R-14-09

System design of backfill

Methods for water handling

Torbjörn Sandén, Lennart Börgesson
Clay Technology AB

September 2014

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1402-3091
SKB R-14-09
ID 1424246

System design of backfill

Methods for water handling

Torbjörn Sandén, Lennart Börgesson
Clay Technology AB

September 2014

Keywords: KBP1003, Water handling, Bentonite pellet, Geotextile, Water storing, Drainage.

Abstract

The main alternative for the backfill design considered by SKB includes emplacement of pre-compacted blocks into most of the tunnel volume, and bentonite pellets to fill up the spaces between blocks and tunnel walls. Pellets will also be placed on the tunnel floor in order provide an even surface on which the backfill blocks can be stacked. One of the main identified problems 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 tunnel the inflowing water may affect the stability of the backfill installation and also cause erosion of the backfill.

Based on earlier investigations, the following limitations regarding water inflow rates have been suggested:

- The maximum allowed water inflow to a 300 meter long deposition tunnel is 5 l/min.
- The maximum allowed point inflow is 0.1 l/min.
- The backfill installation rate should be 6 meters per day, until the deposition tunnel is completed and the construction of the drift end plug has started.

The Forsmark site is assessed to be rather dry, but preliminary modelling of the rock mass shows that about 45 of a total of 207 planned deposition tunnels will have an inflow of more than 10 l/min and 13 tunnels will have inflows of more than 30 litres per minute (Börgesson et al. 2014). Since it is not desirable to reject constructed deposition tunnels, it will be necessary to develop methods and techniques in order to handle these expected water inflows.

A review of different methods for handling inflowing water has been made. The possible techniques identified can be divided according to the following three main principles:

1. **Stop the inflowing water**. This group includes e.g. grouting, local freezing or building of different types of plugs.
2. **Drainage of inflowing water**. Different solutions have been considered but the only one assessed to have potential is to drill a borehole to an adjacent tunnel. Incidentally this is the principle that is planned to be used within the KBS-3H design where all water will be flowing under the distance blocks and supercontainers during the installation time.
3. **Storing the inflowing water**. Water can be stored in the pellet filling or in specially built water storing sections filled with macadam.

Tests with bentonite pellets have been performed earlier in different scales and they have shown that largely the inflowing water can be stored in the macro voids between the bentonite pellets, in the pellet filled slot between backfill blocks and rock. The water storing in the pellet filling is probably enough for the main part of the tunnels but it will be necessary to have other techniques and methods for tunnels with greater inflow rates.

In order to test and improve the pellet storing method a number of new tests have been made at Äspö HRL. Three tests have been made in the so-called steel tunnel, scale approximately 1:2, in order to test the technique with geotextiles as a distributor of water inflows. The geotextiles are planned to be fastened on the rock walls and distribute water coming from one point over a larger area and thereby increase the water storing capability of the pellet filling. The tests have shown that this technique works as expected and can be used at some water inflow intervals. In addition, one test has been made to test the water storing capacity of a pellet filling in full scale, in the TASS tunnel at Äspö. This test also included pellets and geotextile and the results from this test confirmed what was learned in the minor scale.

With the available data regarding water storing in pellets, a conceptual model has been suggested. The model can be used in order to estimate whether it is possible to backfill a tunnel with a certain water inflow distribution without the water reaching the front and thereby disturbing the installation.

At some conditions it may be necessary to build a plug inside a deposition tunnel. Besides the tunnel end plug, which has high demands regarding strength and lifetime, it will probably also be necessary to build different kinds of simplified plugs. These plugs can either be planned, i.e. the preparatory work can be made in advance or they can be used if unscheduled stops of the backfill installation process should occur. A suggestion for a plug classification has been made. The classification includes demands on the different plug types and also a suggestion for design.

With the predicted water inflow distribution at Forsmark as a base, a suggestion for different methods to handle the water has been made for different scenarios. The only method that has been tested in full scale is to store the water in the pellet filling, along with techniques for improvement of this method i.e. the use of geotextiles. The other methods suggested will, however, need further development and testing.

Sammanfattning

Den design av återfyllning som SKB ser som huvudalternativ innebär att förkompakterade block fyller upp huvuddelen av tunnelvolymen och bentonitpellets används för att fylla upp spalterna mellan block och tunnelväggar. Pelletar kommer också att läggas ut på tunnelgolvet som en bädd och därmed forma en yta som lämpar sig för att stapla block på. Ett problem vid installationen kommer att vara vatteninflöde från berget och hur det ska hanteras. Beroende på flödeshastigheter och hur inflödespunkterna är fördelade i tunneln finns det risk för att det inflödande vattnet kan påverka stabiliteten hos inplaceringen och även orsaka erosion av återfyllningsmaterial.

Baserat på tidigare undersökningar har det föreslagits ett antal begränsningar vad gäller vatteninflöde till en deponeringstunnel:

- Det maximalt tillåtna vatteninflödet till en 300 meter lång deponeringstunnel får inte överstiga 5 l/min.
- Det maximalt tillåtna punktinflödet får inte överstiga 0,1 l/min.
- Återfyllningshastigheten bör vara 6 meter per dygn, intill dess att deponeringstunneln är fylld och konstruktionen av tunnelpluggen har startat.

Berget i Forsmark har bedömts vara ganska torrt, men preliminär modellering av bergmatrisen visar att ca 45 av totalt 207 tunnlar kommer att ha ett inflöde på mer än 10 l/min och av dessa kommer ca 13 tunnlar att ha ett inflöde som överstiger 30 l/min (Börgesson et al. 2014). Eftersom det inte är önskvärt att förkasta färdigställda deponeringstunnlar kommer det att vara nödvändigt att utveckla metoder och tekniker för att kunna hantera dessa förväntade vattenflöden.

En genomgång av olika metoder för att hantera inflödande vatten har gjorts. De tekniker som är möjliga har delats upp i följande tre huvudgrupper:

1. **Stoppa det inflödande vattnet**. Denna grupp innefattar t.ex. injektering, lokal frysning eller byggande av olika typer av pluggar.
2. **Dränering av det inflödande vattnet**. Olika lösningar har övervägts men den enda som har bedömts ha potential att användas är att dränera genom ett borrat hål till en angränsande tunnel. Detta är för övrigt den metod som är planerad att användas i designen av KBS-3H där allt vatten rinner ut under bentonitblock och supercontainrar under installationstiden.
3. **Lagring av inflödande vatten**. Vatten kan lagras i pelletfyllningen eller i speciellt byggda vattenlagringssektioner fyllda med makadam.

Tester med bentonitpelletar har genomförts tidigare i olika skalor och de har visat att det inflödande vattnet i stor utsträckning kan lagras i porutrymmena mellan bentonitpelletarna i den pelletfyllda spalten mellan återfyllningsblock och berg. Denna vattenlagring är förmodligen tillräcklig i huvuddelen av tunnlarna men det kommer att vara nödvändigt att ha tillgång till andra metoder i tunnlar med höga inflöden.

För att testa och förbättra metoden att lagra vatten i pellets har det gjorts ett antal ytterligare försök i Äspö HRL. Tre tester har gjorts i den s.k. ståltunneln, skala ca 1:2, för att testa tekniken att fördela det inflödande vattnet med geotextiler. Dessa fästs på bergväggen och fördelar vatten från ett punktinflöde över en större yta och kan därmed öka en pelletfyllnings kapacitet att lagra vatten. Testerna har visat att denna teknik fungerar som förväntat och kommer att vara användbar för vissa inflödesintervall. Det har även genomförts ett försök för att testa vattenlagringsförmågan hos en pelletsfyllning i full skala i TASS tunneln på Äspö. Detta försök innefattade också pelletar och geotextil och resultaten bekräftade vad som hade visats i mindre skala.

Med den data som fanns tillgänglig när det gäller lagring av vatten i pelletfyllning har en konceptuell modell tagits fram som beskriver hur vattnet lagras beroende på inflödeshastighet. Modellen kan användas för att uppskatta om det är möjligt att återfylla en tunnel med en viss vatteninflödesfördelning utan att vattnet hinner fram till fronten och därmed stör installationen.

Under vissa förhållande kan det vara nödvändigt att bygga en plugg i deponeringstunneln. Förutom tunnelpluggen som avslutar deponeringen och har höga krav när det gäller styrka och livslängd kommer det att behövas enklare typer av pluggar. Dessa pluggar kan antingen vara planerade dvs. alla förberedande bergarbeten kan göras innan deponeringen i tunneln startas, eller så kan de användas om det skulle inträffa ett oplanerat stopp av installationen. Ett förslag till klassificering av pluggar har gjorts. Klassificeringen innefattar krav på olika typer av pluggar och även ett förslag på design.

Med de predikterade inflödena i Forsmark som bas har det också gjorts ett förslag för när olika metoder att hantera vatten ska användas. Den enda metod som har testats i full skala är lagring av vatten i en pelletfyllning och även förbättringar av denna metod t ex fördelning av vatten med hjälp av geotextiler. De andra metoder som föreslagits kommer att behöva ytterligare utveckling.

Contents

1 Background

SKB develops and tests different designs of the KBS-3 concept for a final repository of radioactive waste. The work has been going on for several years in order to develop methods for backfilling, sealing and closure of a future repository. A decision has been made to recommend location of the repository to Forsmark. A major reason for this decision was the quality of the rock.

The reference design considered by SKB for backfilling 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. 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. The Forsmark site is assessed to be rather dry, but preliminary studies show that about 45 of in total 207 planned deposition tunnels will have an inflow of more than 10 l/min and 13 tunnels will have inflows of more than 30 liters per minute (Joyce et al. 2013). Since it is desirable that no deposition tunnels should be abandoned, it will be 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.

Tests with bentonite pellets have been performed in different scales and they have shown that largely the inflowing water can be stored in the macro voids between the bentonite pellets, in the pellet filled slot between backfill blocks and rock. The water storing in the pellet filling is probably enough for the main part of the tunnels but it will be necessary to have other techniques and methods for tunnels with high inflow rates. Based on earlier investigations, the following limitations regarding water inflow rates have been estimated (SKB 2010b):

- The maximum allowed water inflow to a 300 meter long deposition tunnel is 5 l/min.
- The maximum allowed point inflow is 0.1 l/min.
- The backfill installation rate should be 6 meters every day, until the deposition tunnel is completed and the construction of the drift end plug has started.

The work presented in this report has been performed within SKB's project System design of Backfill, subproject 6. The objectives of the work have been the following:

- Presentation of different possible methods for the water handling during backfilling.
- A closer investigation of the capacity of the technique to store the inflowing water in the pellet filling. This has been investigated in different scales (laboratory, mock-up and full scale) and a lot of information is available. In addition, subproject 2 within the System design project, has focused on an optimization of the water storing properties of the pellet filling. The results from these different tests have been used in order to make calculations regarding the water storing capacity of the pellet filling and the available time before water reaches the backfill front. The results from these calculations are presented in this report.
- Work out solutions for cases were other methods will be necessary e.g. if unplanned stops of the backfill installation occurs.
- Present an estimation of the number of tunnels that can be handled with "standard" methods and the number of tunnels that require special solutions.

2 Prerequisites for installation

2.1 General

A continuous water flow in a backfilled section will cause erosion of material and can also make it impossible to continue the backfilling in the prescribed way. According to the present reference design the maximum accepted inflow to a 300 meter long deposition tunnel is 5 l/min and the maximum point inflow to one six meter long section is 0.1 l/min (SKB 2010a, b). If these set limits are exceeded, steps must be taken in to ensure that the backfill installation can be made in a safe way.

The exact number of deposition tunnels with inflows higher than the set limits will not be known before construction, but modeling of the rock has shown that there will be a number of tunnels with higher inflow rates. These tunnels will, after completion, probably not be abandoned since the costs for construction are very high but also since there is a limited rock volume available for the repository. This means that it will be necessary to have a toolbox of different methods that can be used in order to handle the water and still be able to install the backfill while maintaining the requirements on the installed backfill.

The frequency of water bearing fractures at Forsmark is expected to be low, which means that the inflow points in a deposition tunnel will be few but instead the inflow rate at these points will be high.

The expected inflow rates at Forsmark have been modeled and reported in two different reports and a compilation of the results is provided below.

2.2 Expected site conditions at Forsmark, report I

The expected inflow to deposition holes and deposition tunnels has been modeled and is reported in Börgesson et al. (2014). The basic model is the same as used in SR-Site (Svensson and Follin 2010) but some modifications have been introduced.

The results from the report regarding expected inflow to deposition tunnels (see Figure 2-1), can be summarized as follows:

Out of a total of 207 tunnels,

- approximately 90 tunnels will have a total inflow > 1 l/min.
- approximately 50 tunnels will have a total inflow > 5 l/min.
- approximately 30 tunnels will have a total inflow > 10 l/min.
- a few tunnels can have a maximum inflow of 50 l/min.

This means that in approximately 25% of the tunnels, the inflow will be higher than the set limit (5 l/min) of the reference design.

In addition to the inflow rates, the effect of grouting has also been modeled. The diagram provided in Figure 2-1 shows that according to this model, the effect of grouting only can be seen for inflow rates larger than 1 l/min. At lower flow rates the two curves, “grouted” and “no grouting”, are following each other very tight.

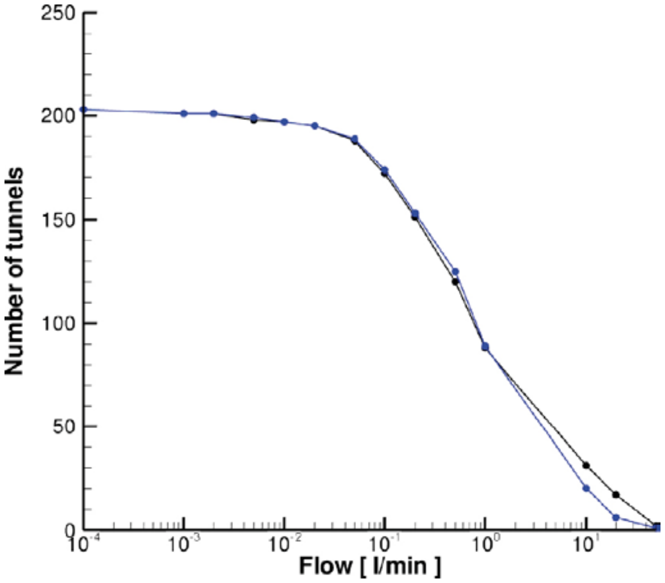


***Figure 2-1.** The number of deposition tunnels plotted versus total inflow to the tunnel. Black line represents "No grouting "and blue "Grouted". (Börgesson et al. 2014).*

2.3 Expected site conditions at Forsmark, report II

Calculations regarding expected inflows at Forsmark have also been made by Joyce et al. (2013). Two figures, taken from the report, are provided in Figure 2-2 and 2-3. The data shown in these diagrams is of high interest for the work with designing different methods for water handling in a future repository.

Five different cases were modeled. The obtained results from the different cases show only small differences and in this report the results from case r0 have been used, see Figure 2-2.

The statistics presented are based on the simulated inflows from ungrouted fractures intersecting underground openings. The results from the report regarding expected inflow to deposition tunnels can be summarized as follows (data evaluated from Figure 2-2):

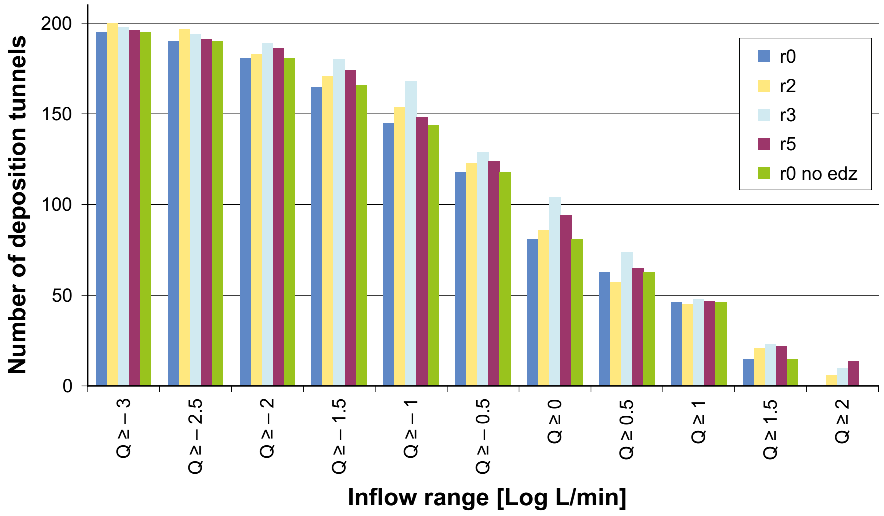


***Figure 2-2.** Comparison of the complementary cumulative distributions of the total inflow to each deposition tunnel (207 tunnels in total). Five different cases have been modeled but the differences are rather small and in this report the results from case r0 have been used. (Joyce et al. 2013)*

Out of a total of 207 tunnels,

- approximately 81 tunnels will have a total inflow of ≥ 1 l/min.
- approximately 63 tunnels will have a total inflow of ≥ 3 l/min.
- approximately 45 tunnels will have a total inflow of ≥ 10 l/min.
- approximately 13 tunnels will have a total inflow of ≥ 30 l/min.

In addition to the calculated total inflow rates to a deposition tunnel, the number of expected inflow points has also been modeled, see Figure 2-3. The diagram shows that in about 70 of the tunnels with an inflow of ≥ 1 l/min, all water is predicted to enter the tunnel in one inflow point.

2.4 Comments

The two reports predict rather similar inflow rates even if Joyce et al. (2013) has a higher number of tunnels with inflow rates larger than 10 l/min, 45 compared to 30 for Börgesson et al. (2014).

To summarize:

- Approximately 50 tunnels (25%) are predicted to have an inflow of more than 5 l/min.
- 30–45 tunnels are predicted to have an inflow of more than 10 l/min.
- A number of tunnels (13) are predicted to have an inflow of 30 to 50 l/min.
- In 70 of the tunnels with a predicted inflow higher than 1 l/min, the water is expected to enter the tunnel in one inflow point.

The modeling results provided shows that actions regarding water handling have to be made in approximately 35–40% of the tunnels. The necessary actions will depend on the inflow rate and the distribution of water bearing fractures in the tunnels.

The results provided are based on models and there is probably a considerably uncertainty about its validity. The effect of pre-grouting was investigated in Börgesson et al. (2014) and according to this model; the effect of grouting only could be seen for inflow rates larger than 1 l/min. The effect of grouting was not taken into account by Joyce et al. (2013).

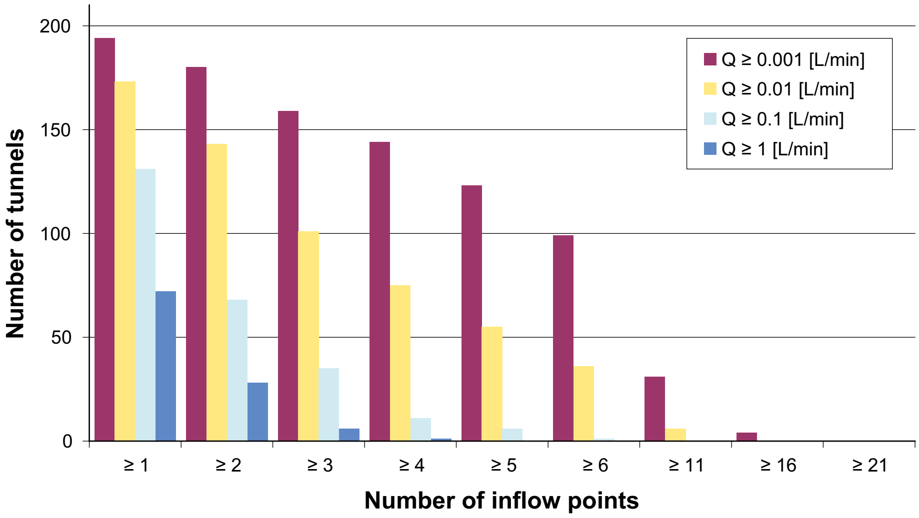


Figure 2-3. *Cumulative plot of the number of tunnels that have a certain number of inflow points for a range of inflow limits for case r0. (Joyce et al. 2013)*

3 Identified methods for handling of inflowing water

3.1 General

Water inflow to the deposition tunnels is expected to be a problem only if the water flows out through the backfilling front and by that jeopardizes the backfilling i.e. piling of blocks and installation of pellets in the remaining slots.

The inflowing water to a deposition tunnel can be handled according to the following three main principles:

1. Stop or decrease the inflowing water.
2. Drain the inflowing water.
3. Store the inflowing water.

With these three principles as a basis a number of different techniques have been suggested. Some of the techniques are well-known and have been tested in different contexts while others need to be investigated more closely. This chapter provides a brief description of the techniques and also an assessment of their usability.

In addition to the suggested techniques to handle water during the backfill installation process it will also be necessary to have methods to handle water in case unplanned stops of the backfill installation would occur, e.g. due to problems with the emplacement equipment. Suggestions for actions under these circumstances are described in chapter 6.

3.2 Description of methods for water handling

3.2.1 General

In a future disposal it will be necessary to have a tool box of different actions and methods that can be used depending on the different conditions that may occur in the deposition tunnels regarding water inflow, distribution of water bearing fracture zones etc. The block diagram in Figure 3-1 shows an overview of the identified methods and also gives an assessment of their ability to be used both from a technical point of view but also from a post closure safety perspective.

- Red boxes. These methods are assessed to include extensive technical difficulties and/or will probably not be acknowledged from a post closure safety perspective.
- Yellow boxes. In tunnels with high inflow rates it will be necessary to use methods that may involve considerable technical efforts. The methods described in the yellow boxes include technical challenges, but are also considered to have high potentials and are recommended to be further investigated.
- Green boxes. Well-known methods that are already in use or have been tested in full scale. There is, however, need for development and adapting of the methods to actual conditions.

Storing of water in the pellet filled slots is the only method that has been investigated in this project, and in which it has been possible to estimate the capacity based on results from different tests, see chapter 4 and 5.

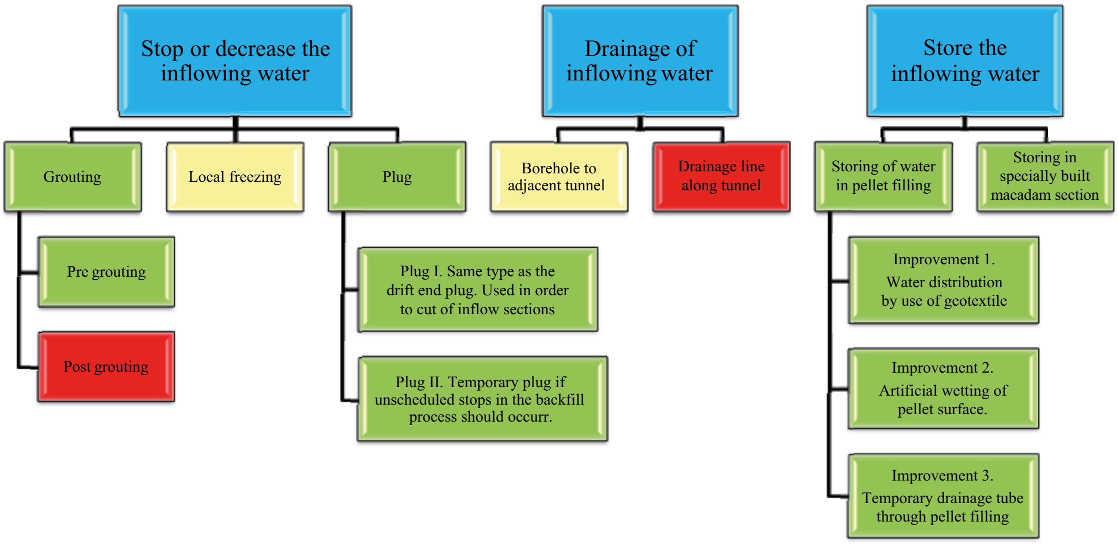


***Figure 3-1.** Block diagram describing the different principles and methods identified in order to handle inflowing water in deposition tunnels.*

3.3 Stop or decrease the inflowing water

3.3.1 Pre-grouting

Pre-grouting of water bearing fractures is a well known method used in order to decrease water inflow to tunnels. The technique is planned to be used also during the future construction of deposition tunnels in the repository at Forsmark. The grouting will probably be made as a selective pre-grouting i.e. the results from analyzes of pilot holes will be used in order to decide if grouting should be used. A successful pre-grouting test was made in the TASS-tunnel (Funehag and Emmelin 2011). It should, however, be mentioned that there always is a risk for non-conformities that may lead to poor result.

3.3.2 Post-grouting

Post-grouting with Silica Sol has been tested at Äspö HRL in the TASS-tunnel and the evaluation of these tests has shown that post-grouting of deposition tunnels probably will be difficult. The results from these tests are, however, not yet reported. Other investigations have been made e.g. by the Swedish Road Administration (2000) where it has been concluded that post-grouting should be avoided depending on difficulties in achieving good results but also because of the fact that it is time consuming and costly.

Post-grouting at large depth (and high water pressure) also has to consider the risk for hydraulic fracturing and damage of the tunnel wall. The distance between tunnel contour and the grouting packer has to be long enough to don't fracture the rock. This increases the difficulty to hit the water-bearing fracture that shall be post-grouted.

3.3.3 Local freezing of water bearing fractures

Freezing is a method that is sometimes used during construction of road and railway tunnels in soil and rock. It is a temporary construction that increases the strength of the soil/rock and prevents water inflow. Special pipes are installed in boreholes and a coolant (salt solution or liquid nitrogen) is circulated until the rock volume around the boreholes is frozen. The use of liquid nitrogen in underground environment is, however, probably not a good idea due to health and safety aspects.

It has not been further investigated in this report if the method is applicable also at rock depths of 400–500 meters. The idea is not to freeze large rock volumes; only local freezing of water bearing fracture zones is of interest. It is assessed that this method has potential to stop water inflows during the installation time and it is recommended that it should be further investigated within another project.

3.3.4 Tunnel plugs

All deposition tunnels are planned to end with a concrete plug. The demands on these plugs will be very high e.g. they should withstand high pressures (water pressure and swelling pressure from the backfill), they should be water tight and they should have a lifetime of several hundred years. It is of course possible to build this kind of plugs also inside the deposition tunnels in order to cut off a water bearing fracture zone but this would be very expensive and time consuming. Since the demands on temporary plugs positioned in deposition drifts would be lower, it would be possible to, instead of using the standard tunnel end plug design, build simplified plugs with a design adapted to the actual conditions. Suggestions for design and design criteria of plugs are further discussed in chapter 6.

3.4 Drainage of inflowing water

3.4.1 Borehole to an adjacent tunnel

A technique assessed to have very high potential in order to handle high water inflows is to drill a borehole from a water bearing fracture zone in a deposition tunnel to an adjacent tunnel. In combination with a macadam filled section, see Section 3.5.2, which collects the water and leads it into the borehole, it would be possible to handle very high water inflows. After finishing the backfill installation in the tunnel and the building of a drift end plug, the borehole must be sealed. A technique for sealing of boreholes has been developed within other SKB projects and should be feasible.

The technique with drainage boreholes has, however, been questioned mainly from a post closure safety point of view because of the fact that the borehole is short-cutting two deposition tunnels. The potential of the technique is, however, great and it is recommended that this method is further investigated.

3.4.2 Drainage line along tunnel

A method that has been investigated by Posiva is to build a drainage line along the deposition tunnel. The drainage line must, however be retrieved after use in order not to function as a high permeable zone after finishing the backfilling of the tunnel. One suggestion investigated was to use thin glass pipes that would break into parts depending on the swelling pressure that will occur after saturation of the bentonite. The technique with drainage lines along the tunnels has, however, been considered to be a risk from a post closure safety point of view, both regarding a remaining permeable zone (if pipes of any material are left) and also in case material, e.g. crushed glass, would be left in the tunnel.

3.4.3 Natural drainage

The step-wise excavation and backfilling of deposition tunnels will in reality cause a transient groundwater situation around the deposition tunnels. Parallel tunnels will share the same groundwater. It is documented from all SKB underground facilities that the inflow decreases by time.

The current logistic plan for step-wise development of the repository is to develop approximately 5 deposition tunnels/year – some years before deposition starts. This leads to a potential for large scale draining over some years before the detailed planning for deposition and backfilling starts.

These aspects of drainage are not very well known and will require further studies (inflow modelling).

3.5 Store the inflowing water

3.5.1 General

There is a large empty space available in the pellet filling around the block stack (approximately 16 m^3/ 6 m tunnel). Outflow of water through the backfilling front is delayed if the water is stored in the pellet filling before it flows downstream.

3.5.2 Store the inflowing water in the pellet filling

In different tests it has been observed that the pellet filling has a large ability to store water (e.g. Dixon et al. 2008a, b). In order to optimize the properties of pellets both regarding the water storing capacity and other functions such as resistance against erosion, a special investigation has been made (Andersson and Sandén 2012). One of the main results was that the shape of the pellets seems to be very important for the ability to store water. Other parameters that influence the pellet fillings possibility to store water are the amount of fines, the granule size distribution and the homogeneity. It was concluded that a pellet filling, consisting of extruded pellets shaped as rods with a diameter of 6 mm and length of 5 to 25 mm, will store water very effectively. This has also been shown in a number of large scale tests, see chapter 5. The behavior is, however, irregular and not always repeatable. An attempt to make a conceptual model of the water storing capacity in the pellet filling during backfilling of a deposition tunnel has been made, see description in chapter 4. Calculations regarding available time before water reaches the backfill front has been made for a number of different inflow scenarios. The ability of bentonite pellets to store water is probably enough in order to avoid problems with inflowing water reaching the backfill front for the main part of the tunnels in a future repository at Forsmark.

Improvement 1: Water distribution by use of geotextile

Tests have shown that despite the pellets ability to store water there will still be large pellet volumes which are dry also after a long time, which means that the method has potential to be improved. If the inflowing water e.g. a point inflow can be distributed over a larger area, the water will get access to more voids between the pellets and the water storing capacity of the pellet filling will increase. The water distribution can e.g. be made by geotextiles, fastened on the rock surface, at strategic places. Different types of geotextiles, their function as water distributor and also methods for fastening on the rock wall have been investigated (Koskinen and Sandén 2014). The number of different types of geotextiles is, however, high and it is assessed that the choice of quality can be further optimized.

Tests in large scale with this method have been performed at Äspö HRL (steel tunnel tests) and also in full scale (TASS-tunnel test), see compilation of results in chapter 5. The results from these tests are promising and have been used in the calculations presented in chapter 4.

Improvement 2: Artificial wetting of pellet surface

A method considered, and also tested during pellet installation in e.g. the steel tunnel tests, is to wet the outermost pellet surface after installation of a backfill section. The pellet installation is made by blowing the pellets into the slots. The main part of the pellets in a section is installed without adding any water but during installation of the final layer, water can be added in the nozzle during the pellet blowing process. This technique results in that the individual pellets stick together and the voids between them partly are filled with water. The wetted pellet wall has certain strength (it is possible to build vertical walls with this technique) and is much tighter than the dry filling which has large voids between the individual pellets. The wetted wall is, however, not saturated and it is difficult to set a figure on the tightness. 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. With this method a larger part of the pellet filling will be used for water storing. Results from the tests performed at Äspö HRL show that the wetted "wall" seems to work according to these ideas, see e.g Koskinen and Sandén (2014) and Johnsson and Sandén (2013).

Improvement 3: Temporary drainage tube through pellet filling

A third improvement of the method to store water in the pellet filling could be to have a temporary tube through the pellet filling, serving as drainage line during the installation of one or two 6-meter sections. This method implies that the inflowing water enters the tunnel in a defined small area so that it can be collected and led into a tube. A possible solution for collecting the water could be to glue a thin plastic or rubber sheet onto the rock surface. The sheet should be prepared in advance for connection of a tube. The equipment does not need to withstand high water pressures. After having fulfilled its function, it must be possible to pull loose the pipe from the rock surface and out from the pellet filling. This technique will need some development and testing. Probably some small parts of the equipment must be left in the tunnel.

3.5.3 Storing in a specially built macadam filled section

Design

An alternative water storing method could be to dedicate a section of the deposition tunnel for this purpose, see Figure 3-2. The principle is that a part of the tunnel is filled with macadam and the inflowing water is stored in the voids in the macadam filling. A suggestion for design can be according to the following:

- Concrete beams are anchored in the rock. Preparatory work can be done before starting the backfilling process.
- The wall against the inner, already backfilled parts, does not have to be completely sealed.
- The downstream wall must, however, be rather tight in order to prevent water from leaking out here instead of filling up the macadam. The maximum water pressure during filling of the section will be 5 meter water column (height of the tunnel). The slots between beams and between beams and rock can probably be sealed with a shotcrete layer. A small slot should be left at the top in order to prevent air from getting trapped in the macadam during the water filling.
- When the macadam section is full, water will leak over to the pellet filling in the next section.
- During the construction of the section and until the backfilling process can be restarted, the macadam filled section has to be drained. This is done through a pipe, casted into the lowest downstream concrete beam. The pipe is equipped with a valve which is closed just before starting up the backfilling again.

Capacity

- A six meter long section of a deposition tunnel has a volume of about 138 m^3. A porosity of the macadam of 40% will result in access to 55 m^3 space for water storing.
- With an inflow of 1 l/min (1.44 m^3/24h) there will be an extra time of 38 days before the macadam section is filled with water.
- The length of a water storing section can be chosen depending on the actual water inflow rate.

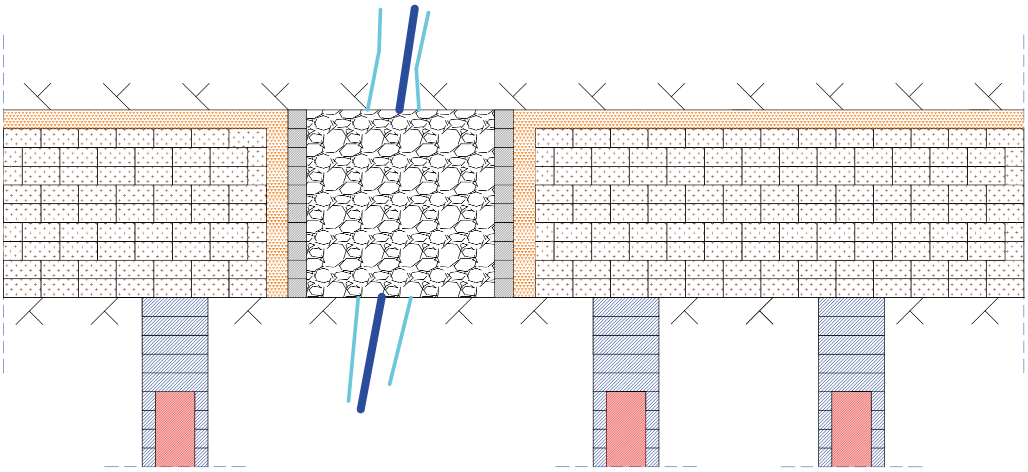


Figure 3-2. *Schematic drawing of a water storing section.*

Comments

- The decision whether a water storing section should be built is preferably taken before the drilling of the deposition holes starts.
- The concrete beams will disintegrate by time and the bentonite will swell into the voids of the macadam filling which will result in a local decrease of the density of the backfill closest to the macadam filled section. The effect of this must be investigated.
- There will probably be some settling of the macadam, leaving an open volume at the top. This issue must also be further investigated.
- Except for the concrete beams and a small amount of steel, no materials will be left in the tunnel.

4 Water storing capacity of backfill pellet filling during installation

4.1 General

The main alternative for the backfill design considered by SKB includes emplacement of pre-compacted blocks into most of the tunnel volume together with bentonite pellets filling up the spaces between blocks and tunnel walls, see Figure 4-1. 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.

In order to increase the understanding regarding how inflowing water moves and/or is absorbed in a pellet filling, whether it can be stored in the available macro voids between the pellets or if it flows through the filling out to the front tests have earlier been made in both laboratory scale, in larger 1/12 scale tests and in half scale tests. One of the most important questions have been to determine the time between the start of the backfill installation until inflowing water is expected to reach the front and how this time is influenced by the water flow rate and the distribution of inflow points. With these tests as a base, a simple conceptual model has been suggested describing how water is stored in a pellet filling depending on inflow rate and position of inflow points. By using the model on a number of different inflow scenarios it has been possible to estimate the available time before the water reaches the backfill front.

Subproject 2 within the System design project has also been carried through with the intention to optimize the design of pellet fillings regarding water storing capacity and to set limits for which inflow rates that can be handled by the bentonite pellets ability to store water (Andersson and Sandén 2012). This project has increased the understanding and also showed that pellets manufactured by extrusion (d = 6 mm) has a larger ability to store water than e.g. compacted pillows or almond shaped pellets for the same type of materials. The differences in behavior between different pellet types depend on differences in the pore system geometry but also on the actual bentonite material.

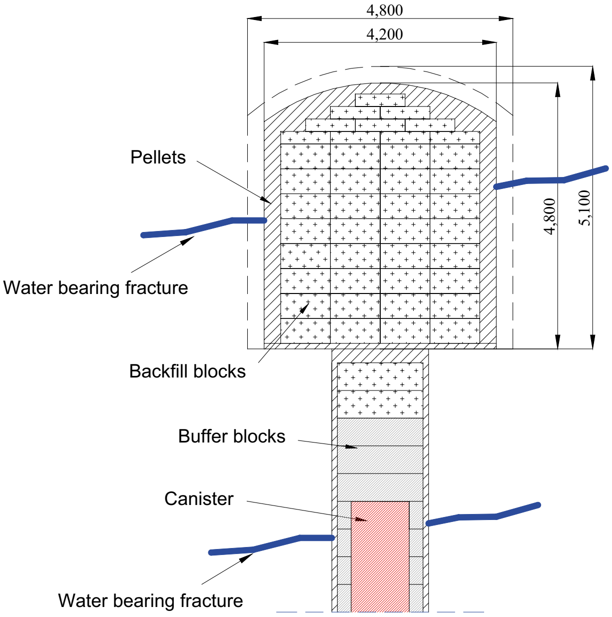


Figure 4-1. *Schematic showing a cross section of a deposition hole and a deposition tunnel.*

4.2 Conceptual model for water storing capacity

4.2.1 General

The conceptual model used for estimating the available time before inflowing water reaches the backfill front is based on tests performed in both laboratory scale and in large scale. A compilation of the results from these tests is provided in Sections 4.2.2 and 4.2.3.

4.2.2 Compilation of results from laboratory tests

Laboratory scale tests have been made in order to simulate the influence of water inflow on the backfill behavior (Sandén et al. 2008). The following processes were studied:

1. Erosion of backfill blocks. Blocks were placed in a steel groove and a constant flow was applied from one end and the amount of eroded material was measured in the other end.
2. Erosion of bentonite pellets. These tests were performed using Plexiglas tubes with an inner diameter of 0.1 meter. A constant water flow was applied from one end and the amount of eroded material was measured in the other end.
3. The water storing capacity and forming of piping channels in bentonite pellets have been investigated with so called large slot tests, see Figure 4-2. The artificial slot simulates the pellet filled space between rock and backfill blocks. The slot has the dimensions 2×1×0.1 m. A single inflow point is positioned 0.5 m from the bottom and 0.3 m from the inner end of the slot; see the photo on the right in Figure 4-2.

In the tests performed with a large slot two kinds of pellets have been used:

- **MX-80 pellets**. Specially made pellets consisting of MX-80 Wyoming bentonite with a smectite content of about 75–80%. The pellets are "pillow" shaped with the dimensions 18×18×8 mm. The pellets are manufactured with the roller compaction method. The dry density of the filling was 932 kg/m^3 and the dry density of the individual pellet 1,780 kg/m^3.
- **Cebogel QSE pellets**. A commercial bentonite pellet with a montmorillonite content of about 80%. Extruded cylindrical rods with a diameter of 6.5 mm and a length of 5–20 mm. The origin of the material is Milos, Greece. The pellets were delivered by Cebo Holland BV. The pellets are manufactured by extrusion i.e. the material is pushed through a matrix. The dry density of the filling was 943 kg/m^3 and the dry density of the individual pellet 1,720 kg/m^3.

Tests were performed with three different water flow rates: 0.01, 0.1 and 1 l/min for each material. The tests showed that the water storing behavior of the pellet filling was strongly influenced by the water flow rate but also by the type of pellet. The photos in Figure 4-2 show e.g. that with an inflow rate of 0.1 l/min the Cebogel pellet filling was almost completely wetted while with the MX-80 filling only the lower part was wetted. The difference in behavior is also shown in the diagram below the photos, where the accumulated water volume before outflow as a function of time is plotted.

The results from the large slot tests can be summarized as follows:

- The three tests with MX-80 pellets resulted in a partial wetting of the filling and then the water flowed in a single channel not affecting the parts that were still dry.
- The behavior of the Cebogel pellets was different. Almost all material was wet before breakthrough (0.01 and 0.1 l/min) and for the highest flow rate (1 l/min) the wetting proceeded after breakthrough resulting in an almost completely wet pellet filling after three hours of testing.
- There are a lot of possible reasons for the difference in behavior between the two pellet types e.g. the shape of the pellets that results in different storage density and influences the size of the macro voids (different resulting pore system geometry) but also the manufacturing techniques that results in different surfaces of the individual pellet which may affect the tendency to swell and seal the surrounding voids. These are properties that will influence the flow resistance and how water is flowing or absorbed by the pellets.

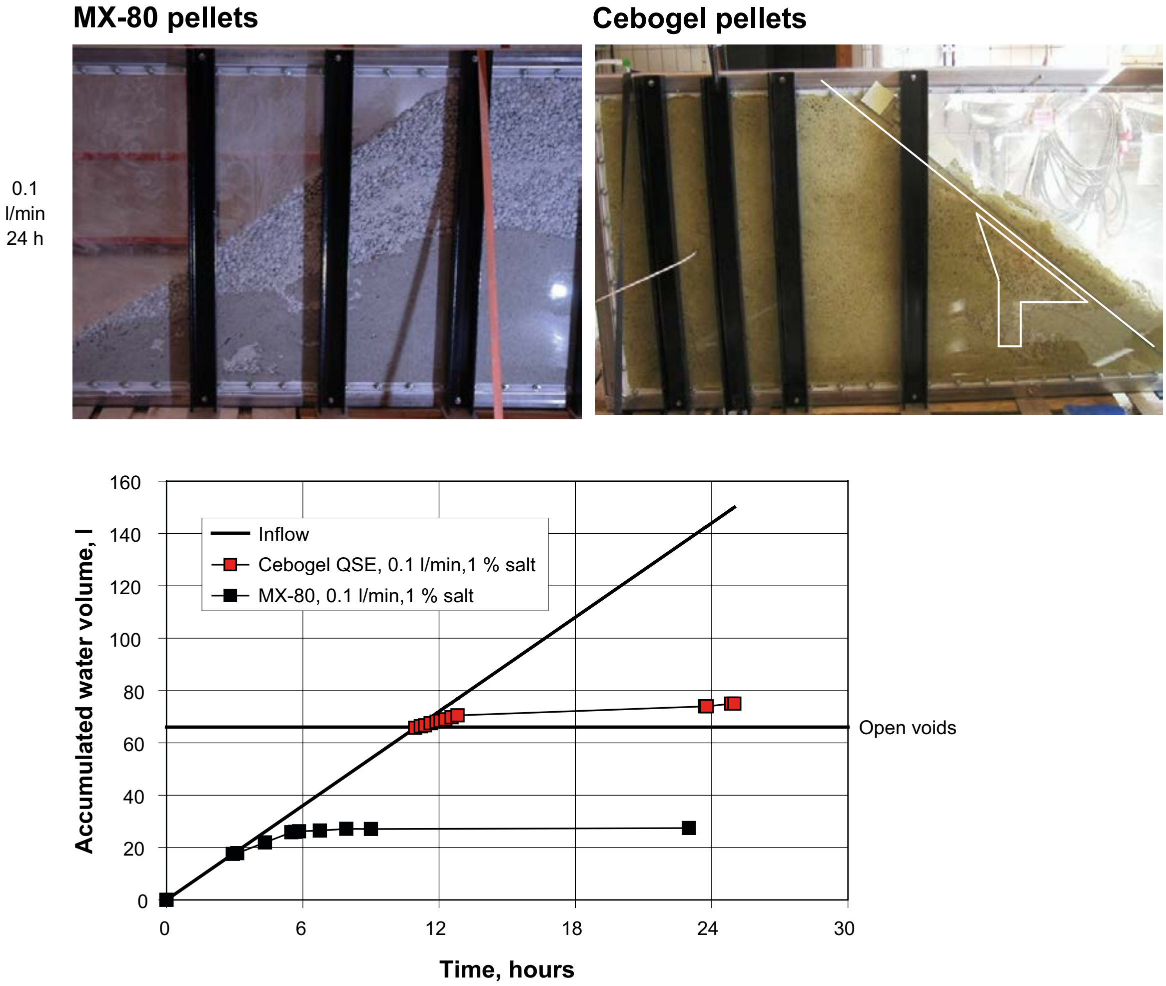


Figure 4-2. ***Upper:*** *Pictures from the two tests performed with a water inflow rate of 0.1 l/min taken after 24 hours.* ***Lower****: Diagram showing the total inflow and the difference between inflow and outflow for the two tests plotted vs. time. The volume of the open voids is calculated from the available pellet volume (approximately 45–48% macro voids in a pellet filling). (Sandén et al. 2008).*

4.2.3 Compilation of results from 1/12 scale tests and half scale tests

In the 1/12 scale tests (Dixon et al. 2008a), a concrete pipe with the diameter 2 m and the length 1.2 m, were used in order to simulate the deposition tunnel, see Figure 4-3. Blocks made of Friedland clay were piled inside the tube and bentonite pellets (Cebogel or Minelco granules) were used to fill up the empty spaces. In total twenty-nine tests were performed in this equipment. The test duration varied between 5 and 120 hours and the water inflow rates between 0.01 and 1 l/min.

The half scale tests (Dixon et al. 2008b) were performed in a steel tunnel constructed at Äspö HRL, see Figure 4-4. The tunnel had a width of 2.75 m, a height of 2.75 m and a length of 6 m. In total 12 tests were performed in this equipment. The equipment was designed to apply water flow at different points and with different flow rates. The test duration varied between 3 and 7 days and the water inflow rates between 0.1 and 5 l/min.

Figure 4-5 shows an example of results from the two different test setups. In the diagram the time to outflow is estimated for different water inflow rates and flow path lengths. The time to first outflow is dependent on both the distance from the inflow point and also the inflow rate.

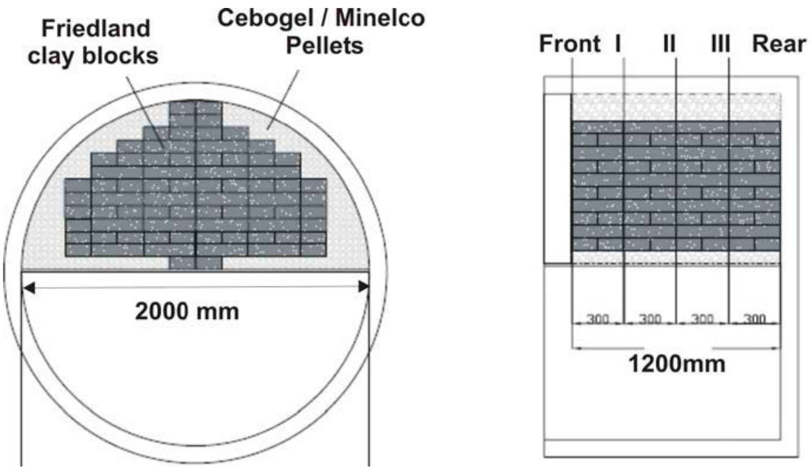


***Figure 4-3.** Schematic showing the 1/12 scale tests (Dixon et al. 2008a).*

***Figure 4-4.** Steel tunnel equipment used in the half scale tests. (Dixon et al. 2008b)*

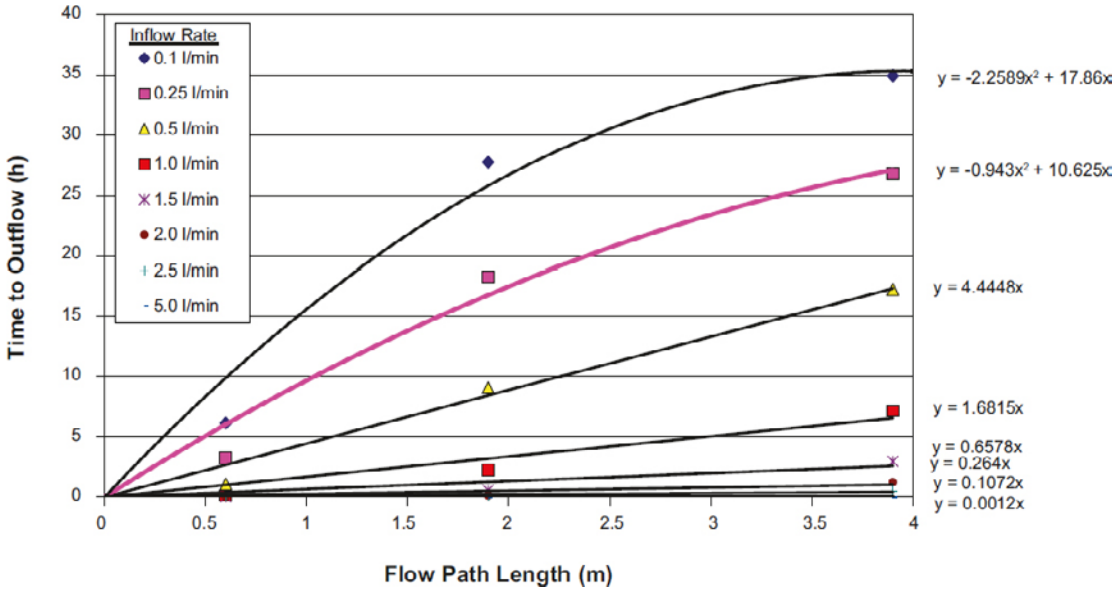


***Figure 4-5.** Length of flow path and estimated time required for water outflow at inflow rates of 0.1 to 5.0 l/min (Dixon et al. 2008b)*

Some important results from the half scale tests are as follows:

- Water entering the tunnel via fractures in the rock wall will move along the tunnel wall surface rather than moving towards the central areas of the backfilled tunnel.
- If the accumulated flow rate is kept below about 0.5 l/min at a single inflow point, the backfill can withstand a few days of interruption in the backfilling process before the water reaches the backfill front provided the distance between the inflow point and the backfill front face is at least 2–3 meters.
- For an accumulated inflow less than 0.1 l/min the system showed a markedly, longer time passed until outflow occurred and a tendency towards a higher degree of initial water uptake by the pellet material before flow along the tunnel wall developed. This means that in regions where the localized inflow is limited to < 0.1 l/min there is a considerable time (several days) before the backfill is likely to begin seeping water.

4.2.4 Suggestion for a conceptual model

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 above. These tests were mainly performed using either MX-80 pellets (laboratory tests) which are manufactured with the roller compaction method or Cebogel pellets (laboratory and scale tests) which are manufactured by extrusion. There was a very clear difference in behavior for these two materials regarding water storing capacity. The tests performed later in order to optimize the pellet properties have shown that extruded pellets with a diameter of 6 mm, made of Asha or IBECO material have a similar type of behavior as the Cebogel pellets which were used in the earlier tests (Andersson and Sandén 2012).

Assumptions

From the results of the tests described above and from laboratory tests made in the EVA project (Börgesson et al. 2014), a general view of how water is transported in a pellet filling can be applied, although the behavior is somewhat irregular and not always repeatable.

1. The pellet fill cannot stop and seal the water inflow into the tunnel.
2. Water will flow in the macro voids between the pellets. The relation between the amount of water that is flowing through the pellet fill and the amount stored in the pellet fill depends e.g. 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 and if there are fines present.
3. The influence of the inflowing water on backfill blocks is small in the short term period required for the normal backfill installation.
4. 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.
5. 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 unwetted parts (This was not true though in the large slot test with Cebogel pellets with an applied flow of 1 l/min. In this test the dry parts continued to take up water at the same time as water was flowing out from the system). This is, however, a conservative assumption.

Conceptual model of inflow behavior for six mm extruded pellets made of Cebogel, Asha NW BFL-L 2010 and IBECO-BF 2011

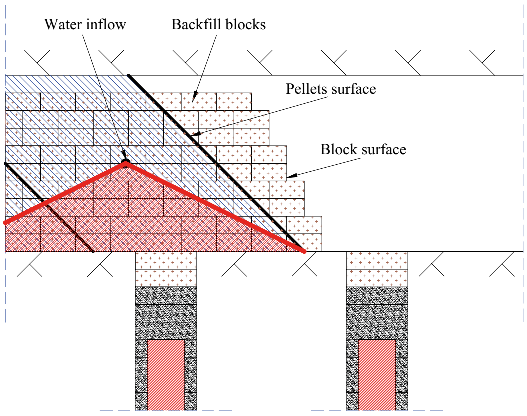
From the results of the different tests with MX-80 and Cebogel pellets the following assumptions/limits were made:

1. At inflow rates (per inflow point) > 0.05 l/min for MX-80 and > 0.3 l/min for Cebogel, the water will flow downwards from the inflow point i.e. the gravimetric force is dominating.
2. At inflow rates (per inflow point) < 0.05 l/min for MX-80 the water will flow upwards from the inflow point and at flow rates < 0.3 l/min for Cebogel, the water will flow almost symmetrical in all directions from the inflow point. This behavior depends on the fact that the bentonite has enough time to swell and seal the pathways, resulting in higher flow resistance which makes the water flow in different directions.

Using the assumptions above, three different scenarios for the wetting of the pellet filling have been made; see Figure 4-6 to 4-8. The figures show the wetting behavior for different inflow rates considering a point inflow situated on the wall in the middle of a six meter long backfill section. The different wetting behaviors result in different available volume (macro voids between the individual pellets) for water storing. 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. 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.

Figure 4-9 shows the results from using the conceptual model to calculatethe time to first outflow for some of the test setups (inflow location 1.5 meter from floor at 1.9 meter from the front face) in the steel tunnel tests. In the figure the time are plotted versus different inflow rates. In addition some test results (Test 3 to 8) are shown. The calculations are in good agreement with the test results for the higher flow rates while there is some deviation for the lower flow rates. The reason for the bad agreement for the lower flow rates is probably the behavior at low flow rates where the wetting front in some cases can progress upwards, see Figure 4-7. There is, as mentioned earlier, also an irregular behavior and the tests are not always repeatable.

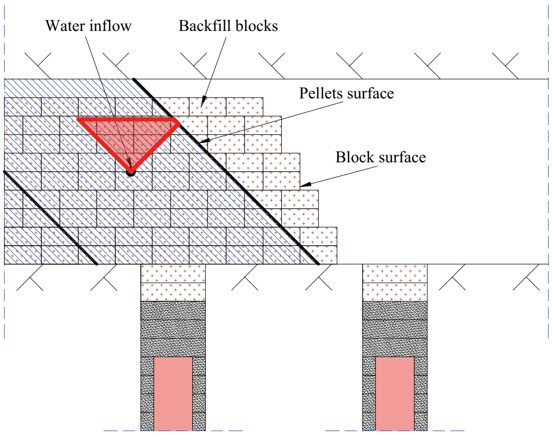
In Figure 4-10 the calculated time to water outflow (based on the conceptual model) for the full scale has been calculated for different inflow rates from a point inflow situated on the wall in the middle of a six meter long backfill section, see Figure 4-6 to 4-8). From the diagram it can be seen that also for a rather high point inflow into one six meter section e.g. 0.5 l/min, the available time until water starts to leak out is about 48 hours. The diagram is of course only valid for this special inflow layout, with one point inflow, and does not take into account the accumulated flow from the earlier installed backfill.



MX-80 pellets: At inflow rates, per inflow point, > 0.05 l/min.
Cebogel pellets: At inflow rates, per inflow point, > 0.3 l/min.

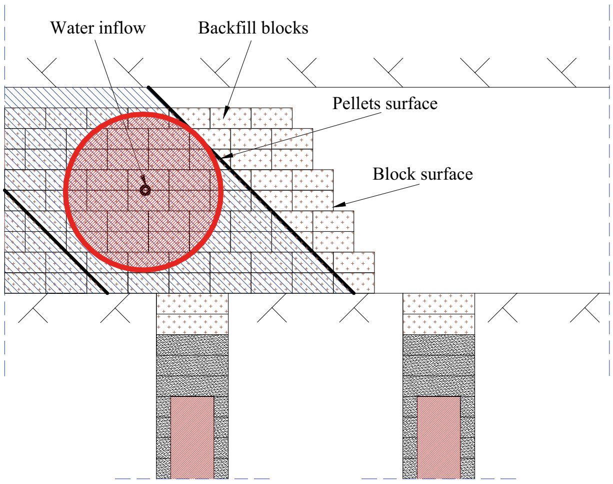
Macro voids available: 1.4 m³
0.05 l/min --> 20 days filling time
0.3 l/min --> 3.3 days filling time

Figure 4-6. *Schematic drawing showing how the pellet filling is wetted at inflow rates > 0.3 l/min.*



MX-80 pellets: At inflow rates, per inflow point, < 0.05 l/min.
Macro voids available: 0.25 m³
0.05 l/min --> 3.5 days filling time

Figure 4-7. *Schematic showing how the pellet filling is wetted at inflow rates < 0.05 l/min (MX-80).*



Cebogel pellets: At inflow rates, per inflow point, < 0.3 l/min.
Macro voids available: 1.8 m³
0.3 l/min --> 4.1 days filling time

Figure 4-8. *Schematic showing how the pellet filling is wetted at inflow rates < 0.3 l/min (Cebogel).*

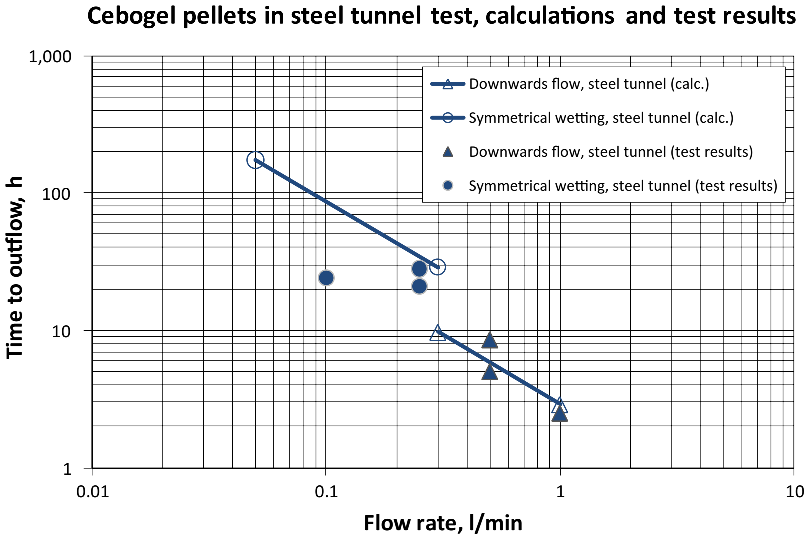


Figure 4-9. *Diagram showing the estimated time to outflow in the steel tunnel tests plotted vs. the flow rate based on the suggested conceptual model for the behavior of Cebogel pellet. In addition some test results are shown (Test 3 to 8).*

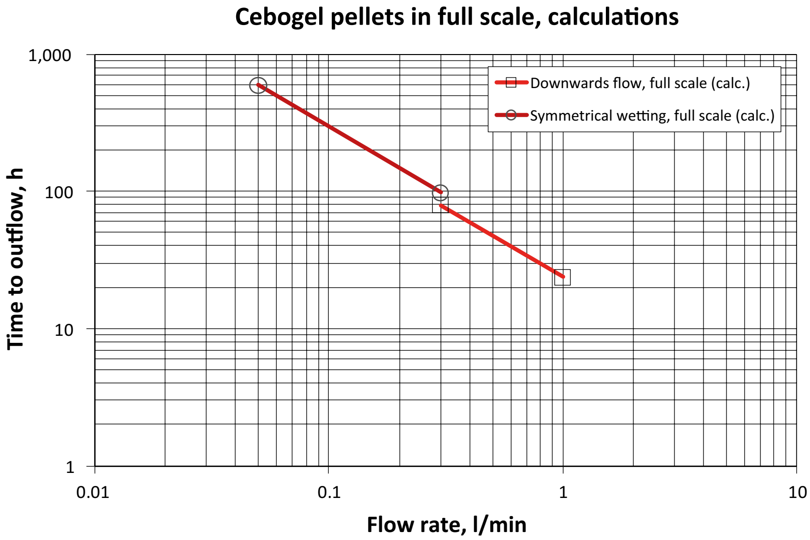


Figure 4-10. *Diagram showing the estimated time to outflow after installation of a six meter section in full scale plotted vs. the flow rate. The calculations are based on the suggested conceptual model for the behavior of 6 mm extruded pellets. In the calculations it is assumed that the inflow is coming from one point according to Figure 4-6 to 4-8.*

4.3 Calculations regarding water storing capacity during backfilling

4.3.1 General

Two important factors that will influence the water storing capacity have been identified:

1. Total water inflow into the deposition tunnel (liters/minute).
2. How the water inflow is distributed in the tunnel i.e. number of inflow points and where they are positioned.

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. As soon as a section is backfilled and the space between backfill blocks and rock is filled with pellets, this inclination will, however, have a very small impact on how water moves in the pellet filling. As shown in the results from the laboratory tests, see Section 4.2, the direction of the water movement in a pellet filling is strongly dependent of the flow rate and at low flow rates the water can even move upwards in the pellet filling.

According to the reference method (SKB), six meters of backfill (blocks and pellets) should be installed every 24 hours. In order to facilitate the installation of backfill and by that guarantee the quality of the installed backfill, it is essential that as little water as possible flows out from the earlier installed backfill section. In order to meet this requirement, the backfilling operation must include that all water from the previously installed six meter long backfill section must be stored in the macro voids of the pellets for at least 24 hours before flowing on to the next section. If the water inflow is higher than what can be stored in the pellet filling it will be necessary to introduce other solutions.

4.3.2 Water storage

A 300 meter long tunnel with an average cross section area of 22.7 m^2 which is filled with backfill blocks to 75% (this figure will vary along a deposition tunnel between 65 and 85% depending on deviations from the nominal tunnel profile) will have a pellets volume of:

$V_{pellets} = 300 \cdot 0.25 \cdot 22.7 = 1{,}702\ \text{m}^3$

47.5% open space i.e. macro voids (determined in laboratory by measuring the bulk density of a pellet filling and the bulk density of individual pellets) yields the total volume available that can be filled with water:

$V_{macrovoids} = 809\ \text{m}^3$

The available volume of macro voids for every six meter backfill section is:

$V_{macrovoids\ per\ section} = 809 \div 50 = 16\ \text{m}^3$

In the scenarios described below, only parts of the available macro voids are used for storage. In the examples it has been assumed that the storage can be increased by distributing the inflowing water over a larger area by use of geotextiles and by that also increase the time to outflow at the backfill front.

4.3.3 Scenarios

Assuming a maximum total inflow rate of 5 liters per minute to a deposition tunnel which is the present limit set, and a maximum inflow of 0.5 l/min to one six meter long section the following examples of scenarios have been considered for the calculations:

1. **The inflow is evenly distributed in the tunnel, 1**. It is assumed that 0.1 l/min is flowing into each six meter section.
2. **The inflow is evenly distributed in the tunnel, 2**. It is assumed that 0.5 l/min is flowing into every fifth six meter section.
3. **The inflow is distributed in three main fracture zones.** This is a reference case received from Posiva adapted to the length of a SKB deposition tunnel.
4. **The inflow is distributed in four main fracture zones with rather high inflow (Forsmark type).** The water inflow in a future repository at Forsmark is believed to mainly come in few zones with rather high inflow rates.

4.3.4 Prerequisites for the calculations

The calculations have been made with the following assumptions:

1. Point inflow located in the middle of the section (length and height) at one side of the tunnel.
2. The inflowing water is stored in the pellet filling according to the conceptual model, see earlier description.
3. When one section is filled according to the conceptual model, all flow is added to the next section.
4. All water flows towards the front after filling of a section.

Four different inflow rates have yielded the time for filling up a section according to Table 4-1.

The assumptions made are considered to be conservative. In order to improve the situation it will probably be necessary to distribute an inflow over a larger area. This means that a larger pellet volume will be involved in the storing. The distribution can be made by mounting stripes of geotextile on the rock surface at special inflow zones, see tests reported in chapter 4. The technique implies, however, that some material has to be left in the tunnel. In the calculations presented it has been assumed that water can be distributed and thereby the time multiplied with two or four.

The calculations have been made as graphical solutions using Excel spread sheets.

Table 4-1 Table showing the time for filling up one section that have been used in the calculations for different inflow rates.

Water inflow to one section (l/min)	Time for filling up one section (days)
0.1	12
0.25	4
0.5	2
1	1

4.3.5 Results

Scenario 1. The inflow is evenly distributed in the tunnel, type 1

In this scenario it is assumed that 0.1 l/min flows into each six meter section, see schematic drawing in Figure 4-11.

The results from the calculations are shown in Figure 4-12. The black line shows the backfill installation rate which is set to one 6 meter long section every 24 hour. The blue dots show the filling rate of each installed section when assuming that 0.1 l/min is flowing into each section.

The calculations can be described according to the following:

1. After installation of the first section, it will take 12 days to fill it up (according to the model, but there is theoretically much more space that can be filled with water).
2. After 12 days, water will start flowing over to the next section. This section was installed 11 days ago and is filled to 11/12. The last part of section #2 will be filled with double rate i.e. water from section #1 is added. This means that section #2 will be filled 12.5 days after starting the backfilling of the tunnel.
3. After 12.5 days water will start to flow into section #3 which has been installed 10.5 days ago. The last part of section #3 will be filled with a rate three times higher than in the beginning. Section 3 will be filled 13 days after starting the backfilling of the tunnel.

According to this calculation the inflowing water will hit the backfill front twenty-two days after starting the backfill installation. If instead the inflowing water from each section could be distributed to both sides of the tunnel the time to the first outflow at the front will increase to forty-four days, see red dots in Figure 4-12. This is very close to the total time needed for installation of backfill in a 300 m long deposition tunnel.

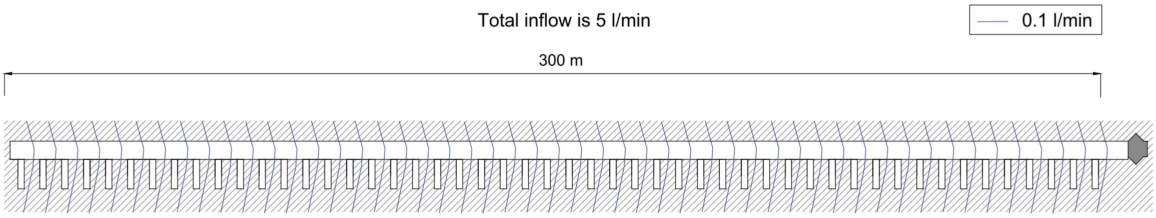


__Figure 4-11.__ Schematic drawing showing the water inflow distribution in scenario 1.

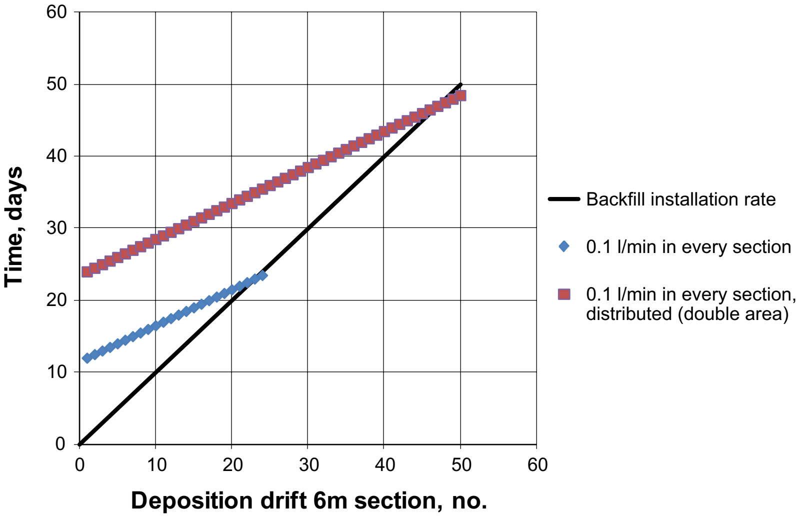


__Figure 4-12.__ The time until a section is filled plotted versus the number of installed sections.

Scenario 2. The inflow is evenly distributed in the tunnel, type 2

In this scenario it is assumed that 0.5 l/min is flowing into every fifth six meter section, see schematic drawing in Figure 4-13.

The results from the calculations are shown in Figure 4-14. The black line shows the backfill installation rate which is set to one 6 meter section every 24 hour. The blue line shows the filling rate of each installed section when assuming that 0.5 l/min is flowing into every fifth section, the green if the inflow is distributed to a two times larger area by geotextile and the purple if the inflow is distributed to a four times larger area by geotextile.

The calculations can be described according to the following:

1. After installation of the first section, it will take 2 days to fill it up with water (according to the model, but there is theoretically much more space that can be filled with water).
2. After 2 days, water will start flowing over to the next section. This section was installed 1 day ago and there is no inflow. Section 2 will be filled in two days and the same goes for section #3, #4 and #5.
3. The filling of section #6 was started day six. This section was filled after 8 days and the water was then flowing to section #7 and #8.
4. Ten days after starting the installation, the inflow from #1 catches up the inflow from section 6, and the filling of section #9 and #10 is made in double rate i.e. one day per section.
5. When the next section with water inflow, #11, is installed the filling of the next sections is made in about 16 hours per section and about fifteen days after installation the inflowing water will hit the backfill front.

If instead the inflowing water from each water bearing section is distributed by use of geotextile to an area twice or four times larger, the water will hit the backfill front 31 or 36 days after installation, respectively, see green and purple line in Figure 4-14.

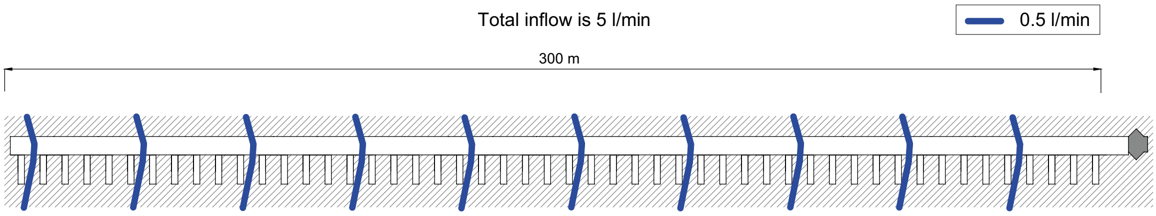


Figure 4-13. *Schematic drawing showing the water inflow distribution in scenario 1.*

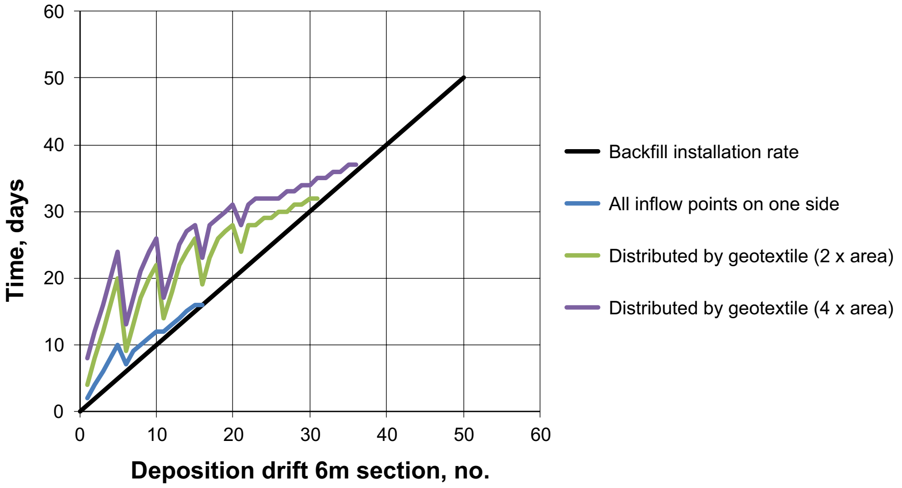


Figure 4-14. *The time until a section is filled plotted versus the number of installed sections.*

Scenario 3. The inflow is distributed in three main fracture zones

This is a reference case received from Posiva which has been adapted to the length of a SKB deposition tunnel; see schematic drawing in Figure 4-15.

The results from the calculations are shown in Figure 4-16. The black line shows the backfill installation rate which is set to one 6 meter section every 24 hour. The green, blue and purple lines show how water inflows from the different fracture zones fills up different sections with water plotted versus the installation rate.

The calculations can be described according to the following:

1. Three "dry" sections will be installed in the beginning.
2. In fracture zone 1, 0.1 l/min is flowing in. It will take 10 days to fill up this section with water and then another ten days for the next section. Water from this fracture zone will never reach the backfill front before the installation of the tunnel is finished and the work with building a plug is ongoing.
3. Water inflow from section #12, #13 and #14 (0.1, 0.25 and 0.1 l/min respectively) i.e. fracture zone 2 will fill up a section in two days which means that the installation rate is faster.
4. Water from fracture zone 2 will after 41 days catch up with water from fracture zone 3 (section #26 and #30). This water will, however, not reach the backfilling front during the installation time.
5. Day 36, the backfill installation has reached fracture zone 4 i.e. section #36, #37 and #38, with a total inflow of 0.45 l/min. This inflow will fill up one section in two days and will therefore not reach the backfilling front during the installation time.

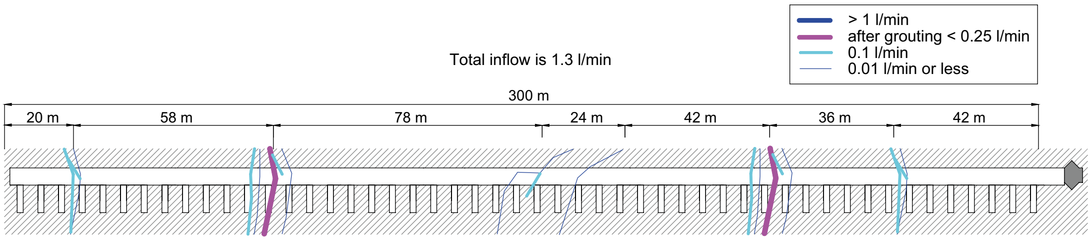


Figure 4-15. *Schematic drawing showing the water inflow distribution in scenario 1.*

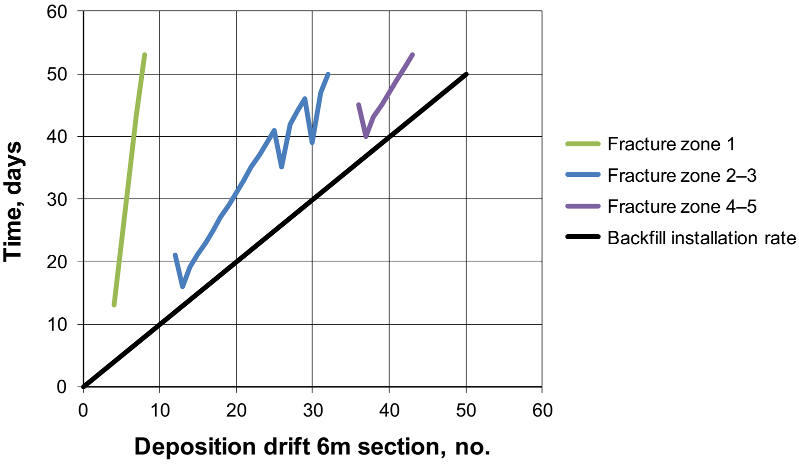


Figure 4-16. *The time until a section is filled plotted versus the number of installed sections.*

Scenario 4. The inflow is distributed in four main fracture zones with rather high inflow (Forsmark type)

The water inflow in a future repository at Forsmark is believed to mainly come in few zones with rather high inflow rates, see schematic drawing in Figure 4-17

The results from the calculations are shown in Figure 4-18. The black line shows the backfill installation rate which is set to one 6 meter section every 24 hour. The presented calculations assume either that all water is flowing into the tunnel in one point on the tunnel wall or that the inflowing water can be distributed to a larger area, either two times larger or four times larger.

The calculations can be described according to the following (blue line, two time's larger area):

1. After installation of the first section (#1 with an inflow of 0.5 l/min), it will take 4 days to fill it up. The following sections are dry and it will take four days to fill up each of them. Water from this fracture zone will not catch up with the installation rate and will not interfere with the other fracture zones.
2. After 9 days the installation has reached section #9 which has an inflow of 0.5 l/min and so has the following section #10. Water from these two sections will need two days in order to fill up one section. Since the following ten sections are dry the installation will be faster than the filling up.
3. After32 days, water from fracture zone 2 will interfere with water from fracture zone 3 in section #23. The filling of each new section is calculated to take one day. Since there at this time are nine dry sections between the water front and the installation front and the rate is the same, the water will not catch up with the front.
4. In section #41 a new water inflow of 0.5 l/min is added. At this time is the water front from the inner sections in section # 32. There will be no interference between the inner water front and the new water from section #41 during the installation time.

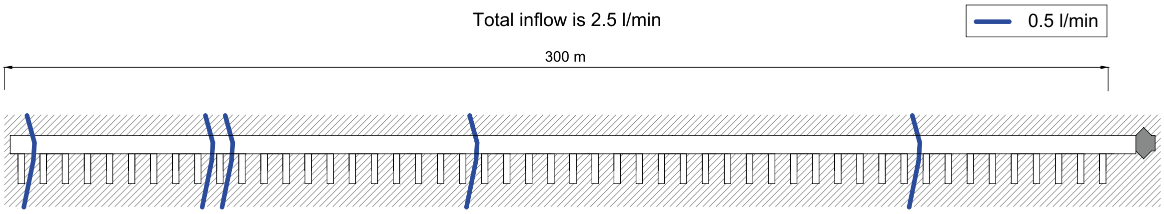


***Figure 4-17.** Schematic drawing showing the water inflow distribution in scenario 4.*

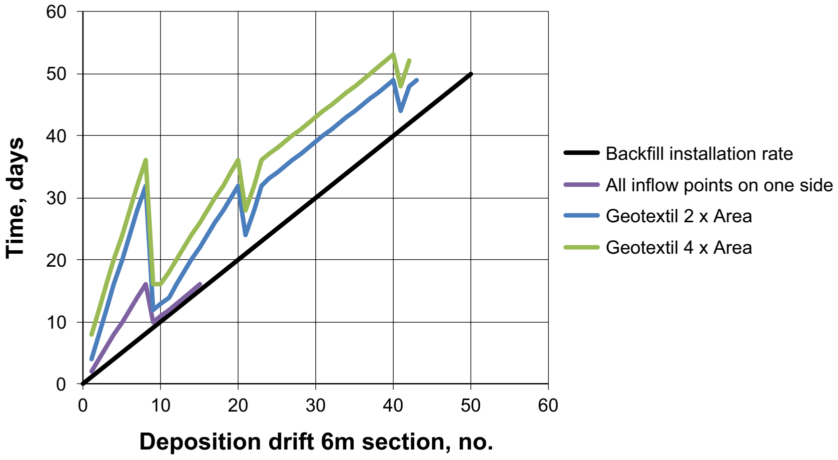


***Figure 4-18.** The time until a section is filled plotted versus the number of installed sections.*

4.3.6 Comments and conclusions

The conceptual model predicting water storing capacity in a pellet filling has been used in order to estimate the available time after installation before inflowing water reaches the installation front. The assumptions made regarding wetting behavior were considered conservative and the later performed large scale tests have confirmed this.

The results from the calculations can be summarized as follows (assuming a backfill installation rate of 6 meter every 24 hour i.e. backfilling a 300 meter long deposition tunnel will take 50 days):

- Scenario 3 and 4 simulate deposition tunnels with a total inflow of between 1.3 and 2.5 l/min. These scenarios represent at least 60% of the deposition tunnels in a future disposal, see chapter 2 and 7. **Results**: At these inflow rates all water is expected to be stored in the pellet filling and the water will not catch up with the installation front during the installation if geotextile is used to distribute the water of the inflow points. The only reservation is that no point inflow higher than 1 l/min is allowed.
- Scenario 1 and 2. Total inflow to 300 m tunnel: 5 l/min. The inflow is evenly distributed either as 0.1 l/min flowing into every 6 meter section or 0.5 l/min flowing into every fifth 6 meter section. **Results**: These inflow rates are according to the calculations a little too high in order to be handled with only water storing in the pellet filling even if completed with geotextiles distributing the water inflow. The water will catch up with the backfill front after 45 and 36 days respectively. The assumptions for the calculations are, however, very conservative and it is possible that it would work in the real case.

The presented estimations of how water is stored in the pellet filling for different water inflow scenarios are based on a general view of how water is transported and stored in a pellet filling. It must, however, be mentioned that the behavior is somewhat irregular and not always repeatable. The estimations made in this chapter should be seen as indications of the water storing behavior and not as exact values.

As mentioned, the scatter in the behavior of a pellet filling regarding water storing capacity is probably large. There are also a number of parameters that influence a pellet fillings possibility to store water e.g. the amount of fines and the homogeneity of the filling. In order to decrease the scatter it will be necessary to:

- Increase the knowledge by performing additional tests.
- Introduce a quality control of both material and of the installation technique.
- Use the suggested improvements i.e. using geotextile for water distribution and wetted pellet layers to hinder the water from entering the front.

In the presented inflow cases, an installation time of 50 days has been used. To this time should also be added time for building of the first parts of the tunnel end plug, Figure 6-1. After installation of filter section, bentonite sealing and concrete beams, it will be possible to drainage the backfill without any risk of losing backfill material by erosion. The installation time for these sections is estimated to 2–4 days provided that the preparatory rock work is made before the backfill installation start.

5 Large scale pellets tests

5.1 General

Tests have been made earlier in laboratory scale and in mock up tests at Äspö HRL in order to test the behavior of bentonite pellets when exposed to water inflows (Dixon et al. 2008a, b).

A number of new tests have been performed within this SKB project. These tests have had different goals but common to all is that bentonite pellets have been used together with water inflow. The results from these tests have been used in order to increase the understanding regarding the water storing capacity of a pellet filling.

The pellets used in all three tests have been manufactured by extrusion. The pellet diameter is 6 mm and the length between 5 and 25 mm. The bentonite used for manufacturing has been Asha NW BFL-L 2010 or Ibeco RWC BF 2011 (trade name and year of delivery).

This chapter gives a brief overview of the three different test types. The complete test results can be found in Johnsson and Sandén (2013), Johnsson (2011) and Koskinen and Sandén (2014).

5.2 Steel tunnel tests

5.2.1 Test layout

These tests are described in detail in Koskinen and Sandén (2014). A schematic drawing of the test equipment is provided in Figure 5.1. The nominal cross section of the tunnel is 7.1 m^2, and the length used in the tests is 4 m. The tunnel walls are not able to withstand the swelling pressure of the fully backfilled tunnel, therefore instead of backfill in the centre of the tunnel there is wooden framework than can deform and fail mechanically if the pressures become too high. The wooden frame was covered with a bentonite geotextile mat to control the movement of any water that managed to penetrate both the pellet and block materials. The blocks, 300×150×75 mm, were mounted two layers deep (300 mm thickness) against the inner frame. The gap between the blocks and the walls (about 150 mm) was filled with pellets.

5.2.2 Test matrix

Three tests were performed during the end of 2012, see Table 5-1. The main objective of the tests was to investigate the effect of geotextiles as a distributor of water from a point inflow on the rock and if it with this method was possible to increase the water storing capacity of the pellet filling. The total space available in the macro voids in the pellet filling was calculated to approximately 2,500 liters. The last column in Table 5-1 shows the amount of water stored in the pellet filling in percent of the total available volume.

Table 5-1. Results from the ½-scale steel tunnel tests. (Koskinen and Sandén 2014).

Test, no.	Geotextile	Inflow rate (l/min)	Time to first outflow (h)	Water stored before outflow (liters)	Water stored before outflow (%)
1. Reference test	No	0.25	30.4	460	18.4
2.	Yes	0.25	39.5	588	23.5
3.	Yes	0.5	53.3	1,600	64.0

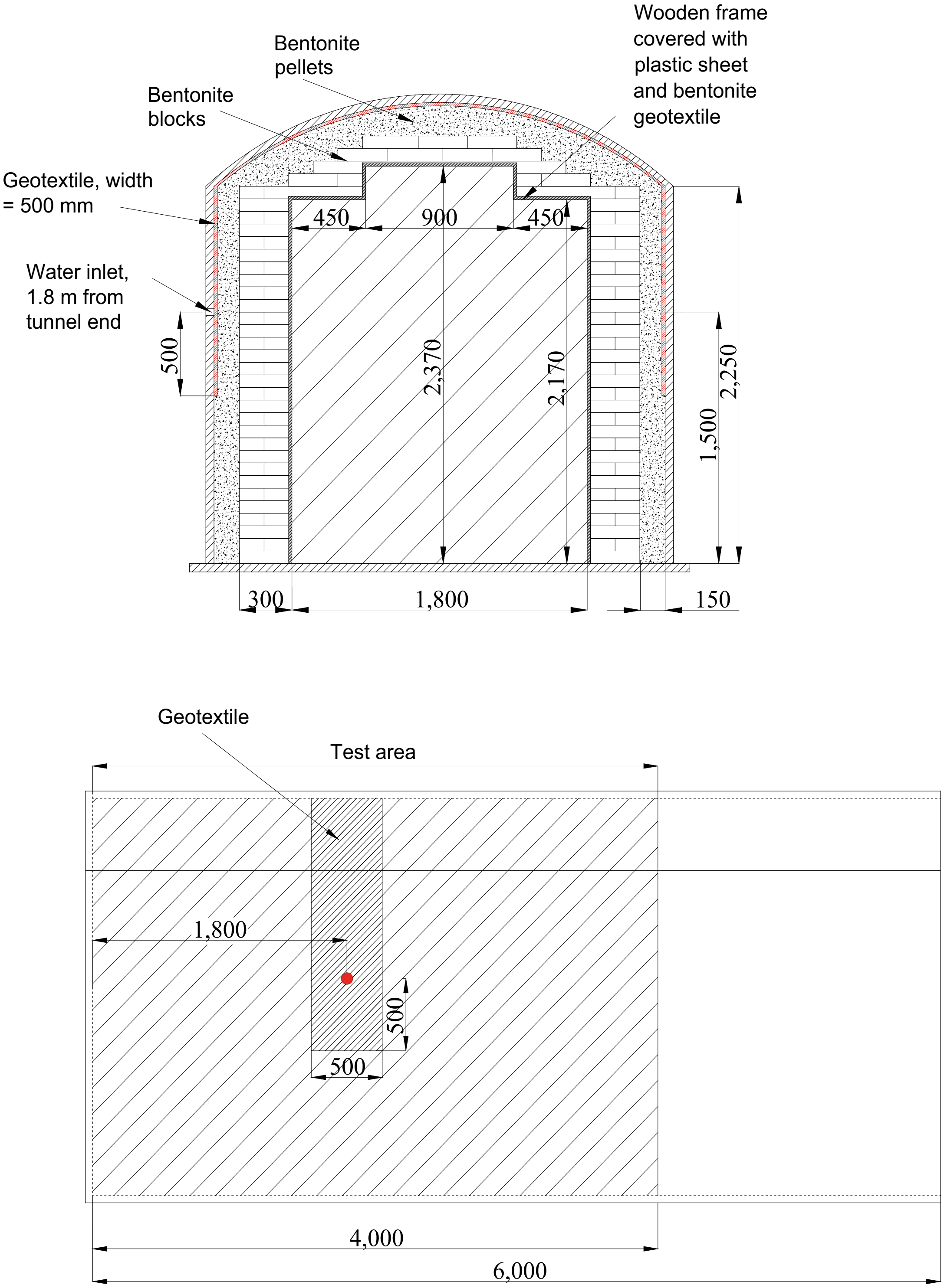


***Figure 5-1.** Schematic of the ½-scale test tunnel. **Upper**: Front view **Lower**: Tunnel seen from the side. (Koskinen and Sandén 2014).*

5.2.3 Test results

The main results from the tests can be compiled as follows:

- The pellet type used in the tests stores water very well. In the reference test it took more than 30 hours before any outflow occurred. It should be considered that this time to outflow was reached with a rather high inflow (0.25 l/min) and in a test which, in terms of the available pellet volume, is much smaller than in the full scale (The mass of pellets installed in a 4 meter long full scale nominal tunnel section will be about 22 tons which should be compared to 5 tons installed in a steel tunnel test).
- The geotextile distributes water according to the plans. Pellets were wetted on both sides of the tunnel and at the roof. The distance from the geotextile to the front is, however, limited and the risk for outflow early in the wetting process is therefore high.
- In the two tests performed with a water inflow rate of 0.25 l/min, with and without geotextile, the water storing in the test performed with geotextile, increased with about 28%. This is somewhat lower than desired but probably depends on the scale i.e. the fact that distance to the front from the geotextile is limited.
- The third test, which was performed with a water inflow rate of 0.5 l/min and with geotextile distributing the water, showed that it is possible to store a lot of water with this method. It took 53.3 hours before any water leaked out at the front which means that 1,600 l of water were stored in the pellet filling.
- The water pressure measurements showed that the water pressure increased in a different way when using geotextile. This probably depends on the fact that the textile is filled rather quickly and that the pellets closest to the filter get some extra time to swell and seal. During the "storing" a lot of pressure peaks occur, showing that the different flow paths seals and that the water has to flow in another direction.

The large differences in water storing capacity between test 2 and test 3 depend probably on a number of various factors. One obvious difference between the tests was that the pellets in test 3 were sieved before installation. This was mainly done in order to avoid dust but might also have influenced results regarding water storing capacity. This kind of tests also includes some random behavior which means that there is a large scatter regarding the water storing capacity for an installed pellet filling. Besides the scatter in water storing capacity and the influence of fines present in the filling, the installation technique and the resulting homogeneity of the filling also may influence the results.

5.3 Full scale pellet installation test in the TASS tunnel

5.3.1 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 drawing in Figure 5-2 and photos in Figure 5-3. 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.

An artificial water inflow was installed four meter from the front, see photo in Figure 5-3. A geotextile stripe was placed over the point inflow. The geotextile started about one meter above the floor and 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 litres of water was added.

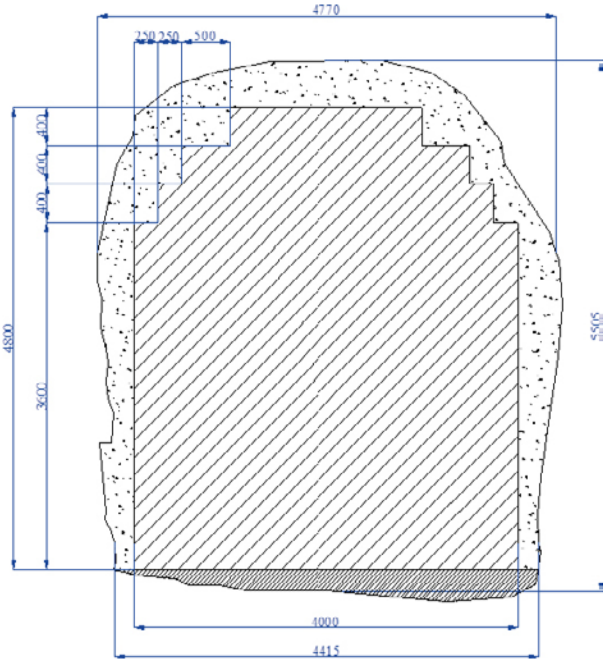


Figure 5-2. *Schematic drawing showing the dimensions of the central mould and the approximate dimensions of the tunnel. (Johnsson and Sandén 2013).*

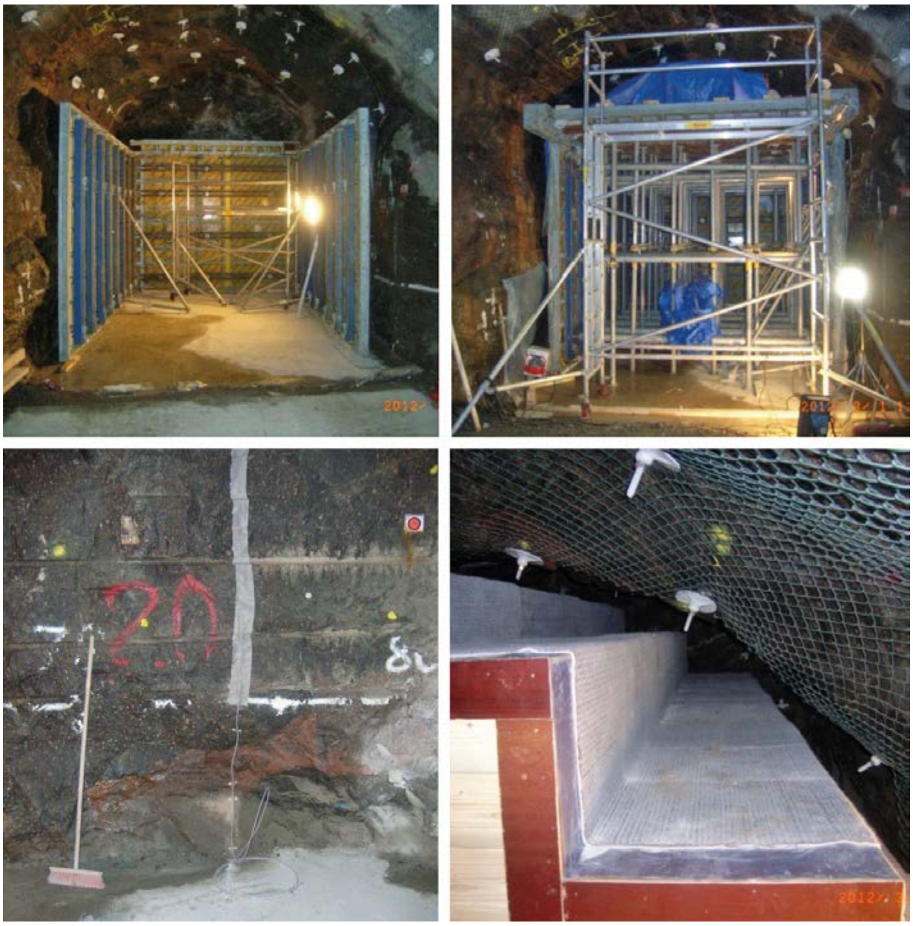


Figure 5-3. *Photos from the preparatory work.* ***Upper left and right****: Installation of the mould simulating a stack of backfill blocks.* ***Lower left****: An artificial water bearing "fracture" (geotextile) was installed four meters from the front. The "fracture" started one meter from the floor 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)*

5.3.2 Test results

The aim with this test was to study the behavior 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 approximately 8.5 m^3, see Figure 5-4. This means that about 56% of the pellet filling should be wetted which is rather close to the results obtained from the sampling.
- The conceptual model, see Section 4.2.4, predicts that it will take about 48 h for a point inflow of 0.5 l/min to reach the backfill front (without geotextile). In the test it took about 118 hours before the first outflow occurred. This probably depends on the fact that the geotextile has distributed the water over a larger area which means that more water could be stored in the pellet filling.
- One of the assumptions in the conceptual model is that after a breakthrough of water at the front, all water will flow out from the pellet filling. This is a conservative assumption that didn't match the laboratory results regarding this pellets type. This full scale test has shown that the water storing continues also after the first breakthrough of water at the front, see Figure 5-4.
- 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.

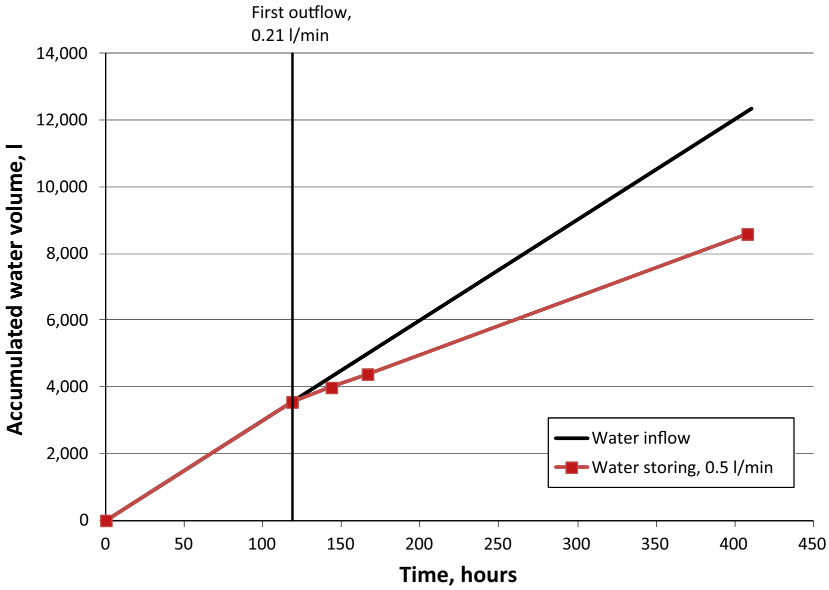


***Figure 5-4.** The accumulated water inflow and water storing plotted versus time. After about 118 hours water starts to flow out but about 60 percent of the inflowing water continues to be stored in the pellet filling. (Johnsson and Sandén 2013)*

5.4 Block stacking on pellet filling

5.4.1 Test layout

These tests are described in detail in Johnsson (2011). A number of block stacking tests have been performed at Äspö HRL, mainly in the Bentonite Laboratory but also in the M-tunnel.

One of the tests that is of special interest for this report is no. 10 since it also included a constant water inflow of 1 l/min into a pellet filling. The main purpose of the test was to study how the pellet bed and the block stack were affected when stacking above a deposition hole with a water inflow. The test was set up on an even concrete floor with a width of 4,200 mm, which is the same as the reference design, and with an inclination of 1%. The upper part of a deposition hole, including the bevel (which is a part of the present KBS-3 design), was built in concrete in full scale, see Figure 5-5.

The floor was covered with leveled pellets within a wooden frame. The pellet bed had an approximate maximum depth of 450 mm from the base of the bevel and of 150 mm for the rest of the surface. During the installation of pellets and blocks there was a constant flow of water, 1 l/min, from the artificial fracture made of a polyamide tube and geotextile, see Figure 5-5.

5.4.2 Test results

The test was terminated after about eight hours. The blocks were removed from the pellet surface and it was possible to study the wetting pattern in the pellet filling, see Figure 5-6. The water had mainly entered at the sides of the stack but also in the gaps between the blocks.

Besides the results from the block stacking, that showed that blocks could be stacked on a pellet filling during a constant water flow without problems with stability, some conclusions can also be made regarding the water storing in the pellet filling:

- The applied water inflow of 1 l/min was stored in the pellet filling during the test time without affecting the block stack. In total more than 480 liters were injected during the test time.
- A certain flow resistance was registered; see Figure 5-7, which indicates that the water was stored in the filling and not flowing free in a channel.
- The water flow tested was twice as high as the recommended upper limit for a six-meter long section and despite this all water was stored during the test time. In a real situation, the block stacking would continue together with installation of pellets in the slots between block and rock walls which would increase the available storing volume. Even if the test time is short, the test evidently shows that water can be stored in a pellet filling also at high inflow rates.
- The test layout included a rather large water inflow in the floor. The water mainly entered the sides of the stack but some water has also been flowing into the gaps between the blocks. The results from e.g. the steel tunnel tests have shown that the backfill blocks are not playing a big role in this kind of short term tests. The higher density of the backfill blocks and the fact that they are positioned close to each other results probably in a fast sealing (increased flow resistance) and the easiest way for the water is too flow in the pellet filling.

Figure 5-5. *Left: Upper part of a deposition hole included the bevel was built in concrete.* ***Right****: Water flow applied as a "fracture" at the edge of the bevel. (Johnsson 2011).*

Figure 5-6. *Photo taken after removal of the blocks. Water has entered mainly on the sides of the stack but also in the gaps between the blocks. (Johnsson 2011).*

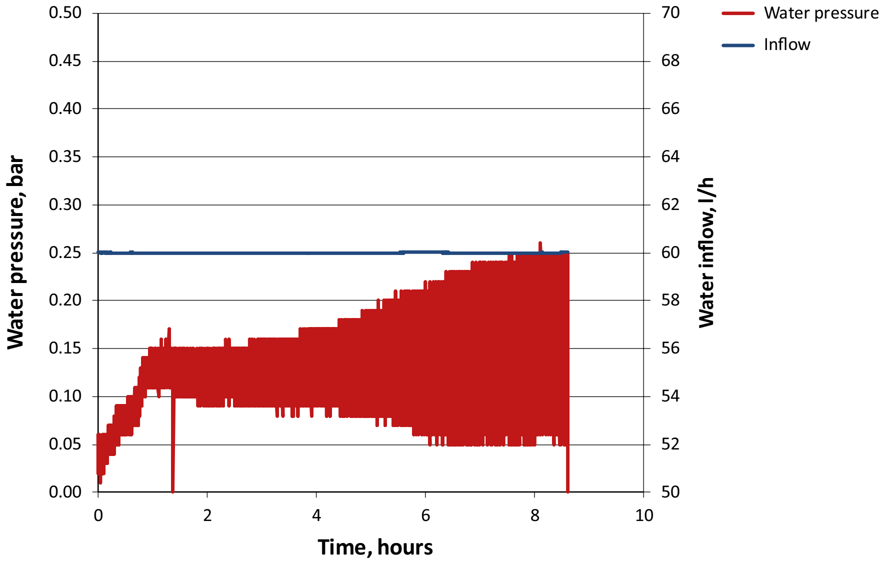


***Figure 5-7.** Water inflow rate and water pressure plotted versus time. (Johnsson 2011).*

6 Plugs

6.1 General

All deposition tunnels are planned to end with a concrete plug. The demands on these plugs will be very high e.g. they should withstand high pressures (water pressure and swelling pressure from the backfill), they should be water tight and they should have a lifetime of a hundred years. It is of course possible to build this kind of plugs also inside the deposition tunnels in order to cut off a water bearing fracture zone but this will be very expensive and time consuming. The proposals in this chapter assume, however, that no deposition tunnels will be abandoned.

Since the demands on temporary plugs positioned in deposition drifts are lower, it is possible to, instead of using the standard tunnel end plug design, build simplified plugs with a design adapted for the actual conditions. Such plugs could also be used in case of an unscheduled stop during the installation phase. A suggestion for a plug classification is provided in Table 6-1.

In this chapter, a number of different plug designs are suggested. None of the designs are, however, investigated in detail and they should therefore be considered as a first draft both regarding design and requirements.

Table 6-1. Suggestions of different plug classes.

Plug class	Planned/Unplanned	Life time	Strength requirements	Design
Class I	Planned	> 100 years	10 MPa (Swelling pressure+full hydrostatic pressure)	Concrete plug with bentonite sealing and drainage layers. There is a need for special rock excavation.
Class II	Planned	approx. 1 year	6 MPa (Low swelling pressure+full hydrostatic pressure)	Concrete plug with drainage layer. There is a need for special rock excavation.
Class III	Unplanned	approx. 2 months	0.5 MPa (Low swelling pressure)	Concrete beams + frame work of steel, drainage layer.
Class IV	Unplanned	approx. 2 weeks	50 kPa Earth pressure from macadam and pellets	Concrete beams, drainage layer.

6.2 Class I and Class II plugs

The demands on a tunnel end plug (Class I) are very high. They should withstand high pressures (water pressure and swelling pressure from the backfill), they should be water tight and they should have a lifetime of more than hundred years. The design of such a plug is shown in Figure 6-1. The properties and requirements of this plug type are investigated in other projects and will not be further treated in this report.

If e.g. a deposition drift crosses a fracture zone with high water inflow rates it could be necessary to build a plug in order to cut off the fracture zone. Such a plug, class II, can be of a more simple construction than the tunnel end plug, and the demands regarding life time and strength can be lower. The design could be similar to a class I plug, but some of the parts can be excluded such as the bentonite sealing and extra drainage sections. A disadvantage is that this type of plug requires a lot of preparation work on the rock, and this must of course be made in advance before the backfilling of the deposition tunnel starts.

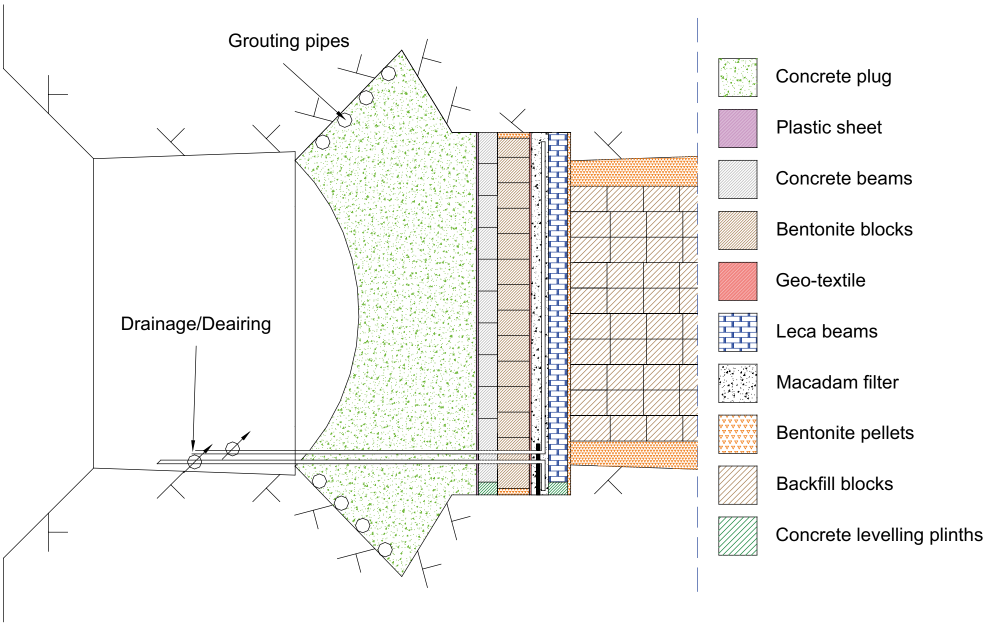


Figure 6-1. *Schematic drawing of a tunnel end plug (class I). This picture was produced in conjunction with the design of the field test within the Dome Plug project (Report in prep.).*

6.3 Techniques for handling of water reaching the backfilling front (unscheduled stops in the backfilling process) – Class III and IV plugs

6.3.1 General

Backfilling of a deposition tunnel should be planned so that there is no risk for water flowing out at the backfill front during the installation time. If a high water flow reaches the front there will be severe problems e.g. erosion of bentonite. The water may also affect the block stack and make it difficult to continue the piling and there will also be problems during the rest of the backfilling since the water always will catch up the front (depending on the flow rate).

However, if there for some reason is an unscheduled stop in the backfilling process, inflowing water may reach the backfill front after some time. When water reaches the backfill front it will, according to experiments and the conceptual model, seep out through the pellet filling between the rock walls and the backfill blocks. It is important to prevent the water from flowing onto the surface of the backfill blocks since they will start to swell rather quickly, and by that complicate the continuation of the block piling.

In order to prevent too large damages on the installed backfill, if an unscheduled stop of the installation process would occur, it will be necessary to take certain actions e.g. building temporary plugs. The two following sections give suggestions for design and construction of such plugs.

6.3.2 Class III and IV

General

In some situations it could be necessary to build a plug within the deposition drift on short notice. One example of a situation is if the backfill installation process cannot proceed according to the plans depending on e.g. mechanical failure of the backfill installation equipment or if the backfill block production does not work. In order to not risk that the previously installed backfill will get so affected by inflowing water that the demands on the function are not fulfilled, it could be necessary to build a plug within a few days (Class IV). If it is foreseen that the installation of backfill cannot be continued within a timeframe of maximum two weeks, it will probably be necessary to strengthen the construction in order to secure the plug for a couple of months (Class III).

A stop in the backfill installation process could e.g. also occur right over a deposition hole. This means that there probably always will be a need for more simple solutions for block handling and pellet installation in order to have the temporary plug built in between two deposition holes which probably is the most suitable position. This is however an issue that has to be further investigated.

6.3.3 Design of class III and IV plug

Examples of design of plugs of class IV are provided in Figure 6-2 and 6-3. The main plug consists of large concrete beams. The beams are anchored to the rock by reinforcement bars casted in boreholes in the rock and then welded to steel plates casted in advance into the beams. Behind the beams there is a drainage layer of macadam. A steel tube should be installed at the bottom, through the beams and into the drainage layer. This design makes it possible to drain water from the inside of the plug and prevent high water pressures to be built up. This type of construction has been built earlier as a part of the Plug project, see photo provided in Figure 6-3. It is assessed that this type of plug can be built in a few days. When a decision to continue the backfilling has been taken, the valve on the drainage tube should be closed. The design includes that a certain amount of steel and concrete will be left in the tunnel.

The demands regarding strength are rather low on this kind of plug. The plug should withstand the earth pressure from the macadam and the pellet filling inside i.e. approximately 50 kPa in total.

If the backfilling process cannot be resumed within a couple of weeks, there may be a swelling pressure from the backfill inside the plug. This will make it necessary to strengthen the plug. This can e.g. be made by mounting of a steel frame outside the plug (Figure 6-4). The frame can be welded together on site and then anchored to the rock.

The suggested designs of temporary plugs are rather simple and will only work in short term i.e. a couple of months.

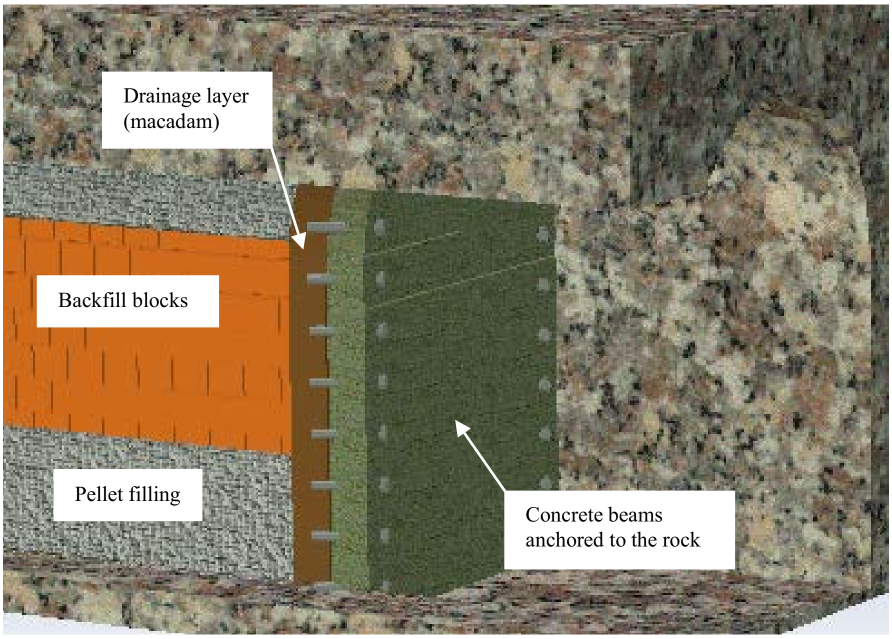


Figure 6-2. *Suggestion for design of a class IV plug.*

Figure 6-3. *Photo showing an example of a temporary plug. The concrete beams are of the same type as the one suggested for a plug of class III and IV. The photo was taken during the installation of the Dome Plug project at Äspö HRL (Report in prep.).*

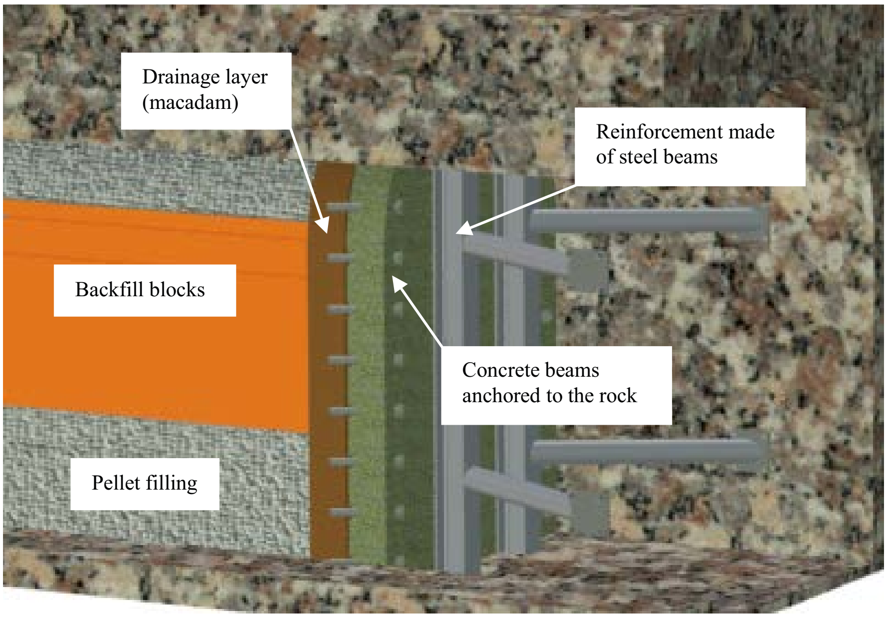


Figure 6-4. *Suggestion for design of a class III plug.*

7 Conclusions and recommendations

7.1 Water inflow predictions

The two reports describing the expected water inflow rates at Forsmark, see chapter 2, give rather similar predictions regarding inflow rates even though Joyce et al. (2013) has a higher number of tunnels with inflow rates larger than 10 l/min, 45 compared to 30 for Börgesson et al. (2014).

From the results presented in the two reports the following inflow conditions can be expected (figures from Joyce et al. 2013):

- Approximately 45 tunnels (out of a total of 207 tunnels) will have a total inflow of ≥ 10 l/min.
- Approximately 63 tunnels will have a total inflow higher than 3 l/min.
- It is expected that there will be a large number of tunnels, about 70, with a total inflow of 1 l/min, where all water inflow enters the tunnel in one point.

The water inflow into these tunnels will require special solutions in order to prevent inflowing water from reaching the backfill front.

As mentioned earlier, the results provided are based on models and there is probably a considerably uncertainty about its validity. The effect of pre-grouting was investigated in Börgesson et al. (2014) and according to this model; the effect of grouting only could be seen for inflow rates larger than 1 l/min. The effect of grouting was not taken into account by Joyce et al. (2013).

7.2 Water storing in the pellet filling

Storing of water in the pellet filling is the only water handling method that has been investigated by tests performed in both laboratory and in large scale. Based on the results from these tests, a conceptual model describing the wetting behavior of a pellet filling has been developed.

The conceptual model has been used, together with a number of conservative assumptions (e.g. that all inflowing water is flowing towards the backfill front) in order to estimate the available time after installation before the inflowing water reaches the backfill front for a number of different inflow scenarios. The results from the latest tests in large scale (steel tunnel test) and in full scale (TASS tunnel) have, however, shown that the estimations of the available time are very conservative and that the available time probably is at least twice as long. The safety margins for these estimations are thus considered large.

- The results from both theoretical estimations of available time and from the latest large scale tests have been used in order to set some limits regarding the possibility to store water in a pellet filling. The behavior is, however, irregular and not always repeatable i.e. the scatter in storing capacity can probably be large. There are also a number of parameters that influence a pellet fillings possibility to store water e.g. the amount of fines and the homogeneity of the filling. In order to decrease the scatter it will be necessary to perform additional tests, and also to have a good quality control of both material and of the installation technique. It is probably also possible to decrease the scatter by using the suggested improvements with geotextiles and wetted pellet layers. The maximum allowed inflow rate to one 6 meter section that can be handled by storing the water in the pellet filling is 0.5 l/min. If geotextile is used in order to distribute the inflowing water over a larger area, preferably in combination with a temporary drainage tube, the maximum allowed inflow rate is 1 l/min. This presupposes, however, that only one or two 6-meter sections in a 300 m long deposition tunnel have these high inflow rates, see next bullet.
- The maximum water inflow to a 300 m long deposition tunnel that can be handled by letting the inflowing water be stored in the pellet filling is between 2.5 and 5 l/min. The exact figure depends strongly on how the water inflow is distributed in the tunnel. One requirement is, however, that no water inflow to one 6-meter section is higher than 1 l/min and another is that geotextile is used in order to distribute the inflowing water in sections with inflow rates between 0.25 and 1 l/min.

7.3 Water handling methods

7.3.1 General

In the present reference design (SKB 2010b) the maximum accepted inflow to a 300 meter long deposition tunnel is 5 l/min and the maximum point inflow is 0.1 l/min. The evaluation of data from the new tests described in this report, shows that these figures seem to be reasonable (some adjustments have been made, e.g. the limit for a single point inflow have been increased). These inflow rates can be handled with standard methods i.e. the inflowing water is stored in the pellet filling, possibly in combination with a geotextile in order to distribute and increase the water storing capacity of the pellet filling. When the inflow rates are higher it will, however, be necessary to introduce other methods.

Table 7-1 shows a compilation of the estimated number of tunnels with a certain water inflow, a maximum allowed water inflow to a single 6 m-section and the recommended water handling methods. The estimated number of tunnels with certain inflow properties is based on the report from Joyce et al. (2013), see also Section 2.3 in this report. The argumentation for the choice of water handling method is presented in the following sections.

7.3.2 Recommended water handling method for different water inflow ranges and distributions

In the main part of the deposition tunnels, approximately 55%, the backfill installation can probably be made without any special actions regarding water handling. In approximately 11% of the tunnels some small actions will be necessary in order to handle the inflowing water. However, in approximately 34% of the deposition tunnels it will be necessary to introduce other techniques for the water handling e.g. building of water storing sections, drainage to an adjacent tunnel or building temporary plugs.

Table 7-1. Table showing an estimation of the proportion of tunnels with certain water inflow conditions that can be handled with the different suggested techniques.

Estimated part of tunnels	Water inflow to 300 m tunnel	Max. water inflow to 6 m section	Water handling method	Remark
55%	0–1 l/min,	< 0.5 l/min	Storing in pellet filling	
2%	1–5 l/min	< 0.5 l/min	In 6 m-sections with inflow rate 0.25 < q6m < 0.5 l/min (q6m = inflow to 6 meter section), geotextiles should be used in order to distribute the inflowing water.	As an option, temporary drainage tubes can be used.
13%	1–5 l/min	0.5 < q6m < l/min (q6m= inflow to 6 meter section)	1. Geotextile 2. Temporary drainage tubes	The water handling method should be chosen depending on how the inflow points are distributed in the tunnel.
6%	1–10 l/min	> 1 l/min	1. Water storing sections 2. Drainage through borehole to adjacent tunnel 3. Local freezing	Drainage through borehole to adjacent tunnel can advantageously be used in combination with a water storing section.
17%	> 10 l/min	> 1 l/min	1. Water storing sections 2. Drainage through borehole to adjacent tunnel 3. Local freezing 4. Tunnel plug	Drainage through borehole to adjacent tunnel can advantageously be used in combination with a water storing section.
7%	> 30 l/min	> 10 l/min	1. Drainage through borehole to adjacent tunnel 2. Tunnel plug	Drainage through borehole to adjacent tunnel can advantageously be used in combination with a water storing section.

The choice of water handling method for different inflow scenarios have been made according to the following (Table 7-1):

- **A total inflow of between 0 and 1 l/min in 300 m tunnel and < 0.5 l/min to a single 6 m-section.** This is, according to the models, the most common water inflow scenario and will occur in approximately 55% of the deposition tunnels. These water inflow rates can be stored in the plain pellet filling without any additional means.
- **A total inflow between 1 and 5 l/min in 300 m tunnel and < 0.5 l/min to a single 6 m-section.** This is, according to the models, not a likely scenario. Only a few tunnels are predicted to have these rather well distributed inflows. The recommended technique for water handling is to install geotextiles in sections where the inflow rates are higher than 0.25 l/min in order to distribute the water and by that get accesses to larger pellet volumes for water storing.
- **A total inflow between 1 and 5 l/min in 300 m tunnel and inflow to a single 6 m section is 0.5 < q6m < 1 l/min** (q6m = inflow to 6 meter section)**.** This is according to the models a scenario that may occur in approximately 13% of the tunnels. The recommended technique for water handling is to install geotextiles in sections where the inflow rates are higher than 0.25 l/min in order to distribute the water. In sections where the inflow rates are higher than 0.5 l/min it is recommended to also use temporary drainage tubes during the installation, see description in Section 3.5.
- **A total inflow between 1 and 10 l/min in 300 m tunnel and > 1 l/min to a single 6 m-section.** This is a scenario that will occur in only about 6% of the tunnels according to the models. In the sections with highest inflow rates it will be necessary to build water storing zones. The capacity of these zones can be chosen by adjusting of the length of the zone, but it is assessed that in practice they are useful for inflow rates between 1 and 2 liters/min. For higher inflow rates to a single 6 m-section it is recommended to drill a drainage borehole to an adjacent tunnel. This solution, preferably in combination with a macadam filled section, will allow drainage during long time. An alternative could be a local freezing of the water bearing zone. This method will, however need further development and testing.
- **A total inflow > 10 l/min in 300 m tunnel and > 1 l/min to a single 6 m-section.** See solutions recommended in previous scenario. An alternative for the sections with highest inflow rates could be to build a Class II plug (planned plug of somewhat simpler construction than the tunnel end plug).
- **A total inflow > 30 l/min in 300 m tunnel and > 10 l/min to a single 6 m-section.** In tunnels with these high water inflow rates is it recommended to either drain the water to an adjacent tunnel (in combination with a macadam filled section) or to cut off the water bearing section with tunnel plugs of class II.

7.3.3 Uncertainties – Recommendations for future work

The method based on water storing in the pellet filling has been tested at Äspö HRL, as also the improvement with geotextile used as a distributor of the inflowing water. The capacity of this method is assessed to be quite well known even of the number of large scale tests is limited and it is recommended for use in tunnels with a total water inflow that is lower than 5 l/min and with a maximum water inflow rate to one 6 meter section < 1 l/min. It is however important to investigate how the location of the inflow points affects the installation procedure and the possibilities to adjust the installation procedure to avoid scheduled stops at times when the front of the backfill is close to a water inflow.

For higher inflow rates i.e. more than 5 l/min in 300 m tunnel or inflow rates higher than 1 l/min in one 6 m section, it will, however, be necessary to also use other methods. The methods assessed to have most potential and that are recommended to be studied and tested further are:

- **Geotextile quality.** Tests have been made with different geotextile qualities but the number of types is large and the final choice should be optimized both regarding function and possibility to fasten on the rock walls.

- **Natural drainage.** The step-wise excavation and backfilling of deposition tunnels will in reality cause a transient groundwater situation around the deposition tunnels. Parallel tunnels will share the same groundwater. It is documented from all SKB underground facilities that the inflow decreases by time. The current logistic plan for step-wise development of the repository is to develop approximately 5 deposition tunnels/year – some years before deposition starts. This leads to a potential for large scale draining over some years before the detailed planning for deposition and backfilling starts. These aspects of drainage are not very well known and will require further studies (inflow modelling).
- **Macadam filled water storing sections**. This is a rather simple method that has the potential to be used in the sections with medium high inflow rates (1–2 l/min). The sections are technically very simple to build and the position in the deposition tunnel can be decided before drilling of the deposition holes. The post closure safety of the design must, however, be investigated.
- **Drainage through borehole to adjacent tunnel**. This is a method that has high potential to be used in the sections with the highest water inflow rates. The technique must probably be used together with a macadam filled section which can collect and lead the water to the borehole. This technique should be further investigated and especially the aspects on post closure safety.
- **Local freezing**. This technique is often used during constructions of road and railway tunnels in e.g. fractured rock or if high water inflows occur. In a future disposal the technique can potentially be used for local freezing of water bearing fracture zones. There are, however, uncertainties regarding whether the technique is suitable also in a future disposal e.g. if it works at a depth of 400–500 meters, how the cooling affects the rock strength and if the procedure will include that some material has to be left in the rock.
- **Temporary plugs**. The development of tunnel end plugs is proceeding within different SKB projects and this design can of course be used also if the plug is to be positioned a certain distance in to a deposition tunnel. More simple plugs that can be used in order to cut off water bearing fracture zones within a deposition tunnel can also be used in case of unscheduled stops in the installation process.

References

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

Andersson L, Sandén T, 2012. Optimization of backfill pellet properties. SKB R-12-18, Svensk Kärnbränslehantering AB.

Börgesson L, Sandén T, Dueck A, Andersson L, Jensen V, Nilsson U, Olsson S, Åkesson M, Kristensson O, Svensson U, 2014. Consequences of water inflow and early water uptake in deposition holes. EVA-project. SKB TR-14-22, Svensk Kärnbränslehantering AB.

Dixon D, Anttila S, Viitanen M, Keto P, 2008a. Tests to determine water uptake behavior of tunnel backfill. SKB R-08-134, Svensk Kärnbränslehantering AB.

Dixon D, Lundin C, Örtendahl E, Hedin M, Ramqvist G, 2008b. Deep repository – engineered barrier system. Half scale tests to examine water uptake by bentonite pellets in a block –pellet backfill system. SKB R-08-132, Svensk Kärnbränslehantering AB.

Funehag J, Emmelin A, 2011. Injekteringen av TASS-tunneln. Design, genomförande och resultat från förinjekteringen. SKB R-10-39, Svensk Kärnbränslehantering AB. (In Swedish.)

Johnsson A, 2011. Tests for evaluation of pellets as foundation bed material. KBP1003-ÅSKAR. SKB P-11-48, Svensk Kärnbränslehantering AB.

Johnsson A, Sandén T, 2013. System design of backfill. Pellet optimization. SKB R-13-47, Svensk Kärnbränslehantering AB.

Joyce S, Swan D, Hartley L, 2013. Calculation of open repository inflows for Forsmark. SKB R-13-21, Svensk Kärnbränslehantering AB.

Koskinen V, Sandén T, 2014. System design of backfill. Distribution of inflowing water by using geotextiles. SKB R-14-10, Svensk Kärnbränslehantering AB.

Sandén T, Börgesson L, Dueck A, Goudarzi R, Lönnqvist M, 2008. Deep repository – Engineered barrier system. Erosion and sealing processes in tunnel backfill materials investigated in laboratory. Baclo project-phase 3. SKB R-08-135, Svensk Kärnbränslehantering AB.

SKB, 2010a. Design, production and initial state of the backfill and plug in deposition tunnels. SKB-TR-10-16, Svensk Kärnbränslehantering AB.

SKB, 2010b. Design, construction and initial state of the underground openings. SKB TR-10-18, Svensk Kärnbränslehantering AB.

Svensson U, Follin S, 2010. Groundwater flow modelling of the excavation and operational phases – Forsmark. SKB R-09-19, Svensk Kärnbränslehantering AB.

Swedish Road Administration, 2000. Tätning av bergtunnlar: förutsättningar, bedömningsgrunder och strategi vid planering och utformning av tätningsinsatser. Borlänge: Vägverket.