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Water handling during backfilling

Development report

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Abstract

The reference method for backfilling of deposition tunnels includes that pre-compacted backfill blocks are filling up the main part of the volume. Bentonite pellets are filling up all gaps between blocks and rock walls and are also used as a bed material to even out the rough rock surface and by that provide a suitable surface on which the backfill blocks can be stacked. Inflowing water may disturb the backfill installation process. Depending on flow rates and also on how the inflow points are distributed in the deposition tunnel the inflowing water may affect the stability of the backfill installation and it could also cause erosion of bentonite. The water inflow is thus of importance for the safety of the repository and is therefore included in the Technical Design Requirements for both SKB's and Posiva's repositories: "*Inflow to deposition tunnel: Less than* limit to be determined in the design *to allow installation of the backfill and plug.*" (Posiva SKB 2017). The work presented in this report gives input to the quantification of the requirement.

This report describes the work performed in order to handle inflowing water during the installation of backfill in KBS-3V deposition tunnels. The project work was divided in the following parts:

1. To develop water handling methods.
2. To establish requirements on the characterization of deposition tunnels regarding water inflow rates and how they are distributed.
3. To update the conceptual model describing water storage in a pellet filling as function of the water inflow rate.
4. To develop a mathematical model describing water storage and spreading in pellet fillings during backfill installation.
5. To design a temporary plug that can be used in case of a temporary stop in the backfill installation process.

Water handling methods

A number of water handling methods have been investigated and developed for a range of different inflow rates:

- *Water storage in the pellet filling*. Investigations have shown that inflowing water largely can be stored in the macro voids between bentonite pellets in the pellet filled gap between backfill blocks and rock. Water storing in the pellet filling is probably enough for the main part of the deposition tunnels. This method is recommended for inflow rates per tunnel up to 0.5 liters/minute.
- *Water distribution by geotextile*. Geotextile pieces that are fastened on the rock wall over a water bearing fracture zone can be used to distribute the inflowing water over a larger area and by that increase the water storage capacity of the pellet filling. This method is recommended for inflow rates per tunnel between 0.5 and 1.0 liters/minute.
- *Temporary drainage*. By connecting a pipe to the geotextile, via a special water collector, inflowing water can be drained out from the inflow point, through the pellet filling. With this method, several sections of backfill can be installed without being affected of the inflowing water. The drainage pipe is retrieved after its usage. This method is recommended for inflow rates per tunnel between 0.5 and 1.0 liters/minute. The method can only be used together with geotextile.
- *Water Storage Section, WSS*. This method includes that a certain section of a deposition tunnel is allocated for water storage. The section is delimited by two walls of concrete beams and the space between the walls is filled with bentonite pellets. By using pellets with high initial degree of saturation, the inflowing water can be stored in the macro voids between the pellets without early swelling and sealing of the bentonite. The length of the WSS can be adjusted depending on the inflow rate. This method is recommended for inflow rates per tunnel between 1 and 5 liters/minute.
- *Drainage borehole to Adjacent Tunnel, DAT*. With a drainage borehole from a water bearing fracture zone to an adjacent tunnel, high inflow rates can be handled. The inflowing water must be collected in a special section and then led into the borehole. It is important that the drainage

borehole afterwards can be sealed efficiently. This method is recommended for inflow rates per tunnel between 1 and 10 liters/minute.

- *Artificially wetted pellet wall*. By adding water on the installed pellets it is possible to build up a wet pellet wall that redirects flowing water and thus prevents it from reaching the backfill front. This method has been tested in laboratory scale but it has been assessed that further tests will be needed before it is ready for implementation in full scale tests.
- *Local freezing*. The method to locally freeze water bearing fracture zone areas has in this project been investigated by having a small workshop with experts in the field. The method has been judged to have large potential but further investigations and tests will be needed before it is ready for implementation in full scale tests.

Besides the methods described above, a number of different methods that have been suggested in earlier projects, were reviewed and rejected depending on either technical difficulties or problems with the post closure safety.

Requirements on water inflow data

Besides the specific inflow from individual inflow points or fracture zones, also the total inflow rate and distribution in a deposition tunnel must be considered when planning the backfill installation process for a specific tunnel. Requirements regarding characterization of water inflows to the constructed deposition tunnels have been suggested. The requirements are based on results from several investigations and tests performed regarding e.g. water storage capacity of a pellet filling and studying the effects of distributing the inflowing water by geotextile materials. Based on the actual inflow conditions of each tunnel, it will be possible to choose the proper water handling methods and make a specific plan for the needed water handling procedures and backfill installation process for every individual deposition tunnel.

Requirements on pellet properties

The results from the tests have shown that it will be necessary to put up requirements regarding the pellet properties regarding water content and density. When manufacturing pellets with the extrusion method (the pellet type used in this project) it is important to have an optimal water content of the raw bentonite. If the water content is too high, it will be impossible to reach the high densities that are necessary in order to achieve the pellet properties needed. In earlier performed test with Asha and Cebogel pellets, where the water storage properties have been assessed to be high, the water content have been between 12 and 20 % and the dry density of the individual pellets has been between 1 810–2 000 kg/m^3 (see e.g. Dixon et al. 2008a, b and Andersson and Sandén 2012). These figures should serve as a guideline for the requirements on the pellet properties.

Update of conceptual model

For the calculations of available time before inflowing water to a pure pellet filling reaches the backfill front face, a simplified conceptual model is suggested to be used. The model is based on experimental data from a large number of different laboratory tests. Different wetting patterns were identified for different ranges of inflow rates and these patterns have been used to define a conceptual model.

Mathematical model

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

Sammanfattning

I referensmetoden för återfyllning av deponeringstunnlar ingår att förkompakterade återfyllningsblock fyller upp huvuddelen av volymen. Bentonitpellets fyller upp alla spalter mellan block och berg och används även som ett bäddmaterial för att jämna ut den ojämna bergytan och skapa ett jämnt underlag på vilket återfyllningsblocken kan staplas. Inflödande vatten från berget kan komma att störa återfyllnadsprocessen. Beroende på inflödeshastighet och på hur inflödespunkterna är fördelade i deponeringstunnlarna kan det inflödande vattnet påverka stabiliteten hos blockstapeln och även leda till erosion av bentonit. Vatteninflödet till en deponeringstunnel har alltså betydelse för säkerheten i slutförvaret och inkluderas därför i konstruktionsförutsättningarna för både SKB's och Posivas slutförvarsanläggningar: Inflöde till deponeringstunnel: *"Mindre än* gräns som sätts under utformningen *för att tillåta installation av återfyllning och plugg"* (författarens översättning) (Posiva SKB 2017). Arbetet som presenteras i denna rapport ger förutsättningar för att kvantifiera inflödeskravet.

Denna rapport beskriver det arbete som utförts för att kunna hantera inflödande vatten i samband med återfyllningen av deponeringstunnlar i KBS-3V konceptet. Projektarbetet kan delas upp i följande delar:

1. Utveckling av olika vattenhanteringstekniker.
2. Etablera krav på karakteriseringen av deponeringstunnlar när det gäller storleken på vatteninflöden och hur de är fördelade i deponeringstunnlarna.
3. Uppdatera den konceptuella modellen som beskriver hur vatten lagras i en pelletsfyllning som en funktion av inflödeshastigheten.
4. Utveckla en matematisk modell som beskriver hur vatten lagras och sprids i en pelletsfyllning i samband med installation av återfyllning.
5. Design av en temporär plugg som är tänkt att användas vid ett tillfälligt stopp i installationsprocessen.

Vattenhanteringsmetoder

Ett antal olika metoder att hantera inflödande vatten har undersökts och utvecklats. Metoderna är anpassade för olika inflödeshastigheter:

- *Vattenlagring i pelletsfyllning*. Undersökningar har visat att inflödande vatten i stor utsträckning kan lagras i makroporerna mellan pelletar i de pelletsfyllda spalterna mellan återfyllningsblocken och bergväggarna. Denna vattenlagring är förmodligen tillräcklig för huvuddelen av deponeringstunnlarna. Denna metod rekommenderas för inflöden upp till 0.5 liter/min per tunnel.
- *Geotextil*. Geotextil som fästs på bergytan över vattenförande sprickzoner fördelar det inflödande vattnet över en större yta och kan därmed öka vattenlagringsförmågan hos en pelletsfyllning. Denna metod rekommenderas för inflöden per tunnel mellan 0.5 och 1.0 liter/minut.
- *Temporär dränering*. Genom att ansluta ett rör till geotextilen, via en speciell vattensamlare, kan det inflödande vattnet dräneras ut från inflödespunkten och genom pelletsfyllningen. Med denna metod kan ett antal sektioner med återfyllning installeras utan att påverkas av inflödande vatten. Dräneringsröret måste återtas efter användandet. Denna metod rekommenderas för inflöden per tunnel mellan 0.5 och 1.0 liter/minut. Temporär dränering kan endast användas tillsammans med geotextil.
- *Vattenlagringssektion, WSS*. Denna metod innebär att en bestämd sektion av deponeringstunneln avdelas för vattenlagring. Sektionen begränsas av två betongväggar och volymen mellan dessa fylls med bentonitpellets. Genom att använda pellets med hög vattenmättnadsgrad kan det inflödande vattnet initialt lagras i porutrymmet mellan pelletarna utan att bentoniten tidigt börjar svälla och täta. Längden på en WSS kan justeras beroende på inflödeshastigheten. Denna metod rekommenderas för inflöden per tunnel mellan 1 och 5 liter/minut.
- *Dränerande borrhål till angränsande tunnel, DAT*. Med ett dränerande borrhål från en vattenförande sprickzon till en angränsande tunnel kan stora vatteninflöden hanteras. Det inflödande vattnet måste samlas i en speciell sektion och sedan ledas vidare in i borrhålet. Det är viktigt att det dränerande borrhålet efter användning kan förslutas effektivt. Denna metod rekommenderas för inflöden per tunnel mellan 1 och 10 liter/minut.

- *Artificiell bevätning av pelletsvägg*. Genom att beväta den installerade pelletsen på ytan kan man bygga en vägg som dirigerar om vattenflöden som kommer inifrån fyllningen och därmed förhindrar vattnet att nå återfyllningsfronten. Denna metod har testats i laboratorieskala men det har bedömts att fler tester behövs innan den är redo för att testas i full skala.
- *Lokal frysning*. Metoden att med hjälp av lokal frysning av en vattenförande sprickzon stoppa vatteninflöden under installationstiden har i detta projekt endast undersökts genom att en mindre workshop med experter på området har genomförts. Metoden har bedömts ha stor potential men ytterligare undersökningar krävs innan den är redo för tester i full skala.

Förutom de metoder som beskrivits ovan fanns det ett antal andra metoder som föreslagits inom tidigare projekt men som efter en genomgång förkastades beroende på bl.a. tekniska svårigheter eller problem med säkerheten efter förslutning.

Krav på inflödesdata

Förutom det specifika inflödet från en sprickzon måste också hänsyn tas till det totala inflödet till en deponeringstunnel, samt hur det är fördelat, när man planerar hur återfyllningen av en deponeringstunnel skall ske. Krav på hur karakteriseringen av en deponeringstunnel skall ske när det gäller vatteninflöden har föreslagits. Kraven baserar sig på resultaten från de undersökningar och tester som gjorts på t.ex. vattenlagringskapaciteten hos en pelletfyllning och hur den påverkas om man kompletterar med att använda geotextil för att fördela vatteninflödet. Med hjälp av den erhållna inflödesdatan kan man sedan välja vattenhanteringsmetod och även upprätta en plan för återfyllningsprocessen för varje enskild deponeringstunnel.

Krav på pelletfyllningens egenskaper

Resultaten från testerna visar att det är nödvändigt att ställa krav på pelletsen när det gäller vattenkvot och densitet. När man tillverkar pellets genom extrudering (den pellettyp som använts i detta projekt) är det viktigt att ha en optimal vattenkvot på råbentoniten. Om vatteninnehållet är för högt blir det omöjligt att nå den höga densitet på pelletsen som är nödvändig för att man ska få de egenskaper som krävs. I tidigare genomförda tester med Asha- och Cebogel-pellets, där vattenlagringsegenskaperna har bedömts vara höga, har vattenkvoten legat på mellan 12 och 20 % och torrdensiteten på de individuella pelletsen mellan 1 810–2 000 kg/m^3 (se t.ex. Dixon et al. 2008a, b samt Andersson och Sandén 2012). Dessa värden för vattenkvot bör tjäna som en riktlinje för kraven på pelletfyllningens egenskaper.

Uppdatering av den konceptuella modellen

För att kunna beräkna den tillgängliga tiden innan inflödande vatten i den rena pelletfyllningen når återfyllningsfronten har en förenklad konceptuell modell föreslagits. Modellen är baserad på experimentell data från ett stort antal tester i laboratorieskala.

Olika bevätningsmönster har kunnat identifieras för olika vatteninflöde och dessa mönster har sedan använts för att definiera en konceptuell modell.

Matematisk modell

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

Tiivistelmä

Suurin osa loppusijoitustunneleiden tilavuudesta on suunnitelman mukaisessa ratkaisussa esitetty täytettäväksi esipuristetuilla täyteainelohkoilla. Täyteainelohkojen ja kalliopintojen väliset raot puolestaan täytetään bentoniittipelletteillä, joilla myös tasoitetaan lattian epätasainen kalliopinta sopivaksi täyttölohkojen asennusta varten. Tämä täyttöprosessi voi häiriintyä kalliosta tulevien vuotovesien johdosta. Vuotovedet voivat vaikuttaa täyteainelohkojen asennuksen stabiilisuuteen sekä aiheuttaa täyttömateriaalien eroosiota. Mahdollisten häiriöiden suuruus riippuu vuotovesien virtausnopeuksista sekä vuotopaikkojen sijainneista tunnelissa. Vuotovedet vaikuttavat merkittävästi loppusijoitustilan turvalliseen toimintaan ja ne on huomioitu sekä SKB:n että Posivan teknisissä vaatimuksissa seuraavalla määrittelyllä: ”*Loppusijoitustunnelin vuotovesien määrä: Vähemmän kuin* suunnitelmissa määritettävät *sallitut raja-arvot täytön ja tulpan asennuksille.*” (Posiva SKB 2017). Tässä raportissa esitetään aineistoa tämän vaatimuksen määrittämiseen.

Tässä raportissa kuvataan KBS-3V konseptin mukaisen täytön asennuksen näkökulmasta vuotovesienhallintaan liittyvää työtä. Tämä työ oli jaettu seuraaviin osiin:

1. Vuotovesienhallintamenelmien kehittäminen.
2. Vaatimusten määrittäminen loppusijoitustunnelien karakterisoinnille vuotovesien virtausten ja sijaintipaikkojen suhteen.
3. Pellettitäytön veden varastointia virtausmäärän suhteen kuvaavan konseptuaalisen mallin päivitys
4. Täyttöprosessin aikana tapahtuvan veden varastoinnin ja kulkeutumisen matemaattisen mallin kehitys.
5. Täyttöprosessin äkillisen pysähtymisen johdosta tarvittavan väliaikaisen tulpan suunnittelu.

Vesienhallintamenetelmät

Työssä tutkittiin ja kehitettiin eri vuotovesien virtausmääräalueille sopivia vesienhallintamenetelmiä:

- *Vuotovesien varastointi pellettitäyttöön*. Täyteainelohkojen ja kallion väliin asennettu bentoniittipellettitäyttö pystyy varastoimaan suurimman osan vuotovesistä pellettien välisiin tyhjätiloihin. Tämä pellettitäytön ominaisuus on luultavasti riittävä vesienhallintamielessä suurimmalle osalle loppusijoitustunneleita aina 0.5 litraa/minuutti tapahtuvaan tunnelin kokonaisvuotoon asti.
- *Vuotovesien levittäminen geotekstiilin avulla*. Vuotokohdan päälle kallioseinään kiinnitetyillä geotekstiileillä vuotovesien virtaus voidaan ohjata suuremmalle alueelle ja kasvattaa näin pellettitäytön veden varastointikapasiteettia. Tätä menetelmää suositellaan käytettäväksi tunnelin kokonaisvuotovesien 0.5–1.0 litraa/minuutti virtausnopeusalueille.
- *Väliaikainen virtausputki*. Vettä voidaan johtaa pellettitäytön läpi käyttämällä geotekstiiliin kiinnitettyä vedenkeräintä ja väliaikaista virtausputkea. Tämä menetelmä mahdollistaa pidempiä täytön asennuskatkoja ilman vuotovesien aiheuttamia häiriöitä. Väliaikainen virtausputki poistetaan pellettitäytöstä käytön jälkeen, vedenkeräimen ja geotekstiilin jäädessä paikoilleen. Tätä menetelmää suositellaan käytettäväksi tunnelin kokonaisvuotovesien 0.5–1.0 litraa/minuutti virtausnopeusalueille. Väliaikaista virtausputkea ei voida käyttää ilman geotekstiilejä.
- *Vedenkeräysalue*. Tässä menetelmässä pitkittäinen osa loppusijoitustunnelia rajataan erityiseksi vedenkeräysalueeksi betoniseinien avulla. Seinien väliin jäävä alue täytetään korkean lähtösaturaatioarvon omaavilla bentoniittipelleteillä. Tällaiset pelletit paisuvat ja tiivistävät hitaammin pellettien väliset tyhjätilat, jolloin saavutetaan tasaisempi kastuminen ja suurempi vedenvarastointikyky. Vedenkeräysalueen pituus määritetään vuotovesien virtausnopeusalueiden mukaisesti. Tätä menetelmää suositellaan käytettäväksi tunnelin kokonaisvuotovesien 1.0–5.0 litraa/minuutti virtausnopeusalueille.

- *Viereiseen tunneliin ohjattu virtaus*. Erittäin korkeiden vuotovesimäärien tapauksessa kahden vierekkäisen tunnelin väliin voidaan porata tilat yhdistävä reikä, johon vuotokohdan vedet ohjataan. Vuotokohtaan rakennetaan erityinen keräysalue, joka kokoaa vuotovedet ennen reikään viemistä. Pitkäaikaisturvallisuuden kannalta on tärkeää pystyä tukkimaan tunneleiden välinen yhdysreikä pysyvästi. Tätä menetelmää suositellaan käytettäväksi tunnelin kokonaisvuotovesien 1.0–10.0 litraa/minuutti virtausnopeusalueille.
- *Esikasteltu pellettiseinä*. Pellettitäytön asennuksen yhteydessä voidaan tietty osa pelleteistä esikastella, jolloin ne muodostavat tiiviin seinän. Tämä seinä estää ja ohjaa vuotovesiä pois asennusrintama-alueelta. Tätä menetelmää on testattu laboratorio-olosuhteissa, mutta menetelmä tarvitsee vielä lisäkehitystä ennen täyden mittakaavan kokeita.
- *Vuotovesien hallinta jäädyttämällä*. Vuotovesiä voidaan hallita jäädyttämällä vuotokohdat paikallisesti. Tätä menetelmää käsiteltiin tässä työssä järjestämällä pieni työpaja alan asiantuntijoiden kesken. Tämän menetelmän soveltamisella todettiin hyviä mahdollisuuksia vuotovesienhallintaan, mutta ennen täyden mittakaavan soveltamista täytyy tehdä lisätutkimuksia ja laboratoriotestejä.

Yllä kuvattujen menetelmien lisäksi, myös joukko aikaisemmissa projekteissa tunnistettuja vesienhallintamenetelmiä arvioitiin ja rajattiin tämän työn ulkopuolelle. Syinä olivat joko tekniset keskeneräisyydet tai pitkäaikaisturvallisuuteen liittyvät ongelmat.

Vuotovesimääritysten vaatimukset

Loppusijoitustunnelin täyttöprosessia suunniteltaessa tulee tietää yksittäisten virtauspisteiden tai halkeama-alueiden lisäksi tunneliin vuotava kokonaisvesimäärä ja sen paikkajakauma. Tässä työssä on esitetty vuotovesienmääritysten vaatimuksia. Nämä vaatimukset perustuvat kokeelliseen toimintaan, kuten esimerkiksi veden varastointikapasiteetin määrityksessä tehtyihin laboratoriokokeisiin sekä vuotovesien geotekstiilillä levittämisen tutkimiseen. Kun yksittäisen loppusijoitustunnelin vuotovedet on kartoitettu, voidaan sille tehdä tarvittaessa erityinen vesiehallintasuunnitelma, joka myös huomioi täytön asennuksen vaatimukset tälle tunnelille.

Pellettien ominaisuuksien vaatimukset

Kokeellinen toiminta on osoittanut, että on tarpeen määrittää käytettävien pellettien ominaisuudet vesimäärän ja tiheyden suhteen. Nämä tulee ottaa huomioon jo pellettien valmistuksen aikana (tässä työssä käytettiin pursottamalla valmistettuja pellettejä) raakamateriaalina toimivassa bentoniitissa. Korkean vesipitoisuuden pelleteillä ei saavuteta loppusijoitustunnelin suunnitelman mukaisia bentoniitin tiheysarvoja. Aikaisemmin Asha ja Cebogel -pelleteillä tehdyissä kokeissa, missä vedenvarastointikyky oli todettu korkeaksi, pellettien vesipitoisuus oli välillä 12–20 % ja kuivatiheys välillä 1 810–2 000 kg/m^3 (Dixon et al. 2008a, b, Andersson and Sandén 2012). Näitä arvoja voidaan käyttää ominaisuusvaatimusten suuntaviivoina.

Konseptuaalisen mallin päivitys

Tässä työssä esitetään yksinkertainen päivitetty konseptuaalinen malli sen ajan määrittämiseksi mikä vuotovesiltä kestää saavuttaa asennuksen täyttörintama. Malli perustuu useiden laboratoriokokeiden tuloksiin. Erilaisia vettymiskuvioita tunnistettiin joukolle virtausmääriä ja näitä tuloksia käytettiin konseptuaalisen mallin luomiseen.

Matemaattinen malli

Tämän matemaattisen mallin tarkoituksena on laskea täytön asennukseen liittyviä aikaikkunoita loppusijoitustunnelin eri vuotovesiskenaarioille. Näin voidaan analysoida sitä saavuttavatko vuotovedet täytön asennusrintaman. Vesien kulkeutuminen esitettiin etenevänä vesirintamana, joka saa vetensä useista tunnelin vuotokohdista. Tällä tavoin voidaan ottaa huomioon kaikki oletettavat vuotovesien määrät ja paikat. Pellettitäytön osittainen vettyminen esitettiin virtausmäärän funktiona, mikä oli johdettu testituloksista. Malli luotiin tarkoituksella geneeriseksi, jolloin sitä voidaan käyttää molempien, SKB:n ja Posivan, tunnelipoikkileikkauksille ja täytön asennusnopeuksille.

Contents

1 Introduction

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

The reference design considered by both SKB and Posiva for backfilling tunnels includes emplacement of pre-compacted blocks in the tunnel and bentonite pellets that fill up the space between the blocks and the tunnel walls, Figure 1-1. Pellets will also be placed on the tunnel floor in order to even out the rough rock surface and by that provide a suitable surface on which the backfill blocks can be piled. The installation of such a backfill system includes technical solutions for automation of block manufacturing, block transports, stacking of blocks, emplacement of pellets etc. The deposition tunnels in the current reference design have an inclination upward, towards tunnel face, to enable drainage of inflowing water away from the backfilling works as long as possible.

One of the main problems identified is how the water inflow to the tunnels should be handled during backfill installation. Depending on flow rates and how the inflow points are distributed in the tunnels the inflowing water may change the backfilling conditions e.g. the initial conditions of the material, the time window available for installation and also the stability of the backfill installation. Flowing water may also cause erosion of the backfill materials. The water inflow is thus of importance for the safety of the repository and is therefore included in the Technical Design Requirements for both SKB's and Posiva's repositories: "*Inflow to deposition tunnel: Less than* limit to be determined in the design *to allow installation of the backfill and plug.*" (Posiva SKB 2017). The work presented in this report gives input to the quantification of the requirement.

Both the Forsmark site in Sweden and the Olkiluoto site in Finland are assessed to be rather dry, but preliminary modelling show that a number of the planned deposition tunnels will have inflow rates of more than 5 liters per minute and in some tunnels the inflow can be more than 30 liters per minute (Joyce et al. 2013, Hartley et al. 2010). It should, however, be emphasized that these figures are based on modelling and that the real inflow situation will not be known until after construction of the deposition tunnels. Since it is desirable that no deposition tunnels should be abandoned, it has been necessary to develop methods and techniques to handle these expected water inflows.

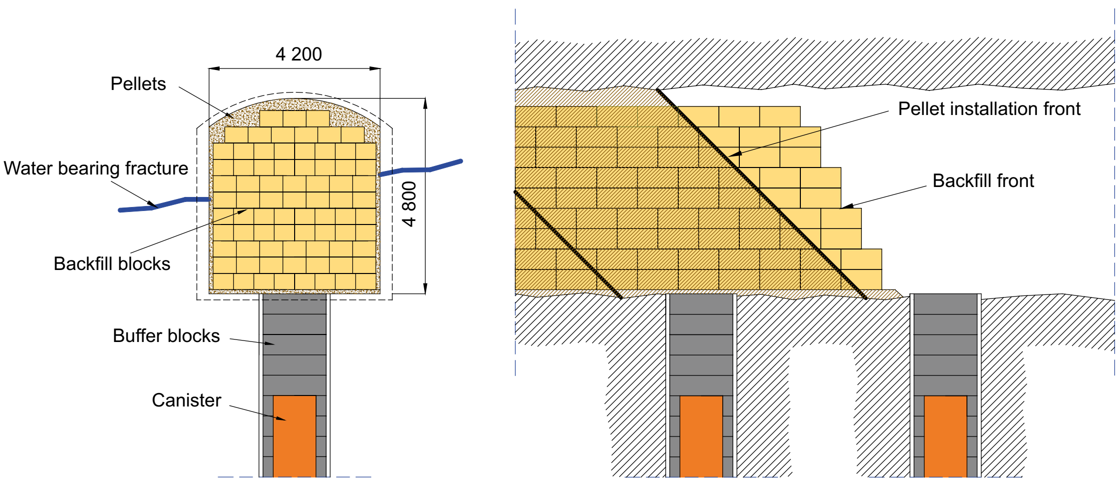

Figure 1-1. *Schematic drawing showing the design for backfill considered by SKB. The given dimensions apply to the nominal tunnel section, see also Chapter 2. The design for backfill considered by Posiva is similar and the only differences are in principle the size of the deposition tunnels and the choice of raw material used for blocks and pellets.*

Different water handling methods have earlier been investigated within the project “System design of backfill” (Sandén and Börgesson 2014). This work has then continued within the present project “Water handling during backfill installation”, KBP1011 (SKB) and K3-2210 (Posiva). This report presents a compilation of the project results and the current state of knowledge regarding water handling methods in a KBS 3V repository.

2 Reference designs of backfill

2.1 General

The present reference methods for backfilling of deposition tunnels are similar for SKB and Posiva. One of the main differences are the dimensions of the tunnels (Posiva has two different tunnel sizes, both somewhat smaller than the SKB tunnel) and thereby are also the block stack sizes and the installed pellet volumes are different. Another difference is the considered installation sequences. SKB is planning to install bentonite buffer and canisters to all deposition holes over the whole length of the deposition tunnel before starting the installation of backfill. Posiva is considering to install buffer and canisters to one to four deposition holes first and thereafter install backfill above this area before continuing the installation of buffer and canisters to the next one to four deposition holes. This means that there will be a difference in the average backfill installation rate which in turn will influence the risk of water reaching the backfill front during the backfill installation process. It should, however, be mentioned that discussions regarding the most suitable installation sequence are ongoing within both SKB and Posiva.

A description of the considered deposition tunnel dimensions is provided in this chapter.

2.2 SKB

A schematic drawing showing the dimensions of an SKB deposition tunnel is provided in Figure 2-1. The drawing shows the nominal tunnel geometry. The accepted volume exceeding the nominal (19.1 m^2) is $0.30 \times A_{nominal} \times L_{blasting}$ round m^3. The accepted largest cross section area exceeding the nominal is $0.35 \times A_{nominal}$ m^2. Additional data regarding the tunnel geometry can be found in SKB (2010a, b). These dimensions are important for the preparation and installation of different water handling methods (see description in Chapter 5) even if more detailed measurements will be necessary when the final positions have been decided.

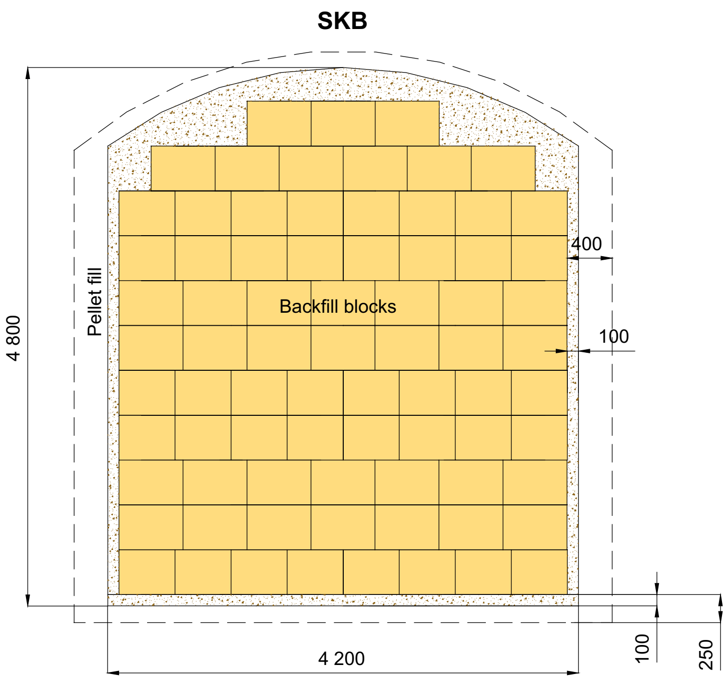

Figure 2-1. *Schematic drawing of a deposition tunnel (SKB).*

2.3 Posiva

Posiva is at the moment considering two different sizes of the deposition tunnels (Keto et al. 2013). The different lengths of the fuel elements from the different nuclear power plants results in different lengths of the canisters, Figure 2-2. The Olkiluoto 1–3 tunnels have a nominal cross-section area of 14.1 m^2 and a maximum of 19.2 m^2. The Loviisa 1–2 tunnels have a nominal cross-section area of 12.7 m^2 and a maximum of 17.5 m^2.

According to the present plans 46 tunnels will be adopted for OL1–2, 48 tunnels for OL3 and 20 tunnels for Loviisa. The final decision regarding the design is, however, not yet taken.

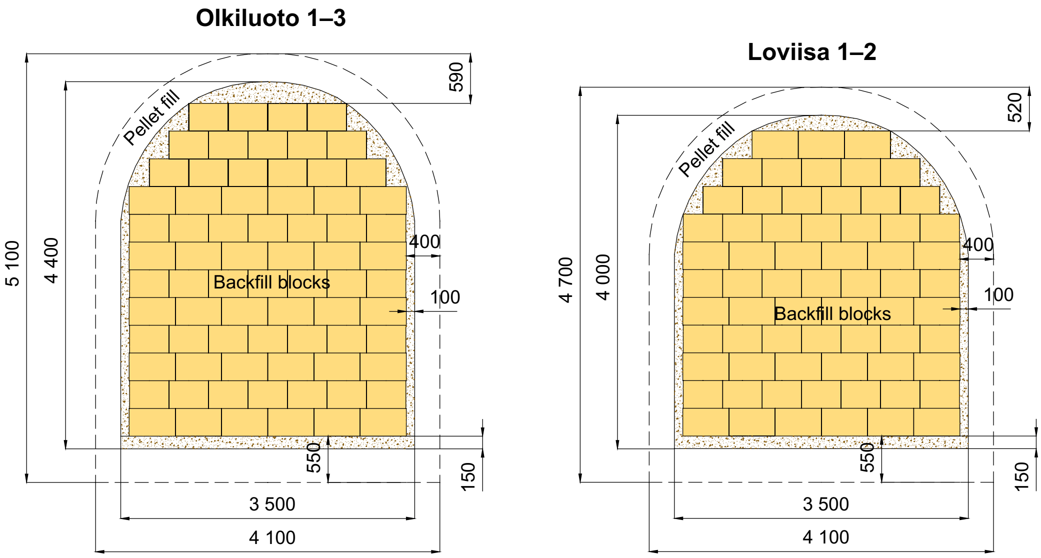

Figure 2-2. *Schematic drawing of a deposition tunnel (Posiva).*

3 Water handling methods considered to be unfeasible

3.1 General

A number of methods have been suggested to have some potential to handle water inflow during backfill installation. Some of these methods have, however, been considered to be unpractical and also to have too vast technical challenges to be further investigated within this project. A few methods were excluded because they possess severe risks considering post closure aspects. This chapter provides a brief description of these methods and why they have been rejected.

3.2 Post-grouting

Pre-grouting of the rock mass has extensively been studied in a number of SKB and Posiva projects as well as in civil engineering projects around the world. Silica SOL is planned to be used in the deposition tunnels as pre-grouting material, in order to limit the water inflow.

Post grouting has so far been considered to be nearly impossible for excavated surfaces, unless extensive use of concrete will be allowed. Based on the current level of knowledge and projected high cost of the development, grouting has not been a further investigated within this project. Even if the method would be improved it is not likely to solve the challenges caused by the inflows, just move the inflow to a new location.

3.3 Copper dam

The method was suggested in 2011 in an internal memo by B+tech Oy on assignment from Posiva. The design includes that a copper plate is positioned between the backfill blocks stacked in the tunnel. The block filling degree is locally very high, possibly up to 95 %. The sealing properties would be provided by the copper plate between the blocks. The method will require small installation tolerances and machining of the rock in order to install the copper plate. Besides that the method is questionable as a water handling method, it is also judged that the installation of a copper dam would delay the installation process significantly as well as raise the cost of the backfill (Koskinen 2017).

3.4 Backfill dam

The method is similar to the copper dam method but without copper. The method is based on the idea that backfill blocks are installed in the deposition tunnel without any pellets in the gaps between blocks and rock. The blocks should be installed with a tolerance to the rock with only a few millimeters which means that the rock surface has to be wire sawed. The swelling bentonite will then seal the gap between the blocks and the rock surface soon after installation.

The method would require machining of the blocks, mechanical grinding or wire sawing of the rock as well as careful installation of the backfill blocks. Even if the bentonite dam is possible to be built, it would require time and effort during the backfill installation process which would be delayed. Based on the uncertainty of the functionality as well as high cost of the method, the method has not been further developed within this project.

3.5 Drainage along tunnel

A method that earlier has been suggested, 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 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.

3.6 Methods including gravel fillings

3.6.1 Water storage section (early design)

The method to build a special water storage section in a deposition tunnel where inflowing water is stored in the voids in a gravel filling has been considered to have severe problems regarding post closure issues. A large volume with free water is considered to largely facilitate future colloid erosion. There is also an obvious risk of local bacteria growth. However, the design of the method has been changed in the sense that the gravel filling has been exchanged to bentonite pellets, see description in Section 5.4. The new design will result in a lower bentonite density locally, but if this can be handled by e.g. introducing a transition zone (a section with a density gradient and where no deposition holes are placed) on both sides of the water storage section, it is believed that the method could be suitable to be used under some circumstances.

3.6.2 Drainage hole to adjacent tunnel (early design)

A water handling method suggested to be used for high inflow rates is to drill a drainage borehole to an adjacent tunnel, see detailed description provided in Section 5.5. The originally suggestion for design included a similar gravel filled section as described in Section 3.6.1. This design has, however, after criticism (same arguments as for a water storage section, see Section 3.6.1) been changed so that the water collection is made in a smaller volume that is countersunk into the rock surface.

3.7 Light plug built of shotcrete

An alternative to the Light fortified concrete plug described in Section 5.8 was initially to construct a pure shotcrete plug. During the development work it became clear that it also was necessary to construct a concrete wall on which the first layers of the shotcrete could be applied. Since the design became almost similar to the other version of a temporary plug, it was decided to instead use shotcrete as an alternative to the steel reinforcement. Both plug designs are presented in Section 5.8.

4 Choice of water handling method

4.1 General

As described in this report, see Section 5.1, a large number of tests performed with bentonite pellets have shown that, largely, inflowing water from the rock can be stored in the macro voids between the bentonite pellets in the pellet filled gap between backfill blocks and rock. This water storing delays the water progression through the backfill and makes backfill installation more predictable. 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.

The groundwater flow at both Forsmark and Olkiluoto has been modelled, see e.g. Joyce et al. (2013) and Hartley et al. (2010). The modelling has predicted that a number of the deposition tunnels will have inflow rates, higher than is expected to be managed by water storage in the pellet filling only. Efforts will be made only to excavate tunnels with low inflows, but it cannot be guaranteed beforehand that some excavated tunnels will have higher flows than the limits set by water storage in the pellets. There is a clear incentive to use as much of the available rock volume and not to abandon tunnels already constructed. This means that it will be necessary to have a toolbox of different methods that can be used in order to handle different water inflow rates to be able to install the backfill while maintaining the requirements of the installed backfill. Such a toolbox has been developed, see descriptions in Chapter 5.

The wetting behaviour of the backfill pellet fill is highly dependent on the distribution of water inflow points in the deposition tunnel. The inflow distribution is also the determining factor when it is decided which water handling method(s) that will be used in order to secure a predictable backfill installation. For these reasons, data about the water inflow distribution into each deposition tunnel is needed.

4.2 Requirements on inflow data

A suggestion for characterization of deposition tunnels regarding water inflow distribution before starting the backfill installation process has been made, see Table 4-1. The specified figures given regarding inflow rates are based on the capacity of the different water handling methods investigated, see Chapter 5. For example, if the total inflow to a deposition tunnel is ≤1 l/min, it will be enough with water storage in the pure pellet filling if there are no fractures with inflow rates larger than 0.25 l/min. In sections were there are inflow rates > 0.25 l/min, geotextile will be used to increase the water storage capacity.

Table 4-1. Suggested requirements on inflow data.

Applicable for:	Suggested requirement on inflow data
All deposition tunnels	The total water inflow into every deposition tunnel shall be determined
Tunnels with total inflow < 0.5 L/min	No further actions are needed.
Tunnels with total inflow between 0.5 and 1 L/min	Identify any fracture zones with inflow rates > 0.5 L/min
Tunnels with total inflow > 1 L/min	Identify any fracture zones with inflow rates > 0.25 L/min.

At present, there are no readily available characterization methods that can supply such detailed information as is requested in Table 4-1. However, the requirements are judged as attainable by several experts working in the SKB projects concerning rock characterization and tunnel production and in the Äspö HRL. The requirements have also been reviewed by Posiva experts in hydrogeology.

The inflow rates in Table 4-1 do not have to be measured in real time. The inflow can be measured during long periods of time and then calculated to an inflow rate of liters per minute. Still, it is judged as challenging to measure inflows quantitatively, both for the total inflow to a tunnel and even more so for individual structures. This might result in the need for further work regarding development of methods for inflow measurements since reliable inflow data is crucial for a robust and reliable repository operation.

4.3 Planning of water handling

Table 4-2 shows roughly how decisions on water handling methods can be made based on how the water inflow into one tunnel is distributed. A similar table was suggested in Sandén and Börgesson (2014). However, based on the knowledge achieved within this project, an updated table is provided. The suggested techniques are based on the fact that 6 meter tunnel is backfilled every 24 h and that the tunnel must be backfilled continuously with this rate until reaching the position where the tunnel end plug should be constructed.

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 gap between backfill blocks and rock. This water storing delays the water progression through the backfill and makes backfill installation more predictable. In an SKB deposition tunnel, in average 5.5 m^3 pellets will be installed every meter. A porosity of approximately 45 % gives an available macro void volume of 2.5 m^3. In practice, only parts of this theoretical volume are used for water storage since the bentonite swell and seal and thereby prevent flow in all directions. The water storage can, however, be increased by using geotextile to distribute the inflow over a larger area. It is estimated that with an inflow rate of 0.25 l/min it will take approx. 40 hours for the inflowing water to reach the front after installation of a 6 meter long backfill section. If also using geotextile it will take 120 hours. Corresponding figures for an inflow rate of 0.5 l/min are 20 hours and 60 hours respectively. 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. The developed water handling methods are described in Chapter 5.

In addition to the water handling methods, a mathematical model has been developed with the objective to calculate the available time for specific deposition tunnels and for specific water inflow scenarios, and to analyze if there is a risk that inflowing water can catch up with the backfill front. The mathematical model is assessed to be an important tool when planning the backfill installation process for a specific tunnel and which water handling methods that should be used. The mathematical model is described in Chapter 6.

When making a plan for the water handling and backfill installation process for an individual deposition tunnel, it is recommended to have margins regarding the calculated time before water will reach the backfill front.

Table 4-2. Table showing how tunnels with certain water inflow conditions can be handled with the different suggested water handling methods.

Water inflow to 300 m tunnel (L/min)	Approximate inflow in one water bearing fracture zone (L/min)	Water handling method
< 0.5		No water handling method is needed apart from backfilling installation as planned.
0.5–1.0*	< 0.25	No water handling method is needed apart from backfilling installation as planned.
	0.25–1.0	Geotextile as a water distributor is needed.
1.0–5.0*	< 0.25	No water handling method is needed apart from backfilling installation as planned.
	0.25–1.0	Geotextile as a water distributor is needed, probably also methods with higher capacity.**
	>1.0	Water handling methods with high capacity** is needed.
> 5.0 L/min*	< 0.25	No water handling method is needed apart from backfilling installation as planned.
	0.25–1.0	Geotextile as a water distributor is needed, probably also methods with higher capacity.**
	>1.0	Water handling methods with high capacity** is needed.

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

** Water handling methods with high capacity have been developed in this project. The methods comprise for example a water storage section (1–5 l/min) and a drainage hole to a neighboring tunnel (> 5 l/min), see descriptions in Section 5.4 and 5.5.

The following concluding remarks on planning of water handling are valid for a deposition tunnel ready for backfilling, i.e. after any grouting activities. The water inflow measurements and distribution are expected to vary with seasons and the excavation and grouting of new tunnels. Hence the inflow measurements should be made as close to the start of the backfilling installation as possible.

- Information about the water bearing fractures must be available, including the inflow rates and the positions in the tunnel. All fracture zones with an inflow >1 L/min must be handled with care.
- After having received all inflow data, a plan for the backfill installation of a specific deposition tunnel can be made. The position of any geotextiles on the rock wall or installation/preparation for other water handling methods should be made before starting the backfill process. Also, the installation of geotextile needs to be taken into account before installing permanent rock reinforcement.
- For tunnels that includes fracture zones with an inflow of more than 0.5 L/min, the inflow must be distributed over a large area to achieve a robust and reliable backfill installation. A method that has been shown to work well is to place geotextile directly over the water bearing fracture. Such simple methods are also needed in many cases where the total inflow to an entire deposition tunnel is larger than 1.0 L/min (except where the individual inflow rates are small, less than 0.25 l/min).
- For individual fracture zones with inflow rates over 1.0 L/min it is necessary to apply water handling methods with high capacity, i.e. inflow distribution using for example geotextile is not sufficient, see Chapter 5.
- For tunnels with a total inflow of over 5.0 L/min it is necessary to apply water handling methods with high capacity (except where the individual inflow rates are small, less than 0.25 L/min), see Chapter 5.

5 Method development

5.1 Water storage in a pellet filling

5.1.1 General

In different tests it has been observed that a bentonite pellet filling has a good ability to store water flowing into the deposition tunnel from the rock, see e.g. Dixon et al. (2008a, b) and Andersson and Sandén (2012). It has also been assessed that this ability probably is 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 and Olkiluoto (Sandén and Börgesson 2014).

In order to further increase the understanding regarding the water storage capacity of a pellet filling, the following tests and investigations have been made within the project Water handling during backfill installation:

1. Laboratory tests in order to investigate how fines present in a pellet filling influences the water storage properties (Sandén and Jensen 2016).
2. Large scale steel tunnel tests have been performed at Äspö HRL. The main objective with these tests was to investigate if geotextile could be used to distribute inflowing water and thereby increase the water storage capacity of the pellet filling but the results were also used to increase the understanding regarding water storage capacity in general. The results from these tests are presented in a report (Sandén 2016), but a compilation of the results are also provided in this chapter.
3. A review of results from relevant tests regarding water storing capacity in pellet fillings performed by SKB and Posiva have been performed. The review has included results from both tests performed in earlier projects but also from the new tests performed within this project. The results have been used to update the conceptual model describing how water is stored in a pellet filling depending on the water inflow rate and the pellet properties. Results regarding how different water inflow rates affect the wetting pattern and the water storing capacity has also been evaluated. This data has also been used to develop a mathematical model describing water storage and spreading in a pellet filling, see Chapter 6 in this report and Åkesson et al. (2017).
4. As a result, from the work, it has also been possible to suggest requirements for the pellet properties regarding water content and density of the individual pellets in order to optimize the water storage capacity of a bentonite pellet filling (Sandén and Jensen 2016).

5.1.2 Definition of water storage capacity

The water storage capacity of a pellet filling is defined as the amount of water that is stored in a pellet filling without the occurrence of a channel flow. The water is often stored according to a certain pattern e.g. symmetrical around the inflow point. The water storage pattern is depending on the water inflow rate and the pellet properties. The water inflow fills the voids between the pellets and the individual pellets also take up water and swell. The swelling closes temporarily the flow paths in one direction, an inflow resistance is generated, and the water starts to flow in another direction. The flow resistance in a pellet filling is, however, rather low and local piping (in small scale) occurs during the water storage.

5.1.3 Theoretical water storage capacity of the pellet fillings (SKB and Posiva)

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

A compilation of data regarding thickness of pellet layers at floor, walls and ceiling for the different tunnel types is provided in Table 5-1. The estimated total pellet volume per meter deposition tunnel is also given in the table. Minimum refers to the nominal cross section area (since under-break is not allowed) and maximum refers to the largest allowable cross section area. In the calculations regarding water storing capacity that has been made, see Åkesson et al. (2017), the average thickness of the pellet gaps has been used. The thickness of the pellet gaps will of course, in the real case, vary along the deposition tunnels and this variation may locally influence the water storage capacity. In a pellet filling there are about 45 % macro voids i.e. the theoretical available volume for water storage is approximately 2.3 m^3 /m tunnel (SKB). Corresponding figures for Posiva are 1.3 m^3 (Olkiluoto) and 1.2 m^3 (Loviisa).

The figures regarding SKB provided in Table 5-1 are based on data regarding nominal tunnel area and the maximum allowed over-break exceeding the nominal (30 %), taken from SKB (2010a, b). The data regarding the dimensions of the block stack are taken from Arvidsson et al. (2015) where an updated backfill reference design is suggested. With these data, and assuming that the over-break of rock is symmetrically distributed around the nominal cross-section, the dimensions of the gaps between block stack and rock walls have been calculated.

The figures regarding Posiva provided in Table 5-1 are based on data taken from Keto et al. (2013), see e.g. Section 2.3.3, Figure 3-8 and Table 3-5 in the report. This means that the shown thickness of the filling in the floor is based on a mixture of sand and bentonite and not really valid for a pellet filling so it will have to be updated at a later stage.

Table 5-1. Compilation of data regarding thickness of pellet layers and the total pellet volume in a backfilled section.

SKB tunnel **Pellet filling data**		**Min**	**Max**	**Average**
Total pellet volume/m (average)	m^3	2.4	8.1	5.2
Thickness of layers				
Floor	mm	100	250	175
Walls	mm	100	400	250
Ceiling (midpoint)	mm	300	600	450
Posiva tunnel, Olkiluoto fuel **Pellet filling data**		**Min**	**Max**	**Average**
Total pellet volume/m (average)	m^3	1.3	4.6	2.9
Thickness of layers				
Floor	mm	150	550	350
Walls	mm	100	400	250
Ceiling (midpoint)	mm	290	590	440
Posiva tunnel, Loviisa fuel **Pellet filling data**		**Min**	**Max**	**Average**
Total pellet volume/m (average)	m^3	1.0	4.1	2.6
Thickness of layers				
Floor	mm	150	550	350
Walls	mm	100	400	250
Ceiling (midpoint)	mm	220	520	370

5.1.4 Influence of fine material

General

The influence of fine material, fines, in a pellet filling has been investigated earlier regarding erosion properties (Sandén et al. 2008). In the project "System Design of Backfill" one of the sub-projects aimed to optimize the pellet filling regarding both erosion properties and water storing capacity (Andersson and Sandén 2012). In these tests it was observed that there was an influence of fines present in the filling regarding sealing and water uptake of the pellet filling. During installation, the fines ended up in layers within the pellet filling, which then prevented the wetting to continue in that direction. Large scale tests were performed at Äspö HRL during 2012 in the steel tunnel test equipment (Koskinen and Sandén 2014) aiming to investigate the water storing capacity of pellet fillings and also if the storing could be improved by using geotextile to distribute the inflowing water over a larger area. One of the tests was performed using sieved pellets i.e. all fines were removed before installation. The results from this test suggested that the water storing capacity increased when no fines were present.

In order to study how the presence of fines influence the water storage capacity of a pellet filling, a new test series has been performed in different scales in a laboratory (Sandén and Jensen 2016). Another objective with the new test series was to compare the water storage properties of pellets manufactured by extrusion from Asha bentonite and the commercial Cebogel QSE pellets.

Small scale tube tests

Test description

Tube tests have been performed in another project earlier in order to determine the water storing capacity for different pellet types (Andersson and Sandén 2012). The test equipment consists of a Plexiglas tube (d=0.1 m, L=1.0 m) that during the test was oriented vertically. The total volume of the tube was 7.85 liters. The pellet filling was held in place by perforated steel plates, mounted at the tube ends, through which the flowing water could easily pass, Figure 5-1. A water inlet (point inflow) was placed at the mid-height of the tube. During the tests time the water inflow rate and the water pressure were registered at decided intervals. The pellet wetting, upwards and downwards from the inflow point level, were documented by notes and photos during test duration.

The new tests series included three types of tests:

1. Tests with pure pellet fillings (sieved pellets).
2. Tests with different amounts of fines mixed with the pellets (5 or 10 %).
3. Tests where fines were placed in layers in the pellet filling, above and below the inflow point.

Example of results

The photo provided in Figure 5-1 shows an example of results. The photo shows three tests performed with Asha pellets (to the left in the figure) and with different contents of fines in the pellet filling. The three corresponding tests performed with Cebogel QSE pellets are shown to the right in the photo. All six tests were performed with a constant water inflow rate of 0.1 L/min. The results from these tests showed that the wetting behavior of the pellet filling was similar for all mixtures independent of the content of fines.

In the tests where fines were positioned in layers, the influence of the wetting behavior was strong. Fines in layers, randomly positioned in a pellet filling can be a disadvantage, locally preventing the wetting process and decreasing the water storage capacity of the filling.

Large scale slot tests

Test description

Besides the small scale tube tests, tests were also performed in larger scale using special designed test equipment, Figure 5-2. The test equipment has been designed as a large slot made of Plexiglas. The Plexiglas was supported by a steel frame. The test equipment has a length of 2 m, a height of 1 m and a width 0.25 m. This width is close to what is the expected dimension of the pellet filled gap between rock and backfill blocks in a deposition tunnel.

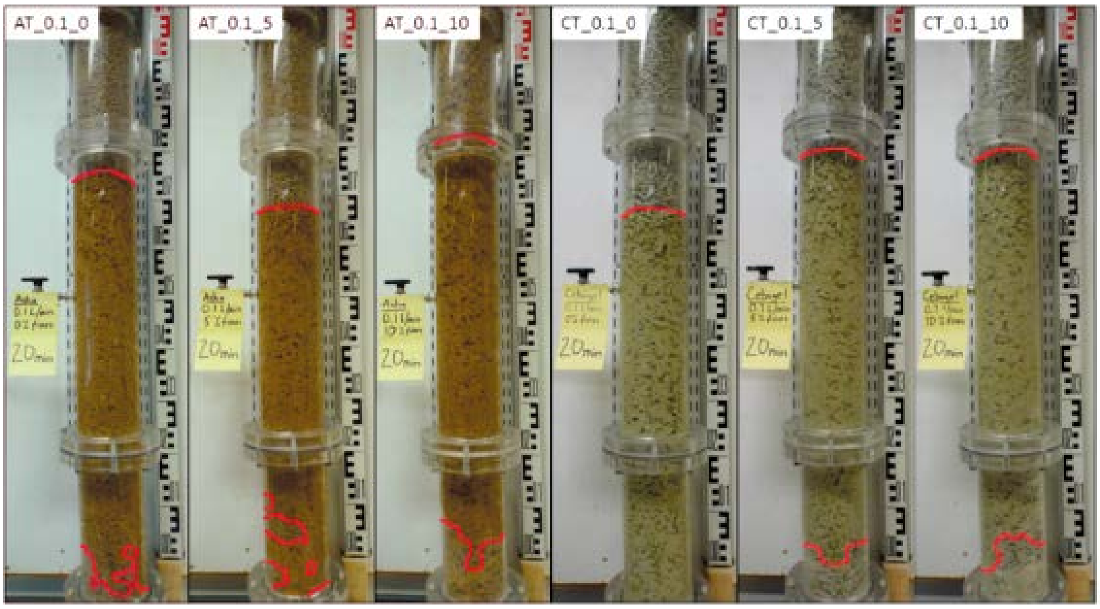

Figure 5-1. Example of results from the tube tests. The photos shows tests performed with both Asha pellets (three tubes to the left) and Cebogel QSE pellets (three tubes to the right). All six tests are performed with the same inflow rate, 0.1 L/min, but with different amounts of fines mixed with the pellets (0, 5 and 10 %). The wetting behavior was similar for all tests.

Figure 5-2. Photo showing the "Large slot test" equipment.

The slot was filled with pellets and then a constant flow rate was applied at the midpoint of one side. The water pressure and the water flow rate were continuously registered during the test duration and photos were taken at decided intervals. The tests were stopped when water reached the top of the slot. Tests were performed with both sieved pellets i.e. all fines were removed but also with fines positioned in layers below and above the water inflow point. The layers were positioned at a distance of about 15 cm below and above the inflow point. At test termination, samples were taken from the pellets in order to determine the water content distribution. These values were then used to produce contour plots showing the wetting pattern at the time for termination.

Example of results

Example of results are provided in Figure 5-3. The photos show the wetting patterns for the two tests performed with Asha pellets and an inflow rate of 0.5 L/min. One of the test was performed with sieved pellets and the other with fines positioned in layers within the filling. With an inflow rate of 0.5 L/min and no fines present in the filling, the water initially flows downwards, but after a certain time for the bentonite to swell and seal, the water front instead proceeds upwards. With the same inflow rate, 0.5 L/min, and fines placed in two layers below and above the inflow point, the lower layer stops the initial flow downwards and instead the water distributes sideways across the fine layer. Finally sealing occurs and the water penetrates the upper layer whereas the same wetting behavior takes place above this layer surface.

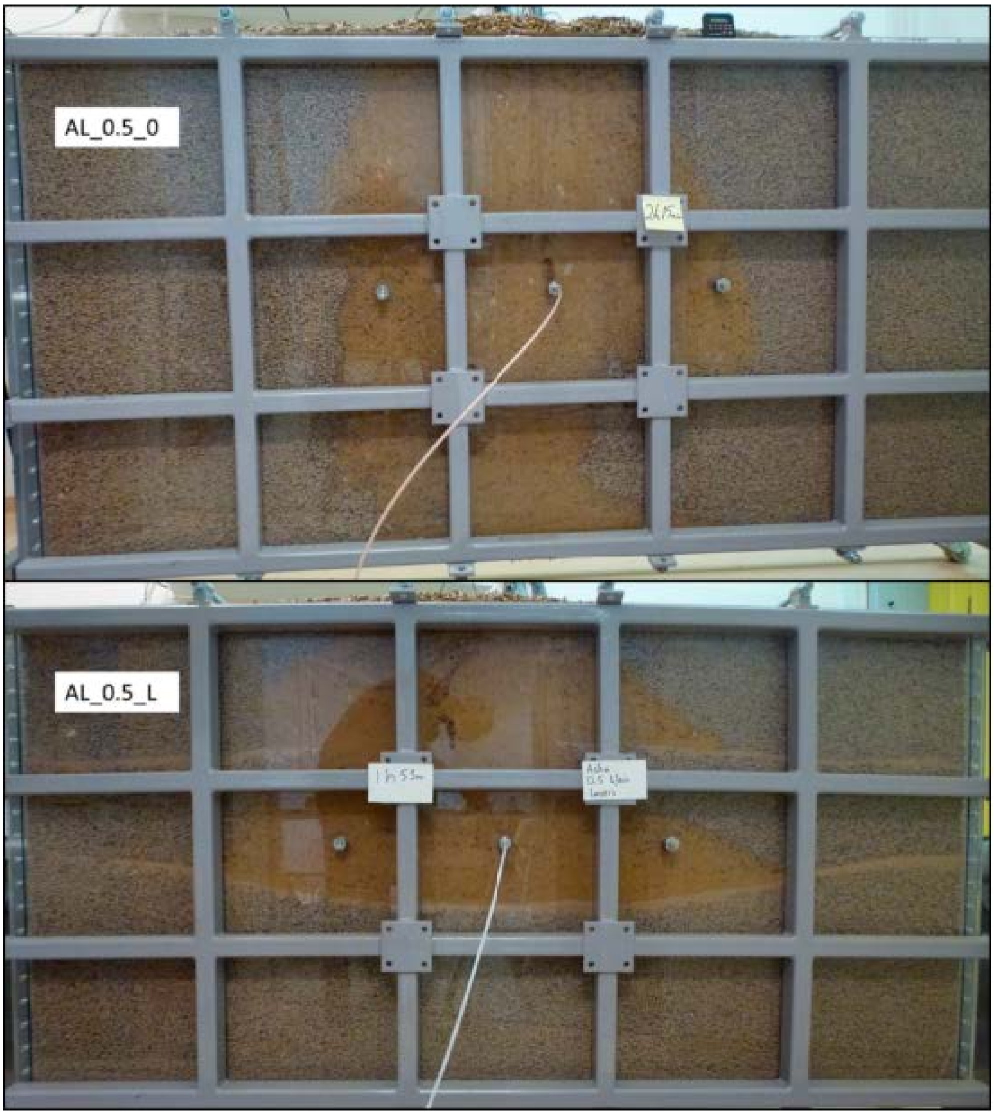

Figure 5-3. *Photos showing the wetting pattern at time for termination. Upper: Test performed with Asha pellets, inflow rate of 0.5 L/min and sieved pellets. Lower: Same as above but with fines placed in layers in the filling.*

Comments and recommendations

The investigations made regarding the influence of fines on the water storage capacity of a pellet filling have resulted in a number of comments and recommendations:

- The presence of fines in a pellet filling depends on if it is present already in the delivered batch or if it is created during installation. To be sure that one gets such a functional pellet filling as possible, it is recommended that all pellets manufactured should be sieved before installation. It is also recommended that the pellet installation equipment (blower, conveyor etc.), should be set so that as little fines as possible are created during installation.
- A simple procedure for testing manufactured backfill pellets regarding water storage capacity should be developed in order to ensure that the function of the pellet filling regarding this issue will be fulfilled during installation. The test may advantageously be based on the tube tests described in this chapter.
- The tests have shown that fines positioned as layers in a pellet filling temporarily will seal very efficiently, within a pellet filling, when water reaches the layer and thereby prevent water from flowing in that direction. This is a technique that could be used to direct the wetting in a certain direction. It has e.g. been discussed to use wetted layers of pellets to prevent water flow but an alternative could be to instead use layers of fines.

5.1.5 Steel tunnel tests

General

In this project, Water handling during backfill installation, five additional tests have been performed in the steel tunnel test equipment (half scale test equipment simulating a part of a deposition tunnel). The new tests were performed with the aim to investigate:

- the water storing capacity of sieved pellets i.e. all fines were removed before installation,
- to test the new glass fiber geotextile,
- to determine the limits regarding which water inflow rate that can be handled with this technique.

Test description

The test tunnel is made of steel, Figure 5-4. The nominal cross section area of the tunnel is 7.1 m^2 and the length is 6 m. The tunnel has a small inclination upward, towards tunnel face, to enable drainage of inflowing water away from the backfilling front (same inclination as in full scale, about 1 %. The usable length for the tests has been 4 m. The tunnel walls are not able to withstand the full swelling pressure of a completely backfilled tunnel and therefore, instead of backfilling the center of the tunnel, there is a wooden framework designed to deform and fail mechanically if the swelling pressures becomes too high. Since the blocks are assessed to be of less importance for the test results, this solution also saves time and money. The wooden frame is covered with a bentonite geotextile mat to prevent movement of any water that has managed to penetrate both the pellet and the block materials. Two different block stacking patterns have been used in the test series. The reason for this was lack of backfill block of the same size. The dimensions of the pellet filled gaps have, however, been almost the same. A difference from the full scale design is that there has not been any floor layer with pellets in the tests. The reason for this has been that the inflow point has been positioned on 1.5 meters from the floor and with the tested water inflow rates, the wetting has proceeded symmetrically around the inflow point and upwards against the crown via the geotextile i.e. a floor layer would not have been involved in the water storing.

The water used in the tests had 1 % salinity (TDS 10 g/l) by mixing 50/50 $NaCl/CaCl_2$. This water type corresponds well to the expected water at the time for installation (Forsmark and Olkiluoto).

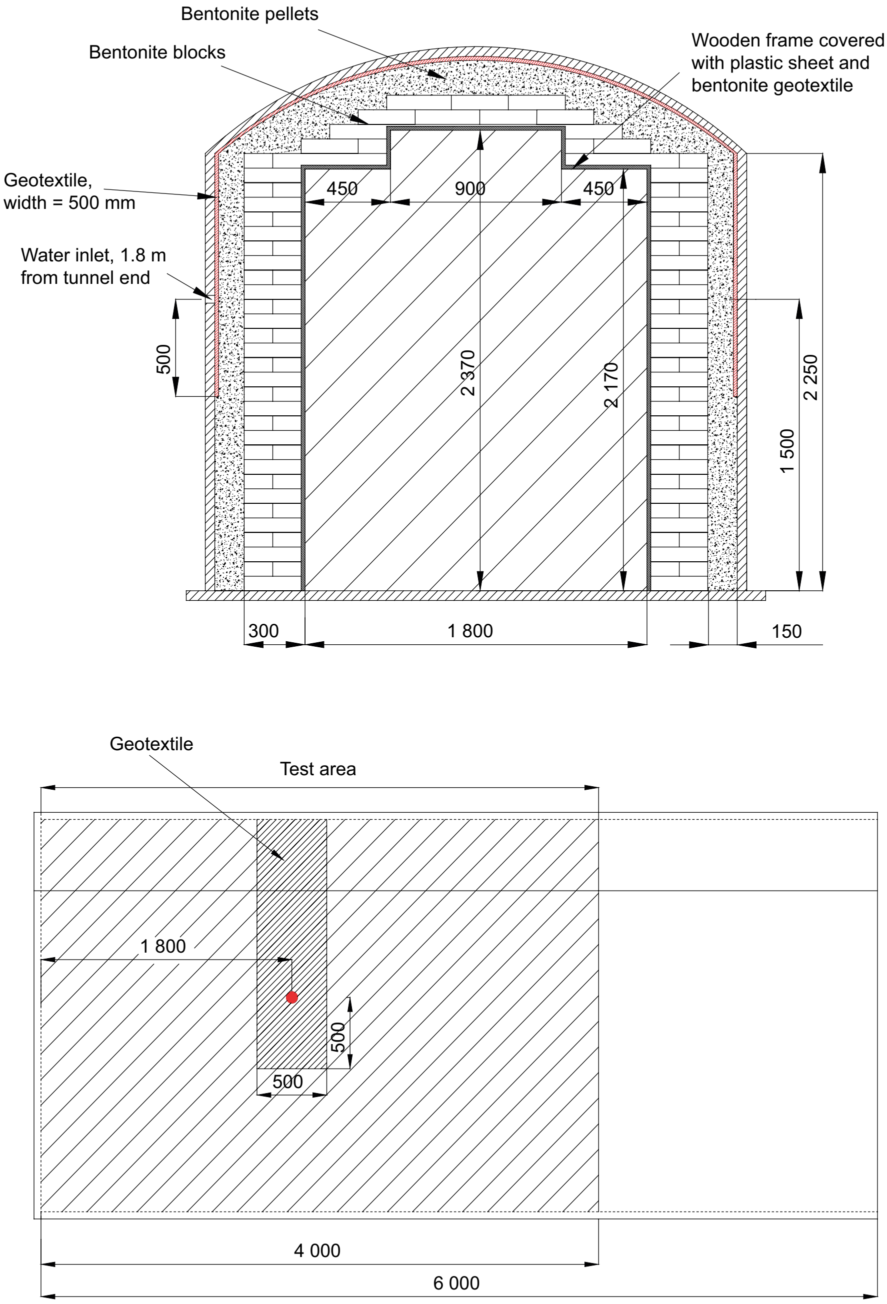

Figure 5-4. *Schematic of the ½-scale test tunnel. Upper: Cross-section showing the central mould of wood, the block stack and the pellets. Lower: Steel tunnel from the long side showing the position of the geotextile. The backfill front can be seen on the right side.*

Geotextile quality

The geotextile used in the tests is manufactured of 100 % glass fiber i.e. there is no organic material, see also Section 5.2.

The thickness of a geotextile sheet is about 1.2 mm and it has a weight of about 1 kg/m^2. The function of the geotextile as a water distributor was despite being thin considered to be good, but could probably be increased additionally if the geotextile e.g. is placed in double layers.

Test matrix

In total five tests were performed in the last steel tunnel test series performed within this project, see compilation in Table 5-2.

Table 5-2. Test matrix for the steel tunnel tests.

Test	Pellet	Flow rate	Geotextile	Comments
Test 1	Asha	0.25	No	Reference test
Test 2	Asha	0.25	Yes	Repeating 2012 test with glass fiber geotextile
Test 3	Asha	0.50	Yes	Repeating 2012 test with glass fiber geotextile
Test 4	Asha	0.50	Yes	Repetition of test 3, but performed using full scale backfill blocks.
Test 5	Asha	1.00	Yes	Extreme case. Including equipment for temporary drainage.

Results

A compilation of the results from the five tests together with important test data and outcomes are presented in Table 5-3.

Water pressure development

The required water pressure in order to keep the inflow rate at a constant level was regularly registered in all tests, Figure 5-5. The maximum pressure varies between 170 kPa (Test 1) and up to almost 250 kPa (Test 5). There is a trend in all five tests that the pressure increases somewhat with time, but the variation in pressure during test time is large. The oscillating behavior depends probably partly on local piping within the pellet filling i.e. the pellets swell and seal and this is followed by an increased water pressure that in turn leads to a local piping, but there is also an oscillation in water pressure that depends on the pump strokes needed to keep up the set flow rate. At maximum capacity the pump works with 160 strokes/minute. Since the pressure logging was made only every ten minutes the data set is not sufficient to do a detailed analysis. In Test 2, Test 3 and Test 4, there were very evident drops in pressure in conjunction with the water breakthroughs. During the test time of Test 5, the pressure sensor stopped working after about 18 hours test time.

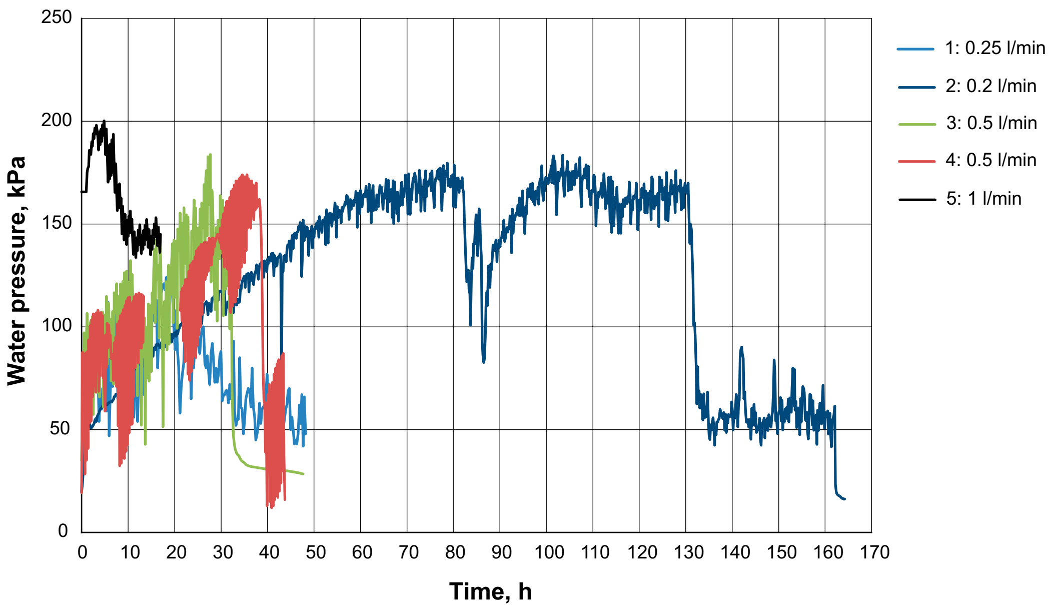

Figure 5-5. Water pressure plotted versus time for all five tests performed in the steel tunnel.

Table 5-3. Compilation of important test data and results.

Test no.	Test duration, h	Installed pellet mass, kg	w pellets at start (average), %	Dry density of pellet filling, kg/m^3	Water added to wall, kg	Flow rate, L/min	Geo-textile	Time to first outflow, h	Water stored before outflow, liters	Water stored before outflow, %	Amount of collapsed bentonite on tunnel floor, kg (wet)	Comments
Test 1	48	5835	17.7	1006	35	0.25	No	35	525	23.7	500	Reference test
Test 2	162	5862	18.0	1008	55	0.20	Yes	132	1762	79.5	696	Some leakages, inflow rate adjusted.
Test 3	32	5820	16.7	1012	68	0.50	Yes	32	960	43.3	65	Low quality blocks (30/70)
Test 4	43	5927	16.8	1012	66	0.50	Yes	38	1140	50.5	292	Repetition of test 3, but performed using full scale backfill blocks.
Test 5	64	5908	18.1	997	84	1.00	Yes	7	420*	18.6	891	Including test of temporary drainage.

* The given figure represent the time after closing the valves to the temporary drainage. In addition, 300–600 liters were stored during the drainage period (43 h).

Water storage capacity data from the steel tunnel tests

The first test in this test series was a reference tests, performed with an inflow rate of 0.25 L/min and without any geotextile installed. In this test 525 liters were stored before outflow occurred. The second test was performed with the same inflow rate (was later adjusted to 0.2 L/min depending on leakages from the steel tunnel) but with geotextile installed. In this test, the water storage increased to 1 955 L/min before breakthrough at the front.

Test 3 and Test 4 were both performed with an inflow rate of 0.5 L/min and with geotextiles mounted on the "rock" walls. The rather early water breakthrough in Test 3, after 32 hours test duration, was believed to partly depend on the low block quality (blocks manufactured with a mixture of 30 % bentonite and 70 % crushed rock were used for this test). The observed leakage came through the gaps between the blocks, see Sandén (2016) and therefore it was decided to repeat this test but instead use backfill blocks manufactured of pure bentonite. In the earlier test series performed in the steel tunnel, it was noticed that the blocks only have had a minor influence on the sealing and water storage and this was originally the reason for exchanging the central parts of the block stack to a wooden frame covered with geotextile and plastic, see Figure 5-4. However, it seems that the block properties, after all, have a certain significance on the test setup. In Test 4 the water breakthrough occurred after 38 hours test. During this time, 1 140 liters of inflowing water were stored in the pellet filling. The photo provided in Figure 5-6 shows the first water breakthrough and the photo in Figure 5-7 shows the backfill front at time for termination.

The last test, Test 5, was performed with an inflow rate of 1 L/min and with geotextile mounted on the "rock" wall. This test also included a function test of equipment for temporary drainage, see description in Section 5.3. The drainage phase did last for 43 hours and during this time approximately 2 000–2 250 liters were drained away. When the valves to the drainage pipes were closed, all inflowing water was stored in the pellet filling. At this high inflow rate it took about seven hours before a breakthrough occurred in the backfill front. During these seven hours, 420 liters were stored in the pellet filling. In conjunction with the dismantling of the test, the roof was lifted away. Figure 5-9 and Figure 5-10 shows the wetting pattern at the crown of the test length.

Water storage data from the performed tests are provided in Table 5-3. Figure 5-8 shows contour plots of the wetting pattern seen on the surface closest to the developed walls and roof for all five tests performed in the steel tunnel. The darker rectangular areas indicate the position of the geotextile and the stars indicate the position of the inflow point. The white areas shows where no samples were taken due to bentonite collapse (bentonite fell down on floor).

Erosion

In the original planning of the test series, it was decided to perform a rough estimation of the total amount of bentonite eroded during test time, by collecting bentonite that had settled in the ditch in front of the steel tunnel. The pump positioned in the ditch was placed in a box so that it was only pumping clear water that was flowing over the walls of the box. However, the water that flowed out from the tests and reached the ditch was seemingly clear and no separate measurement of the bentonite content was made.

All five tests performed, ended with a collapse of bentonite, pellets and/or blocks, that fell down on the floor in front of the backfill face. The amount of bentonite was roughly determined by weighing (wet mass). The data from these measurements are provided in Table 5-3.

Figure 5-6. *Photo showing the first water breakthrough in Test 4.*

Figure 5-7. *Photo showing the backfill front of Test 4 at time for termination.*

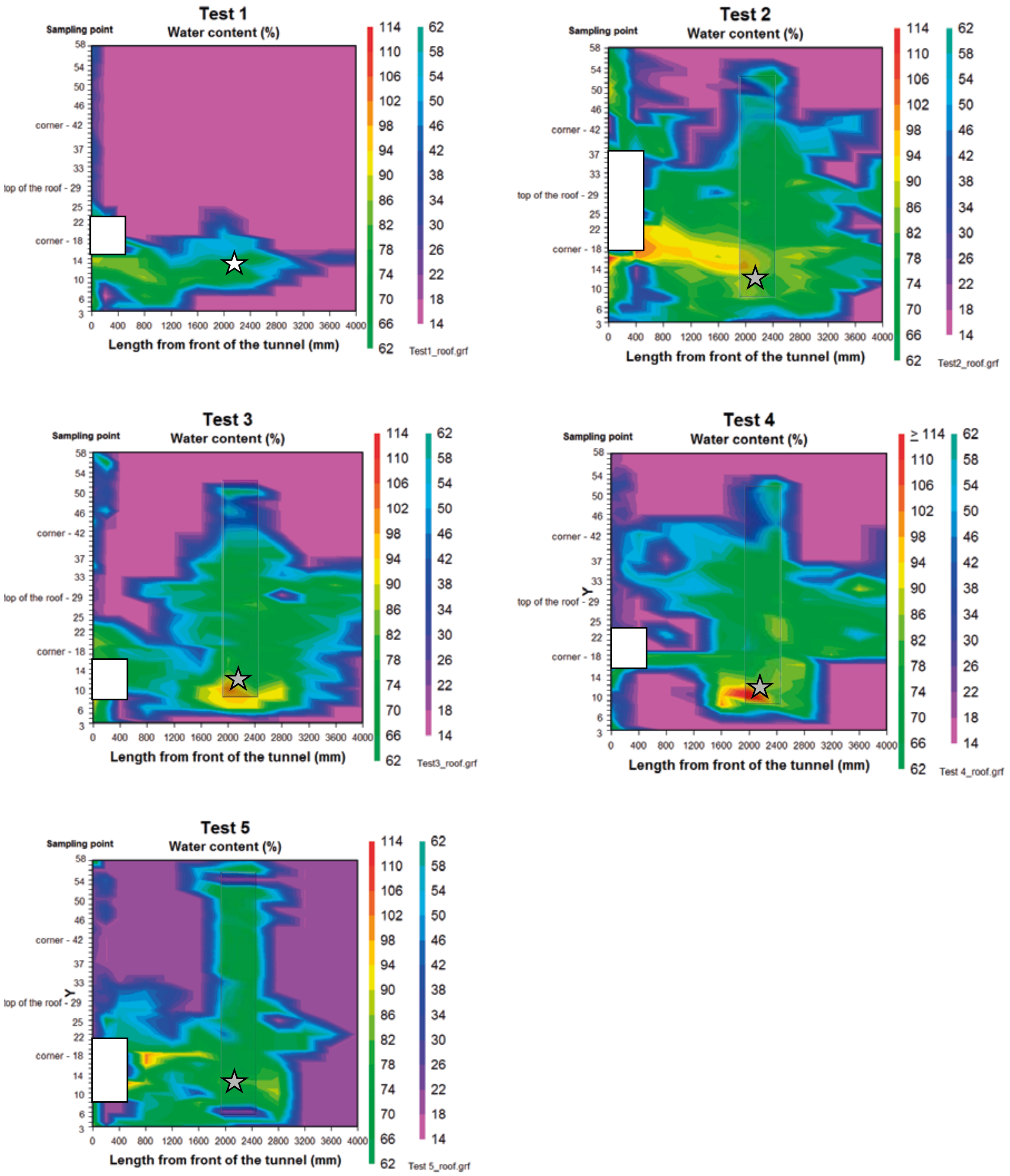

Figure 5-8. *Contour plots showing the wetting pattern seen on the surface closest to the developed walls and roof for all five tests performed in the steel tunnel. The white boxes shows the areas where no samples could be taken due to material loss after the breakthrough. The darker rectangular areas indicate the position of the geotextile and the stars indicate the position of the inflow point.*

Figure 5-9. *Photo showing the pellet ceiling after having removed the steel roof in Test 5.*

Figure 5-10. *Photo showing a cross section of the pellet filling at the top of the tunnel in Test 5. It is obvious that the inflowing water has followed the geotextile up over the top and down on the other side of the tunnel (inflow side to the left in the photo).*

Artificially wetted wall

In order to take advantage of the available test volume in the steel tunnel, the backfill installation in all five tests has ended with an artificially wetted wall built of pellets. Water was added at the nozzle during installation and this resulted in that the pellets were "glued" to each other. The amount of water added has varied between 35 and 84 liters in the tests. The thickness of the wall has been estimated to be 10–20 cm.

The building of artificially wetted pellet walls is considered as a separate water handling method and is also investigated within this project. It is believed that when water flowing from the inside of a pellet filling hits the wetted wall, which is much tighter than the dry pellet filling, the water flow will turn and flow in another direction. It is judged that the wetted wall present in the steel tunnel test also have influenced the results regarding water storage capacity. How great the impact has been is, however, not clear since the wall was not supported by pellets from the outside, as it will be in the full scale.

Investigations regarding artificial wetting of pellet layers are still ongoing, see Section 5.6. The results of the initial tests indicate that the technique can be used to delay early water breakthrough at the backfill front but it is obvious that more tests are needed. The technique has been used in all steel tunnel tests where the effect of geotextile has been investigated. It is therefore for the time being recommended that geotextile and artificial wetting are used together i.e. when geotextile is installed in a section also a wetted pellet wall should be built.

5.1.6 Compilation of results from tests performed within different projects

General

Tests have been performed in different scales and with different types of test equipment, during the last ten years, with the main objective to investigate different processes that may occur during installation of backfill material in a deposition tunnel, such as erosion of bentonite and how inflowing water is either stored or flowing in a pellet filled gap. The tests have mainly been performed using bentonite pellets manufactured by extrusion, since this pellets type have been found to be superior regarding water storing properties (Andersson and Sandén 2012). This chapter provides a compilation of results from the tests. The presented test results originate both from old tests but also from new test series performed to further increase the understanding especially regarding the issue how the presence of fines affects the storing of inflowing water in a pellet filling, see test description in Section 5.1.4.

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

1. Concrete pipe tests. Tests performed in scale 1/12. The tests are reported in Dixon et al. (2008a).
2. Artificial slot tests. Tests have been performed in a number of different test series. The tests are reported in Sandén et al. (2008), Andersson and Sandén (2012) and Sandén and Jensen (2016).
3. Steel tunnel tests. Tests performed in half scale. The tests are reported in Dixon et al. (2008b), Koskinen and Sandén (2014) and in Sandén (2016).
4. Full scale test in TASS tunnel. This test is reported in Johnsson and Sandén (2013).

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

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

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

Wetting pattern and water storage capacity

The water storing capacity of a backfill pellet filling is mainly depending on the pellet properties and of the water inflow rate. Different water inflow rates results in different wetting pattern and the time to first outflow will vary depending on how much water that is stored before the wetting front reaches the backfill front. In the performed tests, the size and shape of the test equipment influences the results, but it is assessed that the wetting pattern and its flow dependence can be studied in different scales (see also Section 5.1.7, paragraph *Scaling of test results to full scale conditions*).

The photos provided in Figure 5-11 shows three examples of different wetting patterns; "Symmetrical/Upwards wetting", "Symmetrical wetting" and "Downwards wetting". The photos are taken from the tests performed at Clay Technology with the B+Tech type test equipment described in Section 2.4.

An assessment of the resulting wetting pattern or wetting behavior has been done for all tests listed in Chapter 2. The graph provided in Figure 5-12 shows the results from the assessments as a function of the inflow rate. The wetting behavior has been divided into five different scenarios. As shown in the graph, there is a large variation in results, but a number of clear trends can be identified:

- Upwards wetting. The wetting proceeds mainly upwards from the inflow point. This behavior has mainly been seen in other pellets types (compacted pellets) when exposed for inflow rates < 0.1 l/min (Sandén and Börgesson 2014).
- Symmetrical/Upwards wetting. The wetting proceeds as a combination of upwards from the inflow point and symmetrically from the inflow point. The behavior has mainly been seen when the pellet filling has been exposed for low and medium high inflow rates, approximately 0–0.25 l/min.
- Symmetrical wetting. The wetting proceeds almost symmetrically around the inflow point. The behavior has mainly been seen when the pellet filling has been exposed for low and medium high inflow rates, approximately 0–0.5 l/min.
- Symmetrical/Downwards wetting. The wetting proceeds as a combination of downwards from the inflow point and symmetrically from the inflow point. The behavior has mainly been seen when the pellet filling has been exposed for low and medium high inflow rates, approximately 0.2–1.0 l/min.
- Downwards wetting. The wetting proceeds mainly downwards from the inflow point. The behavior has mainly been seen in pellet fillings when exposed for inflow rates between 0.6–1.0 l/min or when pellets with very high water content have been used in the tests.

From the results in the graph provided in Figure 5-12, it seems that if the Asha pellets (red dots) are more prone to symmetric/upwards wetting while the Cebogel pellets (green dots) are more prone to symmetric/downwards wetting. The results from the steel tunnel tests performed with Cebogel pellets (green squares) seems, however, to be more similar to the results achieved from the steel tunnel tests performed with Asha pellets. This depends probably on the fact that the Cebogel pellets used in these tests had lower water content, 16 %, and thus had a higher affinity to take up water, while the Cebogel pellets used in the other tests have had a water content of 19–20 % (see also the suggested requirements on pellets properties in Section 5.1.8). It seems thus that relatively small differences in pellet properties can affect the wetting behavior of a pellet filling. There is probably also an influence of the different geometry of the different test types on the results.

The worst behavior from a water storage point of view, is if all inflowing water flows downwards in the pellet filling and then along the floor out to the backfill front, see the lower photo in Figure 5-11. The wetting behavior that should be pursued is a symmetrical wetting around the inflow point. With this wetting pattern the amount of stored water in the pellet filling can be very large. The upwards wetting only seems to occur at very low inflow rates which means that this will not anyway be a problem to handle.

Figure 5-11. *Upper: Photo showing an example of "Symmetric/Upwards"wetting. Middle: Photo showing an example of "Symmetric" wetting. Lower: Photo showing an example of "Downward" wetting.*

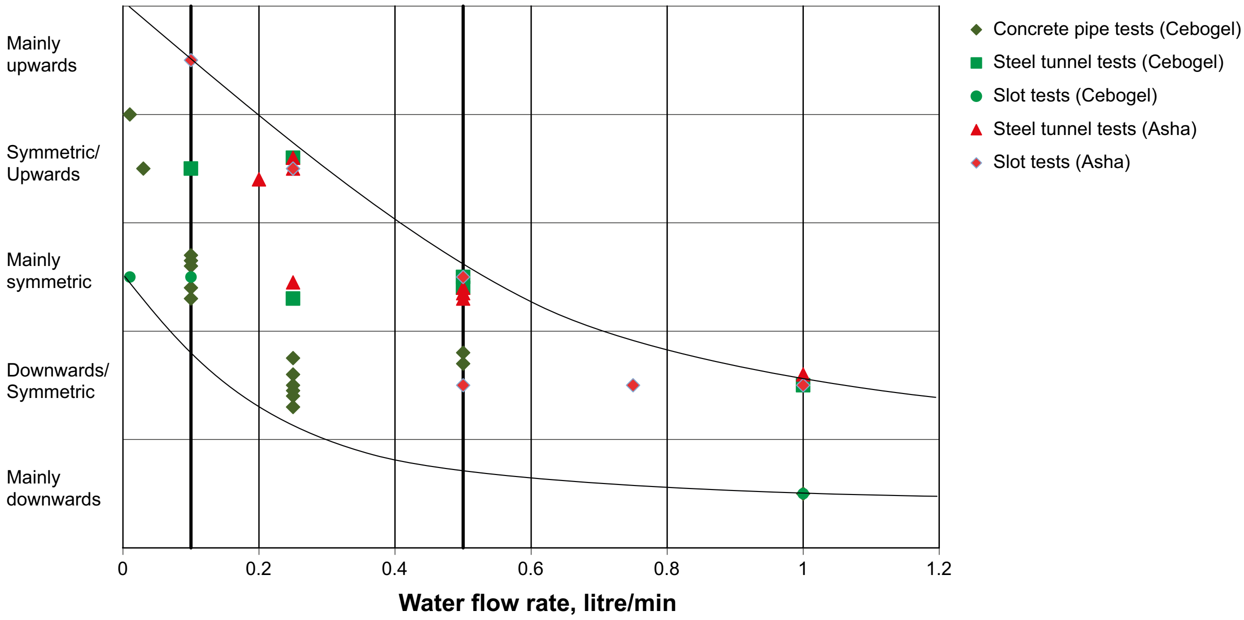

Figure 5-12. *Graph showing the wetting pattern assessed from the results from the tests presented in Chapter 2 plotted versus flow rates. The data points were spread in vertical direction for each category, in order to improve the clarity of the graph.*

The graph provided in Figure 5-13 shows the amount of water stored before outflow occurs plotted versus different inflow rates for the different test types. For the individual test type (different colors) it could be noted, in most cases, that the water storage capacity seems to decrease somewhat for the higher inflow rates i.e. above 0.5 l/min, but also in this graph, the spread in results is large. It should be noted, when comparing the results from different test types with each other that the steel tunnel tests and the single test in the TASS tunnel also included a wetted pellet wall, an effort that probably have increased the water storing capacity, see also discussion in Section 5.1.5.

Influence of geotextile on the water storage behavior

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

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

An important difference between the test series is that the tests performed during 2008, included two tests in each test setup i.e. the steel tunnel was divided in the middle and inflows were applied on both sides. However, as mentioned earlier, no geotextile was used in these tests meaning that the wetting from an inflow point in general only affected the side wall and in some tests also partly the crown (Åkesson et al. 2017, Appendixes 1–6). It has therefore been judged that these tests can be used as reference tests in order to determine the effect of using geotextile.

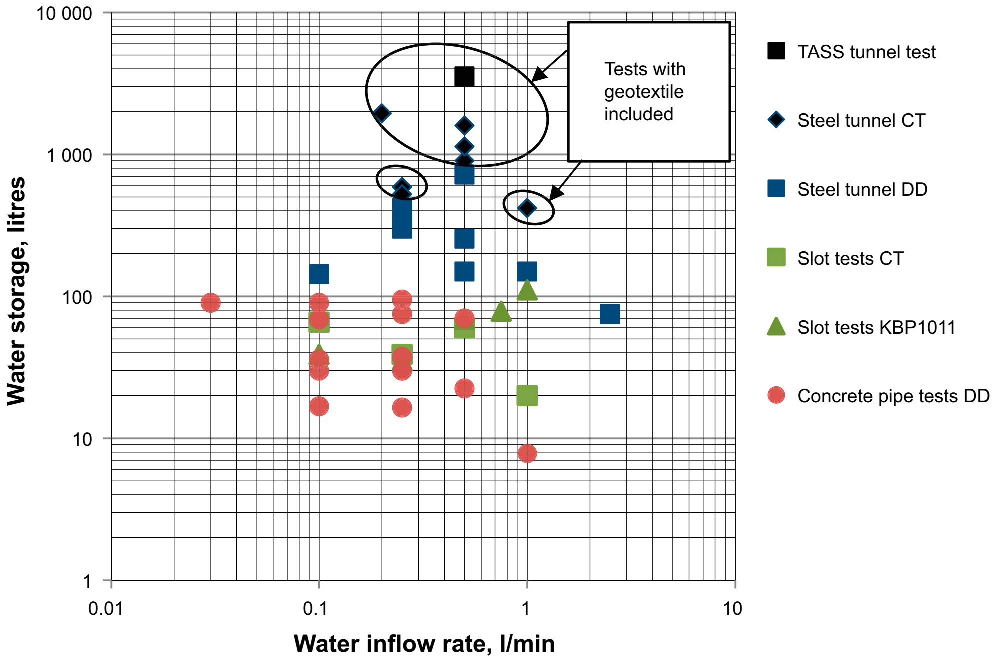

Figure 5-13. *Graph showing the amount of water stored before outflow as a function of the inflow rate. The results are presented for the different test types presented earlier in this chapter.*

In order to study the effect of using geotextile to increase the water storage capacity, the results from all steel tunnel tests regarding water storage capacity before the first outflow occur, are presented in Figure 5-14 as a bar graph. The bars with a "G" on the top indicates that geotextile has been included in the test setup. As shown in the graph, there is an obvious effect of using geotextile to increase the water storage capacity. The effect seems, however, to vary a lot depending on flow rate and probably also somewhat in a random manner:

- **Inflow rate 0.25 l/min**. Two tests were performed during 2008 (no geotextile) and in addition two reference tests without geotextile were performed 2012 and 2015 respectively. The time to first water breakthrough was 21 and 28 hours respectively for the two tests performed 2008. The time to first breakthrough was 30 and 35 hours respectively for the tests performed 2012 and 2015. These figures should be compared with the times achieved when also using geotextile in the test setup; 39.5 hours for the test from 2012 and 132 hours for the test from 2015. The variation in results have been large at these rather low inflow rates, especially the result from the test that was performed 2012 (39.5 hours to first outflow) is assessed to be somewhat strange. One explanation could be that the pellets in this test series were not sieved before use and this may have influenced the results in a negative way (later tests, presented by Sandén and Jensen (2016), have shown that fines have a tendency to end up in layers in the pellet filling during installation, hindering the wetting process to continue past the layer.)
- **Inflow rate 0.5 l/min**. Two tests were performed during 2008 (no geotextile). The time to first water breakthrough was 5 and 8.5 hours respectively for these tests. These figures should be compared with the times achieved when also using geotextile in the test setup; 53.3 hours for the test from 2012 and 32 and 38 hours respectively for the two tests from 2015. The variation in results is large also for this flow rate but although somewhat more consistent.
- **Inflow rate 1.0 l/min**. One test was performed during 2008 with this rather high inflow rate and with no geotextile. The time to first water breakthrough was 2.5 hours for this test. This figure should be compared with the times achieved when also using geotextile in the test setup; 7 hours for the test from 2015.

As described above, there is an obvious effect of using geotextile to increase the water storage capacity (see Figure 5-14). The photo provided in Figure 5-15, shows how the inflowing water has followed the geotextile up over the crown and down on the other side of the tunnel (inflow side to the left in the photo). However, as shown in the photo, there is still a remaining dry layer of pellets close to the block stack.

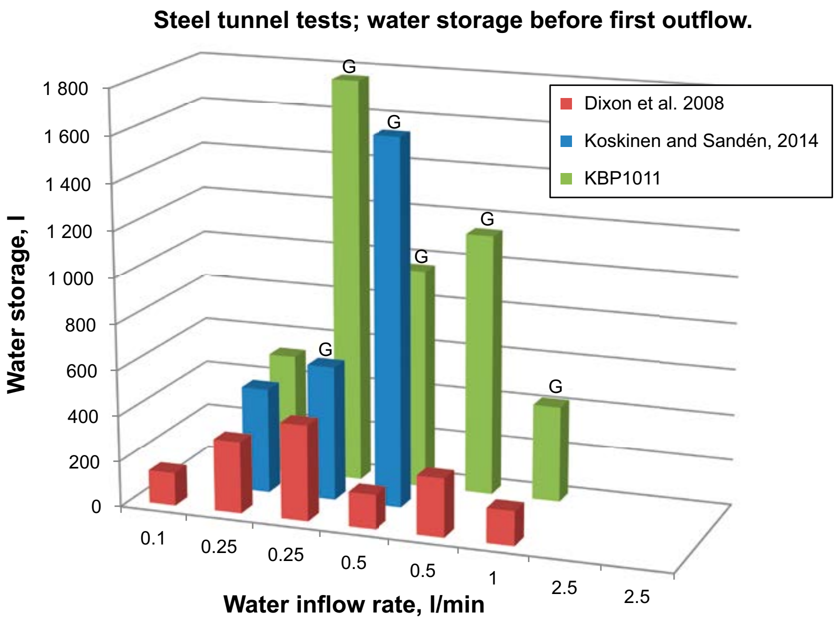

__Figure 5-14.__ Graph showing the determined water storage in a pellet filling installed in the steel tunnel test equipment plotted versus water inflow rate. The bars with a "G" at the top indicates tests performed with geotextile.

__Figure 5-15.__ Photo showing a cross section (close to the installed geotextile) of the pellet filling at the top of the tunnel in Test 5. It is obvious that the inflowing water has followed the geotextile up over the crown and down on the other side of the tunnel (inflow side to the left in the photo). However, as shown in the photo, there is a remaining dry layer of pellets close to the block stack.

Inflow behavior in steel tunnel tests

The graph provided in Figure 5-16 shows the results from the steel tunnel tests performed within three different projects (see description in the paragraph *General* in this section). The test layouts have been similar for these three test series even if there are some differences that probably have influenced the results somewhat:

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

The green triangular dots show the results from the tests performed with Cebogel pellets (no geotextile was used in this test series). These tests should be compared with the two tests performed with Asha pellets (red diamonds), that also were performed without any geotextile. As shown in the graph there is a certain spread in results but also a clear trend that the time to first outflow decrease with increased inflow rate. It seems, however, as if the water storage capacity of the Cebogel pellets is somewhat lower than of the Asha pellets. The pellets used in these tests had all rather similar water content, 16 % for Cebogel and between 16 and 18.7 % for Asha.

The black dots (diamonds) show the results from the tests performed with Asha pellets and geotextile. There is basically one of the geotextile tests that deviates from the other and that is the test performed with an inflow rate of 0.25 l/min. This test (from 2012) resulted in a first outflow after 39 hours which was considered early. One explanation could be that the pellets in this test series were not sieved before use and this may have influenced the results in a negative way (later tests have shown that fines have a tendency to end up in layers in the pellet filling during installation, hindering the wetting process to continue past the layer (Sandén and Jensen 2016).

5.1.7 Conceptual model of water storage

General

As a basis for the calculations regarding available time before inflowing water reaches the backfill front face, a simplified conceptual model is suggested. The model is based on results from the laboratory tests and the scale tests described in Section 5.1.6. The conceptual model consists of two parts: 1) A number of assumptions describing how inflowing water is flowing and how it is affecting a pellet filling and 2) A description of how inflowing water is stored in a pellet filling in a certain pattern depending on the inflow rate, see detailed description in Åkesson et al. (2017).

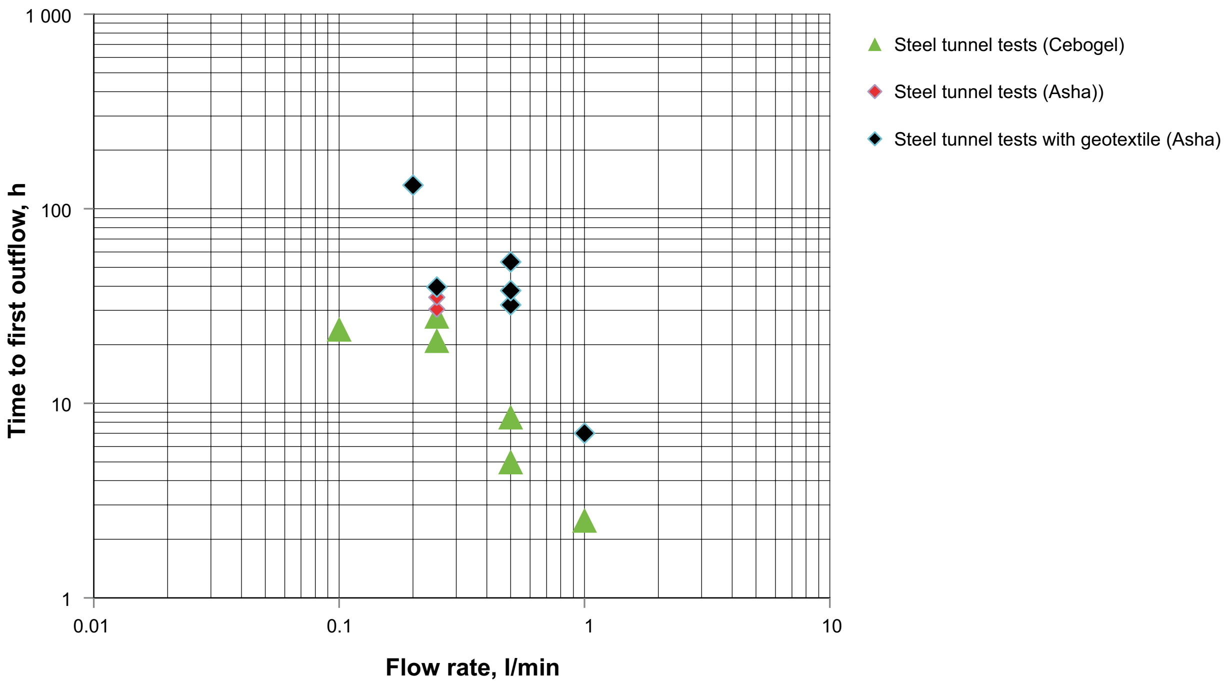

Figure 5-16. *The time to first outflow plotted versus flow rate for the tests performed in the steel tunnel.*

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

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

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

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

Water transport in a pellet filling-general assumptions

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

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

Conceptual model of inflow behavior for six mm extruded pellets made of Cebogel QSE or Asha

Evaluation of the results from all tests performed with pellets where a water inflow has been applied, see Chapter 2, have resulted in an assumption of four different wetting scenarios of the pellet filling that can occur, Figure 5-17. Depending on the water inflow rate different scenarios will occur. In the scenarios described in Figure 5-17 it has been considered that water is flowing into the pellet filled gap from a point inflow, situated on the wall in the middle of a six meter long backfill section.

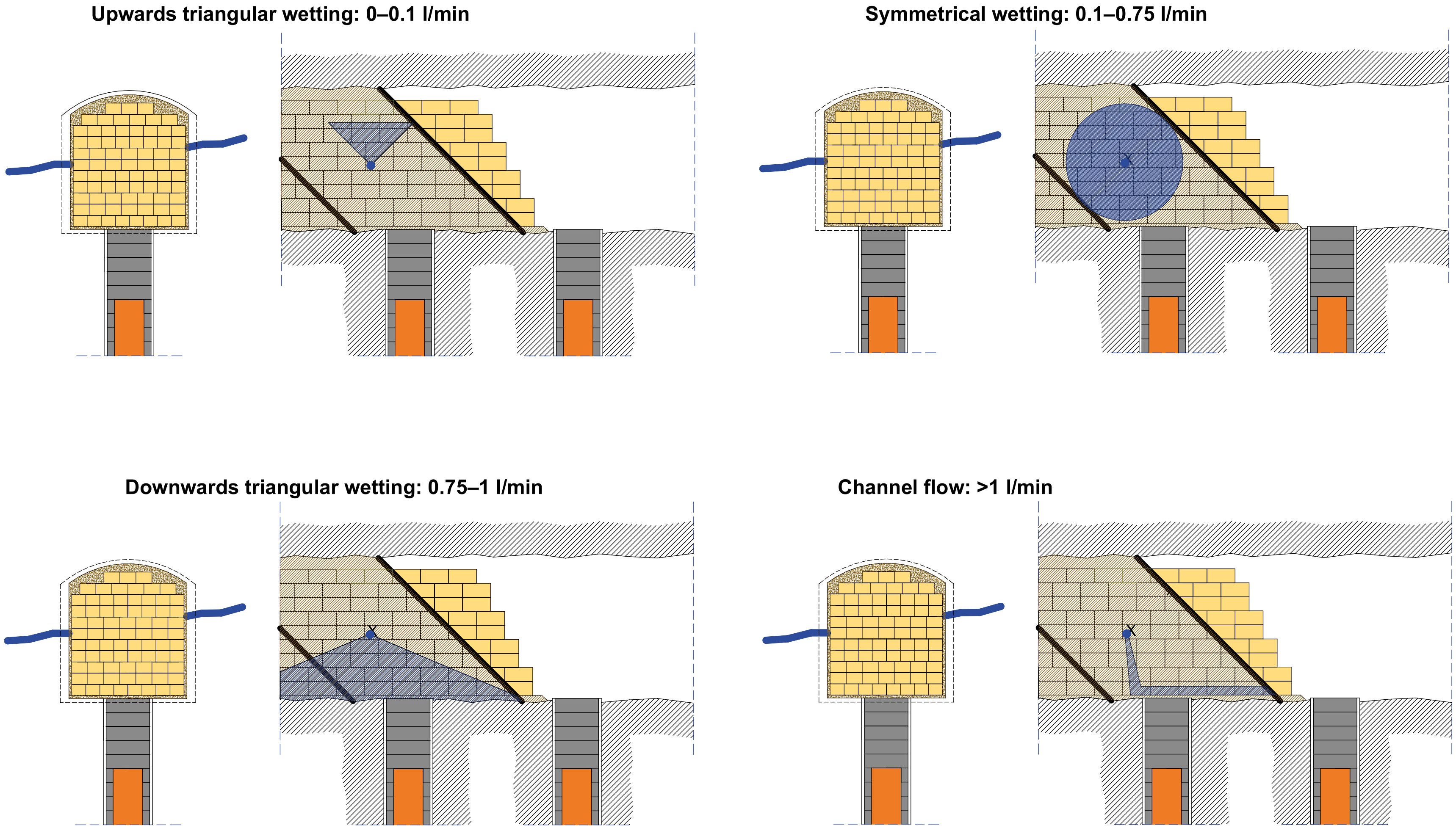

Figure 5-17. *Schematic drawing showing the different wetting behavior identified for different water inflow rates.*

The different wetting behaviors, result in different available volume (macro voids between the individual pellets) for water storing, before water will reach the backfill front. This means that for a certain water inflow rate the available volume for water storing is known and this makes it possible to calculate the time to the first outflow from a 6 meter long section (or a steel tunnel test). This has been the basis for the mathematical model developed; see further description in Chapter 6. In a full scale installation, it is of course important that the installation proceeds faster than the wetting front rate.

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

Scaling of test results to full scale conditions

The test results, from steel-tunnels and the TASS tunnel, were scaled to full-scale conditions. This was performed by multiplication of the experimental time to first outflow value with a specific ratio that is depending on flow rate, flow patterns and corresponding water filled volumes. The tests including geotextile were scaled using the length of the geotextile and the length of the test setup. A detailed description of the scaling is provided in Åkesson et al. (2017).

Relations between time to first outflow and flowrates, as implied by the conceptual model, were included as lines together with the scaled test results in Figure 5-18. The black lines show the conceptual model for water storage in a 6 meter section and the dotted line shows the conceptual model for water storing when using geotextile.

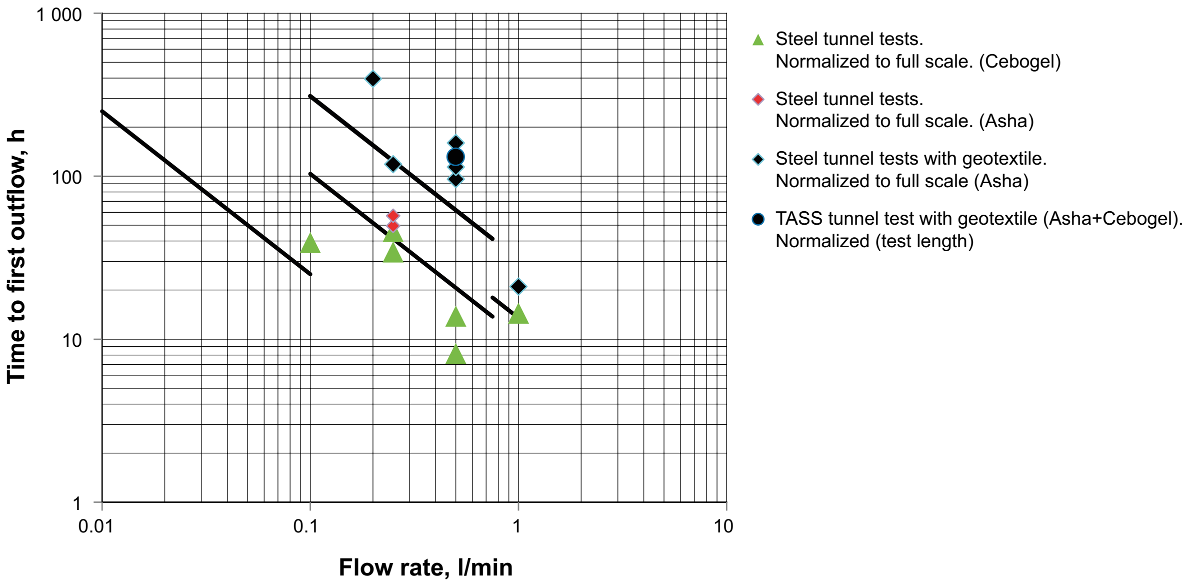

***Figure 5-18.** Graph showing the time to first outflow plotted versus flow rate for the steel tunnels. The results (i.e. the shown data) have been normalized to full scale. The black lines show the conceptual model for water storage in a 6 meter section and the dotted line shows the conceptual model for water storing when using geotextile.*

5.1.8 Pellet properties

The water storage capacity of a pellet filling depends largely on the shape and size of the individual pellets but also on the water content, the density of the individual pellet and the amount and distribution of fines. Tests performed within the project System design of backfill, in order to optimize the water storing capacity of the pellet filling (Andersson and Sandén 2012), showed that extruded pellets with a diameter of 6 mm were superior regarding water storage capacity compared to the other pellet types included in the test matrix (the investigation included three materials, two pellet manufacturing methods and two pellet sizes for each manufacturing method).

The results from the new test series performed within the project "Water handling during backfill installation" have shown that it will be necessary to put up requirements on the pellet properties regarding water content and density. The Cebogel QSE batch delivered in 2015 was found to have completely different properties regarding water storing behavior and later laboratory tests showed that the properties of these pellets were completely different depending on a high water content, about 25 %, and low dry density of the individual pellet, about 1 600 kg/m^3.

When manufacturing pellets with the extrusion method (the pellet type used in this investigation) it is important to have an optimal water content of the raw bentonite. However, if the water content is too high, it will be impossible to reach the high densities that are necessary in order to achieve the pellet properties needed.

In earlier performed test with Asha and Cebogel QSE pellets, see compilation of data provided in Åkesson et al. (2017), where the water storage properties have been assessed to be high, the water content have been between 12 and 20 % and the dry density of the individual pellets has been between 1 810–2 000 kg/m^3, see e.g. Dixon et al. (2008a, b) and Andersson and Sandén (2012). These figures are recommended to serve as a guideline for the requirements on the pellet properties.

5.2 Geotextile

5.2.1 General

The principle behind this water handling method is to distribute the inflowing water so that a larger area of the pellet fill receives the inflowing water and a larger volume of the pellet fill will therefore be available for water storage. In general, the use of a larger part of the pellet volume for water storage is foreseen to delay the water breakthrough at the backfill front.

The development work of the water handling method including geotextile, see Section 5.1.5, has resulted in increased knowledge regarding this technique and its performance. The test results are reported in Sandén (2016).

5.2.2 Functional requirements

1. The method should distribute inflowing water over a larger area and by that increase the water storage capacity of a pellet filling. Based on results from tests in different scales, the method is judged to work for water inflow rates between 0.25 and 1 L/min.
2. The geotextile should be able to be fastened tight on the rock walls. It should also have sufficient strength to withstand the pellet installation process. In the performed tests, shotcrete equipment has been used for the pellet installation. This method is assessed to be rather tough for the geotextile.
3. The geotextile should be manufactured of material that has no or very low content of organic material.

5.2.3 Design description

The influence of using geotextile to increase the water storage capacity of a pellet filling has mainly been investigated in the steel tunnel test equipment at Äspö HRL, see sections 5.1.5 and 5.1.6.

The geotextile is mounted so that it is completely covering the area (water bearing fracture zone) from where the water is flowing. The water will use the geotextile as preferred pathway before entering the pellet fill where the flow resistance is higher. This means that the water inflow will be distributed over all or almost all of the geotextile area.

Depending on where the inflow points are positioned, the geotextile should continue either up on the ceiling and downwards on the other wall (for inflow points on one of the walls) or up along both walls (for inflow points positioned on the floor), to distribute the water over as large area as possible. The geotextile should however not expand along the tunnel length so that the position of two deposition holes are hydraulically connected.

It is not known how the wetting proceeds from one installed backfill section to another. The use of geotextile distributes the inflow over a larger area locally but it is possible that the distributed water flow eventually will gather and accumulate to a more concentrated flow. A possible way to handle this uncertainty could be to install geotextiles at a number of positions in a deposition tunnel regardless if these positions are wet or dry. Water flowing from backfilled sections can be expected to be distributed again when reaching a new geotextile section, see also Åkesson et al. (2017).

The geotextile quality that was tested and also proven to work in this project has the trade name "TG1000CS" and is manufactured by HKO Heat Protection Group. The material is 100 % glass fiber i.e. there is no organic material.

5.2.4 Post closure aspects

The suggested water handling techniques with geotextile placed on the rock walls were discussed at a meeting with experts on post closure safety from Posiva and SKB, see also Chapter 7. A number of open issues were raised at the meeting:

1) **Material**. The width, length and mass of the installed geotextile should be registered. The amount of geotextile is estimated to be relatively small and only used locally. However, all foreign material left in the tunnel should be well characterized. (The geotextile has a weight of about 1 kg/m^2. Installation of geotextile in one section with a width of 1 m and a length of 14 m, ceiling and two walls, will thus result in 14 kg of geotextile. The expected number of water bearing fracture zones in Forsmark and Olkiluoto in the deposition tunnels is low, in most cases 1 to 3 fracture zones per deposition tunnel (Joyce et al. 2013) which means that the amount of geotextile will vary between 14 and 42 kg in most of the tunnels).
2) **Hydraulic conductivity**. What is the resulting hydraulic conductivity after backfill swelling against the geotextile and following homogenization? After installation the hydraulic conductivity will be high in the geotextile (the water is supposed to flow in the geotextile instead of in the bentonite pellet filling). The properties after swelling and homogenization are not known.

5.3 Temporary drainage

5.3.1 General

Geotextile alone (see Section 5.2) is assessed to increase the water storing capacity of a pellet filling for inflow rates between 0.25 and 1 L/min. A method that can be used for the inflow flow rates between 0.5 and 1 L/min, for further delaying the inflowing water from reaching the backfill front is to connect a removable drainage pipe to the geotextile.

The suggested design can be used to allow for short-term drainage of inflow water. The design idea is to drain water from a water bearing structure through a pipe while backfill installation continues. When the backfill installation has reached the end of the pipe it is removed so that there is no remaining open flow path in the tunnel. With this method, the backfill installation gains time to install a buffering pellet volume before the inflowing water starts to affect the backfill.

5.3.2 Functional requirements

1. The method should temporarily drain inflowing water through the pellet filling. The method should work for water inflow rates between 0.5–1.0 L/min.
2. The test method implies that a minor amount of steel (or other possible materials) and gravel has to be left in the deposition tunnel. The design should be made so that this amount of steel and gravel is minimized.
3. The drainage tube must be able to be retrieved after having fulfilled its task.

5.3.3 Design description

General

A drainage pipe is temporarily attached to geotextile since it is necessary to remove it after use. This means that there is a limit of the maximum length. If the pipe is too long, the force required to pull it out will be too high for the approach to be practical.

The temporary drainage design includes the following components:

1. Geotextile.
2. Water collector.
3. Drainage pipe.
4. Connection between collector and pipe including a spring-loaded valve.

Functionality tests

In conjunction with one of the steel tunnel geotextile tests, a new functionality test of the temporary drainage equipment was made. In this test the water inflow rate was set to 1 L/min. Water collectors and drainage tubes were mounted on both sides of the tunnel. The drainage period lasted for 43 h and after that, the valves mounted at the ends of the drainage tubes were closed and the inflowing water could instead fill up the pellet filling. This test is assessed to well simulate a real situation that could occur during backfilling of a deposition tunnel.

The temporary drainage design worked very well also in this test. The rather high inflow rate of 1 L/min was largely drained away through the water collector and the pipes during 43 hours. This extra time could in a real situation be valuable in order to prevent water from reaching the backfill front. During 43 hours almost two new sections of backfill can be installed i.e. 12 meters.

Conclusions

The performed tests have shown that the suggested design for a temporary drainage of a water bearing fracture zone works very well. In both tests there has been a short delay before water starts to flow out through the drainage pipe. This depends probably on the fact that the pellets closest to the inflow point is wetted initially, but as the wetting proceeds, the bentonite swells and the flow resistance increases in the filling which means that it is easier for the water to flow through the geotextile into the water collector and further out through the drainage pipe.

It is required from a long term safety point of view that the design includes that the drainage pipe must be retrieved since it is not allowed to have a highly conductive zone along the deposition tunnel. The maximum length of a drainage pipe that should be retrieved is estimated to be 24 meters. The pipe can be pulled out from the adapter (O-ring seal around the outside of the drainage pipe). The water collector including pipe adapter must, however, be left in the repository.

5.3.4 Post closure aspects

The suggested water handling technique with a temporary drainage pipe was discussed at a meeting with experts on post closure safety from Posiva and SKB. It was suggested that the water collector box should be optimized so make both the collector volume and its void volume as small as possible. These demands have been fulfilled in the new suggested design.

The drainage pipe, leading water from the fracture zone, through the pellet filling, will be retrieved after use, but the water collector will have to be left.

5.4 Water Storing Section, WSS

5.4.1 General

The design idea behind this water handling method is that a section of a tunnel will be used to store water flowing mainly from a water bearing structure with water inflow 1–5 L/min but also from the inner backfilled part of the tunnel. The storage is achieved by building a pellet filled section that contains a large volume of empty pores that can hold the inflowing water and stop it from flowing into the downstream backfill. The water handling method can be used for water inflows in the range of 1–5 L/min.

5.4.2 Functional requirements

The following requirements apply for the water handling method with a WSS:

1. The WSS shall be able to store so much water from a fractured zone that the backfilling front is always kept free from flowing water.
2. The pellet filling in the WSS must have such properties that the large sized pores between the individual pellets are filled with water.
3. The WSS shall be long enough
   a. to cover the entire fractured zone when the inflow rate is in the range of 1–5 L/min,
   b. to have so much empty volume that requirement 1 is fulfilled.
4. In order to not disturb the continued backfill installation, the outer separating wall should not leak more than an ordinary fracture or point inflow where no special actions are planned i.e. < 0.25 L/min.
5. The WSS must, also after long time, function as a mechanical support for the backfill placed on both sides of the section. The swelling backfill bentonite will over time apply a swelling pressure on the low density pellet filled section, which will be compressed. This will result in a transition zone in the backfill (on both sides of the water collector section) with lower backfill density than the average installed density. The length of the transition zone is depending on the length of the water collector section (which in turn depends on the position and angle of the fracture zone) and the compressibility of the pellet filling. The compression of the pellet filling must thus be calculated for every individual WSS. It is assumed that there shall be a smallest allowed distance between a deposition hole and the transition zone of one meter. The minimum distance 1 m is rather arbitrarily chosen and may be changed. Since the position and length of a WSS can be decided before drilling the deposition holes, this requirement will not result in that already drilled deposition holes have to be abandoned.
6. The material left in the backfill shall not adversely influence the engineered barrier system i.e. buffer and backfill. The concrete beams shall be manufactured of low pH cement.
7. The separating walls shall withstand a pressure of 50 kPa.

5.4.3 Design description

In order to delay the water flow downstream along the tunnel from a fracture zone the WSS is built at the fracture zone. The operation principle of a WSS is that there will not be any outflow until the WSS has been filled with water.

The water storage section is achieved by constructing two concrete beam walls across the tunnel perimeter, anchored to the rock walls, and filling the volume between the walls with bentonite pellets.

The design also includes geotextile on the rock surface in the center of the WSS (up to about 0.5 m from the walls). The geotextile will be installed with the purpose to better distribute the inflowing water along the tunnel wall and in this way additional improve the ability of the pellet filling to store the water without having high water pressure.

The design of the components in the WSS is dependent on the functional requirements and the interaction with the neighboring backfill components.

5.4.4 Post-closure aspects

General

The WSS includes a number of post-closure safety aspects on the repository. These aspects should be analyzed and approved:

1. **Material**. The suggested technique includes that a number of different materials are left in the repository.
2. **Smallest allowed distance to a deposition hole**. The deposition tunnels will be mapped in detail regarding positions of water bearing fractures and water inflow rates. After mapping, the exact position of the WSS will be settled and the length of the transition zones calculated. The minimum distance from a deposition hole to the beginning of the transition zone[1] is suggested to be 1 m but this is not yet decided.

5.5 Drainage hole to Adjacent Tunnel, DAT

5.5.1 General

To handle large water inflows, up to 10 L/min, it may be necessary to drain away the inflowing water during the backfill installation. A drainage hole to an adjacent tunnel, DAT, is a method to do such drainage. The main idea is to collect the water from a water-bearing fracture zone in a section and then drain it to an adjacent tunnel through a borehole until the backfilling of the current deposition tunnel is complete, and thereafter seal the borehole.

5.5.2 Functional requirements

The following requirements can be made on the water handling method with a drainage hole to the adjacent tunnel:

1. The method shall be able to drain away inflow rates between 1–10 L/min (the maximum inflow rate to a deposition tunnel when handed over is today set to ten liters per minute) during the time for backfill installation and until the construction of a tunnel end plug is finished.
2. The material left in the backfill shall not adversely influence the engineered barrier system i.e. buffer and backfill.
3. The proposed sealing method using bentonite is deemed as being long term stable and having a very low hydraulic conductivity. However, the long term behavior of the sealing components cannot be checked after installation. Therefore, safety analyses should be carried out to investigate if the drainage hole can stay open without impacting the overall repository safety. This would mean that need for proving that the borehole sealing is extremely reliable in the long term, is diminished.

[1] Zone where the backfill density is affected when the WSS is compressed by the backfill swelling pressure.

5.5.3 Design description

General

The DAT design comprises the following elements (see figure 5-22):

- A water collector that collects all the water from the water bearing structure, installed around the tunnel perimeter.
- A borehole leading from the water collector in the tunnel to be backfilled into an adjacent tunnel.
- The borehole sealing.

All installations (except for the borehole sealing components) will be completed and inspected before backfill operations start. After the backfill installation is completed, the borehole is sealed. The sealing work is performed from the adjacent tunnel into which the water was drained.

Water collector

A water collector that is installed around the tunnel perimeter has been developed. The water collector can be installed before backfill installation starts since it will not interfere with the backfilling equipment or installation process.

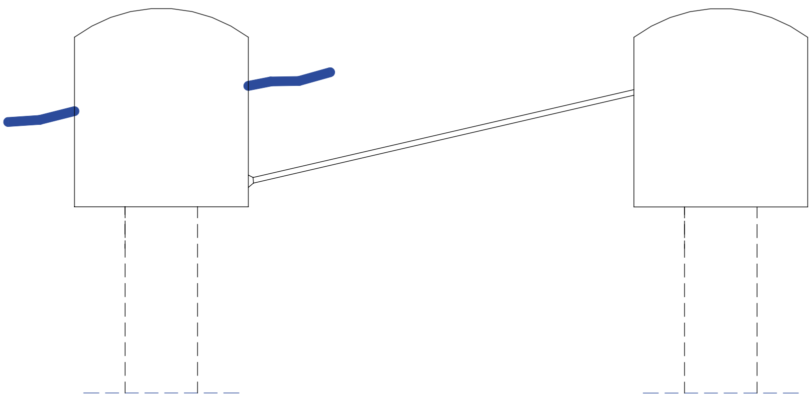

Figure 5-19. *Schematic drawing showing the principle for the water handling technique, Drainage borehole to Adjacent Tunnel, DAT.*

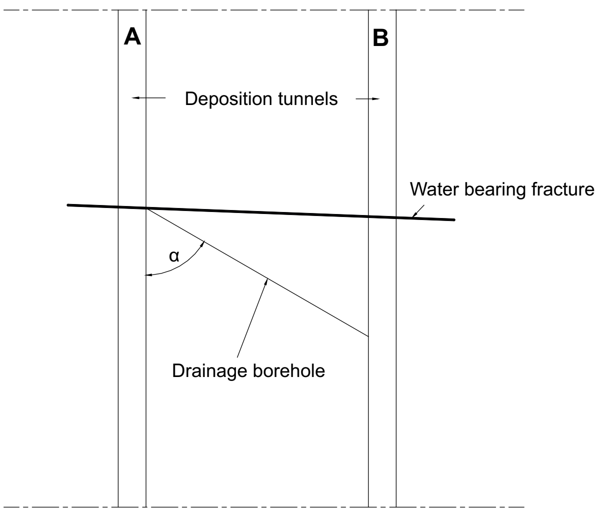

Figure 5-20. *Schematic drawing showing two deposition tunnels and a drainage borehole.*

Drilling and position of borehole

The investigations made regarding the design of the drainage borehole has resulted in the following conclusions/recommendations:

- The drainage boreholes should be drilled with the core drilling technique. The main advantage with this technique is that the drill cores can be visually examined which means that any problems with e.g. passing through fracture zones can easily be identified. It is also assessed that this type of boreholes can be sealed easier since the borehole surfaces are smooth and that the dimensions are more exact compared to percussion drilled boreholes. It is recommended that the drainage boreholes are drilled with a diameter of 76 mm which is a standard core drill size. With this diameter it will be easier to seal the borehole using standard products.
- The drainage borehole will (by definition) be drilled from a section of the deposition tunnel where a water bearing fracture zone is crossing. The direction of the fracture zone in relation to the orientation of the deposition tunnel will influence the direction of the drainage borehole since it will be favorable to avoid drilling the borehole parallel to the fracture zone. A drainage borehole that goes parallel with a water bearing fracture will be more difficult to seal afterwards and the bentonite sealing will also be more exposed to flowing water that may lead to erosion. Figure 5-31 shows an example where a drainage borehole has been drilled from deposition tunnel A to deposition tunnel B. The water bearing fracture (that is the reason for the drainage borehole) crosses the deposition tunnels almost at a perpendicular angle which makes it unsuitable to drill the hole here. Instead the drainage hole should be drilled with an angle (α) relative to the deposition tunnel A. The uncertainty regarding prognosis on the orientation of water bearing fractures is high and it is therefore recommended that an assessment of the most suitable direction of the borehole should be made for every case on site.
- The later sealing of the borehole will be facilitated if the borehole has a certain inclination downwards, seen from the adjacent tunnel, Figure 5-32. Since the borehole should end up in the bottom of the slot, it probably has to be drilled from that tunnel. In order to have enough space for the drill rig, this means that the borehole probably have to begin a certain distance from the floor i.e. not in the low point in the tunnel.
- The entrance to the drainage borehole should be shaped as a funnel, Figure 5-32, in order to facilitate the water flow. In order to prevent gravel to flow or erode into the borehole during the drainage period, it will be needed to attach a net over the entrance. The net can preferably be made of copper.

Water flow resistance

A calculation regarding the flow resistance in a drilled borehole has been made. In the calculation a maximum flow rate of 50 L/min have been used together with a borehole with inner diameter of 56 mm and length of 60 m i.e. a possible worst scenario.

For a relative roughness of 0.1 mm, the pressure drop will be 1.8 kPa and with a relative roughness of 1 mm, the pressure drop will be 3 kPa. There will thus not be any problem to drain the expected inflowing water rates (10 L/min) through a borehole with the suggested diameters and lengths.

Borehole sealing

After having completed the backfilling of the current deposition tunnel and having built a tunnel end plug, the drainage borehole shall be sealed. Different techniques for sealing of investigation boreholes is suggested in Pusch and Ramqvist (2007) and in a technical decision made by SKB, it has been decided to use the so called Basic technique for this type of boreholes. The technique suggested for sealing of drainage boreholes in this report is largely the same with some exceptions:

1. The drainage boreholes suggested in this report, will have a very small inclination compared to the investigation boreholes which in many cases are close to vertical.
2. The length of the drainage boreholes will vary between 25 m (the distance between Posiva deposition tunnels are 25 m and for SKB 40 m) and up to 56 m (the drainage borehole is drilled with a direction of 45° relative to the orientation of an SKB deposition tunnel). The investigation boreholes may have a depth of up to 1 000 m.
3. The drainage boreholes will be placed so that they avoid crossing any major fracture zones. This will facilitate the sealing process.

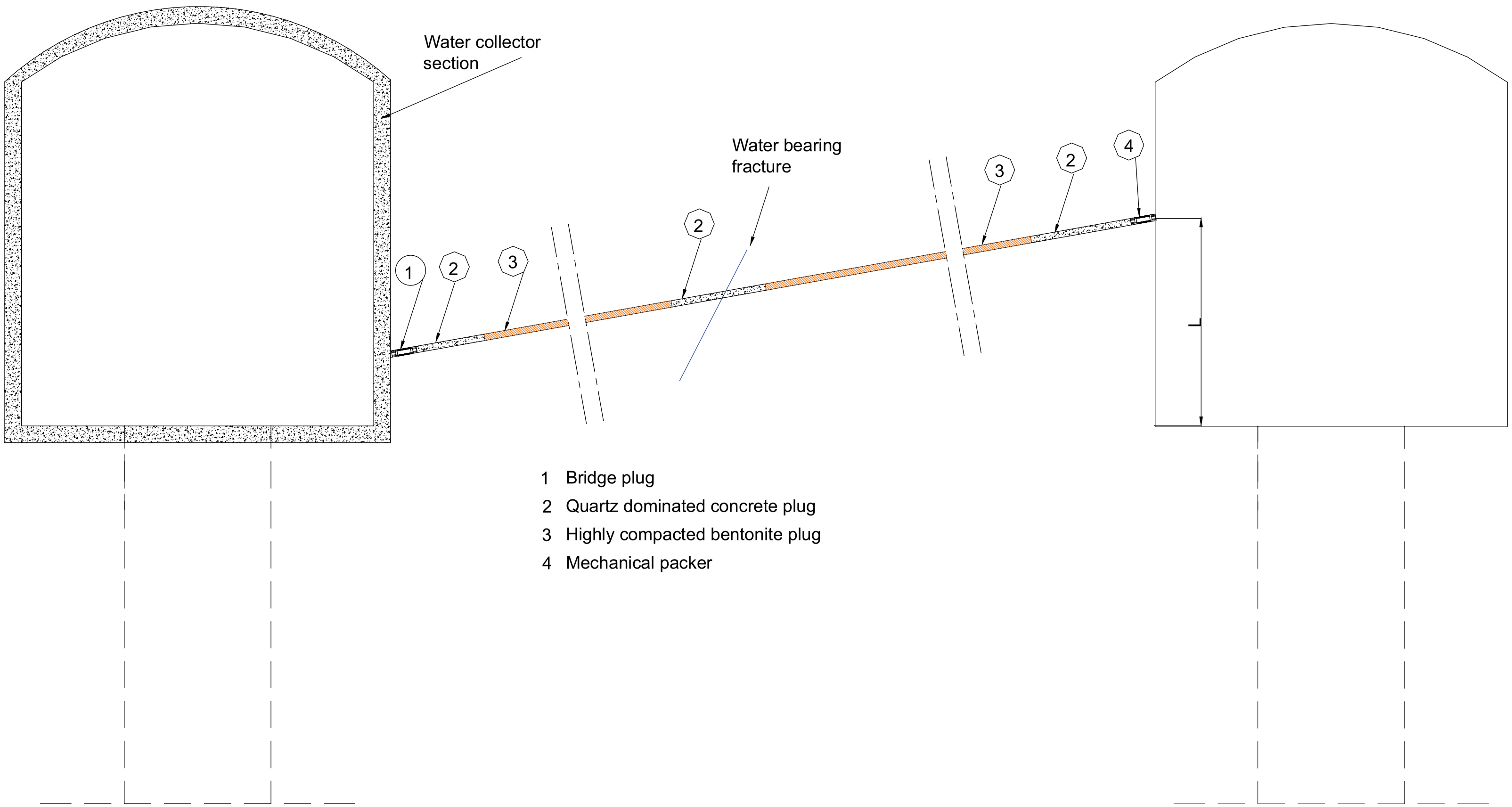

Figure 5-21. *Schematic drawing showing the principal for sealing of a drainage borehole.*

Figure 5-33 shows a schematic drawing of a drainage borehole drilled between two deposition tunnels and also a suggestion for how it could be sealed afterwards. The suggested sealing consists of four main components:

1. Bentonite plugs.
2. Quartz based concrete plugs.
3. Bridge plugs.
4. Mechanical packers.

The sealing principles can be described as follows:

- Highly compacted bentonite plugs are placed in the central parts of the borehole in sections with good rock (no water-bearing fractures). When the bentonite get access to water it will swell and seal the borehole effectively.
- Quarts based plugs are placed at both ends of the drainage borehole and also in other positions if the borehole e.g. is crossing any water-bearing fracture zone. These plugs contains a small amount of low pH cement, about 4 % of the weight. The cement will, however, be dissolved with time and leave a remaining quartz plug with high physical stability in order to support the bentonite plugs. The quartz plugs will also serve as a filter between the bentonite plugs and the gravel filling in the deposition tunnel (water collecting section) and by that prevent bentonite from swelling out in the voids of the gravel filling. A recipe for this kind of plugs have been developed by CBI (Cement och Betong Institutet) and is reported in Pusch et al. (2011).
- The installation of sealing components requires also that two different type of packers are used:
    1. The water outflow rate in the drainage borehole is high, > 5 L/min, and the first action will be to stop this flow. This is made by use of a so-called bridge plug. The bridge plug is installed by use of a drilling machine and will be left in the borehole.
    2. The last component installed in a drainage borehole is a simple mechanical packer. This is used during the hardening of the outermost quartz plug and can later be removed if considered necessary.

5.5.4 Post closure aspects

The suggested water handling techniques with a drainage borehole to an adjacent tunnel was discussed at a meeting with experts on post closure safety from Posiva and SKB. A number of open issues were raised at the meeting:

1. **Material**. The suggested technique includes that a number of different materials have to be left in the repository.
2. **Sealing of the drainage borehole**. Two different statements regarding the sealing of the drainage borehole have been made:
    – The borehole shortcuts two deposition tunnels if the sealing is not working as intended. It was concluded that the design requirements on the borehole sealing should be high and also on the verification. New safety assessment analyses should be made where it is assumed that the sealing has failed.
    – The proposed sealing method using bentonite is deemed as being long term stable and having a very low hydraulic conductivity. However, the long term behavior of the sealing components cannot be checked after installation. Therefore, safety analyses should be carried out to investigate if the drainage hole can stay open without impacting the overall repository safety. This would mean that need for proving that the borehole sealing is extremely reliable in the long term, is diminished.
3. **Water collector**. The water collector should be optimized so that the resulting void volume in the deposition tunnel is minimized. This request has been incorporated into the current design.

5.6 Artificially wetted pellet wall

5.6.1 Introduction and background

By adding water on the installed pellets it is possible to build up a wet pellet wall that redirects flowing water and thus prevents it from reaching the backfill front. This method has been tested in laboratory scale but it has been assessed that further tests will be needed before it is ready for implementation in full scale tests. In this section the current knowledge of the artificially wetted pellet wall is discussed in the scope of a potential water handling technique.

Given the heterogeneous design of the backfill system, and it also has been shown experimentally, that the pellet-filled gap between backfill blocks and host rock will initially be the component most affected by groundwater inflow. This pellet-fill has a potentially large water storage capacity due to its high void volume. Based on this means to induce improved water storage capacity in the pellet-filled region through installation of artificially wetted pellet wall(s) has been studied. The idea behind this method to delay water outflow has been described as follows; "water flowing from the inside of the pellet-filling towards the front will hit the wetted pellet wall which is a much tighter (more dense) than the rest of the pellet-filling and the water will therefore turn back up into the dry parts of the filling. With this method a larger part of the pellet-filling can be used for water storing" (Koskinen 2017) (Figure 5-34). Ultimately water will move beyond the wetted wall, but the backfilling would have progressed substantially further down the tunnel by the time. The possible flow of water towards the tunnel rock floor may also require attention.

5.6.2 Experimental experience from wetted walls

There are both ½-scale mock-up tunnel test results (Dixon et al. 2008a, 2011, Koskinen and Sandén 2014) and laboratory scale test results available wherein the artificially wetted pellet wall method has been used at the front (working) face of the backfilled volume. It is worth mentioning that it is anticipated that a wetted pellet wall on the front face of the backfilled volume will behave differently than a wetted wall within the backfilled volume. This is because there is no pellet material or any other mechanical support behind a wetted wall at the downstream end. The wetted wall can therefore become mechanically unstable and not tight (dense enough) when the water front reaches the wall, jeopardizing or degrading the performance of the wetted wall. In such a situation, sections of bentonite material can fall off the wall, leaving gaps that are generally too large for bentonite material to selfheal, particularly when there is inadequate mechanical confinement (open downstream).

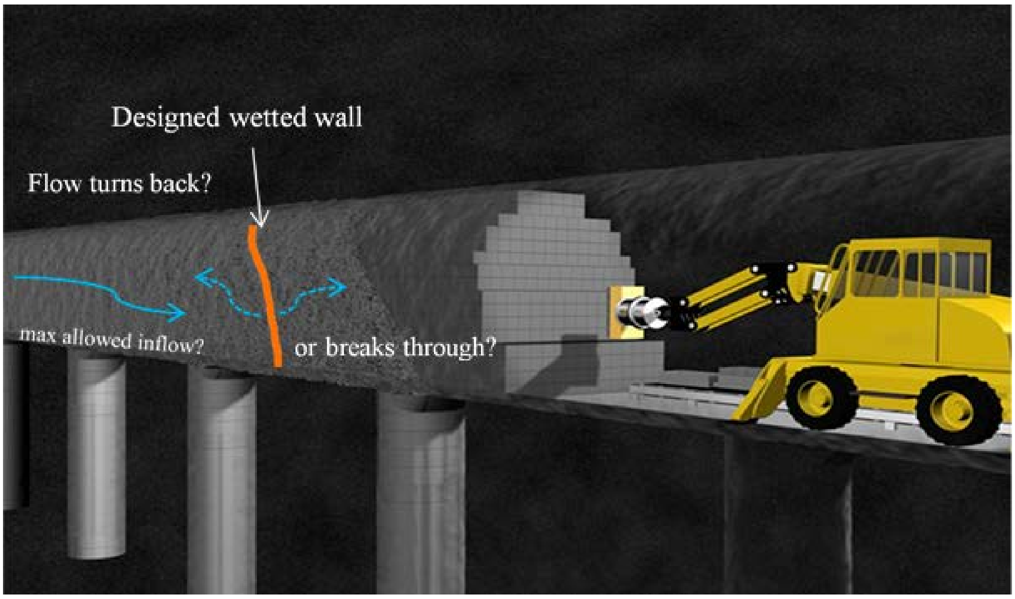

Figure 5-22. *Schematic illustration of artificially wetted pellet wall behavior during backfill installation (adapted, original reference from Posiva's web page).*

In addition, all tests have been single or two-component tests, i.e., complete three- component backfill design, foundation layer, blocks and pellet-filling have not been tested with wetted pellet wall method so far. Generally, it is the foundation layer that has been missing from the mockups and tests.

The tests mentioned above have been conducted by using artificial ground water simulants i.e. salt water (TDS 10 g/l).

Mock-up tunnel tests

Mock-up tunnel tests (1/2-scale) with an artificially wetted pellet wall (at the front face) have been performed at SKB's hard rock laboratory in Äspö, Sweden. In the test setups, the backfill tunnel was made from steel (see Figure 5-35), i.e. results of water distribution and water storage capacity are based solely on post-mortem analysis, and no visual observations are possible during tests except on the front face. In addition, water distribution in large scale tests has attributed to some random aspects of water uptake and infiltration effects behavior, which may cause challenges to interpret the results (Dixon et al. 2008a, b, 2011, Koskinen and Sandén 2014).

The main reason that the artificially wetted pellet wall was used at the front face of installed pellet-filling (Koskinen and Sandén 2014, Dixon et al. 2008b, 2011) was to allow for installation of a nearly vertical face of pellets at the downstream end (Figure 5-35). Although these features are not entirely representative of the artificially wetted pellet walls envisioned for water handling purposes, the wetted fronts used in the above- mentioned tests do permit some analysis on the influence of such features on water infiltration behavior.

Koskinen and Sandén (2014) describe three ½-scale mock-up tests where the focus was testing the water distribution potential of geotextiles. Tests without a wetted pellet front were not done as part of that study. Any results of changed water storage capacity because of wetted pellet wall were therefore not possible to measure. These tests did provide for observation of system behavior and practical information regarding to method was obtained (Koskinen and Sandén 2014). Some of the key features, observations and conclusions are:

- The wetted pellet front was installed as the final stage of pellet installation by adding 90–106 liters of water to the nozzle of the shotcrete hose, i.e., the water was added as a part of pellet-water installation.
- The amount of added water 65–75 L/m^2 with an installed thickness of the wetted wall being 15–20 cm was used. These values corresponding approximately 40 % of the target volume of the wetted pellet front, which is actually close to the void volume value in the pellet-filling. In addition, by assuming dry density of 1 000 kg/m^3 for pellet-filling the amount of added water 0.33–0.50 liters per kilogram of dry pellets can be calculated. The effect of the thickness of the wetted pellet wall has not been tested so far, but it was decided it would be best to keep the thickness as low as practicable (Koskinen 2017). When more water is used for wall installation it reduces the macro void space available for water storage. On the other hand, thicker sections could be more resistant to flows, pellet filling compression and pressure buildups.
- Test against inflow rate of 0.5 L/min, the outflow (after 53 hours) of the system was "explosive" and fist size clumps of clay flew a few meters from the outflow point. This explosion would indicate that behind the wetted pellet front was trapped air which compressed within the pellet-filling. It should be noted that this behavior is closely related to the used steel tunnel test method where the volume is restricted and air cannot escape to larger tunnel volume or rock fractures. Note, exactly the same result was seen in Dixon et al. (2011) tests.

Dixon et al. (2008b, 2011) performed ½-scale mock-up tests for testing water infiltration behavior after emplacement. The wetted pellet fronts were used in the last four tests reported in the 2008 report and also two tests in the 2011 report since, any reference tests were not done, without wetted pellet front at similar test conditions, any results of changed water storage capacity was not possible to get from this work. Below are listed observations and ideas of the wetted pellet front methods by Dixon et al. (2008b).

__Figure 5-23.__ Photographic images of SKB ½-scale steel tunnel mock-up (upper photo), undertaken at Äspö HRL (Dixon et al. 2008b, 2011). The block assembly prior to installation of dry pellet fill (lower left photo) and wetted pellet wall used in later tests (lower right photo) (Dixon et al. 2011).

1. The wetted pellet front was done by adding water at the nozzle of the shotcrete hose, the amount of added water was not informed.
2. There was discernible pressurization (the maximum was less than 200 kPa in all tests).
3. Installation of pellets with some degree of water addition also has the advantage of reducing the potential for the crown regions to be of lower density, or to settle and form a gap between the pellets and the tunnel crown.
4. Dampened pellets can be installed such that they can stand vertically, reducing slumping or the need to deal with the very low natural angle of repose for dry pellet materials and the potential for substantial variations in the density of the placed fill.
5. Fractures were simulated with geotextile which created a gasket type of wetted bentonite area inside the backfill (Dixon et al. 2011). This slowed down the water breakthrough times. Although the actual technique how this wet pellet area was made is different than studied here the principle and effect is the same. This result indicates that the method could be implemented successfully.

Laboratory tests

A series of laboratory scale tests (called wetted pellet front tests) using a transparent pellet box configuration with Cebogel QSE and Asha rod-shaped pellets were performed at B+Tech Oy in 12/2015 (see Figure 5-36). The wetted pellet wall was used at the front face of the installed pellet-filling, as in ½-scale mock-up tests at Äspö HRL as well, but these tests were performed with slope of 40 degrees (as opposed to the vertical wall in mock-up tests).

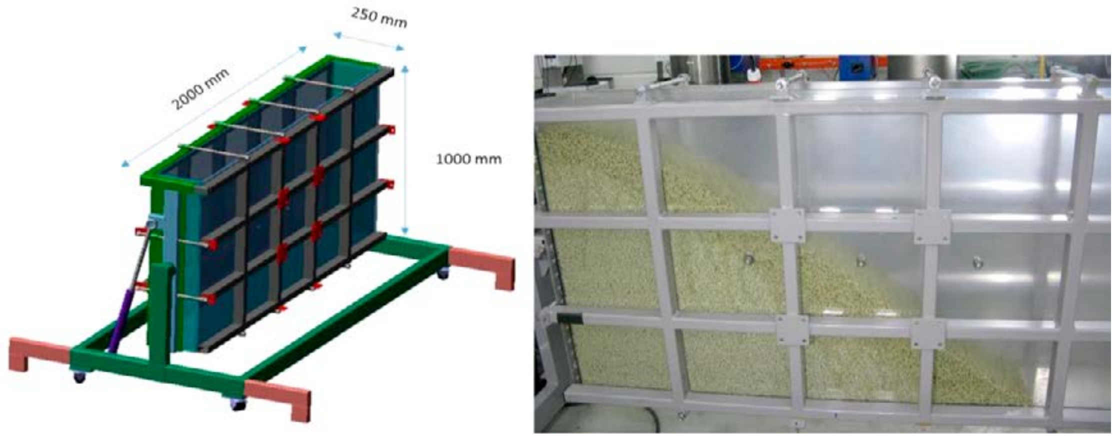

***Figure 5-24.** Schematic illustration of pellet box 250 mm test configuration with inner dimensions and a photographic image of wetted pellet front test. The wetted pellet wall was made along the top surface of the slope. The water inlet was pointwise (diameter 6 mm) and located at the side of box (see blue sphere in left figure).*

The wetted pellet front was made manually, in 6–7 layers and a total thickness was approximately 10–16 cm. Water was just sprayed on the surface of dry pellets followed pouring of dry pellets on top of the wetted ones which were sprayed wet as well and process was repeated until 6–7 layers was done. The amount of added water corresponded to about 40 % of the target volume of the wetted pellet front which means that practically all of the void space between pellets was filled with water. The amount of added water is equivalent to that used in the ½-scale mock-up tests (Koskinen and Sandén 2014).

Each test was terminated after the level of water (exiting from the pellet zone) filled the bottom of the box at the non-pellet filled side to a height of 8 cm (right corner in Figure 5-35). The length of the tests varied from one to five hours depending on the inflow rate. As can be seen from Figure 5-36, the breakthrough times for Cebogel pellets, i.e., the time when water was observed outside of the wetted pellet front (exiting from the pellet-filling), was more or less similar regardless of whether wetted fronts were installed or not (as in the reference cases). A similar result was found in the test with Asha pellets against an inflow rate of 0.25 L/min where the first observation of water outside of the pellet system was observed at a 120 hours after the initiation of inflow, but an open pathway (actual break through) for water exit the system formed after 200 minutes.

The total duration of the tests to meet the termination criterion indicate (see Figure 5-37) as well that the usage of water storage capacity in the pellet-filling was not improved with the wetted pellet walls. In addition, one of the wetted front tests showed that the almost all of the macro void space available for water was used. This indicated higher void ratio usage efficiency which is desired for the method but it actually doesn't show clearly in the test time comparisons. Comparing only the test duration times has some issues which are related to actual test system size and differences with material installations. Small changes in material amounts and slope angle may cause differences. Also when high inflows are used in the conduct of small scale systems, the water filling times are short which makes the capture of changes in behavior problematic.

As seen in this work and other laboratory scale tests as well (Sandén and Börgesson 2014, Martikainen and Schatz 2016), the initial distribution of inflowing groundwater into the pellet volumes (wetting pattern and water filling) is highly dependent on the inflow rate, see also Figure 5-11.

Based on experimental observations of wetting behavior in pellet-filled volumes (Sandén and Börgesson 2014, Martikainen and Schatz 2016), Figure 5-38 shows probable contact locations between inflowing water distributions and wetted pellet walls at different inflow rates.

As mentioned previously, the location of inflow points in the deposition tunnel is another fixed hydrological parameter along with inflow rate. These two parameters together with distance to backfilling front will have a significant effect on wetting, water infiltration behavior during and immediately after backfill emplacement. These are the main environmental parameters which will determine the elapsed time at which when water will exit open backfilled volumes.

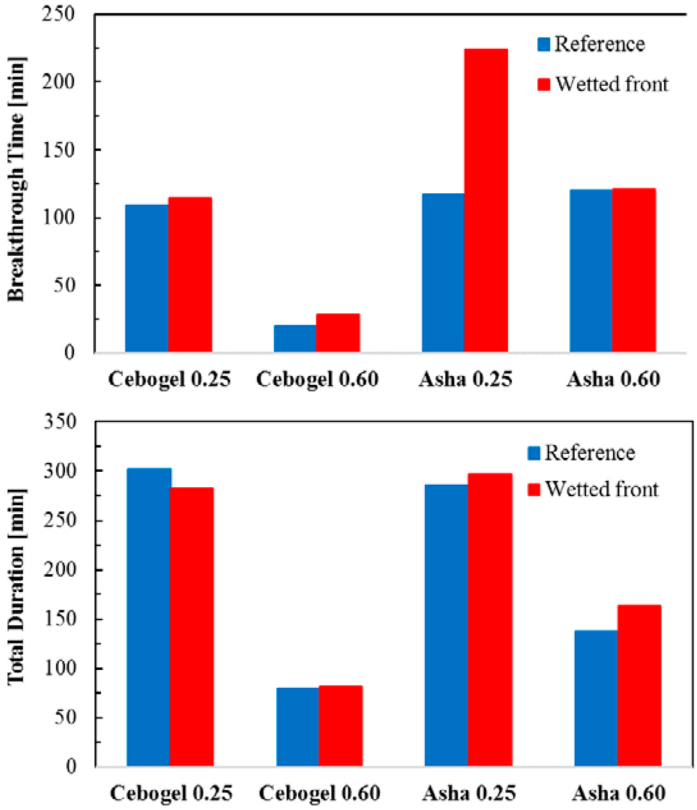

Figure 5-25. *Breakthrough times (top) and total duration (bottom) for wetted pellet front and reference tests with Cebogel and Asha pellets against inflow rates of 0.25 and 0.6 L/min. Blue columns represent reference test without wetted pellet front and red ones with wetted front.*

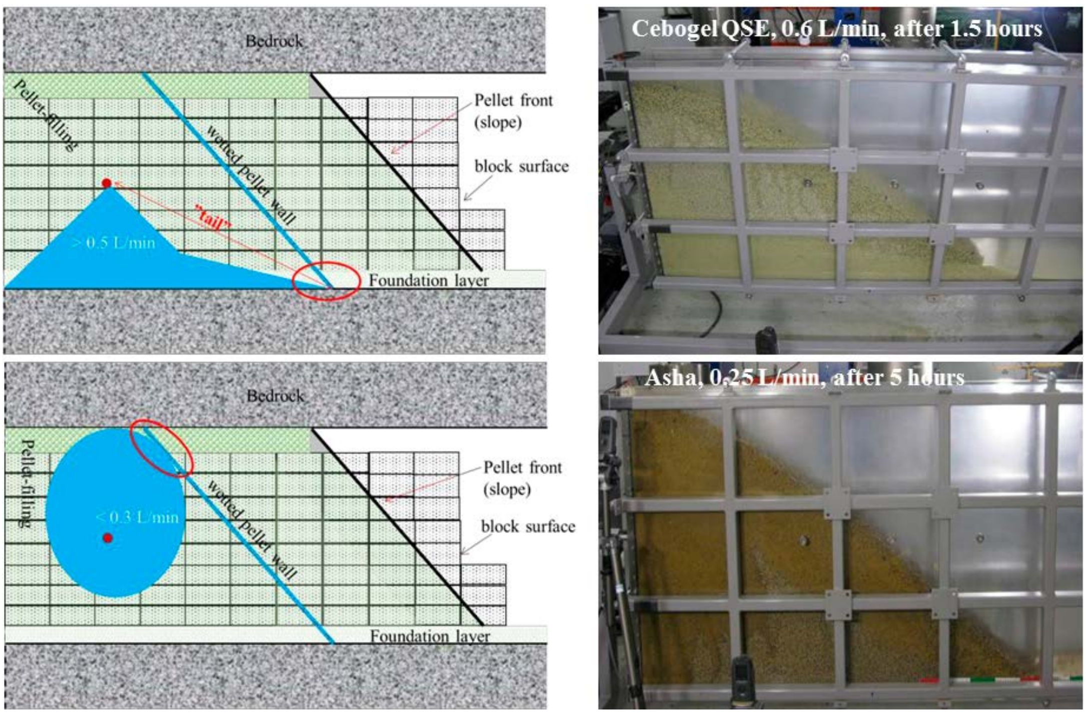

Figure 5-26. *Schematic illustrations (left column) of initial water infiltration behavior with artificially wetted pellet wall (adapted, original reference Sandén and Börgesson 2014) and photographic images (right column) of wetted pellet front tests with Cebogel QSE pellets against inflow rate of 0.25 and 0.6 L/min Red circles in left figures indicate probable contact locations for inflowing water distributions with the wetted pellet walls for two different wetting scenarios.*

The location where an inflowing water distribution will first come into contact with the wetted wall depends strongly on the distance (referred to as a 'tail' in Figure 5-39) between these two features. Assuming that water breaks through the wetted wall, inflowing water will fill the available voids behind the wetted wall. For a situation where the wetted wall remains intact, the region being flooded will see three major pressure-related processes occurring; firstly, compression of air by the inflowing water, then development of swelling pressure in wetted regions and finally once the available volumes are filled, hydraulic pressure will begin to increase. Ultimately it is anticipated that the isolated section of tunnel will bridge into the adjacent region(s) and how this occurs (gradual bleeding of air-water pressure or sudden decompression of isolated region), will also affect subsequent water movement and accumulation.

With time and distance inflowing water distributions will increasingly progress upwards. This directional aspect is another reason why the distance between fractures and wetted pellet fronts is an important factor. This distance also defines the maximum available macro void volume for water retention. The efficiency of the void usage depends on several factors like inflow rate and pellet parameters, but the goal is for the most effective use of void space for water storage to be achieved.

Figure 5-39 shows an illustration of a possible water infiltration situation over a 12 m long section of a backfilled tunnel. The deposition holes that could exist in this section and their effects on water movement have not been taken into account in this scenario. As mentioned earlier, with high inflow rates it is expected that the water will initially flow downwards to the floor (Figure 5-38: Blue area 1). As the wetting progresses (Figure 5-38: Green area 2) the water moves mainly sideways and downwards through the pellet fill. During this period the pathways between macro voids start to close because of bentonite swelling and hence inflow resistance starts to grow. The flow then redirects to a more upwards pattern (Figure 5-38: Yellow area 3), and towards dry pellet volumes at the tunnel crown and the open front. Once the flow has reached the highest levels (Figure 5-39: red area 4 & 5) it will continue to move forward and spread out to sides. The wetting front can now progress along both sides of the tunnel (Figure 5-39: red area 5). At this point it will move along the tunnel crown and reach the open front. It should be noted that since the majority of the water is moving up it is possible that a substantial volume of pellets will remain relatively dry (Figure 5-39: lower right region).

The presented conceptual idea of water infiltration behavior is the best and short description of current understanding, which based on made observations of several downscaled experimental test programs.

From the wetting behavior shown conceptually in Figure 5-39 it is important to recognize possible scale effects. If this wetting behavior is tested in laboratory-type systems, e.g., pellet box equipment ($1 \times 2 \times 0.25$ m), then only a few meters near the inflow (Figure 5-39: inside area 2) are simulated. The larger ½-scale tunnel tests have been executed with 4-meter long installations (Figure 5-39: inside area 3). The distances associated with these mockups therefore need to be taken into account when designing the location of wetted pellet sections in tunnel-scale tests. The use of differing geometries or scales could mean that breakthrough point(s) could change, installation time windows could be unrealistic and the actual performance of the method in an actual deposition tunnel may not be satisfactory. The use of a tight wetted pellet may also result to a situation where water is directed into backfill block stacks. This possible risk has not been assessed in studies yet.

Section conclusions:

- Stand-alone functionality and performance of an artificially wetted pellet wall in delaying water exit has not been yet verified experimentally.
- The actual magnitude of the water handling performance related to macro void volume filling efficiency or gained time has not been determined for flow rates of interest in this study.
- The floor component should be included in larger studies.
- A tight wetted wall could possibly direct inflow into block stack.
- Useful practical information from the installation and design basics has been collected from previous tests from different scales.
- Preliminary information has been gathered from the possible breakthrough point locations.

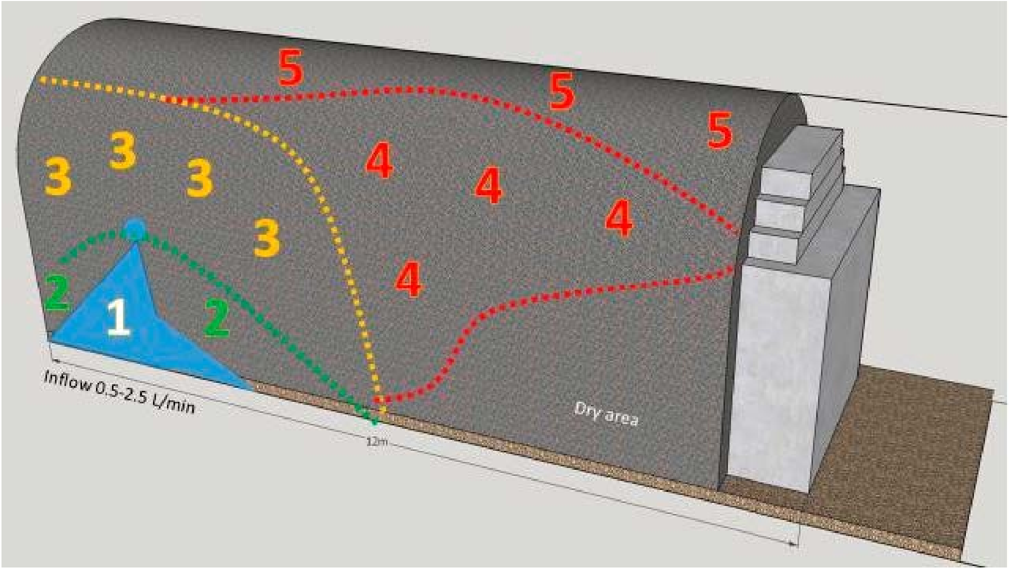

Figure 5-27. *Schematic illustration of anticipated initial water infiltration behavior from high flow (> 0.5 L/min) fracture in a 12 m-long section of deposition tunnel. Water infiltration zones are marked with numbers from 1-5 which correspond to wetting sequence.*

5.6.3 Summary and conclusions

It is proposed that a wetted pellet wall could be used as a water handling method during backfill component installation. The artificially wetted pellets would create water tight section(s) that would direct the inflowing water towards the back of the tunnel rather than allowing it to move forward and potentially out of the downstream face of the tunnel backfill. This would allow more time for the installation operations by slowing down-tunnel movement of water. Installation of the wetted pellet walls would be made using shotcrete equipment, to blow the pellets into place while adding the needed extra water at the nozzle.

Wetted pellet walls have been used in previous steel tunnel tests as part of the tests but not as the main subject of investigation. A preliminary laboratory scale study related to their use was done at the end of 2015. To use artificially wetted pellet walls as a water handling method requires further study and confirmation of the design concept/implementation. Current knowledge of the subject is not complete enough to produce the fully detailed method description needed for full scale testing and final evaluation of the concept.

5.7 Local freezing

5.7.1 Introduction and background

The objective of the work was to evaluate the feasibility of Local Freezing to control groundwater inflows during backfill operations in hard crystalline rock. Ground Freezing is a well known technique but there is not proper information of the use of it in hard good quality rock. The conceptual idea is to freeze the rock around the excavated tunnel to stop the possible inflows. This is not typical in hard crystalline rock where the issue is most often the opposite – to prevent rock from freezing. Because of that, however, the technique to insulate the tunnel surfaces is well known and the tools to evaluate the heat load and need for thermal insulation are well known.

The method is commonly used in civil engineering when building in sand or other loose wet soils where freezing has been used to control groundwater (e.g. in shafts), to mechanically stabilize soils so that the reinforcement can be carried out safely and to enable tunneling through mixed ground.

Earlier state of the art report had recognized freezing as viable option to be used as water handling method in underground repository conditions. Based on this it was added as part of a work package in the joint SKB-Posiva project Water handling during backfill installation. It was also recognized that the information about the usage with crystalline rock was very limited. If the method could be used in crystalline rock at deposition depths, it would provide significant help in several water handling situations. It is even possible that no other methods would be required if the whole length of the tunnel would be for example frozen. However, there were many unknown factors identified that need to be ruled out before the method can be considered for use in deposition tunnels.

Based on the general requirements, the potential risks for long term safety as well as the nature of the method, the method specific preliminary requirements were listed (Table 5-6).

Table 5-6. The method specific requirements for the local freezing.

The freezing agent must be selected so that, if there are leaks, the agent will not be hazardous to the environment and can be removed from the surfaces of the tunnel.
Time of active freezing must be possible to coordinate with the underground operations.
After the active freezing period, the rock must remain frozen for the time needed for backfill installation of a deposition tunnel (around 2 months).
The freezing process shall not cause any additional fracturing of the rock.

For the project, work was commissioned by arranging a workshop with selected experts so they could all express their opinions and get feedback directly from each other. The expected outcome was to have knowledge of the relevant cases, if there are any. If no relevant cases can be found, there would be some expert opinions on the relevance of the risks associated with the method, and recommendations regarding possible tests as a road map.

5.7.2 General about ground freezing

Ground freezing is a process of making water-bearing strata temporarily impermeable and to increase their compressive and shear strength by transforming joint water into ice. Below are some general issues related to ground freezing:

- Freezing is normally used to provide structural underpinning; temporary supports for an excavation or to prevent ground water flow into an excavated area.
- Successful freezing of permeable water-bearing ground affects simultaneously as a seal against water and substantial strengthening of incoherent ground.
- It is applicable to a wide range of soils but it takes considerable time to establish a substantial ice wall and the freezing conditions must be maintained by continued refrigeration as long as required.
- Example of application is e.g. in the Copenhagen Metro project where a pedestrian passage from a new metro station to an existing railway station was constructed underground. Since the existing rail traffic had to continue, the ground had to be frozen to avoid the risk of collapse due to excavation of the transfer tunnel. Two 100 kW chillers located on the surface cooled the soil around the pipes to −24 °C.
- Ground freezing may be used in any soil or rock formation regardless of structure, grain size or permeability.
- However, it is best suited for soft ground rather than rock conditions.
- Freezing may be used for any size, shape or depth of excavation and the same cooling plant can be used from job to job.

5.7.3 Survey and expert's interviews

Three senior experts with significant expertise in ground freezing and freezing of soils and hard rock were interviewed. All the experts had geotechnical background and one has done KBS-3V based research several years. The persons were:

1) Seppo Saarelainen/ PhD in geotechnical engineering, retired.

2) Harri Kivikoski/ Senior Scientist, M.Sc. Tech. Experience in modelling of ground & rock freezing. Repository related research activities.

3) Heikki Onninen/ M.Sc. Tech Dimensioning of thermal insulation in road & railway construction, retired.

Expert opinion

All experts felt that freezing of hard rock to seal groundwater inflow is feasible and well established, but there are certain special issues related to this application that should be taken into account:

a) How long time can be reserved for freezing operation?

b) Can the tunnel be closed for freezing or should it be available for other operations during cooling phase?

c) How much space will be available for freezing pipes and insulation?

d) Is it possible to ream the tunnel to larger width so that the cooling components could be made flush with the tunnel surface?

e) There is no significant difference between ground and rock freezing.

f) How long the tunnel can be sealed in frozen state after cooling system has been dismantled in practice?

g) When dismantling the cooling system, there might be some small rock pieces falling from surfaces.

h) Are there some severe restrictions which affect the selection cooling agent?

i) Liquid nitrogen could be used for initial freezing and some other agent for maintaining the frozen barrier (e.g. 20 % NaCl saline solution).

j) In extreme cases, when there are severe restrictions for other cooling agents, one could use cold air for cooling.

k) Is it possible that the inflow points “travel” to new position after freezing – how long sections should be frozen?

l) Water flow and temperature. The freezing time will be increased by flow which forms a continuing supply of heat energy and, if the flow is large and the water temperature high, freezing may be completely inhibited. The intended use of the method in repository case would be with tunnel sections which have rather high inflow rates up to several L/min.

There was consensus that the freezing can be implemented e.g. by using aluminum surface elements with proper insulation. Nitrogen could be used for fast initial freezing and NaCl solution for maintaining the refrigeration. The cooling circulation system could be outside the tunnel. The pipes to cooling element could be located in the tunnel roof or wall.

Risks

Several of the issues are related to the timetable for cooling and maintenance of sealing after dismantling. There are also issues related to technical design and selection of cooling agent. These are merely optimization and design issues. Underground work safety will be included in these solutions. It seemed that there is little information about the time that sealing is maintained after dismantling. This may be a challenge if the time period is in the range of 2 months. This evidently depends on the operation cycle of the deposition tunnel and should be discussed further.

The last of the issues, however, is more significant. There seems to be little information about the effect of constant inflow on freezing. This is an issue that could be studied and tested in laboratory based on real site specific data (inflow rates, salinity, temperature etc.). With high inflow rates this will most likely be the key point if the technique should be investigated further or implemented to full scale testing.

5.7.4 Conclusions

Freezing of soil and hard rock are technically very similar and experience from soil freezing is applicable. In good quality rock there is no need to stabilize the rock while freezing and therefore it is considered easier by experts.

Freezing is a well-established technique which can be utilized for ground water control in hard crystalline rock. The three important components of freezing are well established: a) design and thermal dimensioning, b) Insulation technique and c) freezing technique.

The salinity of groundwater is not found as an issue by experts even at high salinities such as TDS 70 g/l.

Sealing of constant groundwater inflows at high pressure need to be evaluated further and require additional studies.

The requirements for the method usage time windows (coordination with other underground activities and length of the frozen state period) need to be re-evaluated.

The acceptable water inflow rates after the method has been applied need to be clarified. The reducing limits should be defined i.e. is it acceptable if the inflow rate is reduced from for example 2.0 L/min to 0.5 L/min.

5.8 Light fortified Concrete Plug, LCP

5.8.1 General

Besides the developed methods for water handling it has been assessed that in case of a temporary stop in the backfill installation process, it should be possible to install a temporary plug so that the already installed backfill can be kept in place.

5.8.2 Functional requirements

The functional requirements that have been used on the construction of a temporary plug, were settled in conjunction with the design work. Requirements were partly specified in a State of the art report (Koskinen 2016) but judgements have also been made regarding what is appropriate, within the design work:

1. The maximum operational time for the temporary plug was estimated to one year. A more probable time is perhaps one or two months but in order to increase the utility it was decided to design the plug for an operational time of one year.
2. The maximum swelling pressure from the temporary plug need to withstand is 1 MPa. *Note: During the design work it has been discovered that this requirement is not in complete agreement with the one above, since calculations have shown that the pressure may exceed 1 MPa within one year, see further description in Section 5.8.4.*
3. The plug should be designed so that no water pressure can be acting on the cross-section area, only swelling pressure from the backfill.
4. If possible, the plug should be constructed so that it can be reinforced in steps.

5.8.3 Design description

General

The design idea of the LCP is to build a rather simple plug in short time that can withstand a swelling pressure build-up from the backfill behind it.

The design comprises the following elements:

- The completion of the backfill front behind the plug
- A drainage layer to delay water pressure from acting on the concrete wall.
- A concrete beam wall.
- Reinforcement, installed on the outside (downstream side) of the concrete beam wall.

Completion of the backfill front

The backfill block stack is installed with an inclination in normal backfill operations. In the case where the backfill installation is interrupted and a LCP will be constructed, the backfill front needs to be completed so that it is near vertical. The vertical wall is necessary to achieve an even pressure on the plug from the backfill. A gap will be left between the backfill blocks and the plug. This gap will be filled with backfill pellets.

Drainage layer

A drainage layer will be constructed against the backfill front. The purpose of the drainage layer is to prevent water pressure from acting directly on the concrete beam wall.

Concrete beam wall

The concrete beam wall is a simple construction designed to be erected quickly. The concrete beam wall is anchored to the rock walls but must be reinforced to counteract the eventual swelling pressure from the backfill.

Reinforcement

Two types of reinforcement have been considered: Steel beams and shotcrete. The steel beams are faster to install than the shotcrete and can be removed if there has not been a pressure build-up on the plug. The steel beam reinforcement withstands 1 MPa of swelling pressure. The shotcrete reinforcement is slower in installation due to curing times. This type of reinforcement can be strengthened in steps by the addition of more shotcrete layers and can therefore add withstand larger swelling pressures than 1 MPa which may be necessary in tunnels with large water inflows. The shotcrete reinforcement is not removable.

5.8.4 Swelling pressure development

The models of the temporary concrete plug shows that the total pressure on the plug after one year is highly dependent on how water is transported into the bentonite, and in particular into the backfill blocks. If the drainage layer which confines the pellets filling is well drained, and hence do not supply water to the pellets the pressure on the plug should not reach a higher pressure than about 1 MPa after one year, assuming a thickness of the pellets filling between blocks and plug of at least 10 cm, even if the plug is situated relatively near a fracture. However, if the plug is situated very near a fracture with a substantial inflow, and the drainage layer is not working optimally, such that some water is supplied to the pellets filling via drainage layer, the pressure on the plug might exceed 1 MPa less than one year after installation.

As an example of this the time evolution of the plug pressure is shown in Figure 5-41 from the three models with a 10 cm thick pellets filling and small tunnel radius. The orange line identifies the most likely “wet” scenario to occur, where the pellets column has free access to water (type 1 boundary condition). The red and blue lines identify the type 2 and 3 models, where the pellets column is saturated within a day after installation (hence the plug is situated very near a high-flowing fracture). The blue line represent the case where the drainage layer works as intended, whereas in the model represented by the red line the pellets filling between the blocks and plug is hydrated also via the drainage layer. The plug-pressure time evolution is initially rather similar in the three models, even though the type 1 models shows a slightly slower pressure build up. The main pressure contribution at this stage comes from the swelling of the outer pellets column.

In the type 3 model (red line; nearby fracture, no drainage) the pressure on the plug after one year exceeds the allowed pressure of 1 MPa (it is 1.7MPa). From the time evolution in the figure it can be seen that the build-up of pressure on the plug is gradual and that, according the model, it takes several months before the pressure on the plug exceeds 1 MPa. It should be stressed that the model is not detailed enough to give a minimum time during which the plug pressure will be lower than 1 MPa.

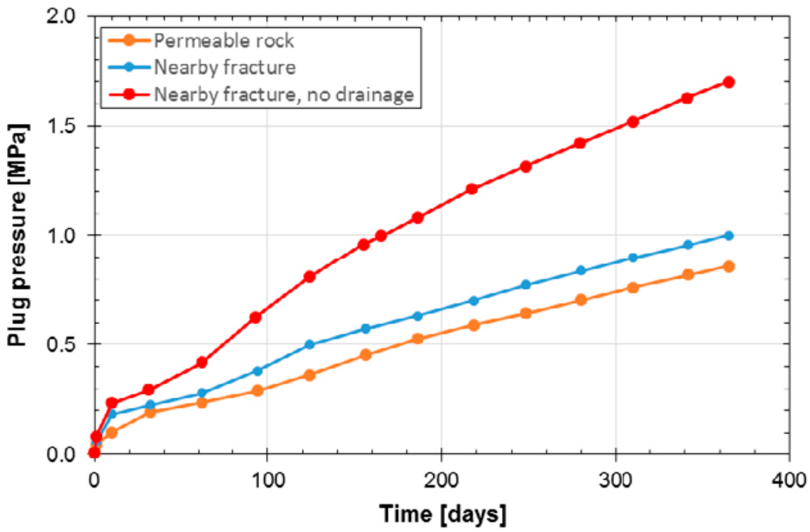

Figure 5-28. *Time evolution of the pressure on the concrete plug from the three models with a small tunnel radius and a 10 cm thick pellets filling between the backfill blocks and the LECA blocks. The orange line identifies the model with permeable rock but no nearby fracture. The blue identifies the model with a nearby fracture and working drainage, while the red line identifies the model with a nearby fracture and no drainage.*

From the modelling results presented here it is clear that the pellets filling between the backfill blocks and drainage layer should be at least 10 cm thick if the pressure on the plug is to remain below or at 1 MPa for one year. Even with this thickness, however, it is recommended that the plug is not placed directly in connection with a high-flowing fracture, and that if a high water inflow is present further down the tunnel, drainage should be ensured to be well-functioning.

5.8.5 Post-closure aspects

The suggested design of a temporary plug was discussed at a meeting with experts on post closure safety from Posiva and SKB. The proposed design was considered acceptable from a post closure perspective.

In the method description describing the construction of a temporary plug, it has been suggested that the plug should be positioned in the middle between two deposition holes. The length of the plug is about 0.6 m. If the reinforcement is removed before the backfilling continues on the downstream side of the plug, the backfill above the closest deposition holes will be unaffected and thus fulfil the requirements regarding swelling pressure and hydraulic conductivity. If the longest version of reinforcement (2.2 m) is used it will reach somewhat past the edge of the nearest downstream deposition hole. If it is judged that the reinforcement must be left in the tunnel, it will probably be necessary to abandon this deposition hole since the requirements on the backfill above not will be fulfilled. This means that the already installed canister in this deposition hole must be retrieved. If a thinner reinforcement that does not reach the next downstream deposition hole is used, the already installed canister in this deposition hole could be left without any extra actions.

6 Mathematical model of water storage and spreading

A mathematical model was developed with the objective to calculate the available time for specific deposition tunnels and for specific water inflow scenarios, and to analyze if there is a risk that inflowing water can catch up with the backfill front (Åkesson et al. 2017). The water transport was represented as progressing water fronts from multiple water inlets in a tunnel, for essentially any combination of inlet positions and flow rates. The partial water-filling of the pellet-filled sections was represented with a flow rate dependent function, which was adopted from results from steel-tunnel tests. The model was intentionally given a general definition which could enable an evaluation of features which are specific for SKB and Posiva, respectively, such as tunnel section area and backfilling rate.

6.1 Model description

A deposition tunnel was represented as a one-dimensional problem (Figure 6-1) with a specified set of water inlets, each one attributed with a coordinate and a flow rate. The protocol for the backfilling of the tunnel was represented with the filling time as a function of the coordinate, which defines a line in a time-space diagram. The filling time function and the inlet coordinate gave the starting time for each water inlet, which came into play once the backfilling front had passed the position for this.

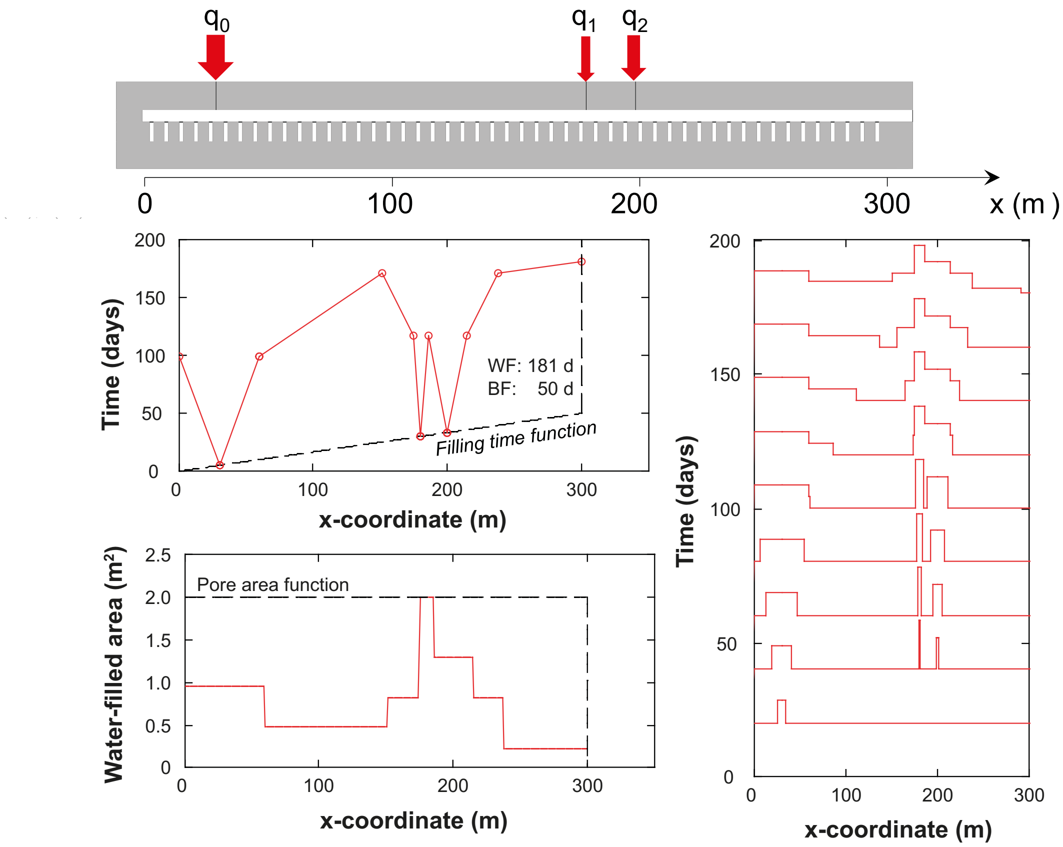

Figure 6-1. Tunnel with 3 water inlets (upper). Tunnel-filling diagram with filling time function (center left). Final water filled area profile with pore area function (bottom left). Area-fraction distribution for different times (right).

The distribution of voids in the backfill which can be water-filled was represented with a pore area function, i.e. the accessible pore volume per unit length. The partial water-filling of the pellet-filled sections was represented with a flow rate dependent area-fraction function. This means that the entire section area was filled as a homogenous progressing front for sufficiently low flow rates. However, only a fraction of the section area was filled at higher flow rates. For water-storage sections it was assumed that the entire area was filled, regardless of the flow rate. The use of geotextiles has been found to lead to a more extensive filling of the accessible pore volume. This behavior was represented with a higher-valued area-fraction function. No attempt was made to use different functions in different tunnel sections. Instead two quantified functions, representing cases with and without geotextiles, were used to analyze the water-filling of the backfill.

The flow from an inlet was assumed to be divided in two equal sub-flows with progressing fronts in two directions along the tunnel (inwards and outwards), i.e. with half the flow rate in each direction. Such a unit was denoted a "plume". These progressing fronts proceeded as long as they did not encounter the tunnel ending or another plume. When a plume encountered the inner tunnel ending it began progressing outwards with the total flow rate. When two plumes encountered each other they merged into one plume with a flow rate equal to the sum of the flow rates of the two original plumes. This spread with progressing fronts in two directions, with half the total flow rate, unless it had a history of encountering the inner tunnel ending, in which case it only progressed outwards with the total flow rate.

The evolution of encountering and merging plumes was modelled through the definition of an algorithm, which essentially was a systematic procedure for calculating where and when the next encounter would take place. This event defined the starting point for a new generation of plumes, with one plume less than in the previous generation (except for tunnel-end encountering events). This meant that the system could be described as a tree with a decreasing number of branches for each generation, ultimately resulting in one remaining main trunk. The output from this can be illustrated in a Tunnel-filling diagram which shows the progress of fronts and the encounter events in a time-space diagram (Figure 6-1). A second algorithm mapped the resulting plume network for a specific time and resulted in a table of coordinate intervals and local flow rates, which in turn were transformed to a water-filled area profile (Figure 6-1), which illustrates how much of the accessible pore volume has been filled at a given time.

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

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

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

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

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

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

6.2 Analysis of inflow scenarios

An analysis was performed for five inflow scenarios. These consisted of seven fractures and inlets (three in one case), and the different cases provide a wide range of flow rates: the highest total inflow was approximately 5 L/min, while the lowest was approximately 0.1 L/min. Each scenario was analyzed both for SKB and Posiva conditions, and each case was investigated for two area-fraction functions: one adopted for conditions with and one without geotextiles:

- The total flow rate in the wettest case was so extensive (~5 L/min) that a water storage section was included for both the SKB and the Posiva conditions. The results for the SKB conditions show that the time for the water-front to reach the outer tunnel end (54 days) was only slightly longer than the time for the backfill-front to reach the tunnel end (50 days). For the Posiva conditions the water-front end-time (89 days) was shorter than backfill-front end-time (103 days). The use of geotextiles had only a marginal influence on the results in this case.

- One case with three inlets and a total flow rate of 1.8 L/min resulted in water-front end-time of 90 and 110 days, for cases with geotextiles and for SKB and Posiva conditions, respectively. This was only marginally longer than the backfill-front end-time, especially for the Posiva case. It was also found that the water-front end-time was shorter than the backfill-front end-time for cases without geotextiles.
- One case with seven inlets and a total flow rate of ~1 L/min showed that the water-front end-time was significantly longer than the backfill-front end-time, even for the cases without geotextiles: 125 and 139 days for SKB and Posiva conditions, respectively (Figure 6-2). With geotextiles the water-front end-time were even longer 286 and 279 days for SKB and Posiva conditions, respectively.
- Cases with total flow rates of ~ 0.5 L/min resulted in water-front end-time several of hundreds of days, which is much longer than the backfill-front end-time. Cases with ~ 0.1 L/min resulted in water-front end-times of several thousands of days.

6.3 Tentative flow rate limits

The described model can apparently be used to assess the feasibility to backfill a tunnel with a specific concept and a specific installation sequence. In principle, it could be possible to use this model for analyzing the predicted inflow scenarios for all tunnels at a site, in order to estimate the number of tunnels requiring different water handling methods. A simpler approach could be to quantify flow rate limits for the feasibility of different method, which could be used as rules of thumb. However, since there are virtually an infinite combination of different inflow scenarios, there is no obvious way how to make a comprehensive definition of such limits. A simple procedure can be to consider cases with only one water inlet, located half-way through the tunnel, and to quantify the flow rate for which the resulting water-front end-time exceeds the backfill-front end-time with a specified margin (10 days was chosen). Results for different methods and WMO conditions are compiled in Table 6-1. It can be noted that the flow rate limits for cases without WSS is for Posiva conditions approximately 25 % lower than the values for SKB. For cases with a WSS the corresponding difference is 43 %.

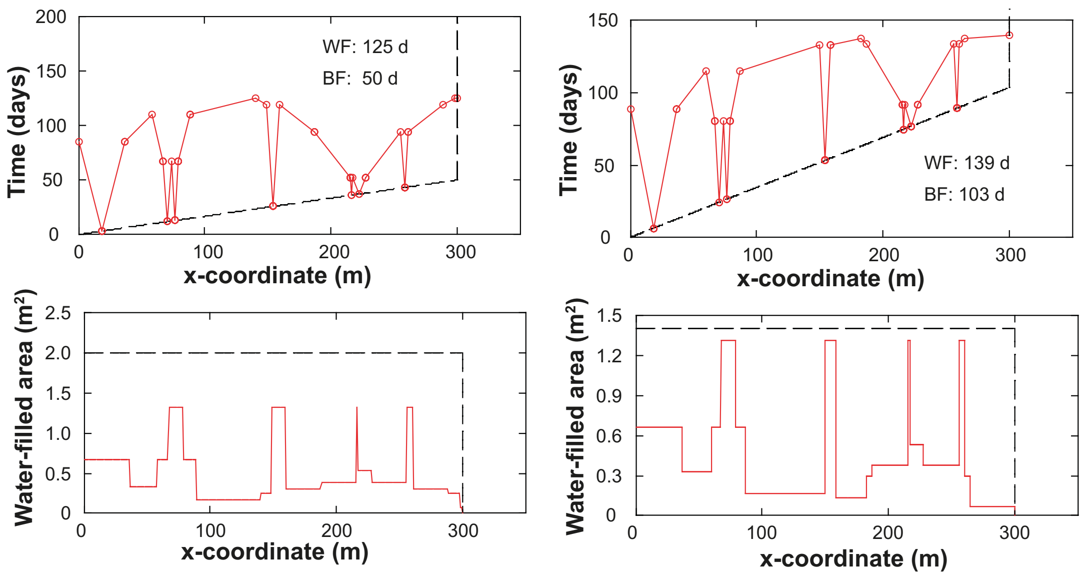

Figure 6-2. *Tunnel-filling diagrams and water-filled area profiles with Case 2 (no geotextiles). (left: SKB; right: Posiva). Water inlets with 0.1 L/min were applied at 70, 76, 154, 216 and 258 m. Water inlets with 0.2 and 0.25 L/min were applied at 18 and 222 m, respectively.*

Table 6-1. Tentative flow rate limits for different methods and conditions.

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

6.4 Uncertainties

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

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

The chosen approach also involves the definition of an area-fraction function. A function on the form $min[1,q_0/q]$ was proposed for this, and this means that the area-fraction equals unity for all flow rates lower than q_0. This may be quite different from upward triangular wetting behavior mentioned above, although it appears to be relevant to assume a completely distributed wetting at very low flow rates. Still, there may be other forms of the area-fraction function that can describe the real process more accurately. In addition, even if the chosen form is relevant, there may still be an uncertainty in the adopted q_0 values. Nevertheless, if new information would suggest that another form of the area-fraction function or another parameter value is more relevant, then it should be quite easy to modify the calculations presented in this chapter. Moreover, the water storage capacity may exhibit a stochastic behaviour, which was not addressed with the chosen approach.

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

7 Post-closure safety aspects

A meeting was held with experts on post closure safety with the main purpose to find any possible objections regarding post closure aspects on the proposed water handling methods. As a result of the meeting, the initially suggested designs of WSS and DAT were radically changed. These two methods included, in the early design, large amounts of sand filling serving as either water storage or water collector. The experts raised major concerns regarding these volumes with free water that could facilitate erosion of buffer and backfill. Another concern was that bacteria could grow in the water. The designs of WSS and DAT presented in this report have been changed and the large amounts of sand fillings removed.

7.1 Conclusions from the meeting

7.1.1 General

Some general statements were made at the meeting:

- The cost-benefit analysis of these methods have to be done considering the application in full scale and in-situ conditions, including the cost for additional work in the safety assessment, not only the technical backfill installation work.
- For all methods it is needed to know the smallest allowed distances to deposition holes and how many of these systems that are allowed in one deposition tunnel.
- Since the suggested methods are motivated by the economic loss of abandoning deposition tunnels or installing a tunnel end plug inside the tunnel, it is suggested that the cost of a new safety assessment work procedure also should be a factor in the judgement to apply a method or not.

7.1.2 Geotextile and temporary drainage

The methods including geotextile and a temporary drainage are viewed as acceptable from a post closure safety perspective as long as a number of open issues are handled:

Geotextile:

- What is the resulting hydraulic conductivity in the interface between rock and the swelling backfill?
- What are the maximum dimensions of the geotextile needed?
- Is it possible to reach 0.1 MPa swelling pressure everywhere in the backfill? Is the requirement applicable for fracture zones? (Judged as a non-issue compared to hydraulic conductivity).
- Evolution of geotextile with time. How does this impact the hydraulic conductivity near the rock wall?
- Should the installation of geotextile be made before or after rock reinforcement? (Worker safety issues).

Temporary drainage:

- Can this method be used when the inflow point is in the floor?
- Optimization of the water collection box. Can the volume be smaller and the gravel removed?
- Optimization of the water collection box. Is it possible to use material that degrades faster over time or breaks when exposed to swelling pressure?

7.1.3 Water storage section

The water storage section should not be used in the repository (this statement concerns the early design which now has been changed).

7.1.4 Drainage borehole to adjacent tunnel

At the meeting it was stated that the water handling method with a drainage borehole to an adjacent tunnel can be used under the condition that the borehole sealing is effective and reliable. The effect of a failed sealing should be investigated in safety assessment analyses of the repository.

However, after review of the method the following comment regarding the borehole sealing was made:

"The proposed sealing method using bentonite is deemed as being long term stable and having a very low hydraulic conductivity. However, the long term behavior of the sealing components cannot be checked after installation. Therefore, safety analyses should be carried out to investigate if the drainage hole can stay open without impacting the overall repository safety. This would mean that need for proving that the borehole sealing is extremely reliable in the long term, is diminished."

7.1.5 Temporary plug

The use of the proposed concrete plug with either steel beam reinforcements or shotcrete reinforcements is viewed as acceptable from a post-closure safety perspective. The amounts and composition of all materials must, however, be known.

8 Summary and conclusions

8.1 General

In the final repositories for nuclear waste, that are planned to be constructed by SKB and Posiva, it is expected that there will be water flowing into the deposition tunnels. The expected modelled water inflow rates will vary from almost dry tunnels and up to a maximum of 10 L/min. Since there is a clear incentive to use as much of the available rock volume and to not abandon already constructed tunnels there has been an aim to develop methods in order to handle the inflowing water of higher rates. The work presented in this report was divided in the following main activities:

1. Laboratory tests to investigate how the fines in the pellet filling influence the water storage capacity.
2. Large scale tests in the Bentonite Laboratory at Äspö. The aim with these tests was to investigate how geotextile can be used to distribute the inflowing water and by that increase the water storing capacity of a pellet filling.
3. Design of different water handling methods. The work has resulted in the development a number of water handling methods that are intended to be tested in full scale tests. Also preliminary laboratory scale tests were commissioned for the method artificially wetted pellet wall.
4. Design of a light fortified concrete plug. This type of plug is intended to be used in case of a temporary stop in the backfilling process.
5. Development of a mathematical model for water storage and spreading in a pellet filling. The model is intended to be used in conjunction with the planning of the backfilling process for each deposition tunnel.
6. Development of requirements on inflow data for deposition tunnels. This data is important when planning the backfilling process for a specific deposition tunnel.

The reporting on these activities are summarized in the Sections 8.2–8.7 below.

8.2 Laboratory tests of bentonite pellets-influence of fines

In different projects it has been observed that fine material present in a pellet filling has a tendency to end up in layers that may prevent the water storing in a specific direction, see e.g. Andersson and Sandén (2012) and Koskinen and Sandén (2014).

In order to study this issue, new test series have been performed within this project in different laboratory scales (Sandén and Jensen 2016).

The investigations have resulted in a number of recommendations, both regarding fines in a pellet filling but also regarding the required properties of the pellet:

- The presence of fines in a pellet filling depends on if it is present already in the delivered batch or if it is created during installation. To be sure that one gets an as functional pellet filling as possible, it is recommended that all pellets manufactured should be sieved before installation. It is also recommended that the pellet installation equipment (blower, conveyor etc.), should be designed so that as little fines as possible are created during installation.
- The properties of the backfill pellets are important in order to achieve a pellet filling with great capacity to store the inflowing water. In earlier performed test with Asha and Cebogel QSE pellets, see compilation of data provided in Åkesson et al. (2017), where the water storage properties have been assessed to be high, the water content have been between 12 and 20 % and the dry density of the individual pellets has been between 1 810–2 000 kg/m^3, see e.g. Dixon et al. (2008a, b) and Andersson and Sandén (2012). These figures are recommended to serve as a guideline for the requirements on the pellet properties.

- A method describing a validation test for backfill pellets regarding water storage capacity should be developed. The test may advantageously be based on e.g. the tube tests or on the large slot tests described Section 5.1.4.

The tests have shown that fines positioned as layers in a pellet filling temporarily will seal very efficiently, within a pellet filling, when water reaches the layer and thereby prevent water from flowing past the layer, see e.g. photos provided in Figure 5-3 and also Sandén and Jensen (2016). This is a technique that possibly also could be used to direct the wetting in a certain direction. It has e.g. been discussed to use wetted layers of pellets to prevent water flow but an alternative could be to instead use layers of fines. This application has, however, not been tested.

8.3 Large scale tests in the Bentonite Laboratory at Äspö studying the influence of geotextile

Tests have earlier been performed within the SKB project "System design of backfill" with the aim to investigate if geotextile can be used as a water distributor during backfill installation. In this project five additional tests were performed in large scale using the same steel tunnel test equipment at the Bentonite Laboratory at Äspö.

A main conclusion from the tests is that there is an obvious effect of using geotextile to increase the water storage capacity. The geotextile distributes the inflowing water over a larger area so that the inflowing water get access to a larger part of the pellet filling, which means that more water can be stored before water flows out towards the backfill front. This increase in water storage capacity for the pellet filling is important since it results in that inflowing water to deposition tunnels with medium high water inflow rates (0.25–1 L/min in one point inflow or fracture zone and with a maximum total inflow of 5 L/min) can be handled using geotextile only, or in combination with temporary drainage, which are assessed to be relatively simple means. (*Simple* meaning that the methods are fast and easy to install and do not interrupt the backfill installation.)

8.4 Design of different water handling methods

The inflowing water to the deposition tunnels can largely be handled by storing the water in the pellet filling surrounding the block stack. By using geotextile to distribute the water over a larger area the water storage capacity can be additionally increased. Predictions (modelling) regarding expected water inflow rates shows, however, that there will be deposition tunnels with inflow rates higher than what can be handled by storing inflowing water in the pellet filling (and improved by using geotextile), and to use these tunnels it would be necessary to develop and use other water handling methods. These methods includes in some cases that new materials (concrete, steel etc.) must be used and left in the deposition tunnels. A meeting has been held with experts on post closure safety in order to find any objections on the suggested water handling methods and also to find what needs to be further developed, see Chapter 7. The outcome from the meeting has strongly influenced and changed the originally design for two of the suggested methods (DAT and WSS). A brief description of the suggested water handling methods and their capacities is provided below.

8.4.1 Water storage in pellet filling

In different tests it has been observed that a bentonite pellet filling has a large ability to store water flowing into the deposition tunnel from the rock, see e.g. Dixon et al. (2008a, b) and Andersson and Sandén (2012). It has also been assessed that this ability probably is enough in order to avoid problems with inflowing water reaching the backfill front for the main part of the tunnels in a future repository (Sandén and Börgesson 2014).

Capacity

The technique to store the inflowing water in the pellet filling surrounding the block stack is estimated to have a capacity to handle inflow rates in one water bearing fracture zone/point inflow < 0.5 L/min. The total inflow to the deposition tunnel should in that case be < 1.0 L/min. If the total inflow is between 1.0 and 5.0 L/min, the maximum inflow to one fracture zone/point inflow is < 0.25 L/min.

8.4.2 Geotextile

The main idea by using geotextiles is to distribute inflowing water from the rock surface over a larger pellet area and by that increase the water storage capacity and delay the water breakthrough at the backfill front. The influence of using geotextile to increase the water storage capacity of a pellet filling has mainly been investigated in the steel tunnel test equipment at Äspö HRL. The results from the tests show that the water storing capacity of a filling clearly increases for inflow rates between 0.25 to 1.0 L/min.

Capacity

The technique to use geotextile to improve the water storing capacity of a pellet filling is estimated to be useful to handle inflow rates in one water bearing fracture zone/point inflow between 0.25 and 1.0 L/min (1.0 L/min is on the limit and it is therefore recommended to also use a temporary drainage in sections with an inflow rate between 0.5 and 1.0 L/min, see next Section). For higher inflow rates there is an obvious risk of channel flow to occur, which probably will lead to a fast outflow of water at the backfill front.

8.4.3 Temporary drainage

In addition to geotextile, and to further delay the inflowing water from reaching the backfill front, it is possible to use a temporary removable drainage pipe. The suggested method includes geotextile to allow for short-term drainage of inflow water. The pipe is temporarily attached to the geotextile since it is necessary to remove it after use. This means that there is a limit of the maximum pipe length. If the pipe is too long, the force required to pull it out will be too high for the approach to be practical.

Capacity

The technique to use a temporary drainage is assessed to be suitable for inflow rates between 0.5 and 1.0 L/min. If there e.g. are a number of sections after each other with inflow rates between 0.25 and 1.0 L/min, it could be necessary to use a temporary drainage in order to achieve extra time for the backfill installation and to avoid water outflow at the front.

8.4.4 Water Storage Section, WSS

In tunnel sections where the inflow rates are rather high, between 1 and 5 L/min, the technique to store water in the pellet filling between rock walls and block stack will not be enough to avoid water outflow at the front. The design idea with WSS is that a section of a tunnel will be used to store water flowing mainly from a fractured zone/point inflow but also from the already inner backfilled part of the tunnel. The storage is achieved by building a pellet filled section, delimited by two concrete beam walls, that contains a large volume of empty pores that can hold the inflowing water and stop it from flowing into the downstream backfill. The storing capacity must be large enough so that the water flow into the outer part of the deposition tunnel will be delayed so that the backfilling of the rest of the tunnel can be done without water penetrating to the backfilling front.

Installation of a WSS will result in a transition zone in the backfill (on both sides of the water collector section) with lower backfill density than the average installed density. It is assumed that there shall be a smallest allowed distance between a deposition hole and the transition zone of one meter. The minimum distance of 1 m is rather arbitrarily chosen and may be changed. Since the position and length of a WSS can be decided before drilling the deposition holes, this requirement will not result in that already drilled deposition holes have to be abandoned.

Capacity

Building of a water storage section is assessed to be suitable for inflow rates between 1.0 and 5.0 L/min. The storing capacity can be set by adjusting the length of the dedicated section and by that also the installed pellet volume. For higher inflow rates than 5 L/min, it is assessed that the length of the pellet filled section will represent a too large part of the deposition tunnel.

8.4.5 Drainage hole to Adjacent Tunnel

A technique assessed to have 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. The main idea is to collect the water from a water bearing fracture zone in a special water collector section and then drain it to an adjacent tunnel through a borehole until the backfilling of the current deposition tunnel is complete, and thereafter seal the borehole.

The principle for the new design of a water collector (the design has been changed due to comments from post closure safety experts, see Chapter 7) is that at the position of a water bearing fracture, which is crossing a deposition tunnel, a slot is cut out from the rock to a depth of approximately 0.2 meters, all around the tunnel periphery. The slot is then covered with a thin steel plate which is bolted to the rock. The space between the steel plate and the rock is filled with gravel that are serving as a filter, leading all inflowing water to the drainage borehole which is drilled from the bottom of the slot to an adjacent tunnel. The installation of this type of water collector can be made in advance which means that the backfill installation process can continue without any stop for construction. The design is assessed to function well for all fractures crossing the deposition tunnel close to perpendicular. However, if a gently dripping fracture zone is crossing the deposition tunnel the installation will be more difficult.

Capacity

According to the present limitations for the project the maximum inflow rate is 10 L/min but it is assessed that this water handling technique can handle also considerably larger inflow rates if necessary.

8.4.6 Artificially wetted pellet wall

By adding water on the installed pellets it is possible to build up a wet pellet wall. Water flowing from the inside of the pellet-filling towards the front hits the wetted pellet wall which is much tighter (more dense) than the rest of the pellet-filling and the water will therefore turn back into the dry parts of the filling. The method has been tested in laboratory scale and also in the large scale steel tunnel tests at Äspö. With this method a larger part of the pellet-filling can be used for water storing. Ultimately water will move beyond the wetted wall, but the backfilling would have progressed substantially further down the tunnel by that time.

The method is not fully developed and it has been assessed that further tests will be needed before it is ready for implementation in full scale tests.

Capacity

The capacity of this method is not known but it is assessed that it can be used together with geotextile as an improvement. The method will probably not be useful for inflow rates higher than 1 L/min.

8.4.7 Local freezing

The objective of the work performed within this project was to evaluate the feasibility of using "Local Freezing" to control groundwater inflows during backfill operations in hard crystalline rock. Ground freezing is a well-known technique but there is no proper information available of the use of it in hard good quality rock. The conceptual idea is to freeze the rock around the excavated tunnel to stop the water inflow. The method is commonly used in civil engineering when building in sand or other loose wet soils where freezing has been used to control groundwater (e.g. in shafts), to mechanically stabilize soils so that the reinforcement can be carried out safely and to enable tunneling through mixed ground.

A workshop has been held with a number of experts in the field. It was concluded that the method has great potential to stop or reduce water inflow but investigations and tests will be necessary.

Capacity

The capacity of this method is not known.

8.5 Light fortified concrete plug

In addition to the developed water handling methods, a suggestion for design of a plug has been made. The plug is intended to be used in case of a temporary stop in the backfill installation process e.g. depending on technical problems with the robot or other repository related stoppages. The design idea is to build a rather simple plug in short time that can withstand a swelling pressure build-up from the backfill behind it. The design consists of a concrete beam wall that can be reinforced by either a steel construction or a shotcrete plug if it is judged to be necessary. The design includes that a pellet filling is installed between the block stack and the wall. This pellet gap has an important role to delay the swelling pressure build-up from the backfill blocks on the wall. The design includes a drainage section that ensures that no water pressure can be built up inside the plug. The plug has been designed to withstand a maximum swelling pressure from the backfill of at least 1 MPa.

8.6 Development of a mathematical model of water storage and spreading

A mathematical model was developed with the objective to calculate the available time for specific deposition tunnels and for specific water inflow scenarios, and to analyze if there is a risk that inflowing water can catch up with the backfill front. The water transport was represented as progressing water fronts from multiple water inlets in a tunnel, for essentially any combination of inlet positions and flow rates. The partial water-filling of the pellets-filled sections was represented with a flow rate dependent function, which was adopted from results from steel-tunnel tests. The model was intentionally given a general definition which could enable an evaluation of features which are specific for SKB and Posiva, respectively, such as tunnel section area and backfilling rate. The model can be used as a tool when planning the backfill installation process for a specific tunnel.

8.7 Requirements on inflow data

A suggestion for characterization of deposition tunnels regarding water inflow distribution before starting the backfill installation process has been made. The requirements are based on results from the investigations and tests performed regarding e.g. water storage capacity of a pellet filling and the effect of using geotextile to distribute the inflowing water. The requirements may be summarized as follows:

1. The total water inflow to every deposition tunnel shall be determined. If the total inflow is < 0.5 L/min, no further actions are needed.
2. If the total inflow to a tunnel is between 0.5 and 1.0 L/min, fracture zones/point inflows with inflow rates > 0.5 L/min shall be identified.
3. If the total inflow to a tunnel is > 1.0 L/min, fracture zones/point inflows with inflow rates > 0.25 L/min shall be identified.

The suggested requirements on mapping of inflow data have been discussed with people responsible for the construction of deposition tunnels within SKB and Posiva and where found to be reasonable.

8.8 Conclusions

Water handling methods

The main objective with work presented in this report was to develop water handling methods for all possible water inflow rates that may occur in deposition tunnels during backfill installation. From the performed investigations on bentonite pellets regarding water storage capacity and the designs of other water handling methods the following conclusions can be made:

- Bentonite pellet is used for filling of all gaps between the backfill block stack and the rock walls. According to present modelling results regarding expected inflow rates in Forsmark and Olkiluoto, the storage of inflowing water in the pellet filling will be enough for the main part of the deposition tunnels. Water storage in the pellet filling is recommended for inflow rates in one fracture zone/point inflow <0.5 L/min and a total inflow to the tunnel of between 0.5 and 1.0 L/min. If there are a number of inflow points with inflow rates < 0.25 L/min the total inflow to the tunnel can be between 1 and 5 L/min.
- By using geotextile to distribute the inflowing water over a larger area, the water storage capacity of a pellet filling can be considerably increased. This is a rather simple method that is recommended to be used in fracture zones/point inflows with inflow rates between 0.25 and 1.0 L/min. It is recommended to also install an artificially wetted pellet wall after a section with geotextile. This method has been included in the steel tunnel test and has also influenced the results. If adding a temporary drainage, connected to the geotextile, the progress of the water front in the pellet filling can be further delayed. Temporary drainage is recommended for inflow rates between 0.5 and 1.0 L/min.
- In fracture zones/point inflows with inflow rates between 1.0 and 5.0 L/min, it is possible to construct a pellet filled section, delimited by two concrete beam walls. This section is planned to be used to store the inflowing water during the continued backfill installation and by that prevent water from reaching the backfill front.
- In fracture zones/point inflows with inflow rates between 5 and 10 L/min, it is recommended to drain the inflowing water to a neighboring tunnel. After having fulfilled the backfilling of the current tunnel, the drainage borehole should be sealed. This method can of course also be used for lower inflow rates and by that e.g. replace WSS.

In addition to the methods described above, it has been discussed to locally freeze the rock around a water bearing fracture zone and by that stop or reduce the inflow rate. This method has so far only been investigated by interviews with experts in the field. From the interviews it was concluded that freezing of hard rock to seal groundwater flow is feasible but it will be necessary to investigate the method further, both theoretically (modelling) and by performing tests.

Light fortified concrete plug

It is judged that it will be possible to construct a temporary plug in relatively short term in case of a temporary stop in the backfill installation process. However, this assumes that you have prepared by having all necessary equipment in storage. The suggested plug has been designed to withstand a maximum swelling pressure from the backfill of at least 1 MPa. Reaching this pressure will, according to the presented modelling results, take between 150 days and one year (depends on the access to water from the rock at the actual position in the tunnel.

Conceptual model

Another objective with the project was to update the conceptual model, describing how water is stored in a pellet filling depending on inflow rates and pellet properties. The results from the new test series, performed within this project, have been used together with a review of results from earlier tests performed within other projects. The water storage behavior in a pellet filling is mainly depending on the water inflow rate, the pellet properties and if fines are present in the filling. As an important outcome from the investigations, the two following recommendations have been made:

- The presence of fines in a pellet filling depends on if it is present already in the delivered batch or if it is created during installation. To be sure that one gets such a functional pellet filling as possible, it is recommended that all pellets manufactured should be sieved before installation. It is also recommended that the pellet installation equipment (blower, conveyor etc.), should be set so that as little fines as possible are created during installation.
- In earlier performed test with Asha an Cebogel QSE pellets, where the water storage properties have been assessed to be high, the water content have been between 12 and 20 % and the dry density of the individual pellets has been between 1 810–2 000 kg/m^3, see e.g. Dixon et al. 2008a, b) and Andersson and Sandén (2012). These figures should serve as a guideline for the requirements on the pellet properties.

Mathematical model

A mathematical model was developed with the objective to calculate the available time for specific deposition tunnels and for specific water inflow scenarios, and to analyze if there is a risk that inflowing water can catch up with the backfill front. The model can be used as a tool when planning the backfill installation process for a specific tunnel.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.
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A CO-OPERATION REPORT BETWEEN SVENSK KÄRNBRÄNSLEHANTERING AB AND POSIVA OY

SKB's and Posiva's programmes both aim at the disposal of spent nuclear fuel based on the KBS-3 concept. Formal cooperation between the companies has been in effect since 2001. In 2014 the companies agreed on extended cooperation where SKB and Posiva share the vision "Operating optimised facilities in 2030". To further enhance the cooperation, Posiva and SKB started a series of joint reports in 2016, which includes this report.