. The method is suitable for inflow rates between 1 and 5 l/min.

5.2.6 Drainage borehole to Adjacent Tunnel, DAT

A drainage borehole is drilled from the current deposition tunnel to an adjacent tunnel. For the design to work, it will also be necessary to construct a special water collector section in the current deposition tunnel that is collecting the inflowing water and leading it into the drainage borehole. The water collector can either be a section of the whole deposition tunnel or a wedge shaped volume countersunk into the tunnel periphery. The method is intended to be used for inflow rates between 5 and 10 l/min. However, the method is judged to also work well for both lower and higher inflow rates. Characterization of deposition tunnels

All deposition tunnels should be characterized regarding the water inflow distribution. Both the total water inflow to a deposition tunnel and the position of water bearing fractures with inflow rates higher than 0.25 l/min should be noted. With this information as a base, a specific water handling plan can be developed for each individual tunnel. This means that the exact position and size of e.g. a water storing section or a drainage borehole to an adjacent tunnel can be decided even before the drilling of the deposition holes has started.

With the different suggested water handling methods, it will be necessary to handle all inflow rates in a deposition tunnel up to 10 l/min, which is the set requirement from the project.

Table 5-1 shows roughly how decisions on water handling methods can be made based on how the water inflow into one tunnel is distributed. The suggested techniques are based on the fact that 6 meter tunnel is backfilled every 24 h and that the tunnel must be backfilled continuously with this rate until reaching the position where the tunnel end plug should be constructed.

Table 5-1. Table showing how tunnels with certain water inflow conditions can be handled with the different suggested water handling methods.

Water inflow to 300 m tunnel (l/min)	Approximate inflow in one water bearing fracture zone (l/min)	Water handling method
< 0,5		No water handling method is needed apart from backfilling installation as planned.
0,5–1,0[1]	< 0,5	No water handling method is needed apart from backfilling installation as planned.
	0,5–1,0	Geotextile as a water distributor is needed.
1,0–5,0[1]	< 0,25	No water handling method is needed apart from backfilling installation as planned.
	0,25–1,0	Geotextile as a water distributor is needed, probably also methods with higher capacity.[2]
	> 1,0	Water handling methods with high capacity[2] is needed.
> 5,0 l/min[1]	< 0,25	No water handling method is needed apart from backfilling installation as planned.
	0,25–1,0	Geotextile as a water distributor is needed, probably also methods with higher capacity.[2]
	> 1,0	Water handling methods with high capacity[2] is needed.

[1] NB: For tunnels where the total inflow is around 1 l/min and above a thorough evaluation of the tunnel is needed concerning water handling during backfilling for that specific tunnel. Such evaluation must include where the water bearing structures are located, the inflow from each structure and the distance between them.

[2] Water handling methods with high capacity are being developed in a joint SKB-Posiva project. The methods comprise for example a water storage section and a drainage hole to a neighbouring tunnel. The reporting of the methods has not been completed when this document is written.

When setting up a water handling plan for a specific deposition tunnel it is important to know the installation sequence of buffer, canister and backfill. This is an important parameter that will influence on where the water front is positioned in relation to the backfill front.

Note that the figures in Table 5-1 are preliminary. After the initial mapping of inflow points and inflow rates, a detailed water handling plan can be done for every individual deposition tunnel, see also Chapter 6.

6 Mathematical model of storage and spreading of water in pellets fillings

6.1 Introduction

This chapter presents a mathematical model of water storage and spreading of water in a pellets filling during backfill installation. The objective of this is to calculate the available time for specific deposition tunnels and for specific water inflow scenarios, and to analyse if there is a risk that inflowing water can catch up with the backfill front. The water transport is represented as progressing water fronts from multiple water inlets in a tunnel, for essential any combination of inlet positions and flow rates. The partial water-filling of the pellets-filled sections is represented with a flow rate dependent function, which is adopted from steel-tunnel test results. The model is intentionally given a general definition which could enable an evaluation of features which are specific for SKB and Posiva, respectively, such as tunnel section area and backfilling rate.

The following features and conditions were used as input for the model:

i. Tunnel length (e.g. 300 m).

ii. Water inlets, i.e. an array of fracture coordinates and flow rates.

iii. Rate of backfilling (e.g. 6 m/day for SKB and 2.9 m/day for Posiva).

iv. Pore area (i.e. accessible pore volume per unit length), e.g. in pellets-filled slots (2 m^2 for SKB and 1.4 m^2 for Posiva) and in water-storage sections (11 m^2 for SKB and 8.3 m^2 for Posiva).

v. The water-filled fraction of the pore area was assumed to be controlled by the flow rate. This area-fraction function was calibrated for SKB and Posiva conditions, respectively, and for cases with or without geotextiles.

The models is generally described in section 6.2. An adoption of parameter values is presented in Section 6.3. An analysis of several inflow scenarios is presented in Section 6.4. Finally, a tentative definition of flow rate limits for different method, and also the uncertainties of the model is discussed in Section 6.5.

6.2 Model description

A deposition tunnel is represented as a one-dimensional problem with x=0 at the inner end of the tunnel (Figure 6-1). A set of n water inlets or fractures (denoted i: 0, 1, → n-1) are specified, each one with a coordinate (x_i) and a flow rate (q_i). The protocol for the backfilling of the tunnel is represented with the filling time as a function of the coordinate $t_f(x)$. This therefore defines a line in a time-space diagram which represents the progress of the backfilling front. The filling time function and the inlet coordinate gives the starting time for each water inlet, $t_i = t_f(x_i)$. This means that the inlets come into play once the backfilling front has passed the positions of these. Before that, it is assumed that the inflow is efficiently drained from the tunnel with no relevance for the wetting of the backfill.

The distribution of voids in the backfill which can be water-filled (i.e. in the pellets-filled slots and in the water-storage sections) is represented with a pore area function A(x), i.e. the accessible pore volume per unit length. This function can potentially also be used for representation of temporary drainage and drainage bore holes. The partial water-filling of the pellets-filled sections is represented with a flow rate dependent area-fraction function $r_f(q)$. This means that the entire section area is filled as a homogenous progressing front for sufficiently low flow rates. However, only a fraction of the section area is filled at higher flow rates. For water-storage sections it is assumed that the entire area is filled, regardless of the flow rate, which means that the area-fraction function is defined as a function of the coordinate as well $r_f(q,x)$. The use of geotextiles has been found to lead to a more extensive filling of the accessible pore volume. This behaviour is represented with a higher-valued area-fraction function. No attempt is made to use different functions in different tunnel sections.

Instead two quantified functions, representing cases with and without geotextiles, are used to analyse the water-filling of the backfill.

The flow from an inlet is assumed to be divided in two equal sub-flows with progressing fronts in two directions along the tunnel (inwards and outwards), i.e. with half the flow rate ($q_i/2$) in each direction. Such a unit is denoted a "plume". These progressing fronts will proceed as long as they don't encounter the tunnel ending or another plume. When a plume encounters the inner tunnel ending it will only progress outwards with the total flow rate (i.e. q_i). When two plumes encounter each other they will merge into one plume with a flow rate equal to the sum of the flow rates of the two original plumes (e.g. $q_i + q_{i+1}$). This will spread with progressing fronts in two directions, with half the total flow rate, unless it has a history of encountering the inner tunnel ending, in which case it will only progress outwards with the total flow rate.

The evolution of encountering and merging plumes is essentially quite simple which doesn't have to take any advanced transport equations into account. Nevertheless, there is no direct method (i.e. a mathematical expression) for how to calculate this evolution and the simplest way to do it is through the definition of an algorithm, denoted the *Plume network algorithm*. In principle, it could be possible to develop a graphical method in which the encounter events were found with a ruler. Still, such a method would be governed by a set of rules which basically would correspond to the defined algorithm. The algorithm is essentially a systematic procedure for calculating where and when the next encounter will take place. This event defines the starting point for a new generation of plumes, with one plume less than in the previous generation (except for tunnel-end encountering events).

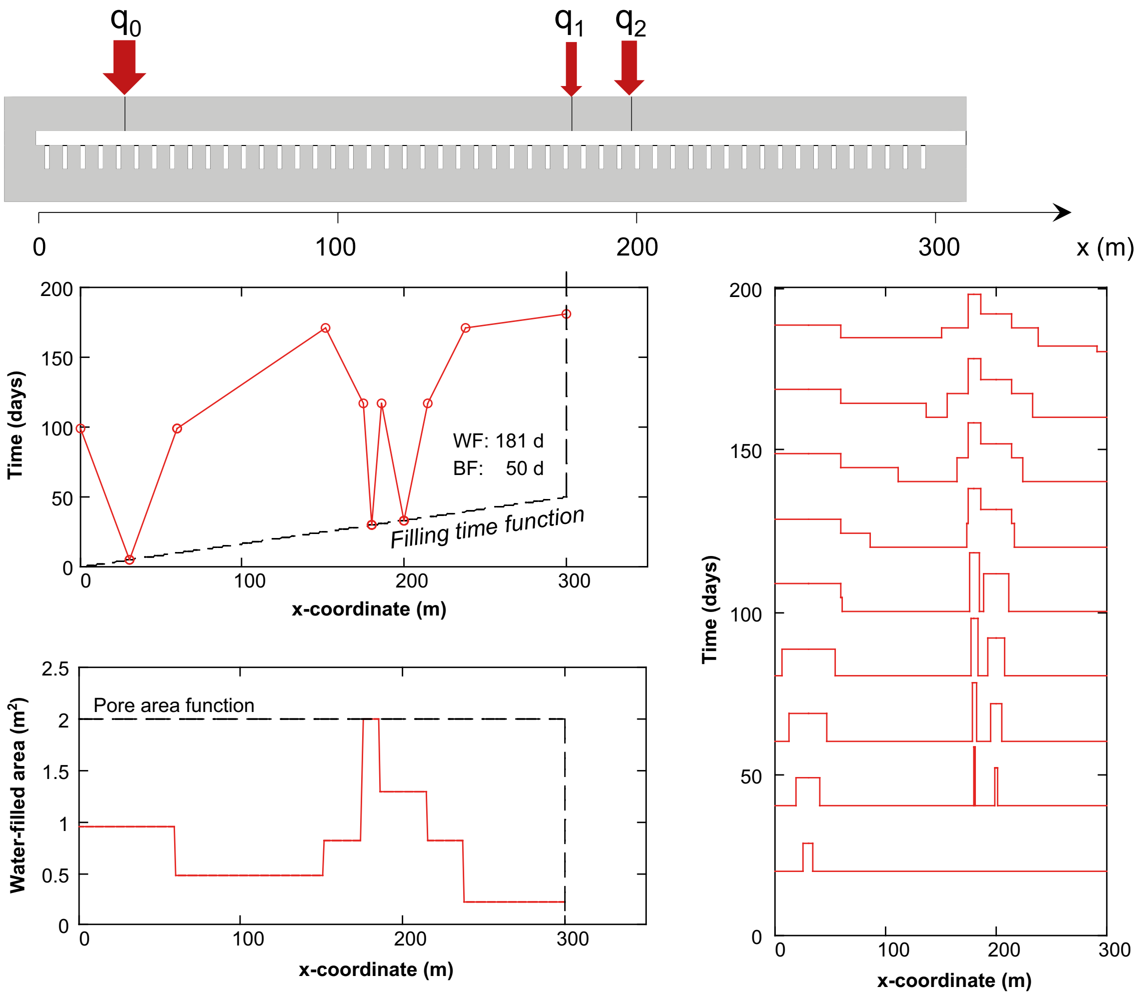


Figure 6-1. *Tunnel with 3 water inlets (upper). Tunnel-filling diagram with filling time function (center left). Final water filled area profile with pore area function (bottom left). Area-fraction distribution for different times (right).*

This means that the system can be described as a tree (or a river system) with a decreasing number of branches for each generation, ultimately resulting in one remaining main trunk. The output from this can be illustrated in a Tunnel-filling diagram which shows the progress of fronts and the encounter events in a time-space diagram.

A second algorithm, denoted the *Flow rate profile algorithm,* is subsequently defined. This algorithm maps the plume network (found with the previous algorithm) for a specific time and results in a table of coordinate intervals and local flow rates. This table can in turn be transformed to a water-filled area profile, which illustrates how much of the accessible pore volume has been filled at a given time. This profile can also give a verification that the water-filled volume corresponds to the accumulated inflow.

6.3 Parameter value adoption

The analysis of the inflow scenarios presented in the next section is based on a set of parameters and restrictions. The adoption of these are presented below.

Tunnel length

A general tunnel length of 300 m is used both for SKB and for Posiva.

Filling time function

For SKB a filling rate of 6 m per day is used. For Posiva the corresponding rate is 2.9 m per day. This is based on the procedure that backfilling will take place with 5 m per day during 8 days, after which a period will follow with 6 days without backfilling.

Pore area function

For SKB a general pore area of 2.0 m^2 is used, and for Posiva the corresponding area is 1.4 m^2. These values are based on the assumption that 47.5 % of average pellets volume per unit length (i.e. area) is accessible for water filling. The average pellets area is 4.2 m^2 for the SKB tunnel and 2.9 m^2 for the Posiva tunnel.

The pore area of a water storage sections is quantified as the product of the porosity of the filling material (here assumed to be 49.6 %) and the average tunnel section area (SKB: 22.7 m^2; and Posiva: 16.64 m^2). This leads to the following pore areas: SKB: 11 m^2; and Posiva: 8.3 m^2. The length of the water storage section can be adjusted although a maximum length of 10 m is assumed in this analysis.

A water storage section is represented as a rectangular function superimposed on a constant value representing the pellets filling.

Area-fraction function

A flow rate dependence of the area-fraction function is adopted on the following form:

$$r_f(q) = \min\left[1, \frac{q_0}{q}\right] \qquad (6\text{-}1)$$

The q_0 parameter is adopted from results from tunnel tests (Figure 6-2). The experimental data are presented as the time of first outflow from a tunnel section with a specific length as a function of the flow rate. This can thus be compared with the following theoretical expression for the outflow time:

$$t_{out} = \frac{L \cdot A \cdot r_f(q)}{q} \qquad (6\text{-}2)$$

where L is the length of the tunnel section (6 m) and A is the pore-area of the pellets filling (SKB: 2 m^2; and Posiva: 1.4 m^2). Two cases are adopted for each WMO, one adopted for an installed geotextile (green lines in Figure 6-2) and one without any geotextile (blue lines). The red lines corresponds to a complete filling of the pore volume. Finally, the black dashed lines reflect the backfilling rates.

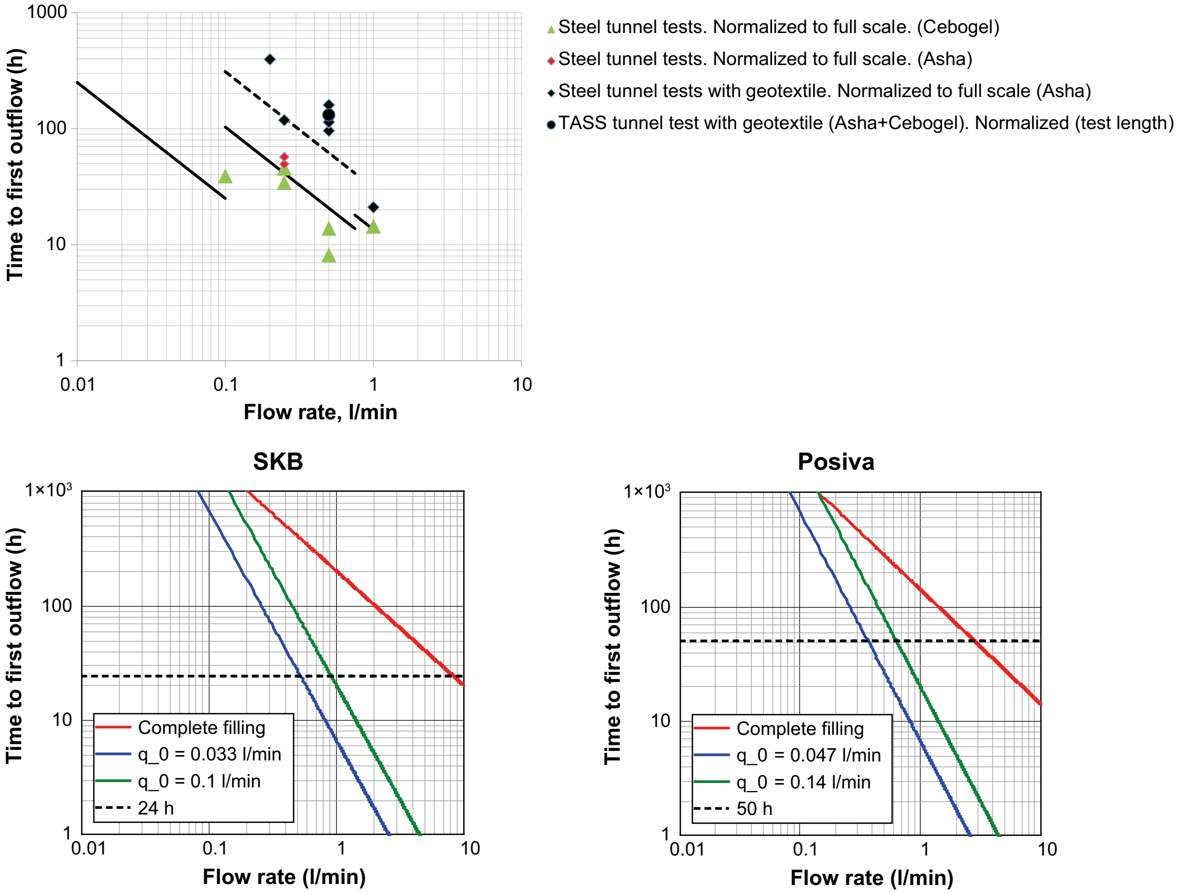


Figure 6-2. *Tunnel test results (upper). Calibration of fraction area function for SKB tunnel section (left) and Posiva tunnel section (right).*

For SKB conditions, the backfilling rate of 6 m per day corresponds to 24 h. Flow rates higher than the intersection between this line and the adopted functions are therefore critical: for cases without geotextile this is 0.52 l/min and with geotextile it is 0.91 l/min. For Posiva's backfilling rate, 2.9 m per day, this is represented with a line at 50 h. The corresponding limits for critical flow rates are 0.36 and 0.63 l/min for cases without and with geotextiles, respectively.

6.4 Analysis of inflow scenarios

This analysis is primarily performed for four inflow scenarios outlined by Keto et al. (2013) (Figure 6-3). Each case consists of seven fractures and inlets, and the different cases provide a wide range of flow rates: Case 1 represent a wet tunnel with a total inflow of approximately 5 l/min, and Case 4 is a dry tunnel with a total inflow of approximately 0.1 l/min (Table 6-1). Results for Case 1 to 4 for SKB conditions are shown Figure 6-4 to Figure 6-7. Corresponding results for Posiva conditions are shown in Figure 6-8 to Figure 6-11. Each analysed case is investigated for two area-fraction functions: one adopted for conditions with and one without geotextiles.

It can be noted that flow rate from the 6th fracture in Case 1 is so extensive (4.5 l/min) that a water storage section with a maximum length (10 m) is included for both the SKB and the Posiva conditions. The results for the SKB conditions show that the time for the water-front to reach the outer tunnel end (54 days) is only slightly longer than the time for the backfill-front to reach the tunnel end (50 days), Figure 6-4. For the Posiva conditions the water-front end-time (89 days) is actually shorter than backfill-front end-time (103 days) Figure 6-8. It can be noted that the use of geotextiles has only a marginal influence on the results, which are dominated by the flow rate and the position of the main fracture, as well as the capacity of the water storing section.

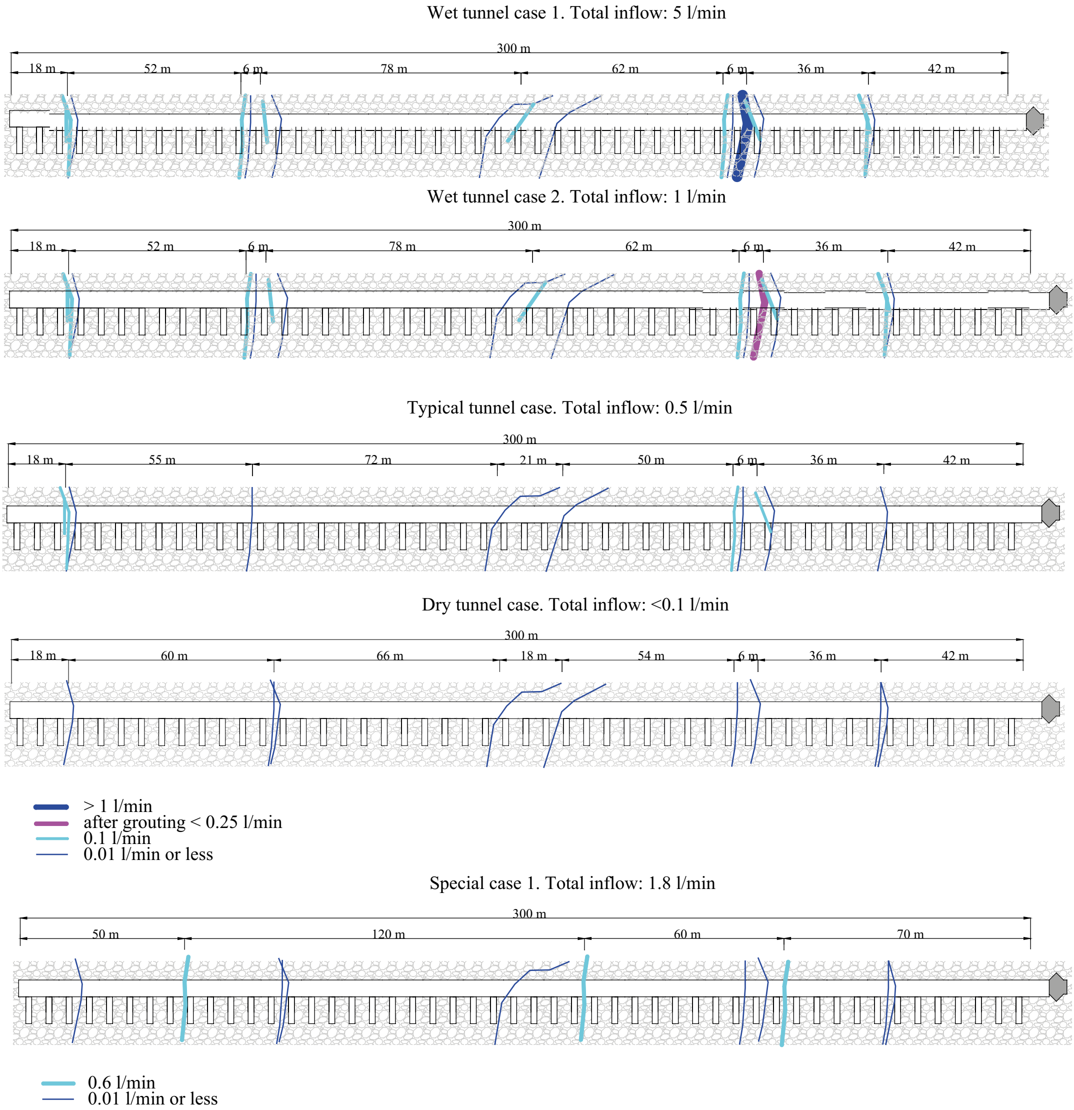


Figure 6-3. *Schematic drawing of inflow scenarios. Upper graph shows Case 1 to Case 4. Lower graph shows extra case (Case 5).*

Table 6-1. Positions and flow rates of fractures.

Case	Distance from inner end and flow rate						
	Fracture 1	**Fracture 2**	**Fracture 3**	**Fracture 4**	**Fracture 5**	**Fracture 6**	**Fracture 7**
1	18 m/ 0.2 l/min	70 m/ 0.1 l/min	76 m/ 0.1 l/min	154 m/ 0.1 l/min	216 m/ 0.1 l/min	222 m/ 4.5 l/min	258 m/ 0.1 l/min
2	18 m/ 0.2 l/min	70 m/ 0.1 l/min	76 m/ 0.1 l/min	154 m/ 0.1 l/min	216 m/ 0.1 l/min	222 m/ 0.25 l/min	258 m/ 0.1 l/min
3	18 m/ 0.2 l/min	73 m/ 0.01 l/min	145 m/ 0.01 l/min	166 m/ 0.01 l/min	216 m/ 0.1 l/min	222 m/ 0.1 l/min	258 m/ 0.01 l/min
4	18 m/ 0.01 l/min	78 m/ 0.02 l/min	144 m/ 0.01 l/min	162 m/ 0.01 l/min	216 m/ 0.01 l/min	222 m/ 0.01 l/min	258 m/ 0.02 l/min
5	50 m/ 0.6 l/min	170 m/ 0.6 l/min	230 m/ 0.6 l/min	–	–	–	–

The flow rates of the water inlets in Case 2 are more distributed than in Case 1, although more than a third of the total flow rate (almost 1 l/min) originates from the tunnel section at the position 216–222 m. The results for the SKB conditions show that the water-front end-time is significantly longer than the backfill-front end-time: 125 days without and 286 days with geotextile (Figure 6-5). For the Posiva conditions the water-front end-time is also longer than the backfill-front end-time although the difference is less significant: 139 days without and 279 days with geotextile (Figure 6-9).

The total inflow in Case 3 was significantly dominated by the inlets in two sections: 0.2 l/min close to the inner end, and 0.2 l/min in the section at the positions 216–222 m. Even if these inlets are of equal size, the inner one has a larger influence on the entire evolution due to the early encounter with the inner end. This means that the subsequent progress of the water-front is then determined by the total flow rate rather than half the value. The results for the SKB conditions show that the water-front end-time is much longer than the backfill-front end-time: 243 days without and 678 days with geotextile (Figure 6-6). The corresponding times for the Posiva conditions are 252 and 577 days, respectively (Figure 6-10).

The total flow rate in Case 4 is slightly less than 0.1 l/min which means the water-front end-time is very much longer than the backfill-front end-time, approximately 4 200 days for SKB conditions (Figure 6-7) and 3 000 days for Posiva conditions (Figure 6-11). The use of geotextile has only a marginal influence on the results since the area-fraction is essentially equal to unity for these low flow rates.

The total flow rates for Case 5 is 1.8 l/min (Figure 6-3) and is chosen to provide a scenario in-between Case 1 and 2 presented above. Results for this case are shown in Figure 6-12 for SKB and Posiva conditions, for which the water-front end-time is 90 and 110 days, respectively. It can be noted that this is only marginally longer than the backfill-front end-time, especially for the Posiva case. Only cases with geotextile are shown, simply for the reason that the water-front end-time is shorter than the backfill-front end-time for cases without geotextiles.

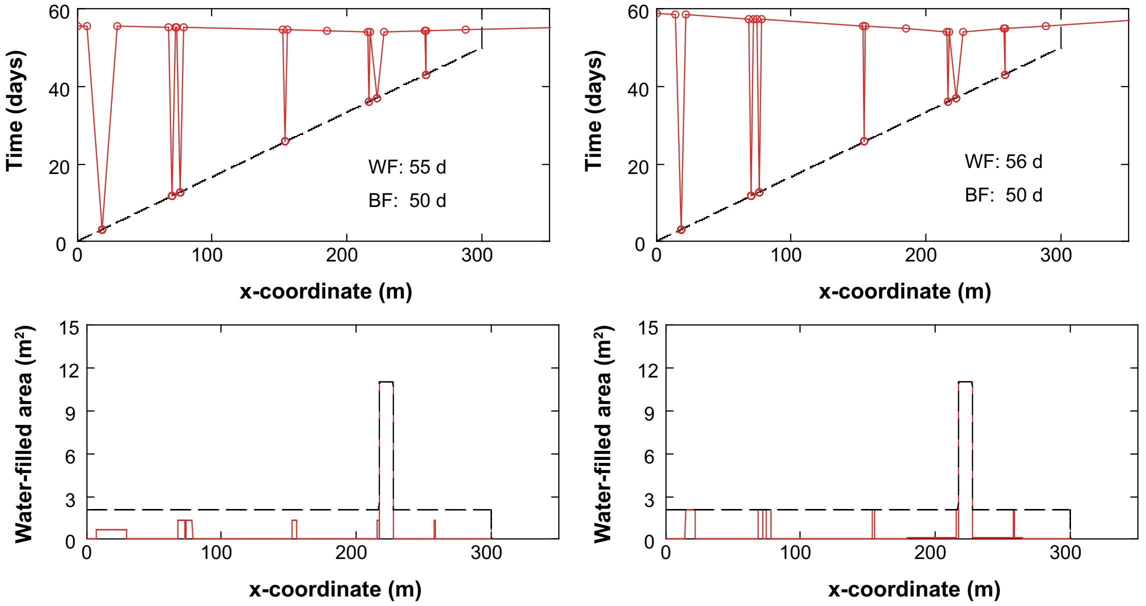


Figure 6-4. *Tunnel-filling diagrams and water-filled area profiles. SKB case 1 (left: no geotextile; right: with geotextile).*

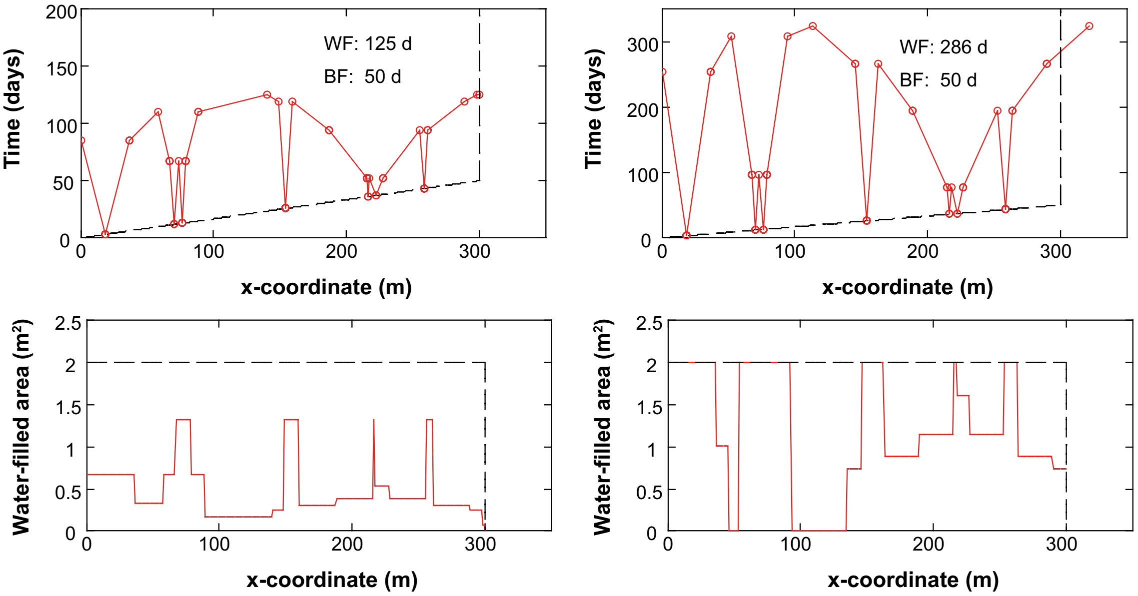


Figure 6-5. *Tunnel-filling diagrams and water-filled area profiles. SKB case 2 (left: no geotextile; right: with geotextile).*

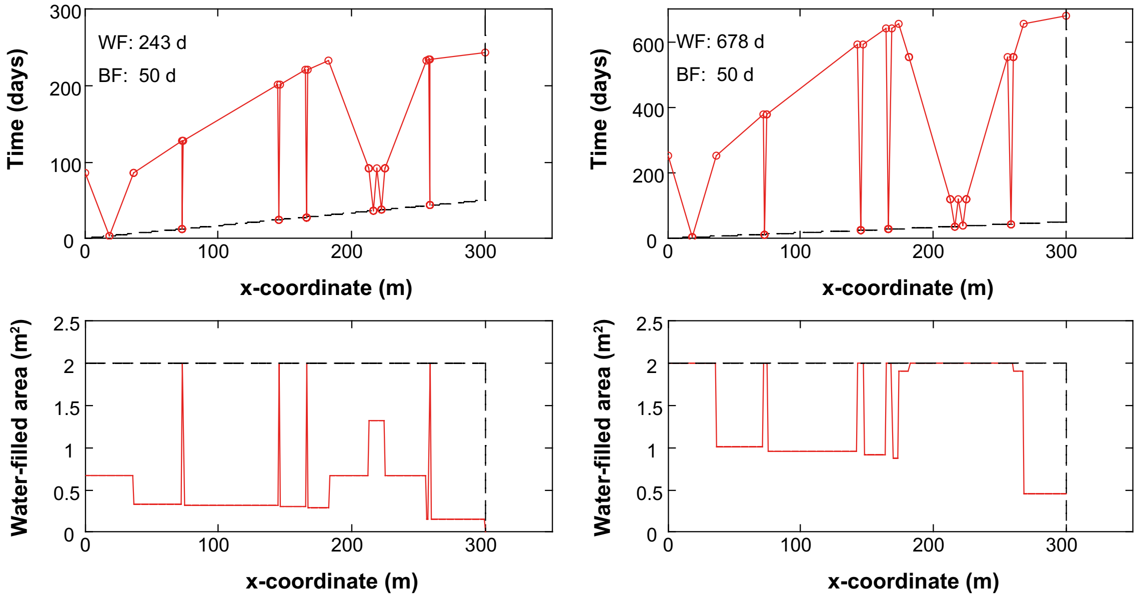


Figure 6-6. *Tunnel-filling diagrams and water-filled area profiles. SKB case 3 (left: no geotextile; right: with geotextile).*

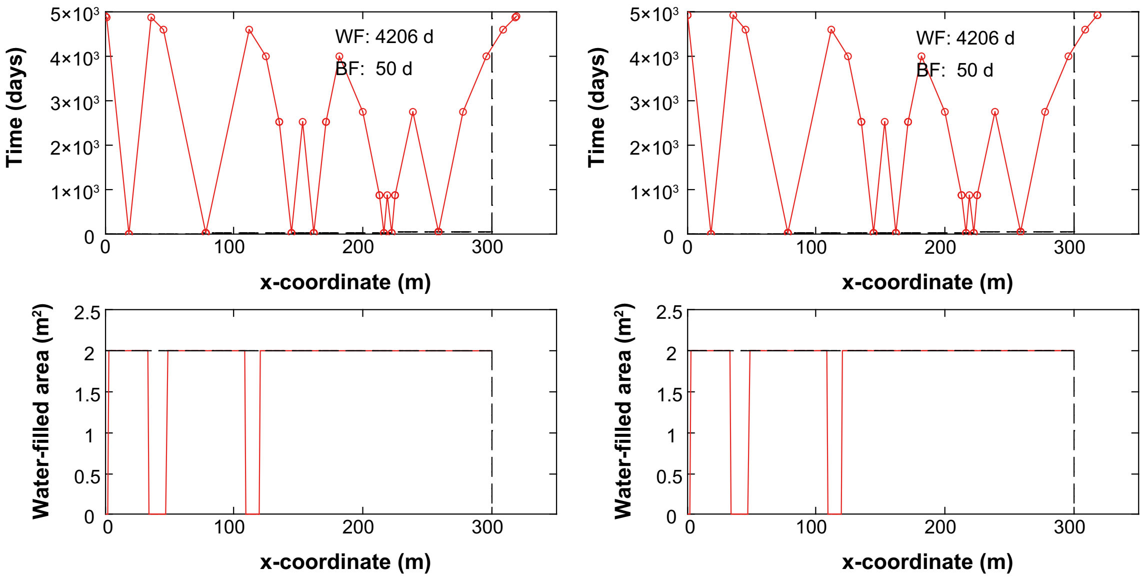


Figure 6-7. *Tunnel-filling diagrams and water-filled area profiles. SKB case 4 (left: no geotextile; right: with geotextile).*

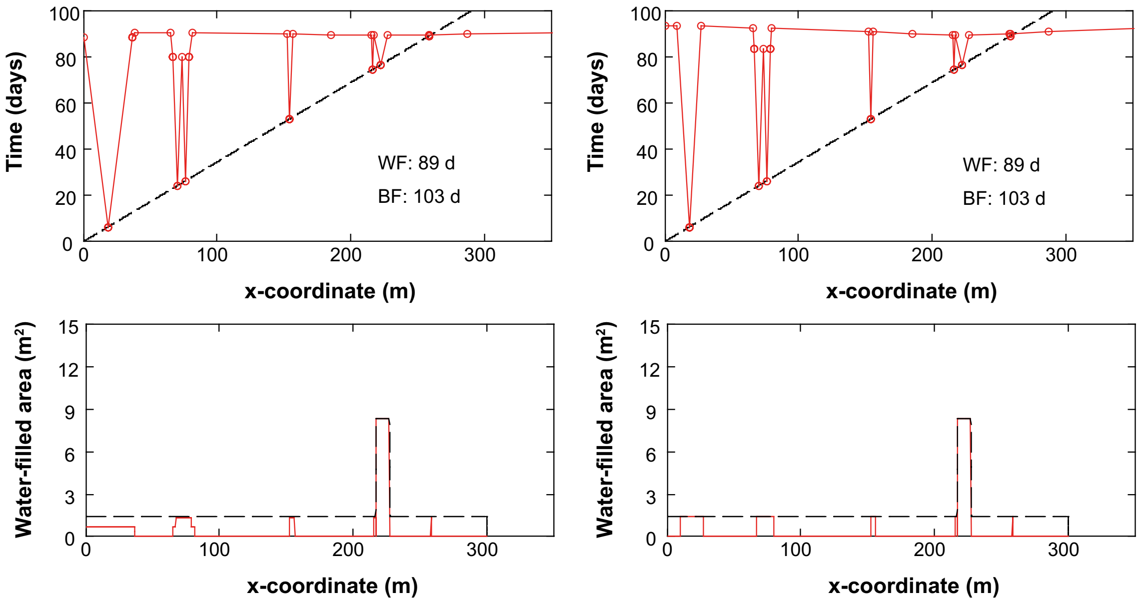


Figure 6-8. *Tunnel-filling diagrams and water-filled area profiles. Posiva case 1 (left: no geotextile; right: with geotextile).*

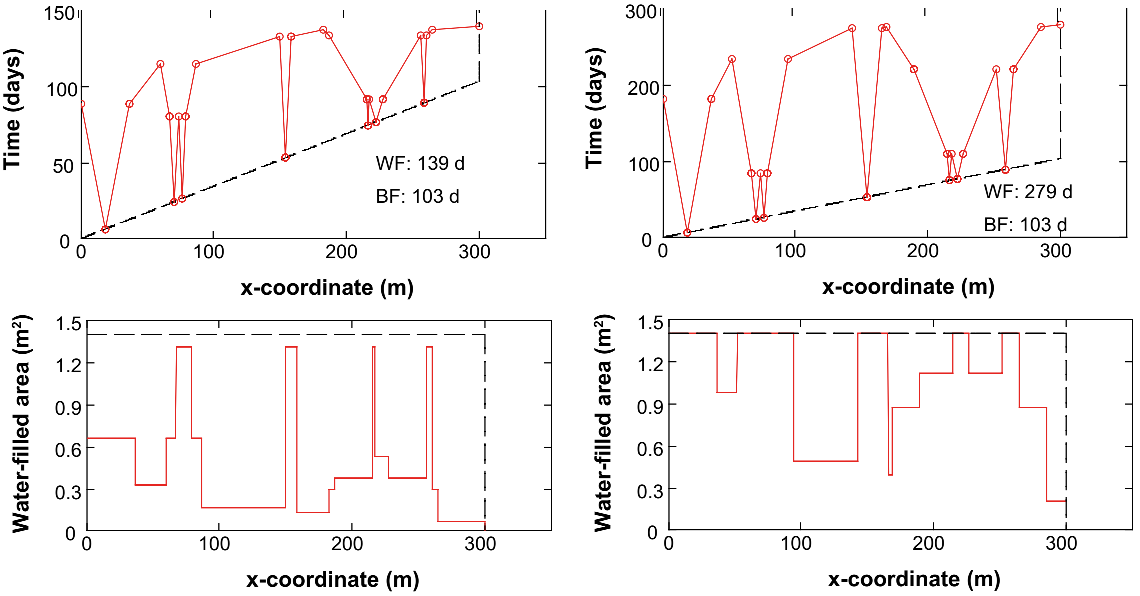


Figure 6-9. *Tunnel-filling diagrams and water-filled area profiles. Posiva case 2 (left: no geotextile; right: with geotextile).*

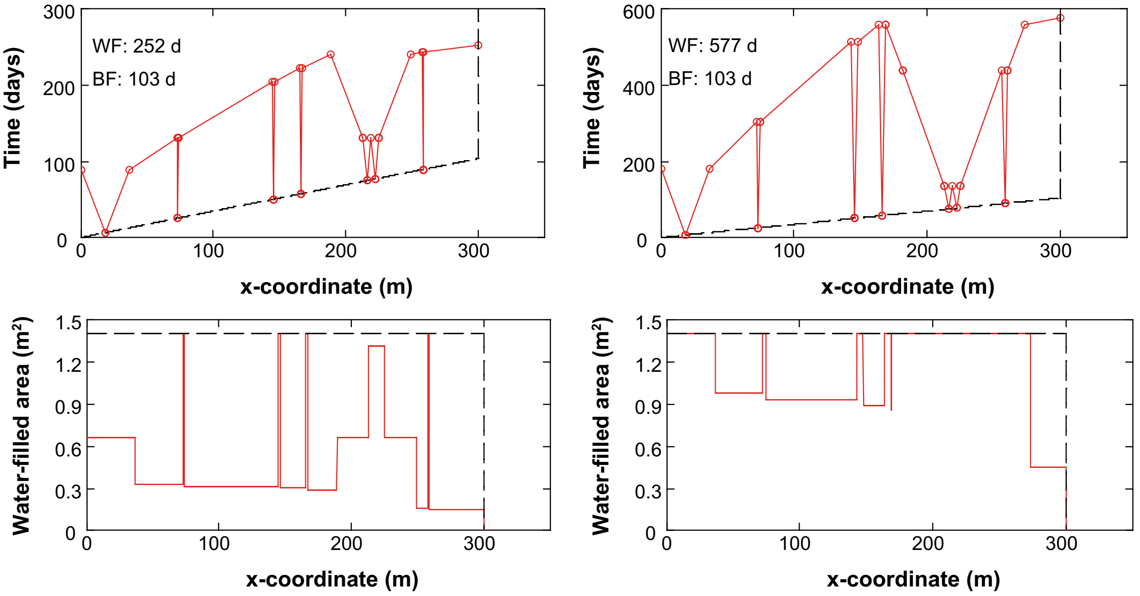


Figure 6-10. *Tunnel-filling diagrams and water-filled area profiles. Posiva case 3 (left: no geotextile; right: with geotextile).*

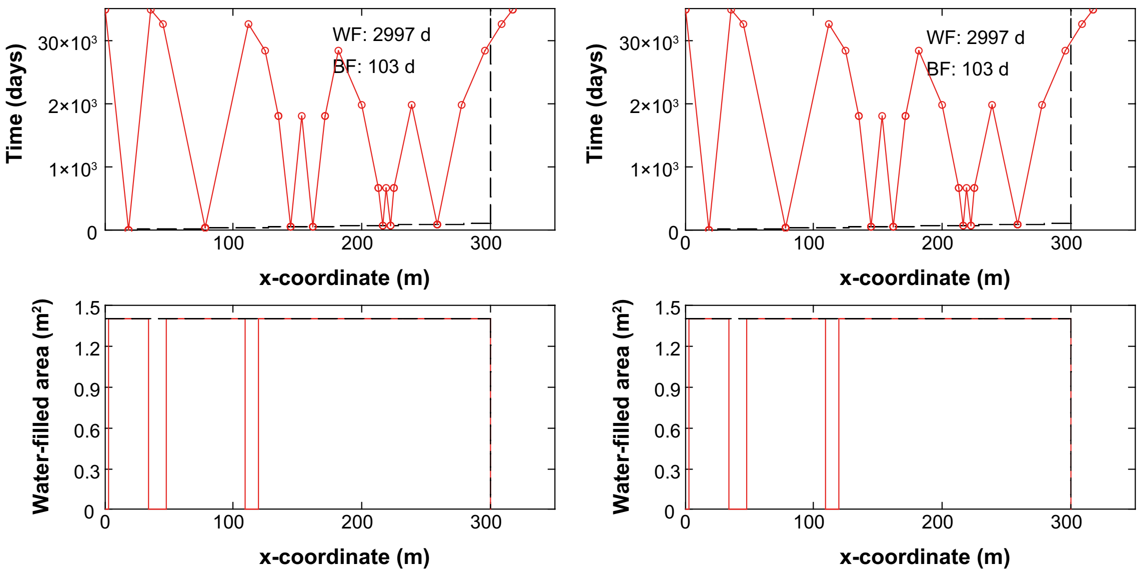


Figure 6-11. Tunnel-filling diagrams and water-filled area profiles. Posiva case 4 (left: no geotextile; right: with geotextile).

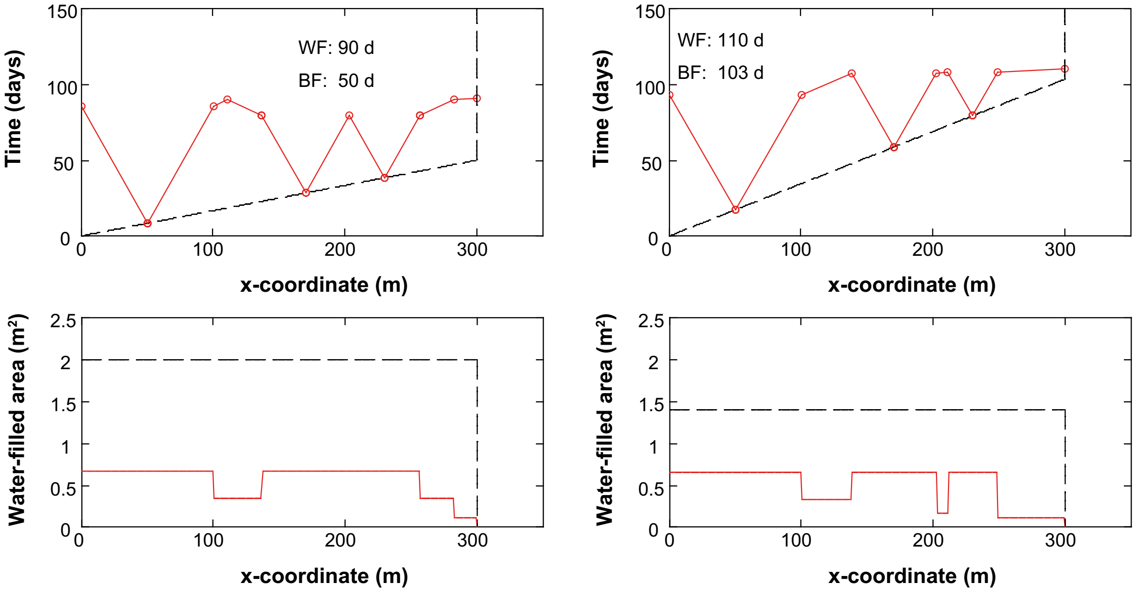


Figure 6-12. Tunnel-filling diagrams and water-filled area profiles. Case 5 and with geotextile. SKB (left) and Posiva (right).

6.5 Discussion

Tentative flow rate limits

The described model can apparently be used to assess the feasibility to backfill a tunnel with a specific concept and a specific installation sequence. In principle, it could be possible to use this model for analysing the predicted inflow scenarios (presented by Joyce et al. 2013) for all tunnels at the Forsmark site, in order to estimate the number of tunnels requiring different water handling methods. A simpler approach could be to quantify flow rate limits for the feasibility of different method, which could be used as rules of thumb. However, since there are virtually an infinite combination of different inflow scenarios, there is no obvious way how to make a comprehensive definition of such limits.

A simple procedure that way have some merits is to consider cases with only one water inlet, located half-way through the tunnel (coordinate: 150 m), and to quantify the flow rate for which the resulting water-front end-time exceeds the backfill-front end-time. A margin between these two events can be motivated by the time needed to secure the backfill behind the end-plug tunnel, and to have an overall safety margin. An interval of 10 days is chosen for this purpose. The progressing water front for two cases (with geotextile and with a water storage section) are illustrated in Figure 6-13. The model described above can be used (by trial and error) to calculate such flow rate limits. However, an analytical expression can also be derived for this:

$$q_{\max} = \frac{A_w \cdot L_w}{2 \cdot t \cdot r_q} + \sqrt{\left(\frac{A_w \cdot L_w}{2 \cdot t \cdot r_q}\right)^2 + \frac{2 \cdot A \cdot (L - L_w) \cdot q_0}{t \cdot r_q}} \qquad (6\text{-}3)$$

A and A_w are the pore areas of the pellets-filled slots and the water storage section, respectively. L and L_w are the lengths of the tunnel and water storage section, respectively. The time t is the sum of half the backfill-front end-time and the margin, q_0 is the parameter in the area-fraction function, see Equation (6-1), and r_q is the unit conversion from l/min to m^3/day (=1.44). Results for different methods and WMO conditions are compiled in Table 6-2. It can be noted that the flow rate limits for cases without WSS is for Posiva conditions approximately 25 % lower than the values for SKB. This is given by the square-root of the time ratio ($\sqrt{t_{Posiva}/t_{SKB}}$), so that the corresponding difference would be 30 % if the 10 day margin would be omitted. For cases with a WSS the corresponding difference is 43 %.

Uncertainties

Even if the described model can take a variety of scenarios and conditions into account, it should be stressed that there are a number of uncertainties inherent in the method.

With the chosen approach, the plumes are assumed to fill a constant fraction of the section area which depends on the flow rate. This gives rise to the rectangular segments of the water-filled area profiles (Figure 6-14). Moreover, once the front has passed a certain position, there is no subsequent wetting along this position. This description differs to some extent from the conceptual model that has been considered previously (see Section 3.3) in which different wetting behaviours are found for different flow rates, e.g. upwards and downwards triangular wetting. However, these descriptions were based on experimental data from tests which simulated backfilled sections with a quite limited length. There is no corresponding data which shows how these behaviours develop along longer sections and longer time-scales.

Table 6-2. Tentative flow rate limits for different methods and conditions.

Method	SKB	Posiva
Water storage section	3.0 l/min	1.7 l/min
Geotextile	1.5 l/min	1.2 l/min
No geotextile	0.9 l/min	0.7 l/min

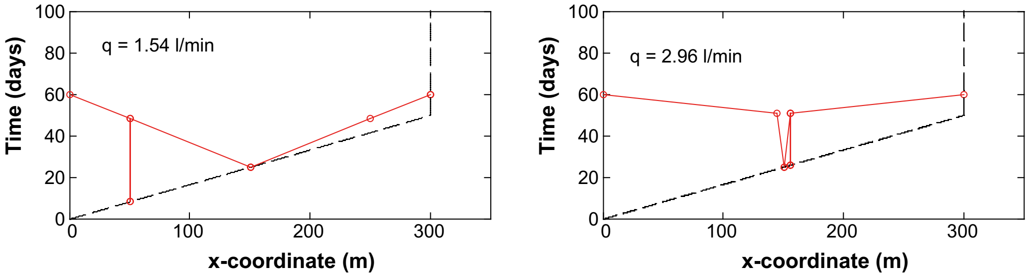
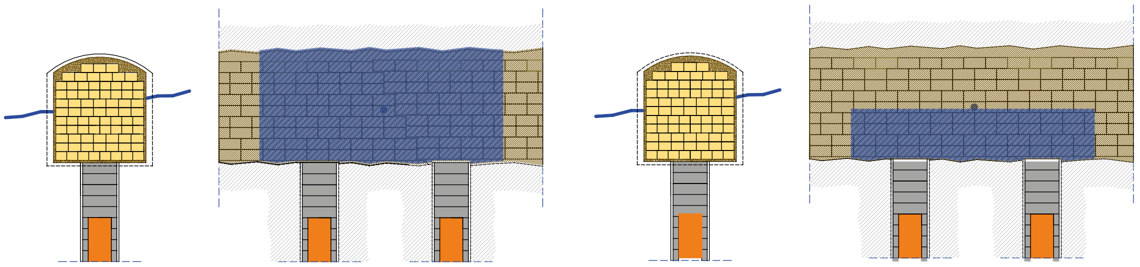


Figure 6-13. *Tunnel-filling diagrams for flow rate limit calculations. Cases with geotextile (left) and WSS (right).*

Complete water-filling: 0-0.1 l/min

Partial water-filling: 0.2 l/min



Partial water-filling: 0.5 l/min

Partial water-filling: 1 l/min

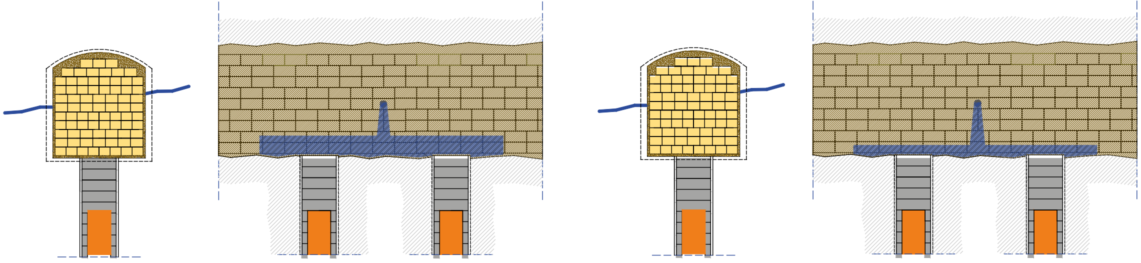


Figure 6-14. *Schematic drawing illustrating different wetting behaviour implicit from the approach with a flow rate dependent area-fraction function. Flow rate values correspond to a SKB case with geotextile.*

The chosen approach also involves the definition of an area-fraction function. A function on the form $min[1,q_0/q]$ is proposed for this, and this means that the area-fraction equals unity for all flow rates lower than q_0. This may be quite different from upward triangular wetting behaviour mentioned above, although it appears to be relevant to assume a completely distributed wetting at very low flow rates. Still, there may be other forms of the area-fraction function that can describe the real process more accurately. In addition, even if the chosen form is relevant, there may still be an uncertainty in the adopted q_0 values. It should for instance be noted that there is only one experimental point from a full-scale experiment in Figure 6-2. The three-fold increase of the area-fraction when a geotextile is used (q_0 values for SKB conditions of 0.033 and 0.1 l/min, respectively) can tentatively be motivated by the notion that the geotextile give rise to several plumes, for instance on the opposite side of the tunnel and in the tunnel ceiling. Nevertheless, if new information would suggest that another form of the area-fraction function or another parameter value is more relevant, then it should be quite easy to modify the calculations presented in this chapter.

Finally, the chosen approach involves the division of a water flow in two-equal sub-flows with progressing fronts in two directions along the tunnel. There appears to be some justification for this, considering the triangular or symmetrical wetting behaviour found in experiments. Still, it may eventually be evident that there are a preference for some direction (for instance outwards). But if so, then it should be a quite limited task to generalize the model presented here for a variety of division schemes, perhaps incorporating a stochastic behaviour as well.

Potential development

The presented model is implemented in a MathCad spreadsheet. In order to make the model accessible to several users it may be of interest to implement and compile this in a general computer language (e.g. Fortran), which would mean that it can be distributed as an executable file.

7 Comments and final conclusions

Compilation of test results

The wetting behaviour has been divided into five different scenarios:

- Upwards wetting. Inflow rates 0–0.1 l/min.
- Symmetrical wetting. Inflow rates, approximately 0.1–0.75 l/min.
- Downwards triangular wetting. Inflow rates, approximately 0.75–1.0 l/min.
- Downwards wetting. Inflow rates > 1.0 l/min or when pellets with inadequate properties is used.

The pellet properties influences the water storage capacity. In the evaluated tests, the pellet had a water content between 12 and 20 % and the dry density of the individual pellets have been between 1 810–2 000 kg/m^3. Only extruded pellets were considered.

There is a significant effect of using geotextile to increase the water storage capacity. A conservative judgement of the test results is that the water storage capacity increases with a factor 3 for flow rates between 0.25–1.0 l/min. This increase in water storage capacity is assessed to be very important in order to facilitate the backfill installation process. However, it is possible that a distributed water flow eventually will gather and accumulate to a more concentrated flow. A possible way to handle this uncertainty could be to install geotextiles at a number of positions in a deposition tunnel regardless if there are water inflow or not.

Conceptual model

The results from steel tunnel tests show that the water storage in a pure pellet filling is enough in order to handle inflow rates up to < 0.25 l/min i.e. the time to first outflow takes more than 24 hours (due to SKB installation sequence). When the inflow is 0.25 l/min or higher it will be necessary to use geotextile in order to distribute the inflowing water over a larger area and by that earn some extra time before water will reach the backfill front. The effect of using geotextile to increase the water storage capacity is unquestionable. The water storage capacity seems to increase with at least a factor 3. This means that for an inflow rate of 0.5 l/min, the time to first outflow from the section will be about 60 hours. With an inflow rate of 1.0 l/min, the time to first outflow will be about 20 hours which will be on the limit. It is therefore recommended to also use temporary drainage equipment for inflow rates between 0.5 and 1 l/min. It is thus judged that geotextile, possibly in combination with e.g. temporary drainage equipment, can be used for inflow rates up to 1 l/min. At higher inflow rates there will be a risk of local piping through the pellet filling out to the front.

Installation sequence

The differences in the assumed installation sequences between SKB and Posiva will affect the water handling strategies needed. The most important differences are:

- Differences in tunnel size and thereby available pellet volume for water storage.
- Backfill installation rate. (SKB has assumed 6 m in 24 hours and Posiva 5 m in 24 hours).
- Installation sequence. SKB has assumed a continuous backfill installation of a deposition tunnel while Posiva has assumed that the backfilling is made in 40-metere long sections with temporary stops of 6 days for installation of buffer, canister and preparatory work of the next 40 meter long section.

Water handling methods

All deposition tunnels should be characterized regarding the water inflow distribution. Both the total water inflow to a deposition tunnel and the position of water bearing fractures with inflow rates higher than 0.25 l/min should be noted. With this information as a base, a specific water handling plan can be developed for each individual tunnel. This means that the exact position and size of e.g. geotextiles a water storing section or a drainage borehole to an adjacent tunnel can be decided even before the drilling of the deposition holes has started. With the different suggested water handling methods, it will be necessary to handle all inflow rates in a deposition tunnel up to 10 l/min, which is the set requirement from the project. When setting up a water handling plan for a specific deposition tunnel it is important to know the installation sequence of buffer, canister and backfill. This is a parameter that will have great influence on where the water front is positioned in relation to the backfill front.

The utility of a temporary drainage is probably quite limited, since the “two day respite”, which is the gain of the method, is generally marginal in comparison to the time needed to backfill a tunnel. Still, it way be valuable close to the outer end of the tunnel.

Mathematical model

The described mathematical model is apparently a flexible tool which can be used to assess the feasibility to backfill a tunnel with a specific concept and a specific installation sequence. In principle, it could be possible to use this model for analysing the predicted inflow scenarios for all tunnels at a specific site, in order to estimate the number of tunnels requiring different water handling methods. It should nevertheless be stressed that there are a number of uncertainties inherent in the method, especially regarding the progressing fronts at high flow rates, the partial filling of the pore area and the interpretation of data from steel tunnel tests.

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Appendix 1

Wetting pattern from Steel tunnel test 3

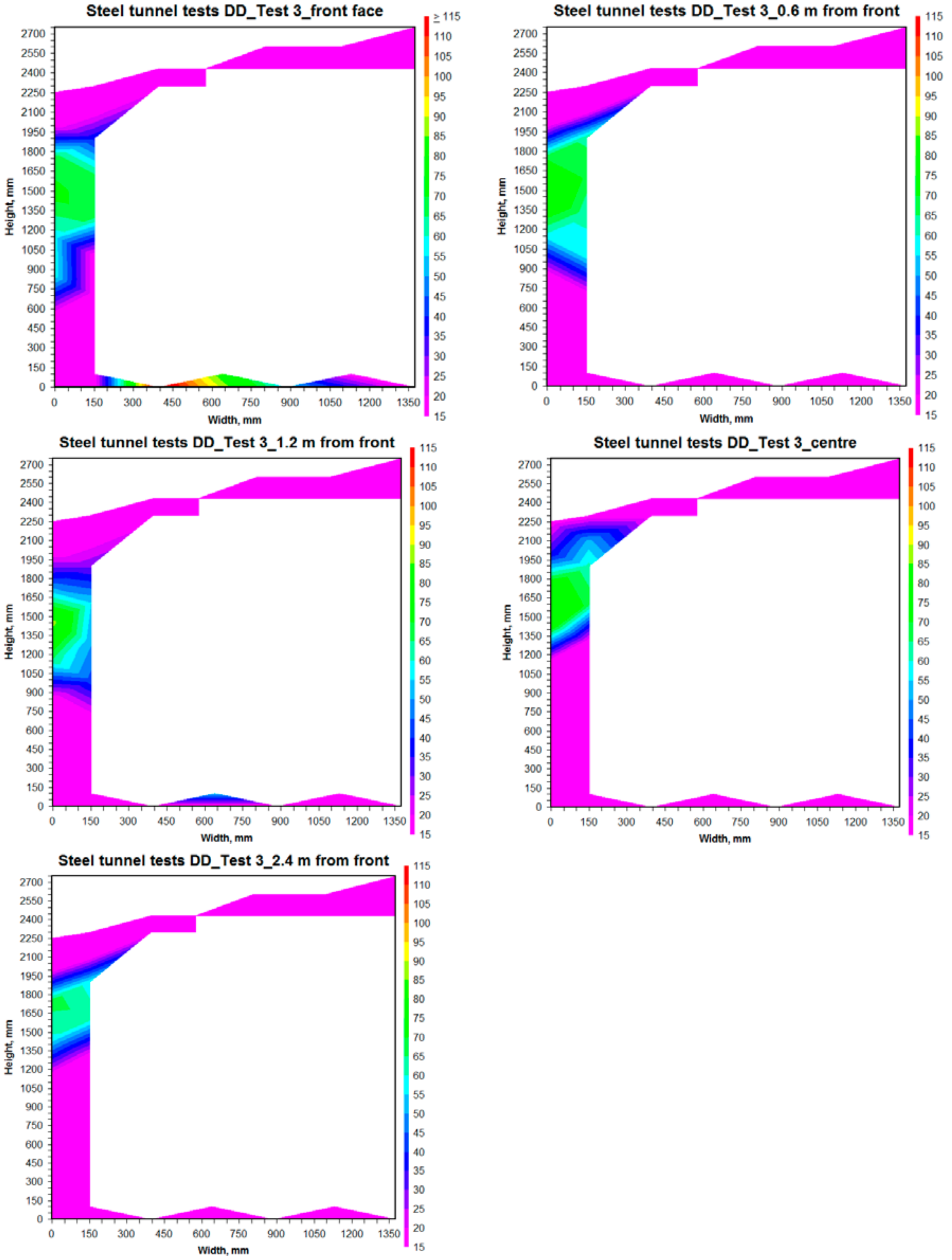

Figure A1-1. *The graphs show the water content distribution in the pellet filling for Test 3. The three innermost sections planned for sampling (3.0, 3.6 and 4.0 m from front) were not wetted and no sampling was done (Dixon et al. 2008b).*

Appendix 2

Wetting pattern from Steel tunnel test 4

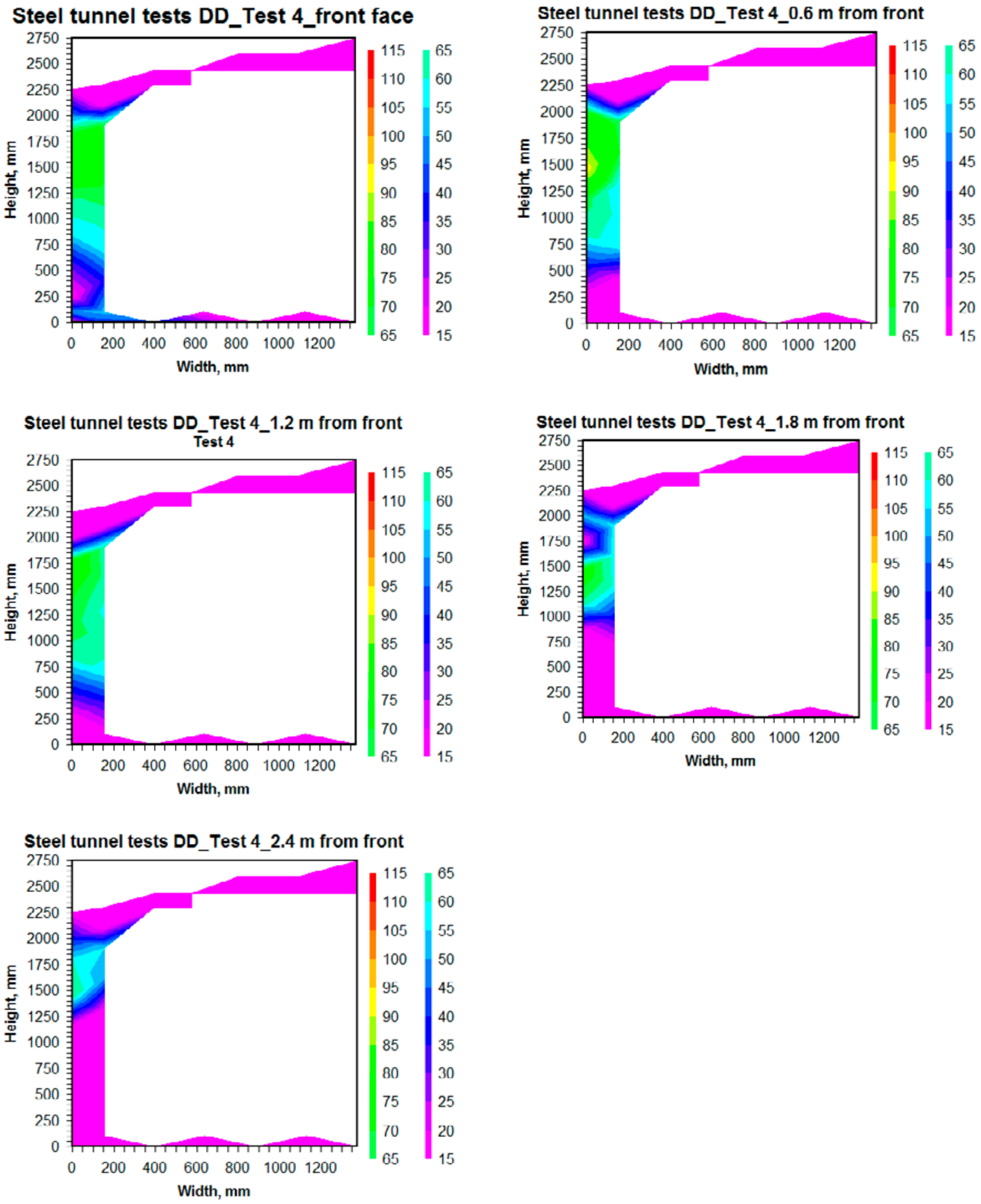

Figure A2-1. The graphs show the water content distribution in the pellet filling for Test 4. The three innermost sections planned for sampling (3.0, 3.6 and 4.0 m from front) were not wetted and no sampling was done (Dixon et al. 2008b).

Appendix 3

Wetting pattern from Steel tunnel test 5

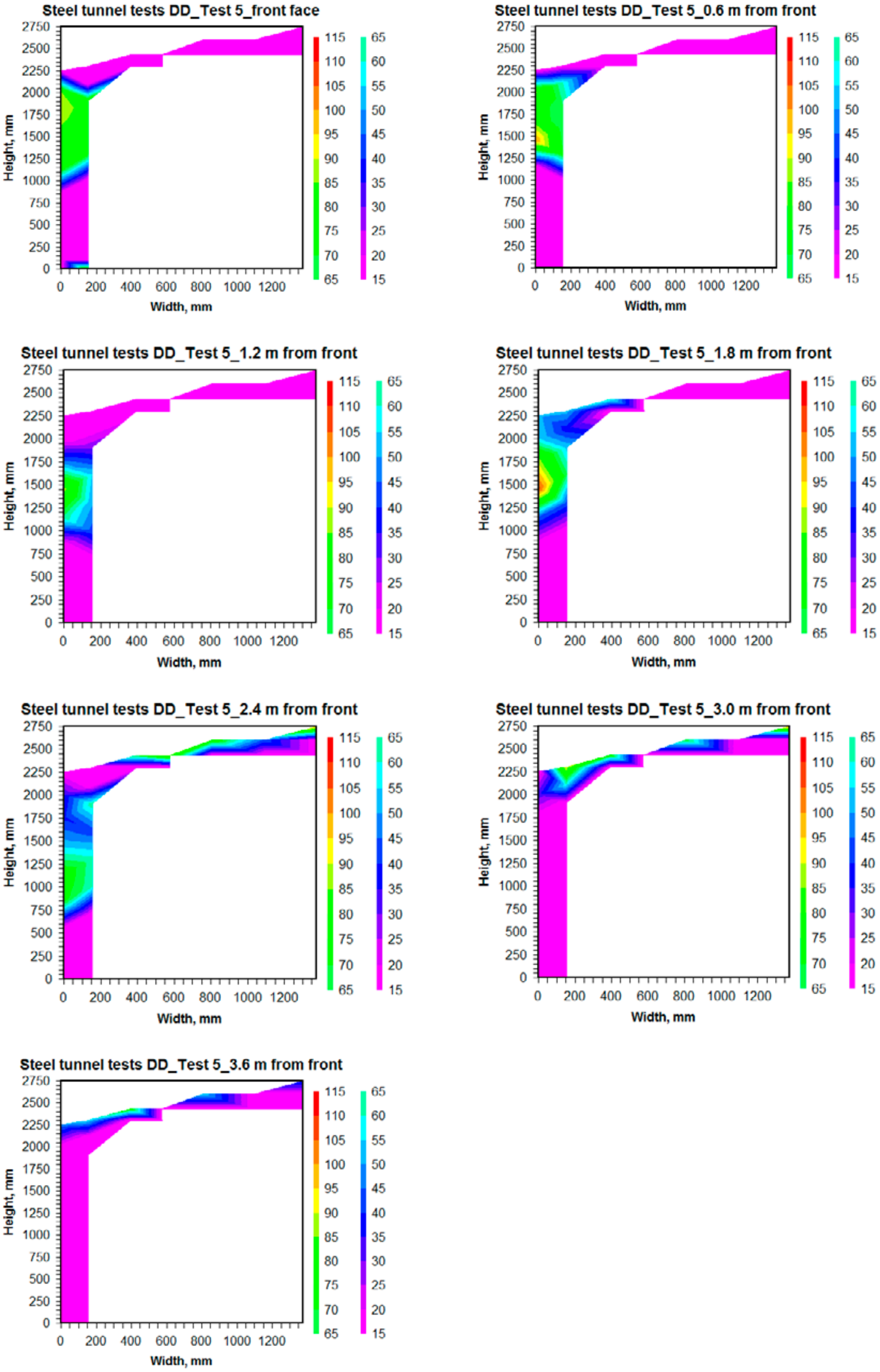

Figure A3-1. *The graphs show the water content distribution in the pellet filling for Test 5. The innermost section planned for sampling (4.0 m from front) was not wetted and no sampling was done (Dixon et al. 2008b).*

Appendix 4

Wetting pattern from Steel tunnel test 6

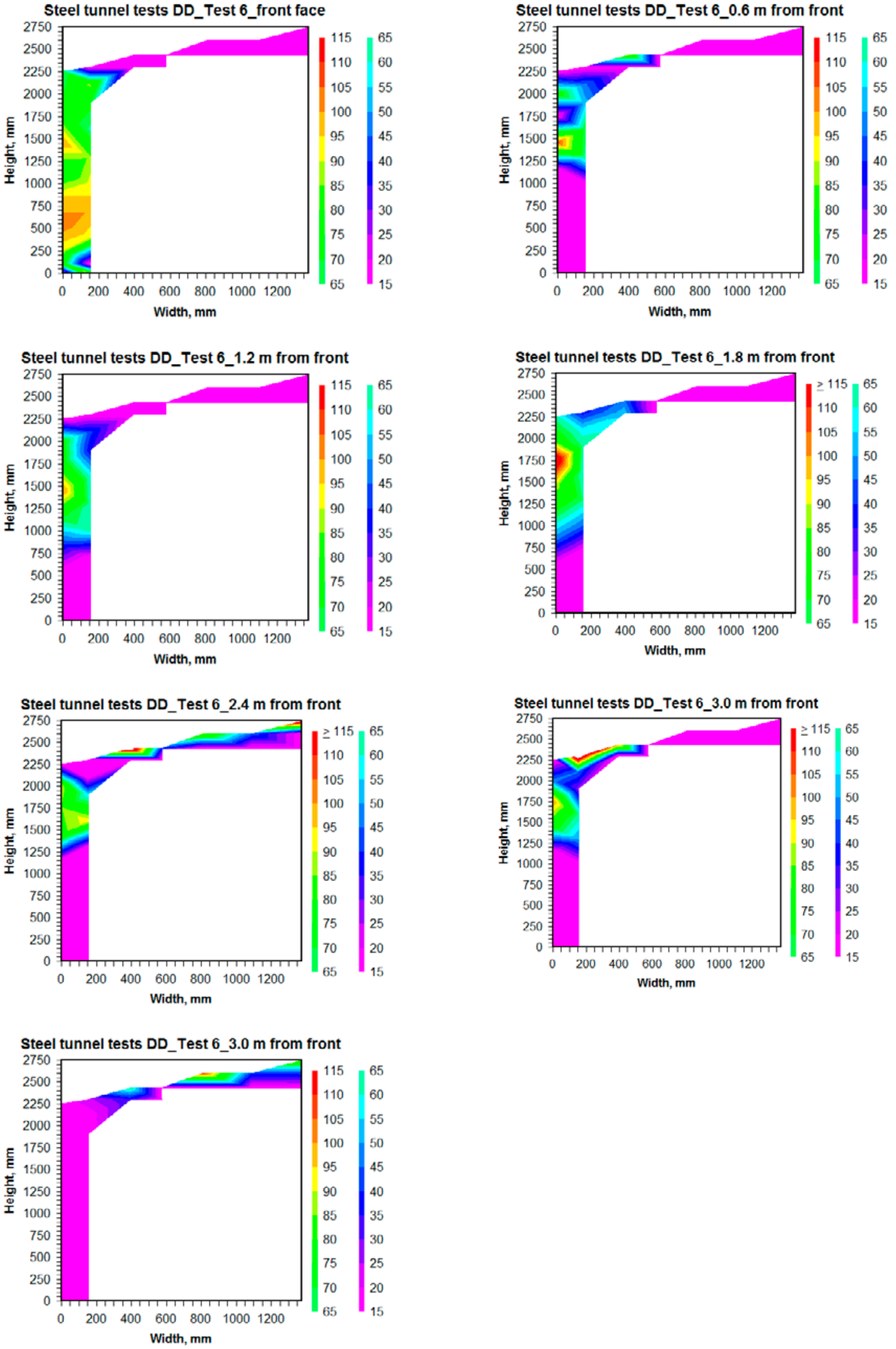

Figure A4-1. *The graphs show the water content distribution in the pellet filling for Test 6. The innermost section planned for sampling (4.0 m from front) was not wetted and no sampling was done (Dixon et al. 2008b).*

Appendix 5

Wetting pattern from Steel tunnel test 7

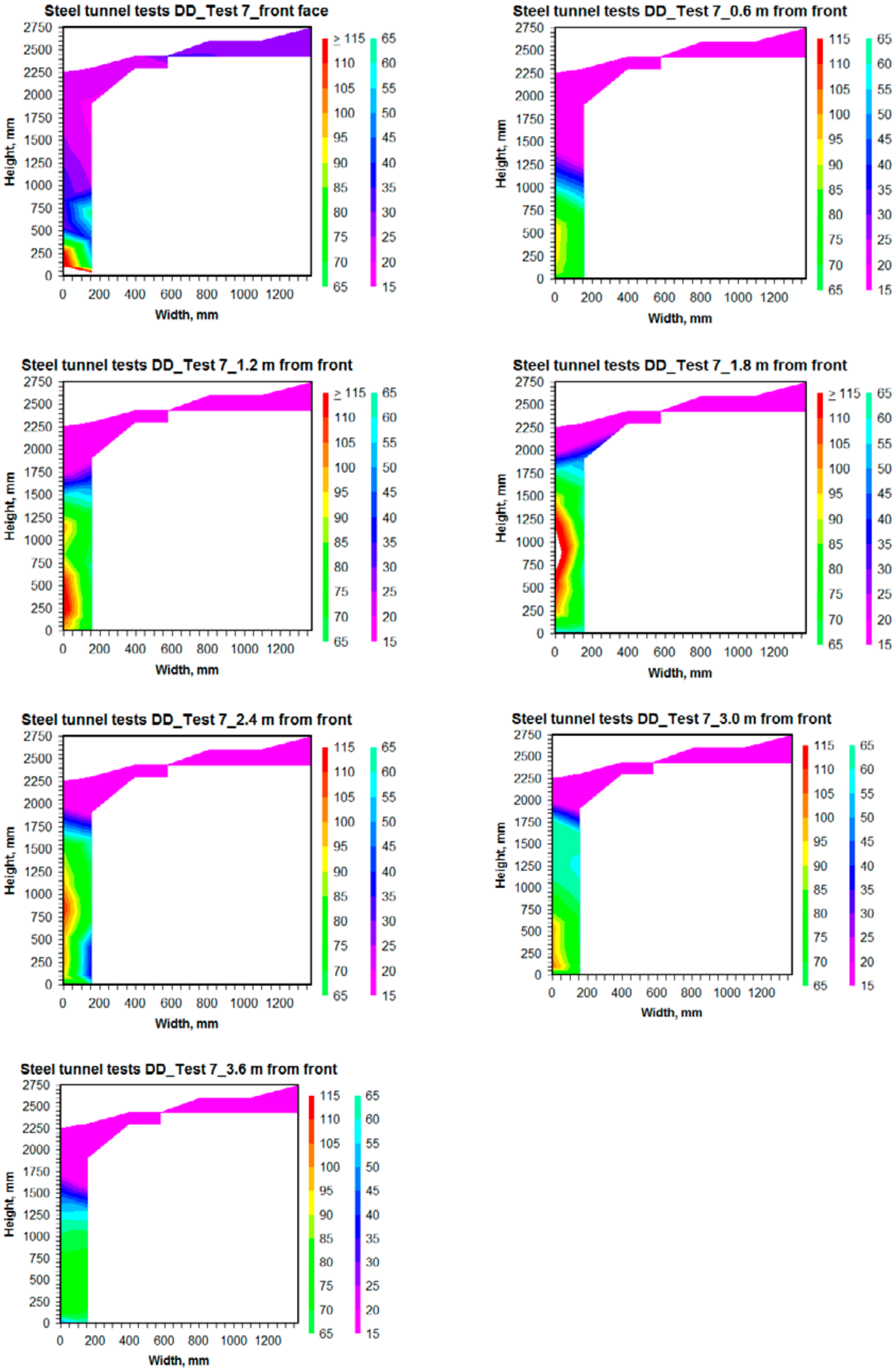

Figure A5-1. The graphs show the water content distribution in the pellet filling for Test 7. The innermost section planned for sampling (4.0 m from front) was not wetted and no sampling was done (Dixon et al. 2008b).

Appendix 6

Wetting pattern from Steel tunnel test 8

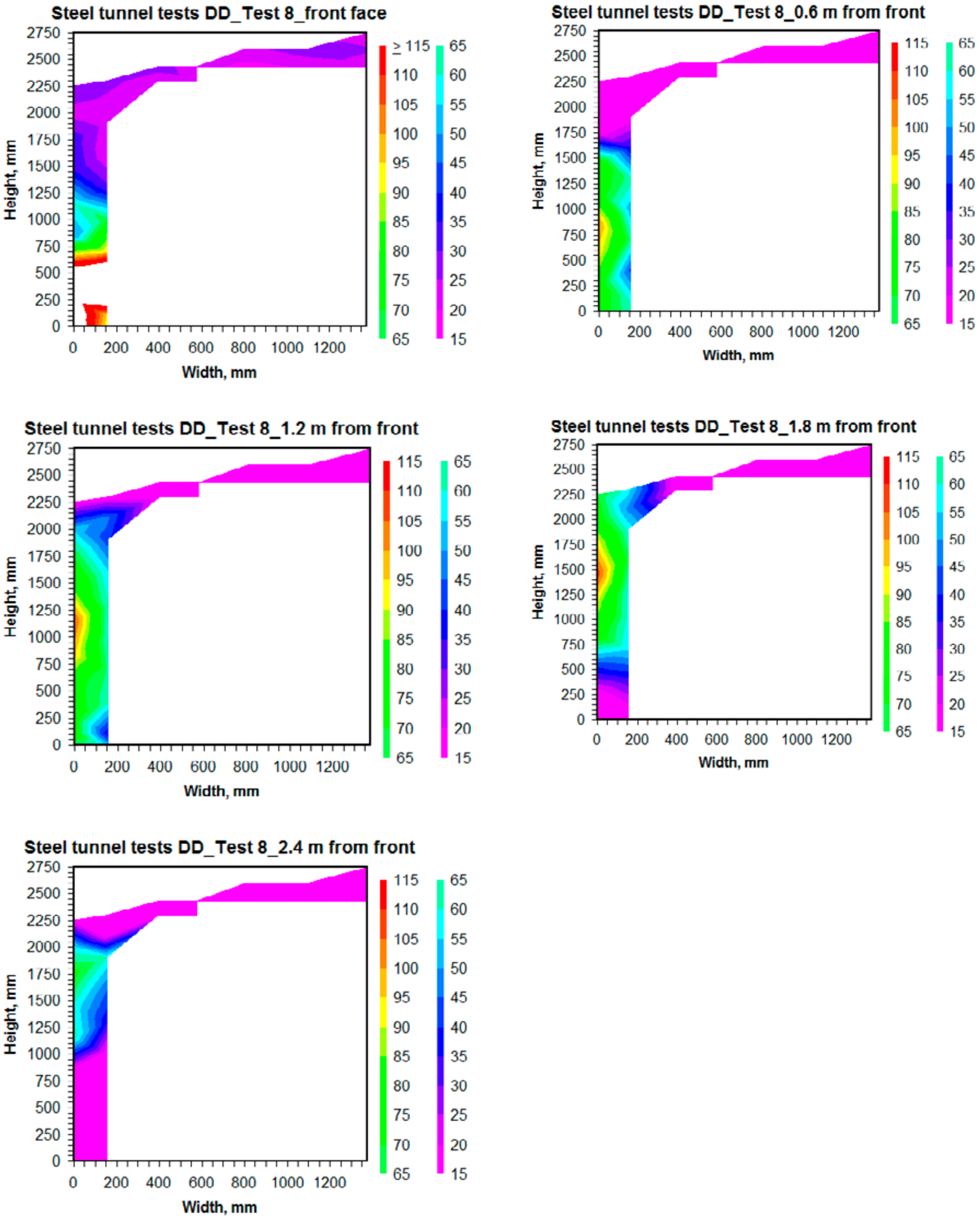

Figure A6-1. *The graphs show the water content distribution in the pellet filling for Test 8. The three innermost sections planned for sampling (3.0, 3.6 and 4.0 m from front) were not wetted and no sampling was done (Dixon et al. 2008b).*

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