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Hans Wimelius, Svensk Kärnbränslehantering AB

Roland Pusch, Geodevelopment International AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

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

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Hans Wimelius, Svensk Kärnbränslehantering AB

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Summary

By definition for the SKB repository concept, the backfill of KBS-3V deposition tunnels must be so designed that transport of dissolved matter is controlled by diffusion and not by advective water flow. This requires that the hydraulic conductivity of the backfill does not exceed about E-10 m/s. The backfilling materials also have to adequately resist compression caused by upward expansion of the buffer. It must also exert an effective pressure of at least 100 kPa on the rock in order to provide support to the rock and minimize spalling of the rock. These criteria are fulfilled by several approaches and options for backfill materials, placed and compacted layer wise or in the form of blocks of compacted clay powder. Based on the experience from comprehensive lab studies and considering practical issues, SKB has selected a concept where the major part of the backfill consists of stacked blocks that are surrounded by clay pellets. Using this concept a basis for a detailed evaluation, a study of three different techniques for placing the blocks has been undertaken. The three block placement techniques examined are the "Block", "Robot", and "Module" methods. They involve different block sizes and techniques for handling and placing the blocks but the same way of preparing the foundation bed of the blocks and placing the pellet filling.

The blasted tunnels have a varying cross section, caused by the orientation of the blast-holes. This requires that a varying fraction of blocks be installed in the backfilling along the blasted tunnel interval if sufficiently high density and low hydraulic conductivity is to be achieved. The efficiency of filling will depend on the type of clay used in the blocks. For example, using Friedland clay for block preparation, the filling efficiency must be 80% while it can be reduced to 60% if more smectite-rich clay is used. The use of a clay with high smectite content increases margins and is concluded to be superior from emplacement point of view.

Besides the requirement for the functional criteria, there are a lot of conditions that will affect the performance, like water inflow, rate of deposition of canisters, distance between deposition holes and how the sequences between deposition and backfilling are combined. This report will describe these conditions and how they affect backfilling.

The "Block" method for backfilling implies individual handling and placement of the blocks. This is relatively tedious and may cause problems by unacceptable delay in backfilling rate if even minor disturbances were to occur. The "Robot" method is more rational since the handling of the blocks is fully automatic but it requires a unique system design that must be developed and tested. In combination with other backfilling activities, like removal of buffer protection sheets, installation of pellets and adjustment of floor beds, the "Robot" method is estimated to be difficult to apply. Both of these methods also rely on a vacuum technique for lifting and handling the blocks. This technique has a greater risk for operational mishap than use of tractors with forks for lifting coherent sets of blocks, which is the basis for the third block placement technique ("Module" method). These three concepts were examined with respect to the entire sequence of transporting, placing the blocks and filling the remaining volume with pellets and it has been concluded that the "Module" method is superior to the others by being safer and quicker. The conclusions of this study are as follows:

- All three methods fulfil demands and criteria. At present, only blocks of the size required for the "Block" and "Robot" methods can be manufactured on an industrial scale.
- The "Block" method has been investigated and tested on a full scale more than the other methods.
- The "Robot" method has sufficient potential to become more rational than the "Block" method.
- The "Module" method has sufficient potential to become more time-saving and robust than the other methods, providing a very high quality of the backfill.

- The “Block” method is proposed as the reference method in the “line report” since the basis for assessment of the performance and accuracy is more extensive than for the other methods.
- Development of the “Robot” method is recommended as a complement to the reference method.
- The “Module” method has sufficient potential to become the safest and most time-saving technique. It is recommended that the module method be investigated and tested to a level that makes it comparable to the proposed reference method.

The pellet filling, which is common to all the methods, is the least well defined and safe part of the backfilling process. Possible heterogeneities in the fill are hard to identify and may remain undetected. For all the methods the backfilling is integrated with removal of the buffer protection components and placement of pellets in the deposition holes.

Evaluation of the degree of backfilling requires very careful determination of the volume of the tunnels and installed clay materials. All clay components have to be weighed and the density, calculated on the basis of the weight and the volume of the filled tunnel space, compared with the required value. The postulated maximum allowed unfilled space of 2% for 60% block filling means that placement and checking of blocks and pellets must be made with high precision.

Performed studies and tests, which are the basis of this report, show that all the involved activities need to be further developed.

Sammanfattning

Definitionsmässigt skall återfyllningen i deponeringstunnlarna för KBS-3V utföras så att transport av lösta ämnen bestäms av diffusion och inte av vattenflöde, vilket svarar mot en hydraulisk konduktivitet av högst cirka E-10 m/s. Återfyllnaden måste också klara komprimeringskraven. Komprimeringen av återfyllnaden skall vara liten för att förhindra att bufferten i deponeringshålen expanderar uppåt. Den måste också utöva ett effektivtryck av minst 100 kPa för att begränsa bergutfall och uppåtriktad expansion av bufferten. Dessa kriterier uppfylls av flera materialkombinationer, fyllda och packade lagervis eller i form av kompakterade block av lerpulver. Med laboratorieförsök och hänsyn till praktiska omständigheter som grund valde SKB ett koncept som innebär att huvuddelen av fyllningen består av staplade block kringfyllda av lerpelletar. Det tillämpades i det här rapporterade projektet, som omfattade undersökning av tre olika sätt att placera blocken: ”Blockmetoden”, ”Robotmetoden” och ”Modulmetoden”. De innebär användning av olika storlekar av block samt olika sätt att hantera och placera dem, men samma sätt för att bygga bäddar och att installera pellets.

De sprängda tunnlarna har oregelbunden form på grund av nödvändig borrhålsstickning, vilket leder till krav på varierande andel block längs salvan för att nå erforderlig hög densitet och låg genomsläpplighet. Blockfyllnadsgraden är en nyckelfråga för att uppnå erforderlig densitet och täthet hos återfyllningen. Använder man Friedlandlera för framställning av kompakterade block måste blockfyllnadsgraden vara 80 % medan den kan vara så låg som 60 % vid användning av mera smektitrik lera. Den sistnämnda möjligheten ger större marginaler och bedöms vara mest lämplig med hänsyn till återfyllnadsarbetet.

Förutom kraven mot funktionsindikatorerna så finns det många styrande förutsättningar som påverkar utförandet, som vatteninflöde, takten för deponering av kapslar, avstånd mellan deponeringshålen samt hur sekvenserna mellan deponering och återfyllnad kombineras. Denna rapport kommer att redogöra för detta.

”Blockmetoden” innebär individuell hantering och placering av blocken. Den är härigenom relativt sett långsam och kan ge problem med fördröjning redan vid mindre störningar. Metoden är den mest utprovade i dagsläget. ”Robotmetoden” är rationellare eftersom blockhanteringen är helautomatisk. Lämplig robotteknik finns tillgänglig men anpassning till återfyllningens förhållanden och krav återstår, vilket kräver utvecklingsarbete i kombination med tester. Med tanke på övriga moment i tunneln vid återfyllning, som återtag av buffertskydd, fyllning med pelletar i deponeringshål, resterande fyllning av deponeringshål och ramp upp till tunnelgolvet, utläggning av bottenbädd samt pelletarinstallation efter inplacering av återfyllningsblocken finns det sekvenser som inte är fullt utredda idag. Båda metoderna innebär användning av vacuumteknik för lyftning och hantering av blocken, vilket innebär större risker än användning av gaffeltruck, som utnyttjas av den tredje tekniken, ”Modulmetoden”, för hantering av större block. De tre koncepten undersöktes med avseende på hela sekvensen av transport och placering av block, fyllning av pelletar, med slutsatsen att:

- Alla tre metoderna uppfyller kraven. Endast block i de storlekar ”Blockmetoden” och ”Robotmetoden” förutsätter, bedöms i dag kunna tillverkas i industriell skala.
- Blockmetoden är den metod som är mest studerad och provad i fullstor skala idag.
- Robotmetoden bedöms kunna leda till en effektivare ”Blockmetod”.
- Modulmetoden har potential att bli snabbare och robustare med bibehållen hög kvalitet hos återfyllen.
- Blockmetoden föreslås som referensmetod i linjerapporten till följd av det säkrare underlaget som finns för bedömning av metodens prestanda och kvalitet.

- Utveckling av metoden med robotteknik föreslås studeras vidare som komplement till referensmetoden.
- ”Modulmetoden” har potential att utvecklas till en säkrare och snabbare metod. Den rekommenderas också för fortsatt undersökning och storskalig prövning till en kunskapsnivå som gör den möjlig att jämföras med den föreslagna referensmetoden.

Pelletarfyllningen, som är densamma för alla metoderna, är det minst väldefinierade och säkra återfyllningsmomentet. Möjliga heterogeniteter i pelletarfyllningen kan vara svåra att upptäcka vid kontroll. För samtliga metoder är återfyllningen samhörig med avlägsnande av anordningarna för buffertskydd och fyllning av pelletar i deponeringshålen.

Kontrollen av återfyllnadsgraden kräver en mycket noggrann beräkning av tunnelns och lerkomponenternas volym. Installerad bentonit vägs och kontrolleras mot sektionens volym. Kravet på max 2 % ofylld volym vid återfyllnad med 60 % block ställer höga krav på installationsmetoder och stor exakthet i kontrollen.

Utförda studier och tester som ligger till grund för denna rapport visar att utvecklingsarbete återstår för alla ingående aktiviteter.

Contents

1 Introduction

For the SKB repository concept backfilling of KBS-3V deposition tunnels (Figure 1-1) should be made so that transport of dissolved matter is controlled by diffusion and not by water flow. This requires that the hydraulic conductivity of the backfill does not exceed E-10 m/s. The backfill should also exert an effective pressure of at least 100 kPa on the rock. This criterion is intended to ensure that the risk of rock blocks falling from the roof and walls is eliminated. A system requirement is that the compressibility of the backfill must be low enough to minimize upwards expansion of the bentonite[1] buffer. Compressible backfill may reduce the density of the upper part of the buffer which possibly cause tension stresses in the canisters /1/. Also, the sensitivity of the backfill to erosion and piping caused by inflowing water during the construction phase and soon thereafter should be small.

The concept of backfilling the tunnels using compacted blocks of smectite clay and pellets produced from smectite clay is briefly described in this report, focus being on practical issues like handling and placement of the backfill materials. The hydraulic and mechanical performance of the backfill are not discussed in this document as its focus is on potential methodologies for its placement.

Selection of a suitable backfill material, which must contain smectite clay in order to fulfil the criterion of providing compressibility and a low hydraulic conductivity has been an important issue since the introduction of the KBS-3V concept. This is both because of the requirement that its physical properties must continue to meet its performance criteria for at least 100,000 years /9/, and because it must be placeable using simple and safe techniques. It is also important that the cost of material and its placement are reasonable.

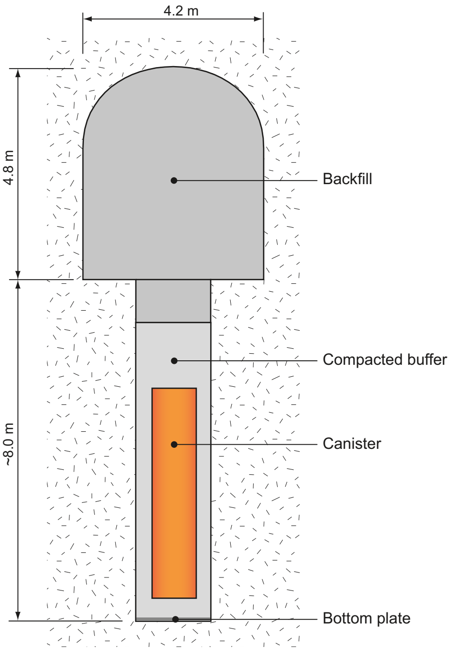

***Figure 1-1.** Schematic section of a KBS-3V deposition tunnel showing the major engineered barriers, i.e. the canister, the bentonite1 buffer, and the backfill /2/.*

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[1] Bentonite is the commercial/geological term used to describe products and materials containing smectitic clays originating from altered volcanic ash. It is commonly used as a synonym for smectite clay dominated by montmorillonite-type clay minerals, and so is the term used in this report.

The matter of selecting and placing backfills in tunnels has been under consideration since the KBS-3V concept was proposed some thirty years ago and a number of laboratory investigations and a few large-scale tests have been performed /5,8,15,16/. Recent experiments have shown that the inflow of water during the backfilling process is a determinant of the required rate of placement, and of the optimal type of backfill material. Two comprehensive studies have been performed for investigating these matters, one being related to the impact of water inflow /8/, and the other focusing on practical issues related to handling and placement of backfills of blocks and pellets. The present report deals with the latter two aspects. Three different backfilling methods are described in the report: 1) the “Block”, 2) the “Robot”, and 3) the “Module” methods.

1.1 Scope of the project

The scope of the project is to identify possible methods for placing blocks and pellets in KBS-3V deposition tunnels and to investigate their applicability. The starting point was to find practical and robust techniques for constructing the backfill so that defined criteria regarding density and rate of placement are fulfilled. The first step was to gain an overall view of what is needed and what is possible. Understanding of all influencing factors and what experience is available for each of the individual work processes was created. It was necessary to consider all the operational steps in the various alternative procedures for placing the components. Special attention has been given to defining the sequence of component installation and to assess the time required for each with regards to water inflow and placement of one canister a day.

The most important was to calculate and estimate possible backfilling degree of blocks and also calculate final dry density in deposition tunnels. To do this it was necessary to analyse variations in the tunnel profile of the blasted rock and what its impact on the degree of filling will be.

It is necessary to recognize that conditions underground will include varying water inflow rates and locations and that this will impact on the placement of blocks and pellets. This will be especially important with respect to the time required to accomplish backfill installation and what the consequences of possible deviations from the generic backfilling plans will be. The intention of such studies has been to become acquainted with the practical aspects of installation of all the components and to get a general view of how their future performance will be affected by the varying rock conditions. In summary, the goal of this study has been to collect all presently available data and experience related to tunnel backfilling in order to establish a basis for deciding what materials and techniques can be used for backfilling of KBS-3V deposition tunnels. This also requires keeping in mind the prevailing conditions and parallel activities that will be occurring in a repository. The report is a condensed version of a number of working reports, leaving much of the detailed descriptions and data to the Appendices.

1.2 Background

1.2.1 The KBS-3V concept

The key barriers to migration of radionuclides from the spent fuel are the copper/iron canisters and the surrounding highly compacted clay buffer as depicted in Figure 1-1. The backfill is to ensure that the deposition tunnels become major flow paths in the repository rock, and to provide mechanical support to the buffer and rock. Placement of the backfill into the tunnels above the deposition holes containing the canisters (spaced 6–8 m apart depending on the thermal properties of the rock) can be achieved in several ways. The basic plan is to install the canisters at a rate of one per day in separate tunnels. The required rate of backfilling of them is hence 6–8 m per day. Any interruption in this procedure can cause problems, especially related to areas where the inflow of water from the rock is significant. It is therefore important to select backfill materials and use placement techniques that minimize such difficulties and that are simple and safe. The physical properties of the backfill installed should also have a sufficient margin in their as-placed state so as to ensure that they will achieve their required performance.

1.2.2 Criteria

The criteria specified for the backfill in SR-Can are /3/:

- The swelling pressure must be at least 100 kPa.
- The hydraulic conductivity of the backfill in bulk should not exceed E-10 m/s.
- The compression of the backfill by the expanding buffer should not cause reduction of the buffers water saturated density to less than 1,950 kg/m^3. /4,5/

1.2.3 Physical properties of clay materials

A number of clay-based backfilling materials and techniques for placing them have been considered and tested in SKB's comprehensive R&D work. Their geotechnical properties are summarized in Table 1-1. Based on experience from earth dam construction the backfills originally considered for repository backfilling were mixtures of clay and suitably graded silt/sand/gravel ("BMT"-type), /6, 7/. These data show that mixtures with 10 and 20% clay do not fulfil the hydraulic criterion, while a clay content of 30% does. However, the safety margin with respect to hydraulic and swelling behaviour would be inadequate even for the higher clay content backfill. This is particularly the case if over the long-term (100,000 years) some conversion of the smectite to minerals of lower swelling capacity were to occur. As a result of these considerations, mixtures of this type (10–30% bentonite), were abandoned in the design work. Instead, materials with very high clay content were selected for consideration as candidate backfills and the first such high-clay-content material to be investigated was the mixed-layer (smectite/illite/mica) Friedland clay.

Table 1-1. Hydraulic conductivity (K) and swelling pressure (p_s) of backfill mixtures of MX-80 clay and ballast material of BMT type with a density at saturation of 2,100 kg/m^3 (1,600 kg/m^3 dry density). Corresponding data for Friedland clay and the more smectite-rich clay MX-80 clay, commonly used as a reference, are given as well /5,6,7/. The highest conductivity and lowest swelling pressure refer to tests with salt water.

Clay content, weight percent	Density, first value is dry density, second density at water saturation kg/m3	*K*, m/s	p_s, kPa	*Backfill material*
10	1,750/2,100	E-8 to E-7	20 to 100	Mixture of MX-80 and BMT-type ballast
20	1,750/2,100	E-10 to E-9	100 to 200	Mixture of MX-80 and BMT-type ballast
30	1,750/2,100	E-11 to E-10	200 to 500	Mixture of MX-80 and BMT-type ballast
50	17502,100	E-12 to E-10	1,000 to 2,000	Mixture of MX-80 and BMT-type ballast
90	1,750/2,100	5E-13 to 5E-12	>1,500	Friedland clay
90	1,510/1,950	E-11 to E-10	300 to 400	Friedland clay
90	1,430/1,900	5E-11 to 5E-10	150 to 200	Friedland clay
90	1,750/2,100	5E-14 to E-13	>10,000	MX-80
90	1,510/1,950	E-13 to 5E-13	3,000	MX-80
90	1,430/1,900	2E-13 to E-12	1,500	MX-80
90	1,270/1,800	5E-13 to 5E-12	600 to 800	MX-80
90	1,110/1,700	E-12 to 5E-11	200 to 500	MX-80

Table 1-1 shows swelling pressure and hydraulic conductivity data for mixtures of MX-80 clay and ballast material of BMT type with a saturated density of 2,100 kg/m^3 (1,600 kg/m^3 dry density) as well as data for Friedland clay and more smectite-rich clay represented by MX-80 clay[2] /5,6,7/. The highest conductivity and lowest swelling pressure values in Table 1-1 refer to tests done using salt water (3.5% $CaCl_2$ solution). Based on these data it would appear that Friedland clay will likely prove suitable as a backfill if an average water saturated density of 1,950 kg/m^3 (dry density 1,500 kg/m^3) can be reached. The hydraulic conductivity and swelling pressure of Friedland clay are described in detail in Figures 1-2 and 1-3 /5,6,7/ with special respect to the impact of salt water.

In principle, the hydraulic performance of the backfill should be such that it is not more permeable than the surrounding rock, which requires definition of the conductivity of the excavation-disturbed zone (EDZ) and of the flow-retarding impact of plugs cutting them off. For conducting safety calculations these matters are avoided by requiring the backfill to be so composed and constructed that transport of dissolved matter is controlled by diffusion and not by water flow. This is equivalent to the specified maximum allowed net hydraulic conductivity of E-10 m/s, which implies that the average saturated density of a backfill dominated by Friedland clay should be at least 1,950 kg/m^3, corresponding to a dry density of about 1,500 kg/m^3. For equally dense MX-80 and similar smectite-rich clay materials the hydraulic conductivity is about 100–500 times lower as illustrated by Table 1-1.

The criterion that the backfill should exert a swelling pressure of at least 100 kPa on the surrounding rock for avoiding rock fall is fulfilled by a backfill of Friedland clay with a saturated density of 1,900 kg/m^3 (dry density 1,425 kg/m^3), Table 1-1. For a density of 1,950 kg/m^3, (dry density 1,500 kg/m^3), the data in this table show that the swelling pressure of the backfill will be approximately 300 kPa, which is more than required. For equally dense MX-80 and similar smectite-rich clay materials the swelling pressure is more than five times higher. In practice, if the emplaced density criterion is met there will be no risk that the swelling pressure and rock-supporting capacity will be insufficient.

For assessing the performance of backfill over the long-term one has to take potential degradation of the clay minerals and changes in density by compression under expected glacier loads into consideration /4,5/. These processes have different impacts on the hydraulic performance and expandability. The first assumes a slow conversion of the mixed-layer swelling clay minerals to be muscovite yielding some increase in hydraulic conductivity, the second process implies some slight compression, leading to some minor reduction in hydraulic conductivity. The negative effect of clay mineral conversion under anticipated repository conditions is believed to be relatively small in mixed layer clays and significantly smaller than for smectite-dominated backfills /1/. Assuming that the degradation has the form of conversion of 10% of expandable minerals to non-expandable in 100,000 years, and that it is inversibly related to the hydraulic conductivity, the required density at water saturation for fulfilling the criterion of E-10 m/s is estimated to be 2,050 kg/m^3 (dry density 1,670 kg/m^3).

Degradation of the clay minerals and changes in density by compression under expected glacier loads affect the swelling pressure exerted by the backfill. The expected slow conversion of the mixed-layer minerals to muscovite will cause some minor loss in expandability and swelling pressure but presumably less than for smectite-rich backfills /4,5/. Glacier loads and slight compression could result in an increase in swelling pressure /9/. The negative effect of clay mineral conversion is believed to be relatively small and significantly smaller than for smectite-dominated backfills and it would probably be compensated by increasing the density at water saturation to 2,050 kg/m^3 (dry density 1,670 kg/m^3).

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[2] The data for other clays with comparable smectite content, like those from Greece, India and Turkey, show that they are commonly of slightly lower quality than MX-80. Thus, two presently considered candidate clays termed “Milos”, “Cebogel”, and “Asha” /Appendix 4/ have been reported to be 2 to 4 times more permeable for the dry densities 1,270 and 1,430 kg/m^3 than MX-80 and 10 to 100 times more permeable for the dry density 1,110 kg/m^3.

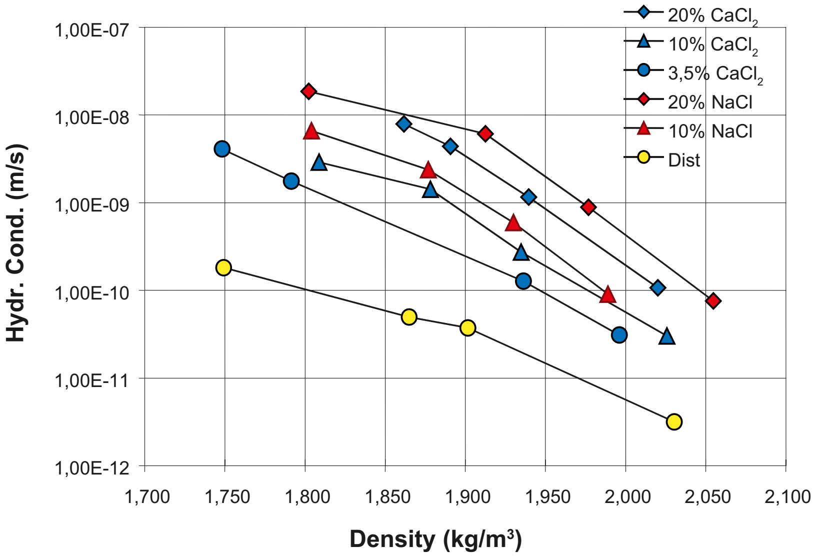

Figure 1-2. *Relationship between water saturated density and hydraulic conductivity of Friedland clay with special respect to the impact of salt water /1/.*

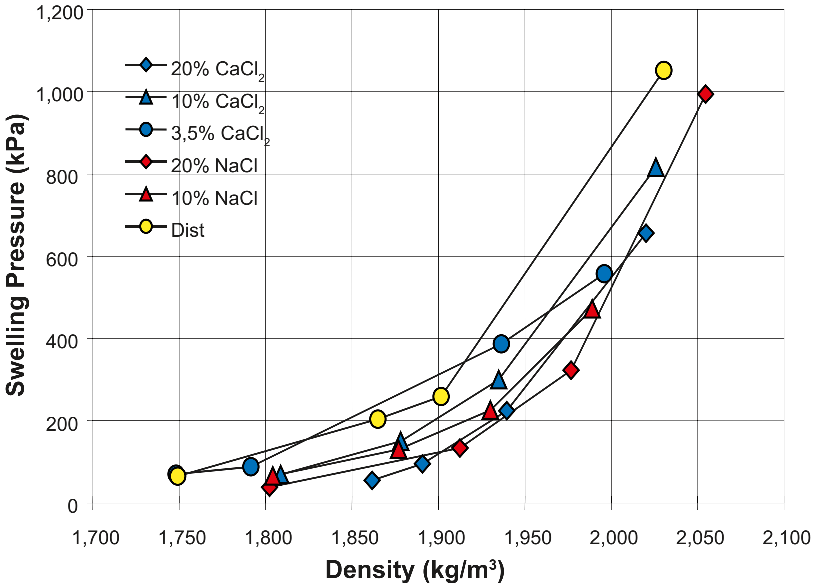

Figure 1-3. *Relationship between density at water saturation and swelling pressure of Friedland clay with special respect to the impact of salt water /1/. .*

Other exogenic effects that need to be considered are 1) seismic impact, and 2) freezing. Strong seismic events can possibly cause liquefaction of the loosely layered pellet fill early after placing the backfill but such effects can be neglected once the maturation process has occurred /9,10/. Where inflow of water is very low the risk of liquefaction can persist for tens of years or even longer. The risk of freezing will be somewhat higher than for the dense buffer and ice lensing will start at temperatures that are only slightly lower than 0°C. The risk of freezing can be eliminated by locating the repository deeper than about 300 m /1,9/.

1.2.4 Earlier backfilling experience

The highest hydraulic conductivity and lowest swelling pressure in Table 1-1 refer to water saturated specimens tested using 3.5 g/l $CaCl_2$ solution. The rather small impact of saline porewater on the physical properties of Friedland clay made it attractive as backfilling material. Large-scale filling and compaction tests were made in the Äspö URL to investigate the compactability of the clay using a technique developed for placement of mixtures of graded ballast (aggregate) and 30% MX-80 bentonite. This technique involved placement of material to form 0.3-m-thick inclined layers using a 400 kg vibratory plate compactor mounted on a tractor (Figure 1-4). This concept includes use of a vibratory roof compactor for densifying material close to the roof. The lowermost sketch in this figure shows the concave nature of the layers that could be achieved based on the nature of the mobility of the carrier and an easily rotated connection to the vibratory plate /7/. This approach worked for MX-80 clay/ballast mixtures while tests with Friedland clay showed that the clay was not sufficiently coherent to stay in place at the roof. In order to ensure sufficiently good physical interaction of backfills of these sorts and the tunnel roof placement of precompacted clay blocks in the uppermost regions of the tunnel would be required.

The resulting inclination of the in situ compacted backfill layers of Friedland clay was about 25 degrees and the evaluated median dry density about 1,450 kg/m^3, yielding a density of about 1,900 kg/m^3 at complete water saturation. As shown by Table 1-1 the hydraulic conductivity in salt environment could be too high while the swelling pressure would be adequate.

Based on the results of the field and lab experiments it was decided to continue using Friedland clay as a potentially suitable backfill material but the need for achieving a higher density led to the concept of assemblies of very well fitted highly compacted blocks of this clay (“masonries”) surrounded by a pellet fill. Calculations done based on anticipated filling efficiencies, joints and gaps as well as complete homogenization of the backfill blocks indicated that the net density would be acceptable provided that the blockfilling degree is at least 80% for the accepted safety margin with respect to the functional indicators /5/. The “Baclo” project /8/ included a serie of experiments in which the impact of inflowing water from the rock on the stability and wetting process of the pellet/block system was studied. An another project which was calculating suitable filling degree was the project that will be described in the present report. It comprised predictions and evaluations of the degree of filling KBS-3V deposition tunnels with special respect to the most suitable design and construction principle. Figure 1-5 shows schematically the backfill system that was tested at Äspö.

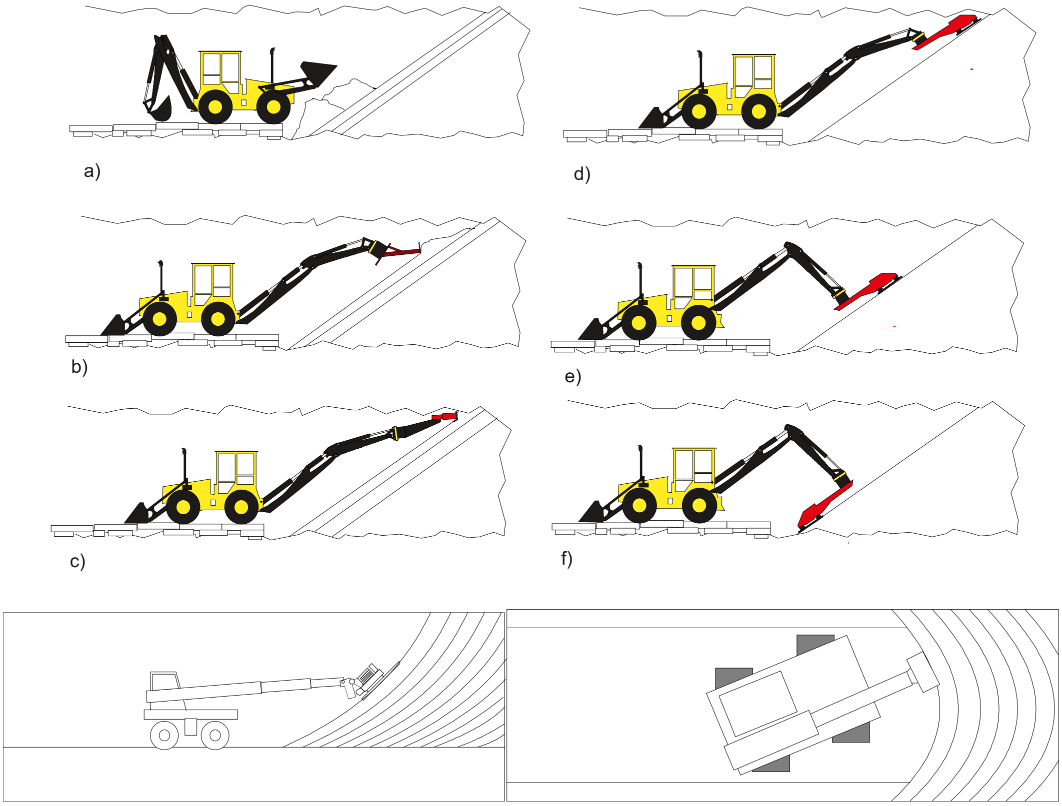

Figure 1-4. *Illustration of application (a, b, c) and compaction (d,e,f) of backfill according to the latest version of the "inclined layer principle".*

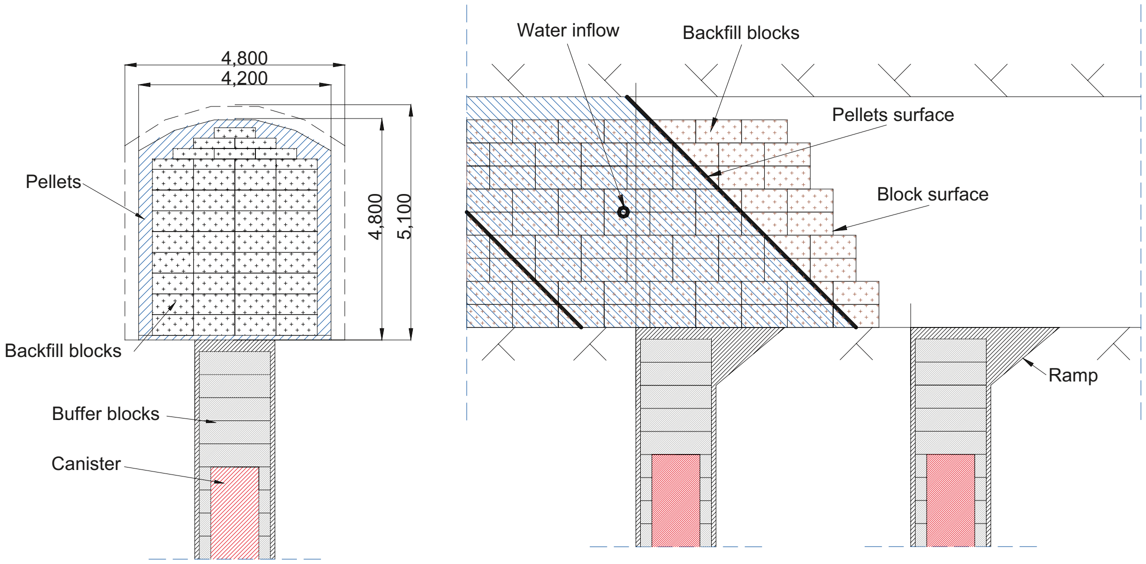

Figure 1-5. *Schematic picture of the backfill system tested at Äspö. Left: Cross section of the deposition tunnel with smectite-rich clay pellets surrounding masonry of blocks of Friedland clay. Right: Longitudinal section showing sloping pellet fill on both sides of the masonry.*

2 The sequences for backfilling and deposition

2.1 General

We will distinguish here between “deposition”, which refers to the placement of buffer and canisters and associated matters, and “backfilling”, comprising placement of blocks of clay and pellet fill in the regions beyond the deposition volume. It is essential to consider how and in what order one should emplace the various components in the deposition holes and the backfill components in the tunnels. The basic processes to be followed can be to either complete all parts of the deposition sequence hole by hole, or to run them in parallel in separate tunnels, completing deposition and backfilling as separate activities. In operating parallel operations it is necessary to examine how the sequence of placing the components in the deposition holes is planned and implemented, as well as determining potential disruptive processes.

The canister deposition process involves several sub-activities, such as temporary installation of equipment and materials, e.g. buffer protection sheets to prevent direct contact between rock and buffer, and drainage to keep the borehole dry. As a result it is important to have a good understanding of the installation process and potentially degrading events that may occur.

By combining the completion of the deposition holes and the tunnel backfilling activities several alternatives can be identified for production-friendly construction.

2.2 Description of the deposition sequence

2.2.1 Preparative work

The activities required for preparing to place the components in the deposition holes are not particularly time or operationally sensitive but can and should be performed well before the start of deposition and backfilling.

To facilitate handling of heavy objects in the preparative work, a bolt capable of taking loads of 10–50 kN should be anchored in the roof over the centre of each deposition hole. Alternatively, a crane can be used but it may disturb other activities in the tunnel.

The required sub-activities that have been identified and taken to be conceptual, are listed below.

Concrete foundation of canisters

The implementation of the activities in the deposition holes requires that concrete foundations have been constructed at the base of them, hence making up the first activity.

The concrete slabs serve to carry the heavy canisters and they must be covered by copper plates (Figure 2-1) for preventing upward leakage of water through them, for which the concrete must have a smooth upper surface. This can be achieved by using relatively low-viscous concrete with low-pH cement and ordinary vibration tools. The upper surfaces of the foundations have to be plane, even, and perfectly horizontal. An alternative technique to level the base of the emplacement hole using pellets is also proposed. Its applicability depends on the possibility of combining the placement of canisters and buffer in the holes with the backfilling of the tunnel, as described in Section 2.4.

Figure 2-1. Deposition hole with bottom plate and ramp for making placement of the canister possible.

Protective steel plates over deposition holes

It is proposed that all the deposition holes will be temporarily covered by steel plates reinforced by steel frameworks, Figure 2-2. This figure shows the case where a ramp (bevel) has been cut in the floor next to a hole, providing sufficient space for the machine used for placing the canisters. The plate must support traffic load and will ultimately be removed in conjunction with backfilling. The plates have openings of sufficient size to allow work in the deposition holes without hindrance. These openings will be covered by strong steel lids when work is being performed in the holes, thereby facilitating activities in the tunnel. The plates must be equipped with fences when the holes are to be opened and they should have tight seals at the rock contact for minimizing water inflow in the deposition holes.

The steel cover plate is replaced by the gamma gate[3] in the canister placement phase, and re-installed afterwards. The plate must be so designed and constructed that it allows mounting and tight attachment of the buffer protection sheet.

Draining of deposition holes

When required, the lids are opened and pumps installed to drain the deposition holes. Dewatering of a fully-flooded hole is expected to be about 6 hours. The water is discharged to a dewatering system through pipes located at one of the tunnel walls.

Rinsing and cleaning of deposition holes

The deposition holes are carefully rinsed to remove rock fragments that may have fallen to the bottom of the holes and by removing loose pieces of rock from the rock at bottom and walls. The walls are then carefully cleaned by washing using pressurized water. Cleaning is important because if fragments fall from the rock when the buffer protection sheet is being installed or removed it can have significant negative consequences associated with delays caused by operations needed to achieve its recovery.

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[3] Radiation protection shield

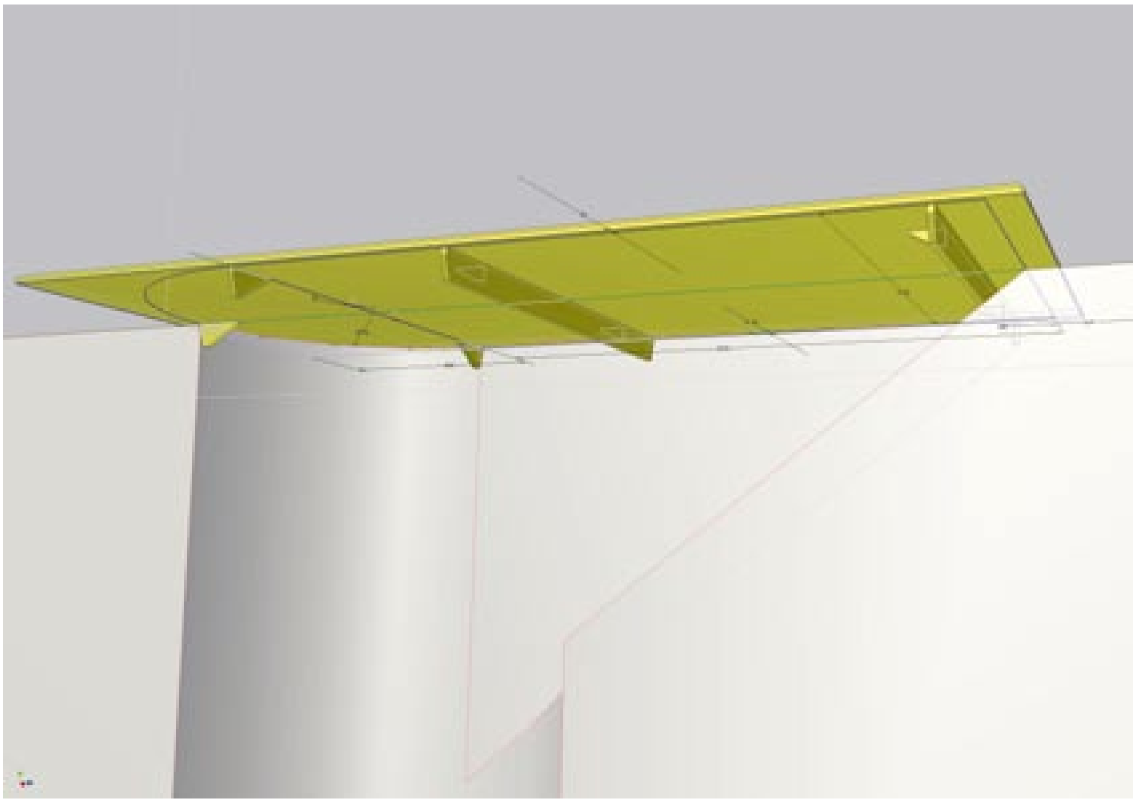

Figure 2-2. *Protective steel plate over deposition holes.*

Acceptance of deposition holes

After drainage, rinsing and cleaning the deposition holes, visual inspection of each hole is done and measurements performed to determine its geometry. Thus, deviations from the intended vertical orientation of the axis of the hole will be measured and documented. This will allow the evenness and possible inclination of the bottom plate to be determined. The size of the space between the buffer blocks to be installed and the rock is then calculated, compared to requirements set for installation of the buffer protection shield and for filling with the pellets. The inflow of water is also checked in order to identify possible changes from the initially-measured conditions. Based on all of these measurements a final decision is made as to whether the deposition hole can be accepted for canister installation.

Installation of drainage and pump alarm in deposition holes

Two tubes with 18 mm outer diameter reaching down to the bottom of the deposition holes are placed adjacent to the rock. They are anchored at the bottom and connected to the drainage system. At this stage an alarm system for the pumps is installed for controlling the water level. Drainage and alarm sensors are mounted so that they can be easily removed in conjunction with the filling of pellets in the deposition holes.

Buffer protection in deposition holes

Figure 2-3 shows a mock-up of the buffer protection sheet in a deposition hole. It is made of thick rubber and serves to protect the buffer and pellets from inflowing water and moisture from the rock. The sheet is lowered in the deposition hole and tightly attached to the bottom plate at the bottom of the hole. The rubber sheet is held in place by being clamped to the steel frame at the tunnel floor. It must extend into the ramp adjacent to the deposition hole, otherwise it has to be lowered before the canister and buffer blocks can be emplaced. The entire operation of placing and removal of the protection sheet is described in detail in a separate report /11/.

Figure 2-3. *Buffer protection sheet separating buffer blocks from the rock.*

2.2.2 Installation of buffer and deposition of canister

Placement of the buffer in the deposition holes

The main steps in the placement of the canisters and buffer can be performed in one continuous process immediately followed by backfilling of the tunnel. Alternatively, canister deposition and tunnel backfilling can be made in parallel in separate tunnels as described in Section 2.4. This latter procedure is preferable and probably necessary and is therefore the reference sequence /11/.

The first step in installing the buffer and canister is to open the lid in the steel plate and check that the rubber sheet that is necessary for water inflow control is in place and tight. The buffer installation equipment is then moved to the deposition hole and the buffer blocks inserted (Figure 2-4). The exact geometrical shape of the stacks of blocks and of the gap between blocks and rock is then measured and documented.

Placement of the canisters and upper buffer blocks, and filling of pellets in the holes

The first step is to install the gamma gate while maintaining the frame of the steel plate in position so as to avoid inflow of water and contaminants into the hole. The gamma gate or a portion of it is first removed and the shielded canister is then brought to the hole and inserted by use of the equipment developed for this purpose. The gamma gate is closed after placing the canister and the equipment used for buffer placement is then again moved onto the hole, the gamma gate opened and the upper buffer blocks inserted so that they almost reach up to the floor. When these buffer blocks are in place the gamma gate is removed. The whole procedure ends with re-installation of the steel plate for making it possible to bring in equipment for emplacement of blocks and pellets for the tunnel backfilling process. The major steps are illustrated in Figure 2-5, excepting for the release of the buffer protection sheet, which is described in a separate report /11/.

The pellets for filling the space between buffer blocks and rock in the deposition holes are poured in after removal of the buffer protection sheet. It is removed when the latest applied backfill is close to the respective hole following a scheme that includes all other activities, transport of equipments, detachment of drainages etc. These activities are described in the backfilling sequence, section 2.3.3.

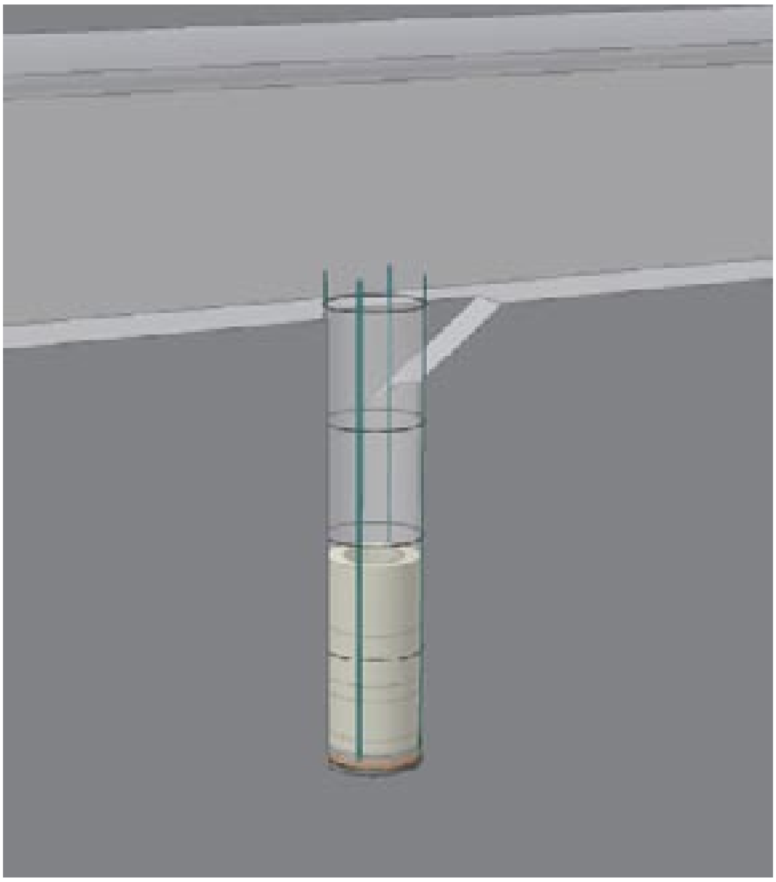

Figure 2-4. *Installed buffer. The four green lines represent straps for hoisting the buffer protection sheet.*

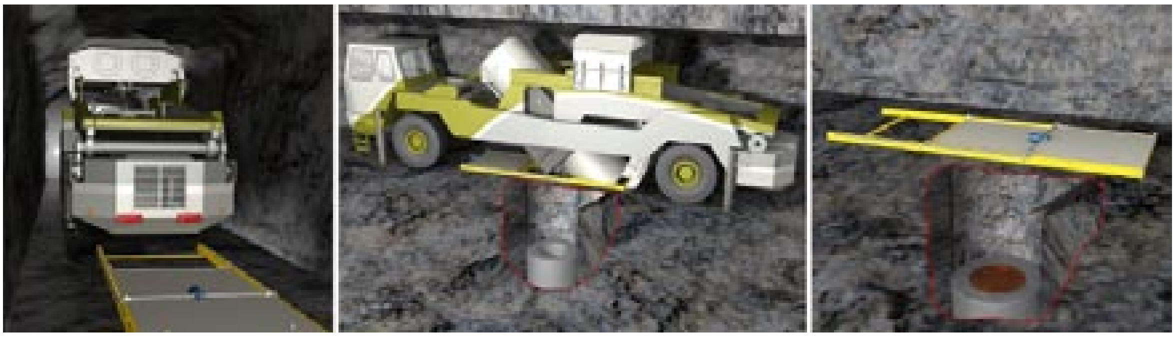

Figure 2-5. *Deposition of canister. Left: Canister placement machine. Center: Insertion of canister. Right: Gamma-gate placed over the deposition hole.*

2.3 Description of the backfilling sequence

2.3.1 General

The backfilling rate is determined by the number of canisters that will be deposited per day, the distance between deposition holes, and the water inflow. The backfilling shall be made at the same rate as the placement of canisters, the progress rate hence being 6–8 m per day. Theoretically, several tunnels can be backfilled in parallel operations in order to provide sufficient capacity. In practice, the backfilling rate will be determined by water inflow in the tunnels. A certain inflow rate from the rock into the tunnel can be handled if the various activities in the tunnel, like canister and buffer placement and removal of buffer protection sheets etc, run smoothly but any significant interruption will cause increase wetting of the placed backfill and softening of its outer part. The slower the backfilling rate, the more problems with water affecting the backfill will hence appear.

The backfilling rate is determined by number of canisters which will be deposit every year, the distance between deposition holes and also by water inflow. The backfilling shall be done in the same rate as the canister is deposited. Theoretically, many tunnels can be backfilled at the same time to manage the capacity demands, which is the same as the centre distance between the deposit holes a day. Practically, the backfilling rate is determined by water inflow in the tunnels. A low backfilling rate will increase the risk due to the fact that the water will react with the clay.

According to the reference concept, the backfilling rate when working in one tunnel is estimated to be approximately 4 meters/day, using the "Block" method. Decision on whether backfilling shall be executed in more than one tunnel at a time depends on how many canisters that shall be deposited each year and on the distance between them.

The backfilling operation in the deposition tunnels starts with construction of the foundation bed of crushed bentonite or pellets and followed by placement of clay blocks, and filling of remaining voids with pellets (Figure 2-6). The backfilling sequence also includes removal of the buffer protection sheet installed around the buffer-canister assembly and filling of pellets in the space between rock and buffer blocks as well as in the ramp in the floor at the respective deposition hole.

2.3.2 Preparative work for backfilling

To minimize disturbance in the backfilling procedure the entire tunnel is prepared before placing the various components. This includes the temporary service installations indicated in Figure 2-7. Prior to this the tunnel walls, roof and floor are scanned using appropriate surveying methods (laser, camera technique and alike) to determine the volume of the tunnel. The accuracy of the evaluated tunnel volume is of fundamental importance in determining the degree of block filling that can be achieved.

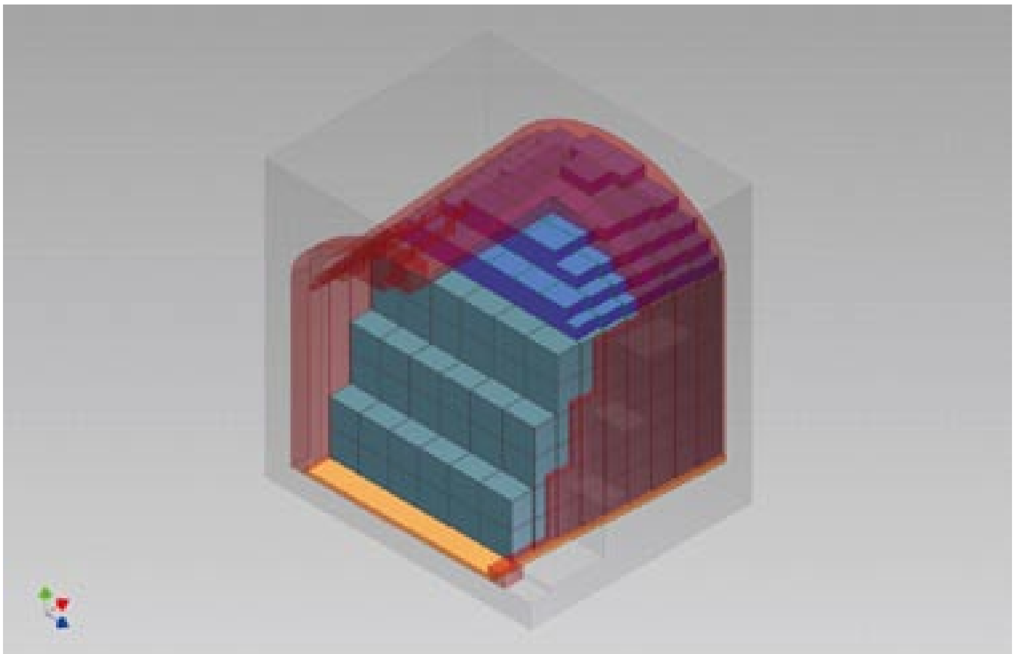

Figure 2-6. Foundation bed (yellow), blocks (green and blue), and pellet fill (red) in deposition tunnel. Deposition hole and associated ramp are not shown.

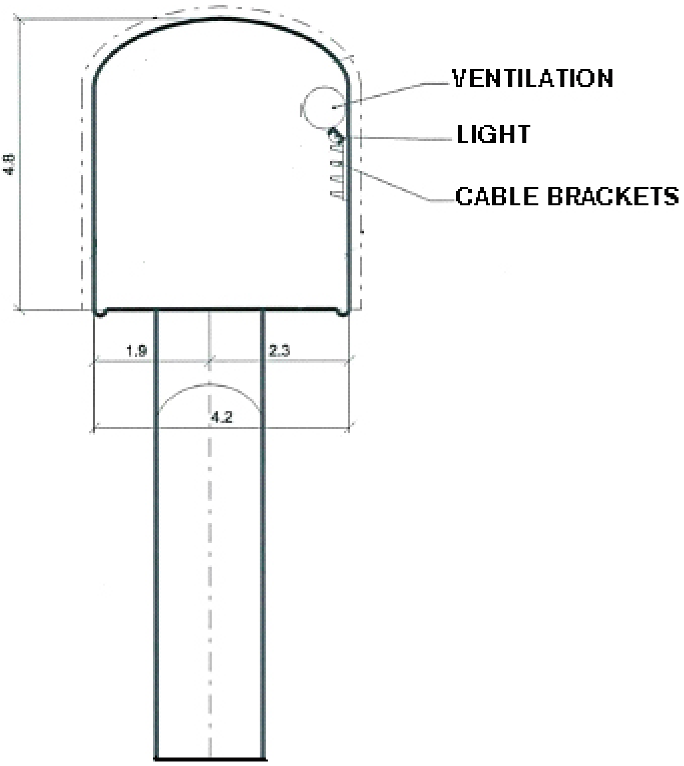

Figure 2-7. *Temporary installations made before starting backfilling.*

Temporary installations

Ventilation, electric power, compressed air for the drainage system and illumination are installed to the extent required and sufficiently well protected from damage by vehicles and equipment. At this stage the steel plates over the deposition holes should be in place.

Depending on how the tunnel floor has been prepared it may be necessary to smooth it by use of jack hammers, by casting low-pH concrete, or possibly by constructing a temporary road on the floor. It has not yet been decided if such a road is required and how it should be removed before the backfilling operation starts. One way could be to use gravel compacted gravel of sufficient bearing capacity and then removing it when its purpose has been fulfilled.

Introducing more activities at the backfilling front than the ones involved in placing and transporting materials and equipment will affect the backfilling rate and potentially also its quality and a temporary road would certainly be a substantial additional activity. If it is ultimately considered necessary for repository operations then such construction would require backfilling in more than one tunnel so that the criterion that each tunnel must be backfilled over 6–8 m length per day can be met. Backfilling rate per tunnel will then be lower, which underlines the need for limited inflow of water in the tunnels, which may require grouting of the rock and/or techniques for drainage.

2.3.3 Installation of backfill

A more detailed description is reported in Appendix 1.

Backfilling of the ramp

The ramps complicate and increase the risk of delaying the backfilling operation. Filling of the ramps and tunnel must be made separately since the ramps have to be filled before construction of the foundation beds can start. The axial length of the beds can not be adaptated to the filling of ramps, which means that the bed units may end right above the ramps. The material in the ramp that is not covered by a foundation bed will therefore be exposed to water inflow for at least six hours, which is sufficiently long to cause sorption of water and will probably require removal of it before the next bed installation can start. An even more serious effect is that the fill in the ramps will be compressed by the heavy blocks placed on them and cause settlement and uneven movement of the placed blocks and possibly even unstable conditions. This risk can be minimized by using compacted clay blocks instead of pellets but the curved shape of the ramp will make it difficult to reach good fitting and low porosity of the block fill in reasonable time. In both cases water will flow down the ramp and start expansion and softening of the fill. Granulate, placed and compacted in 150 mm thick layers (Figure 2-8) represent a better alternative than pellets since compaction will make the fill less compressible but there are still doubts whether the bearing capacity and resistance to compression under the block load will be acceptable.

Construction of the foundation bed

Material: The bed will consist of smectite-rich (>70%) bentonite granulates or pellets. It is required that the compression under the load of the block masonries is small for which the density of the bed must be high enough. Two materials have been investigated with respect to compressibility and behaviour at wetting as reported in Section 6.1.3.

Technique: The material is spread out on the floor and compacted with a vibratory plate in layers, up to 150 mm thick, to a dry density of at least 1,200 kg/m$^{3.}$ The density is determined by levelling the top of the bed and measuring the length and width, basing the calculation on the actual weight of the material placed as described in Section 7.1.5. The top surface must have the same inclination as the average value of the tunnel. The practical difficulties in preparing each bed unit so that they fit the preceding unit vertically and laterally must not be underestimated.

The construction length is selected with due respect to the frequency and location of the spots where water flows in from the rock, and to the rate of water inflow; in practice it can be taken as about 2 meters. The length of the bed is partly determined by the equipment used for placement of blocks and pellets in the tunnel, both respecting load capacity, reach, and accuracy. The results from the scanning of the tunnel profile are used for calculating the required amount of material for each construction interval.

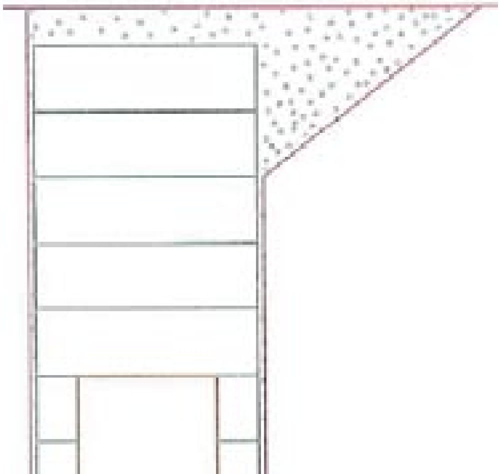

Figure 2-8. *Figure shows a deposit hole with buffer and backfilled ramp. The two upper buffer blocks are theoretically belonging to the backfilling but will be installed at the same time as the buffer installation.*

Construction of block masonries

The block placement procedure must be adapted to the inflow of water from the rock. The assemblage must remain stable until the pellets in the space between the blocks and the rock have been filled. The pellets then provide support to the blocks and prevent them from moving significantly.

The blocks are stacked from the foundation bed up to the roof. The construction length of each unit should be the same as that of the foundation bed, i.e. 1–4 m, with a probable average length of 2 m. Where the inflow of water is very small this length can be increased up to about 4 m. The selected length depends on how accurately the pellets can be installed into the space between blocks and rock with respect to density and homogeneity, and on the reach of the block-placing equipment. Depending on how the blocks are placed and their geometry, the front surface of the block assembly can be vertical or stepped (Figure 1-3).

After completing each block-filled unit the topography and geometry of its front surface are measured to allow for calculation of the volume occupied. Knowing the volume of the respective tunnel length interval and the volume of the installed blocks one can determine the degree of block-filling and pellet-filling of the tunnel. The measured weight of the backfill components gives the average density of the block and pellet fills.

Pellet-filling of the tunnel

The pellets are installed immediately after completion of the associated block assembly. The length can be up to 4–5 meters, depending on the inflow of water. The technique for placing the pellets can be simple pouring through a tube in the lowest part of the space, moving and pushing by use of augers, mechanical throwing via conveyors, or blowing by use of a suitably adapted shotcreting technique.

After completing the filling of pellets along the perimeter of each block-filled unit the position of the visible surface of the pellet fill is measured. This is done in order to calculate its volume, which gives the degree of filling of the available space. Knowing the volume of the corresponding length of the tunnel and the weight of the pellet fill its average density and hydraulic conductivity once saturation is achieved can be predicted.

Removal of temporary installations

Parallel to the backfilling operation the temporary installations, i.e. the ventilation tubes, electric cables, and illumination in the tunnel have to be removed, and also the alarm sensors and drains in the deposition holes.

Removal of buffer protection sheet

The sheet is hoisted out of the emplacement hole by use of rubber straps attached to it. This must be made in two steps because of the limited tunnel height. The force is measured for making sure that the sheet is not stuck or breaks. If such mishaps occur the canister and the buffer blocks may have to be removed from the hole and also part of the backfill. This will have a very serious impact on the entire canister and backfill installation operation. The staff must be well trained and there must be immediate access to reserve equipment in case of failing machines, cranes and any additional tools required.

Removal of the buffer protection sheet (rubber) and filling the space between blocks and rock in the deposition holes with pellets prior to backfilling is a difficult process. It may, in fact, jeopardize the entire backfilling operation should complications associated with its removal develop. At present no maximum allowed time between removing the rubber sheet and installing tunnel backfill into the volume above the deposition hole can be specified. In practice, allowable time for these operations is controlled by the inflow of water from the rock as is presently being investigated in the “Baclo” project /8/.

It seems possible to complete the various steps in the backfilling process so that the buffer protection sheet can be omitted as described in Section 2.4.

Filling of pellets in the deposition holes

Pellets are blown in the gap between the rock and the buffer blocks to the upper surface of the top block. The steel plate covering the "ramp" adjacent to the deposition hole is removed to allow pellet placement while maintaining the steel frame around the hole so as to minimize inflow of water. The pellets in the ramp will be compacted layerwise to high density up to floor level. Once the deposition hole and ramp are backfilled, the steel frame above the deposition hole is removed for continuing the backfilling operations to be undertaken.

2.4 Combination of deposition and backfilling operations

Based on the present understanding of the risk of erosion of placed buffer, decommissioning of parallel activities must be made close to the previously constructed block masonry.

Parallel activities influence the efficiency of the backfilling. They cause delay in the placement of blocks and pellets and thereby lead to softening or fluidity of the pellet filling. Such activities are:

- Removal of electric cables, illumination and ventilation.
- Removal of steel plates temporarily placed over the deposition holes.
- Decommissioning of alarm and drainage systems in the deposition holes.
- Removal of rubber sheets serving as buffer protection.
- Filling of pellets in the deposition holes.
- Backfilling of the "ramps" at the upper ends of the deposition holes.

Current investigations aim at defining more precisely the time required for all these activities for estimating the impact of concordant erosion of the buffer in the holes and of the placed backfill components.

Some of these activities can be avoided or made less disturbing depending on how canister installation and backfill placement can be combined and performed with respect to time. Sequential placement is being considered in the present project.

Two alternatives have been outlined and will be described here but other combinations can be developed as detailed design progresses and operational requirements become clearer.

Alternative I:

The first alternative (Figure 2-9), which is SKB's reference method, implies partly parallel work in five separate deposition tunnels. The activities are:

- Tunnel No 1, preparative work (installation of drainage, alarm, buffer protection sheets).
- Tunnel No 2, placement of buffer blocks in all holes.
- Tunnel No 3, placement of canister and uppermost buffer blocks.
- Tunnel No 4, backfilling of tunnel, removal of buffer protection sheet, pellet filling of deposition holes.
- Tunnel No 5, backfilling of tunnel, removal of buffer protection sheet, pellet filling of deposition holes.

The advantage of this activity-by-activity procedure is that it provides flexibility and robustness. Hence, the applicability of the principle of deposition of one canister a day will not depend on whether the placement of buffer and associated activities need longer time or have to be repeated, since the various activities are performed in different tunnels. If, for instance, the gap between buffer blocks and rock turns out to be too small to remove the buffer protection sheet, there may be sufficient time to solve the problem without affecting overall disposal activities.

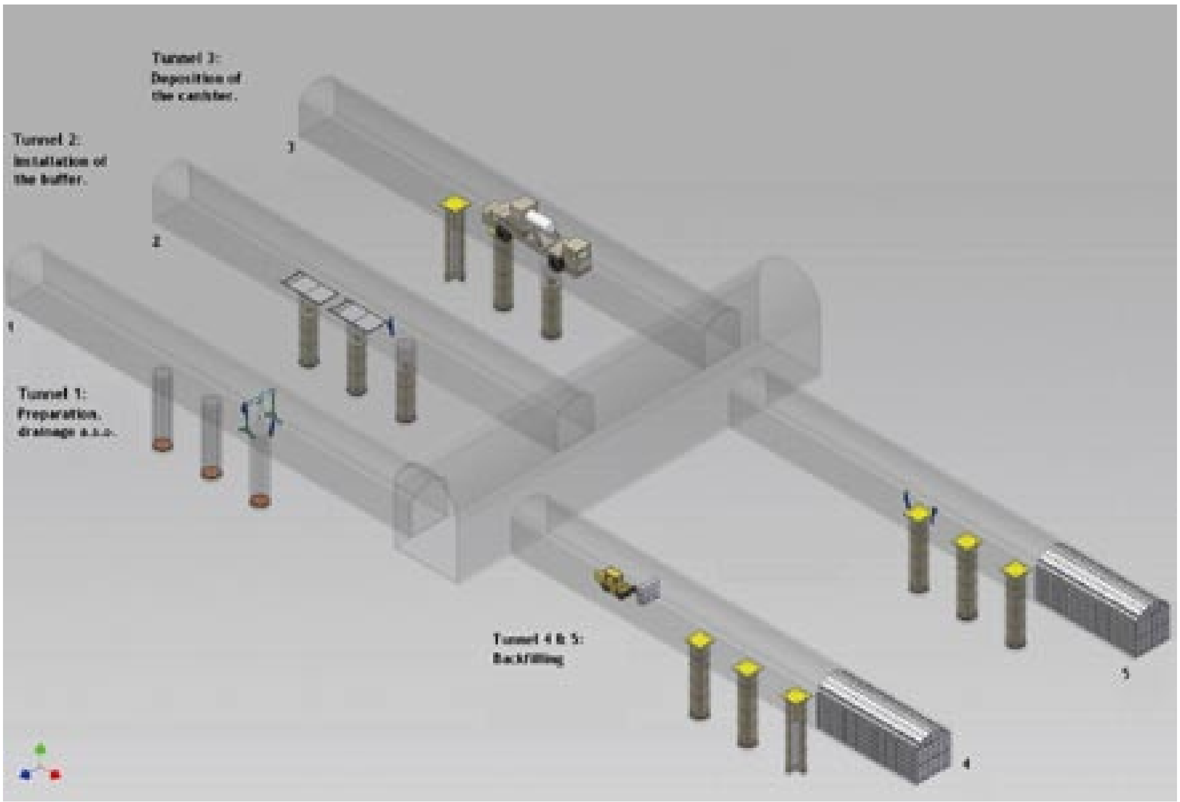

Figure 2-9. Sequence of operations in deposition holes and tunnel: Alternative I.

The buffer protection sheets are not removed in parallel with the backfilling of Tunnels No 4 and 5, since this would interrupt the backfilling processes and initiate softening of placed buffer blocks. Disregarding from the possible impact of inflowing water, the estimated rate of backfilling would be 4 m per day if the blocks in the tunnels are placed individually, while it would be 8 m per day for two tunnels operating in parallel. Without any disturbance from parallel activities the backfilling rate is estimated to be 6 m per tunnel and day. If the blocks are placed in units the rate can be higher than this. One realizes, however, that problems with removal of the buffer protection sheets may still arise, reducing the effective rate of backfilling. However, it seems to be possible to do all the activities in deposition holes remote to the front of the backfilling but it means that the buffer in these holes can be exposed to humid air and water for up to 80 hours.

Alternative II:

This alternative involves the following parallel activities in three tunnels (Figure 2-10):

- Tunnel No 1, preparative work (emptying of deposition hole).
- Tunnel No 2, buffer block placement, canister placement and backfilling.
- Tunnel No 3, backfilling, buffer block placement and canister placement.

The preparative work required for this alternative is the same as in the first, but excludes use of buffer protection sheets, drainage of the deposition holes, and installation of alarms.

The conduct of the installation process begins with placement of buffer blocks, canister and pellets in the innermost deposition holes in Tunnel No 2 in the first day. The next day buffer, canister and pellets are placed in the innermost hole in Tunnel No 3, following the principle of interchangeable placement of buffer and canister hole-by-hole in the two tunnels. Backfilling goes on continuously in Tunnels 2 and 3 but is interrupted by placement of buffer, canister and pellets in the deposition holes. These interruptions last for about 12 hours, implying that the next

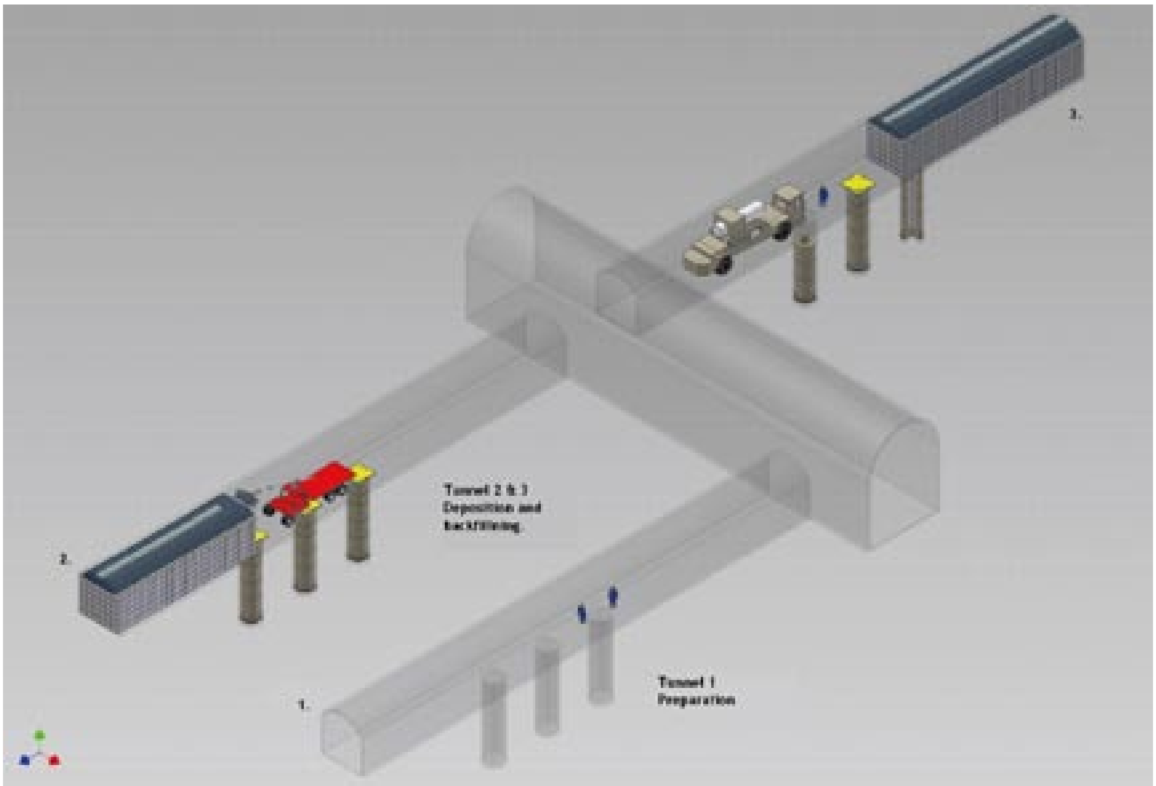

***Figure 2-10.** Sequence of operations in deposition holes and tunnels: Alternative II.*

36 hours are available for backfilling the tunnels, at which time the next interruption will take place for placement of buffer, canister and pellets. In these 36 hours the entire tunnel space, up to 8 m length needs to be backfilled.

The advantage of this alternative is that there is no need for placement and removal of buffer protection sheets, alarm and drainage equipment. A disadvantage is that the buffer in the deposition holes may be exposed to inflowing water and moist air for about 36 hours. If the holes are drained so that no water accumulates at the bottom RH will still be 100% in the air, which causes hydration and risk of shallow disintegration of the buffer blocks /12/. The sensitiveness of the buffer is related to choice of material and water ratio. This impact is, however, somewhat reduced by the pellet fill surrounding the blocks.

Comments

Alternative II can be modified to provide a more production-friendly standard and lower risks during construction in the ways listed below. This would simplify the whole installation procedure. They need to be combined and require some changes in the design of the buffer arrangements in the deposition holes:

- The presently proposed bottom plate of low-pH concrete in the deposition holes is replaced by a compacted pellet bed, installed in conjunction with the placement of the buffer blocks and canister.
- The diameter of the buffer blocks is increased so that the distance to the rock becomes 20 mm and the gap between canister and buffer is 60 mm. This would allow elimination of pellets between buffer and rock, and the need of an absolutely horizontal and plane bottom bed. Nor do the deposition holes have to be bored perfectly vertically.
- Elimination of buffer protection sheets and pellets in the deposition holes by which the buffer blocks come in contact with the rock early after placement. This is not expected to cause difficulties as concluded from the BMT experiments at Stripa /6/.
- Delay by unforeseen problems is less likely because the number of activities is smaller.

These changes, which may be combined with filling the outermost annular gap of the deposition holes with smectitic mud with a certain content of quartz filler (to plug/contact grout fractures so that buffer clay cannot readily escape through them), could make placement of buffer and canisters simpler and safer /1/. It may also be possible to fill the space between the canister and buffer with pellets although this has to be made remotely.

2.5 Other influencing factors

In addition to the work in the tunnels, the sequencing of activities comprising transport of backfilling materials, machines/equipments, and canisters from the facilities on the ground level to the central storage at depth and from there to the deposition tunnels must be conducted without hindrance and delay. Upward transport of excavated rock must run parallel to the downward transport activities. In addition to these flow lines, routine maintenance and necessary repairs must be conducted so that disturbance to overall operations is minimized. Power supply, elevator transport, and drainage of the entire repository are the most essential basic functions during the entire operational period. Necessary temporary storage of backfill materials and canisters is required in order to avoid stoppages in the placement caused by power failure or maintenance of access ways. Backup supply of electric power must be available for a number of safety and operational purposes.

2.5.1 Clay blocks

Both the large buffer blocks and the smaller ones for tunnel backfilling are to be prepared in a special building on the ground surface. The clay material for the latter purpose is preliminarily assumed to be an expandable commercial clay material that is ground and dried for compaction in forms under a pressure of at least 25 MPa[4] /17/. The shape and weight of these blocks depend on the method selected for their placement. The blocks must be coherent and have sharp edges when they come on site. Blocks with dimensions 600x500x800 mm can be produced by currently available technology /3,7,12/.

It is essential that the properties of freshly compacted blocks are preserved throughout the entire series of transport, handling and placement. This requires that the blocks are wrapped in tight plastic sheets in robust transport containers and stored in rooms with RH<70%.

2.5.2 Pellets

Pellets are delivered from the manufacturer in bulk bags weighing about 1 ton /3,12/. Like the blocks the material must be protected from water and humid air. They are preferably stored in RH-controlled silos underground. It is estimated that three to four different pellet types will be required for different purposes. Transport and maintaining of a current supply will be done by conventional bulk trucks using the large ramp from the ground surface or by use of a “skip”. The required daily amount is about 50 m^3, corresponding to 7 deliveries per day. For comparison, 7,000 m^3 of bentonite granules were placed in the gap between the 25 m diameter and 50 m high concrete silo and the surrounding rock in the SFR repository in about one week /12/.

2.5.3 Logistics

Transport of blocks from the production facility on the ground surface down to the temporary storage or directly to the deposition tunnels can be made by use of the elevator for material transport, “skip”, or by trucks using the ramp. The skip, which is estimated to carry 15 t loads,

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[4] This pressure can be discussed. By increasing it the density achieved increases and hence swelling pressure and expandability of the blocks of clay can be substantially increased and the hydraulic conductivity decreased.

offers the most rational and safe way of transportation. The shape and size of the transport containers determine the transport capacity as described in the appendices. There must also be an alternative transport plan for unexpected stoppages of elevator service. This problem can be solved by intermediate storage of material adequate for at least 8 m of tunnel backfilling.

Use of the skip must not cause critical conditions in the transportation of buffer blocks and blocks for backfilling. It is suitable and rational to use it for surge transport to the central storage at the repository level. Here, sufficient amounts of backfill materials should be stored to allow at least one day of backfilling operations.

Emptying of the skip and transport to a suitable space in the central storage is made by use of tractors or special vehicles that are also used for further transport to the deposition tunnels. For individual handling and placement of blocks great care must be taken in putting them in place in the correct order. This will require labelling and care in placing them in transport containers as well as at the subsequent removal from the containers (Figure 2-11).

2.5.4 Service and maintenance

All the transportation and installation equipment used for backfilling must be regularly inspected and serviced. The ambition should be to use robust and simple equipment but the requirement to simplify the operators' demanding precision work still makes use of advanced techniques necessary. A very important criterion is that the backfilling operation must not be significantly delayed by malfunctioning machines. Hence, it is important to identify possible problems at once so that spare equipment can be put into operation. Most of it can be kept in special buildings on the ground level where service and repair are provided but the most indispensable reserve equipment, like block-placing units, should be continuously available at the repository level.

Figure 2-11. *Delivery of blocks to the deposition tunnels for placing them on site.*

3 Conditions for backfilling

3.1 General

The basic performance criteria are those specified in Section 1.2.2. For construction of the backfill, a number of practical issues will also have to be considered, like geometrical assumptions for the tunnel, rock contour and inflow of water from the rock, Figure 3-1 illustrates the system of deposition tunnels extending from the primary tunnels, which are connected to the central room and serve as transport tunnels. The length of the deposition tunnels may vary between 100 and 300 m depending on the presence of fracture zones.

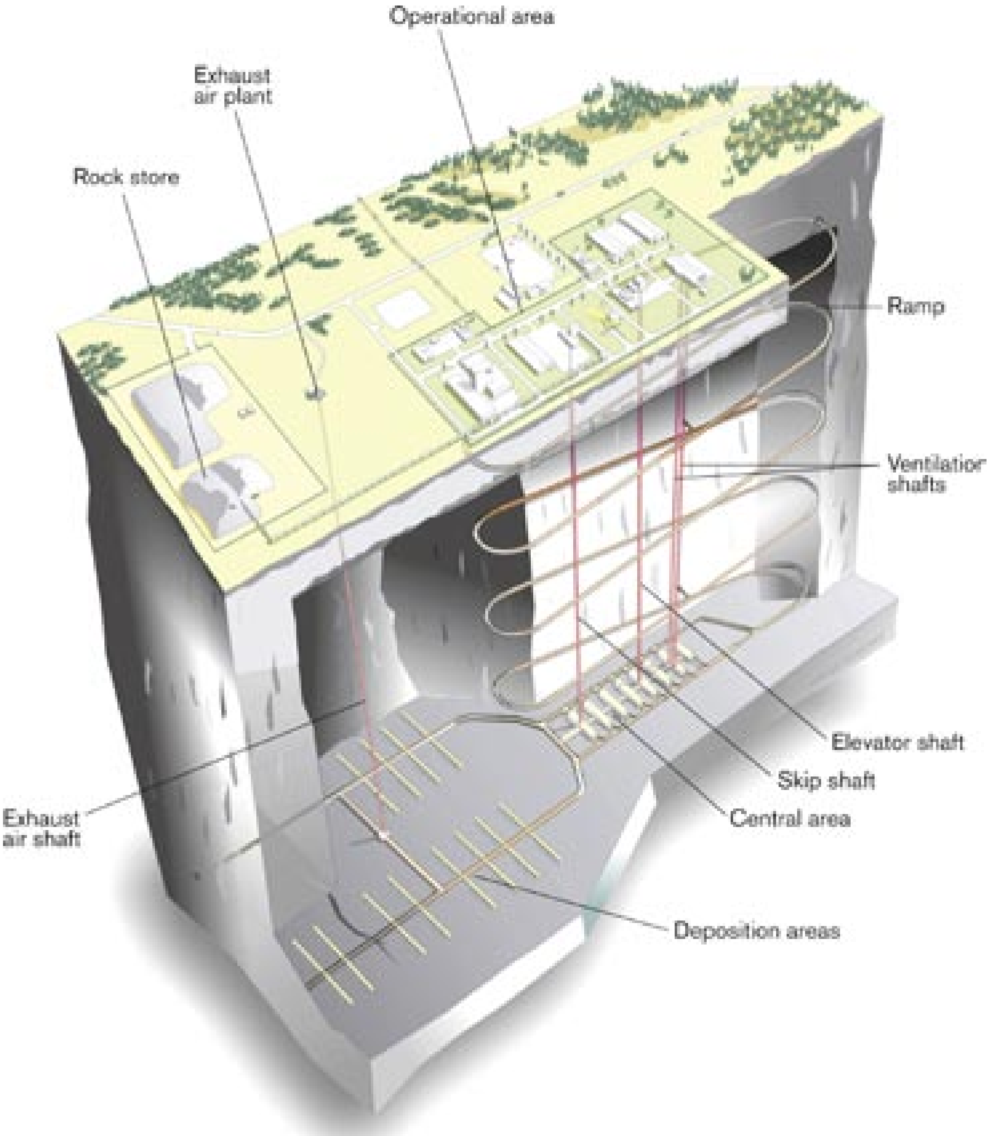

***Figure 3-1.** Overview of the KBS-3V repository with systems of primary tunnels and deposition tunnels /2/.*

3.2 Geometry and conditions at the start of backfilling

The theoretical cross section of the blasted tunnels is 4.2 m width and 4.8 m height. It is presently required to cut the aforementioned ramps adjacent to the deposition holes in order to provide enough space for placing the canisters (Figure 1-5). The tunnels shall have an inclination of 1% towards the primary tunnels for self-drainage.

The contour of the floor depends on the method employed for preparing the tunnel floor. If it is made by traditional, careful blasting, the floor will be irregular with amplitudes about 0.3 m for each blasting round. These irregularities may make it necessary to construct a temporary road or to remodel it by jack hammering, or to cast low-pH concrete locally on it. The following criteria must be fulfilled:

- Before backfilling is started the floor must be so prepared that vehicles can move on it with only limited bumps and vibration, and the deposition holes must be covered by steel plates until backfilling has reached them.
- To facilitate backfilling operations, rock bolts in the roof installed for stabilizing the rock have to be cut off immediately below the nuts so that they do not extend inside the theoretical tunnel profile.
- Boreholes used for grouting must be plugged using a not yet decided technique; overcoring and plugging by use of methods worked out by SKB for borehole sealing is an alternative /13/.
- Bolts used as references for scanning of tunnel contours shall remain.
- Excavation of no more than 30% rock additional to what is represented by the theoretical tunnel profile ("over-excavation") is acceptable.
- The look-outs[5] in the roof must not extent by more than 200 mm from the theoretical tunnel profile for fulfilling the conditions defined for limiting the compressibility of the backfill under the upward pressure exerted by the buffer in the deposition holes.

The evenness of the floor is of great importance with respect to transport of materials and equipments. Processes such as wire sawing will theoretically give a perfectly smooth surface, but this will have to be demonstrated at full scale before a decision can be taken on whether it is useful and cost-effective. Blasting will give an irregular floor topography that requires filling and compaction of a suitable clay material to yield a plane surface before placement of blocks can start. Irrespective of the technique for preparation of the floor and its nature, a foundation bed is required unless the tunnels are dry and the floor perfectly smooth. A temporary road bed for wheel-driven equipment has been considered but the idea is considered impractical since its placement and subsequent removal would affect all the activities in the backfilling process and hence cause delay. The ramps shown in Figure 1-5 at the upper end of the deposition holes are planned for making placement of canisters possible – the height of the tunnels will not allow them to be held vertically above the deposition holes for subsequent submergence – and they will cause delay of the backfilling process by requiring filling and compaction before the foundation bed can be constructed, most probably with water flowing into them[6].

Where extensive rock fall and local widening of the tunnel have occurred, special measures may be necessary to fill the space with low pH-concrete[7] so that the block filling process can proceed without disturbance. Alternatively, the rock fall can be shaped to make it possible to install pellet if not concrete is allowable. The rock fall has to be open to make it possible to install dry pellet.

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[5] Reach-out of blast holes from the axial direction at the tunnel, expressed in mm.

[6] The construction of ramps is presently being discussed. At the preparation of this report no decision had been taken on this issue.

[7] Ongoing investigations that have led to acceptance of concrete with low-pH cement and 100% quartz aggregate in plugging of deep boreholes in the repository area, may make such concrete acceptable also elsewhere in it.

3.2.1 Rock excavation influence on backfilling density

A first, important geometrical feature that determines the degree of block filling is the orientation of the walls and roof. They follow the orientation of the blast-holes and hence give the typical shape indicated in Figure 3-2.

The look-outs are up to 200–300 mm deep in the walls and up to 200 mm in the roof and the floor. Locally the look-outs can be deeper than that.

The thickness of the pellet fill between buffer and the backfill, and between the blocks in the backfill and the tunnel roof, must be limited because these fills will be compressed by the upward expanding buffer, which will thereby become less dense. Since the net density at water saturation must be at least 1,950 kg/m^3 the distance between blocks and tunnel roof should not exceed 300 mm according to the theoretical concept. The amount of over-excavated rock contributes to the reduction of buffer density and should not be higher than 30% for each blasting round. In practice it is estimated to be about 20%, which hence provides sufficient margins taking deviations from the intended blast hole orientation, rock fall etc into consideration. As illustrated by Figure 3-3 the width and height of the tunnel varies linearly over the length of each blast round, which means that the density of the backfill varies accordingly.

The allowed content of voids and the dry density of the pellet fill is directly determined by the degree of block filling, which is controlled by the amount of over-excavated rock. Scanning of the tunnel contour and calculation of the over-excavated rock have been made in the TASS tunnel at Äspö /14/. The areas of eight sections in blast rounds 4 and 5 are shown in Table 3-1[8], the positions of which are given by Figure 3-3.

Sections 3 and 7 (Figure 3-4) show the least suitable location of a deposition hole for reaching a high density of the upper part of the buffer. Section 3 represents a block filling degree about 70%, and Section 7 a degree of about 71%.

The most suitable position of a deposition hole for reaching a high density of the backfill would be represented by Sections 1 and 5 in Figure 3-3. Section 1 corresponds to a block-filling degree of about 78% and Section 5 a degree of about 80%.

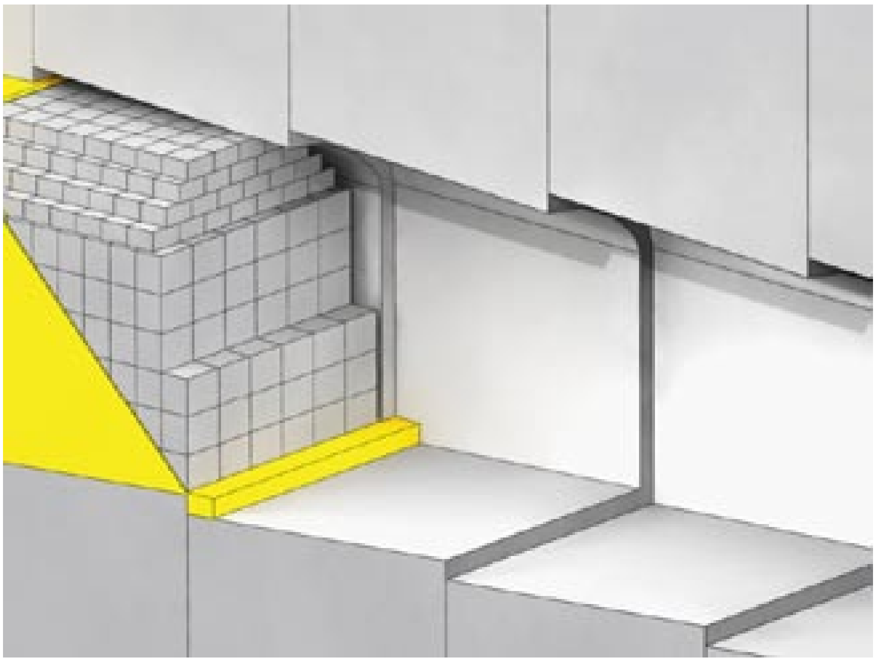

Figure 3-2. Tunnel backfilled with blocks and pellets (yellow). The picture illustrates the look-outs, i.e. the stepwise changed tunnel contour caused by the orientation of the blast holes.

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[8] The tunnel has not yet been completed and the data are therefore preliminary.

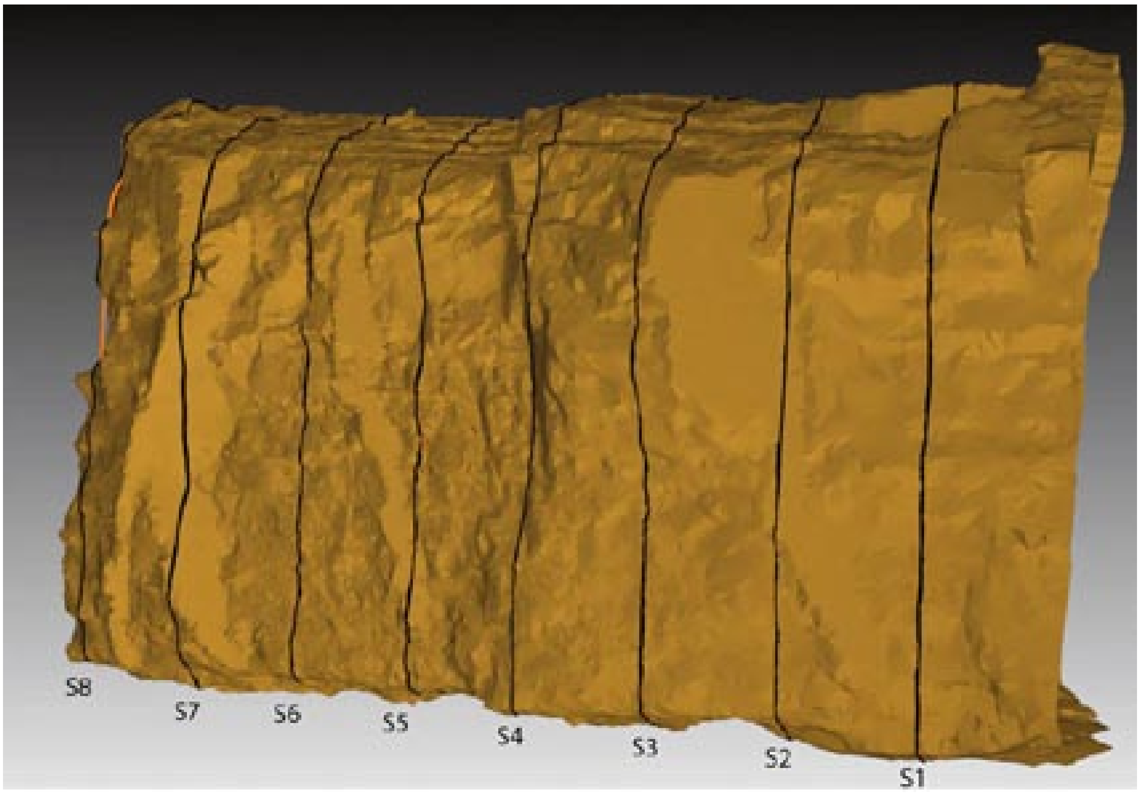

Figure 3-3. *The figure shows an overview of the sections in blasting sections 4 and 5 in TASS-tunnel at the Äspö Laboratory.*

Table 3-1. Areas of the different cross-sections.

Section	Actual Excavated Cross-section, (m²)	Theoretical Cross-section, (m²)	Difference, (m²)
1	21,38	18,93	2,45
2	22,44	18,93	3,51
3	23,96	18,93	5,03
4	23,04	18,93	4,11
5	20,96	18,93	2,03
6	21,81	18,93	2,88
7	23,72	18,93	4,79
8	22,64	18,93	3,71

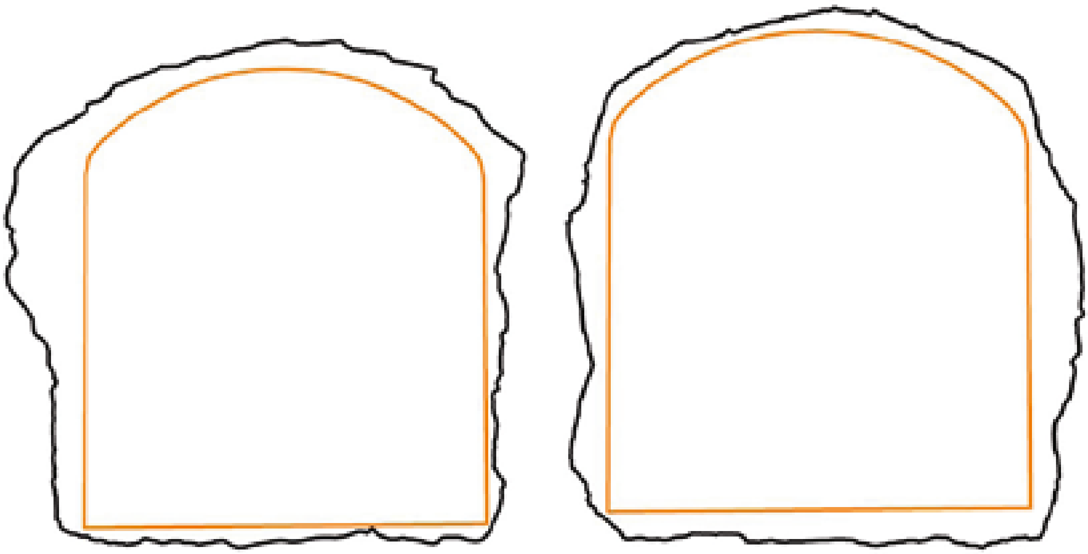

Figure 3-4. Sections 3 and 7 located about 1 m from the bottom charge of the blast round. They represent the least suitable location for a deposition hole with respect to the density of the backfill.

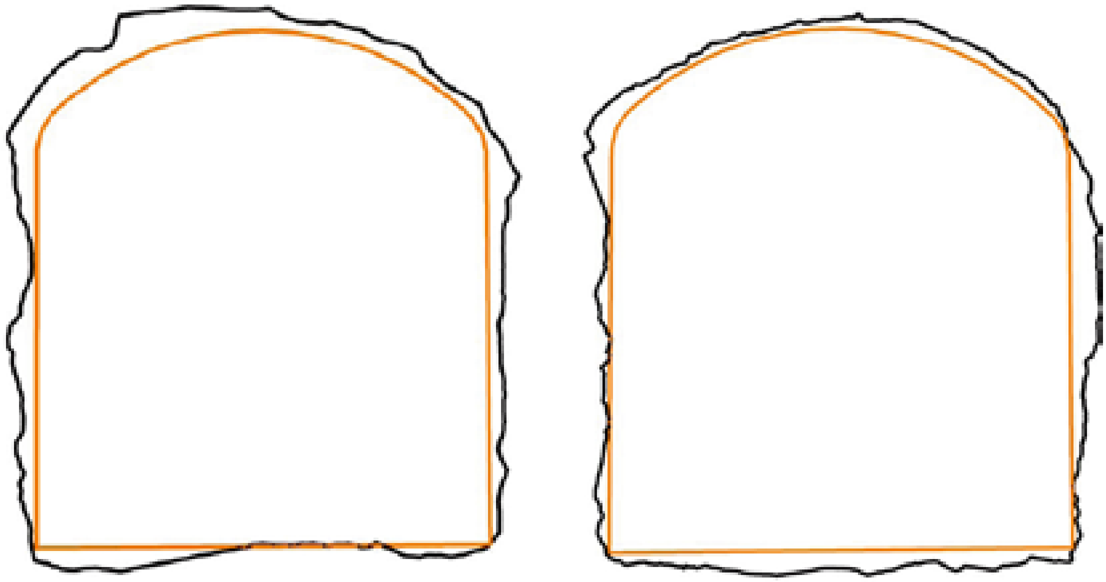

Figure 3-5. Section 1 and 5, located about one metre from the start section in the blast round.

Density issues

For certifying that the function of the backfill is in accordance with the requirements it must have a certain minimum density. The lowest allowable percentage of blocks where the tunnel width is at maximum depends on the type of clay material and density of the blocks, which is a function of the compressive stress used at the manufacturing of the blocks.

As specified in the list of criteria the compressibility of the backfill must be so small that the upward expansion of the uppermost part of the buffer does not reduce its density to less than 1,950 kg/m^3 at water saturation. This requires that the density of the backfill is sufficiently high.

The proposed stacking principle is simple, straight forward and can be applied along the entire tunnel (Figure 3-6). The rest of the space is filled with pellets. As mentioned earlier the theoretical cross section would allow for a block-filling degree of 89%, corresponding to a cross section area of 16.8 m^2, but this requires use of two block types for best adaptation to the theoretical cross section profile, which has an area of about 18.9 m^2.

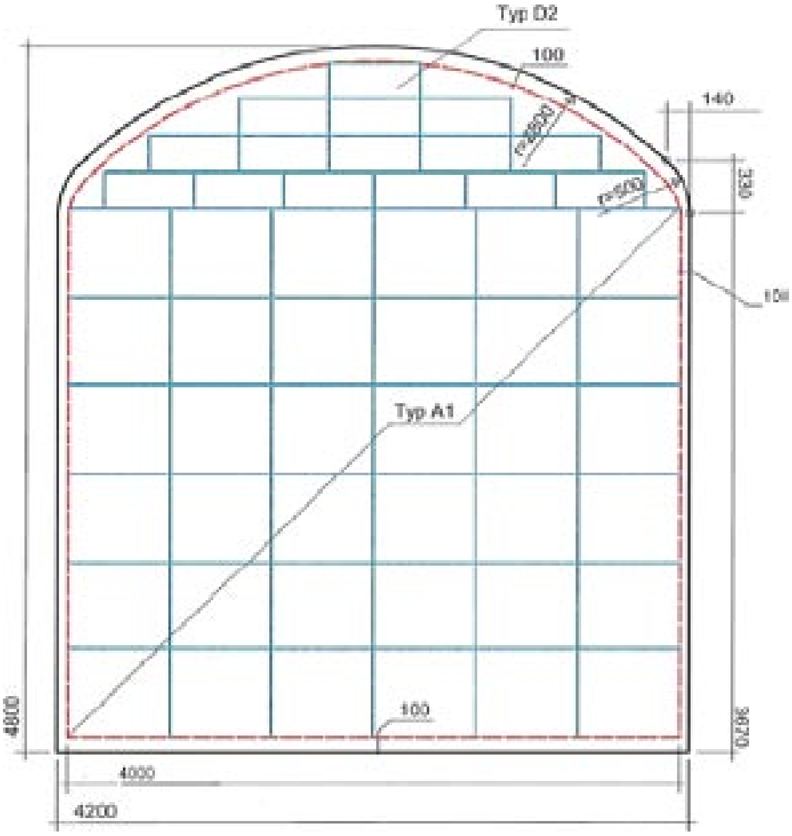

Figure 3-6. Smallest tunnel section with blocks placed with minimum distance of 100 mm from the theoretical rock contour.

Theoretically, tunnel segments of 4 m length and of the type shown in Figure 3-2, i.e. with plane contour and the widest part having 400 mm distance between the block masonry and the rock and the smallest rock- block gap of 100 mm distance, can be filled to an average degree of block filling of 79%. If the widest space is 300 mm and the smallest 100 mm it can be increased to 82%.

Naturally, larger look-outs mean that a larger space needs to be filled with pellets around the block assemblies. It is important to realize that if the inclination of the blasted tunnel does not agree with that of the planned, theoretical tunnel, more material will be required also in the foundation bed.

The basis of the present study was that a suitable design for the deposition tunnels would allow them to be filled to at least 80% with blocks of Friedland clay, regularly stacked so that the distance to the rock is 100 mm or more. However, it has been studied which degree could be achieved of block filling with regards to production oriented installation methods and sufficient margins for the emplacement. A lower value, about 73%, would be more realistically achievable unless the tunnel excavation is made by using very careful contour blasting. The positive aspects of a reduced proportion of block installation would be larger physical clearances between the rock and the blocks and hence the possibility to use more production-accommodated and robust methods for rock excavation and backfill installation. It would, however, require use of more smectite-rich clay in order to reach the required physical properties (hydraulic conductivity and swelling pressure).

3.2.2 Development of blasting technique to provide a suitable rock contour

Further deviation from the theoretical shape is caused by the limited straightness of the drill rods and the deviation of drill holes used in excavation from their intended orientation caused by fracture planes and variations in petrology. Blasting sections are calculated to be approximately 4.5 m in the deep repository. The most important difference between planned and achieved tunnel shape is caused by the orientation of natural fractures. Rock fragments of varying size and shape fall from the rock leaving a very irregular contour. These effects combine to cause considerable variations in the actual degree of block filling. Also, they will cause variation of the width of the pellet fillings along each blasting round from 100 mm at minimum to 400 mm and occasionally more than that, depending on the impact of blasting.

In the ongoing project "Sealing of tunnels at great depth" at Äspö /14/, the matter of look-outs and irregular contours is a focus and numerical models have been used to facilitate comparison with actual tunnel profiles. Scanning of tunnel contours to allow calculation of the degree of block filling and modelling has been made taking the reference pattern in Figure 3-6. In each of the modelling attempts a tunnel length corresponding to two blast rounds has been considered, one with 300 mm look-out and the other with 200 mm. An example of this activity is illustrated by Figure 3-7, which shows the deviation from the theoretical contour and the actually recorded. The parts extending into the tunnel naturally have to be removed with a minimum of disturbance to the remaining rock.

Calculation of over-excavated rock for the two blasted rounds gave a figure of 19%. A very important conclusion from the modelling was that the average block filling degree may be about 73% under normal circumstances. In summary, preliminary data indicate that over-excavation of rock is expected to be about 20% and locally even higher, implying a block-filling degree of 73%. Figure 3-8 illustrates how the pellet fill (brown) around the block masonry (grey) appears.

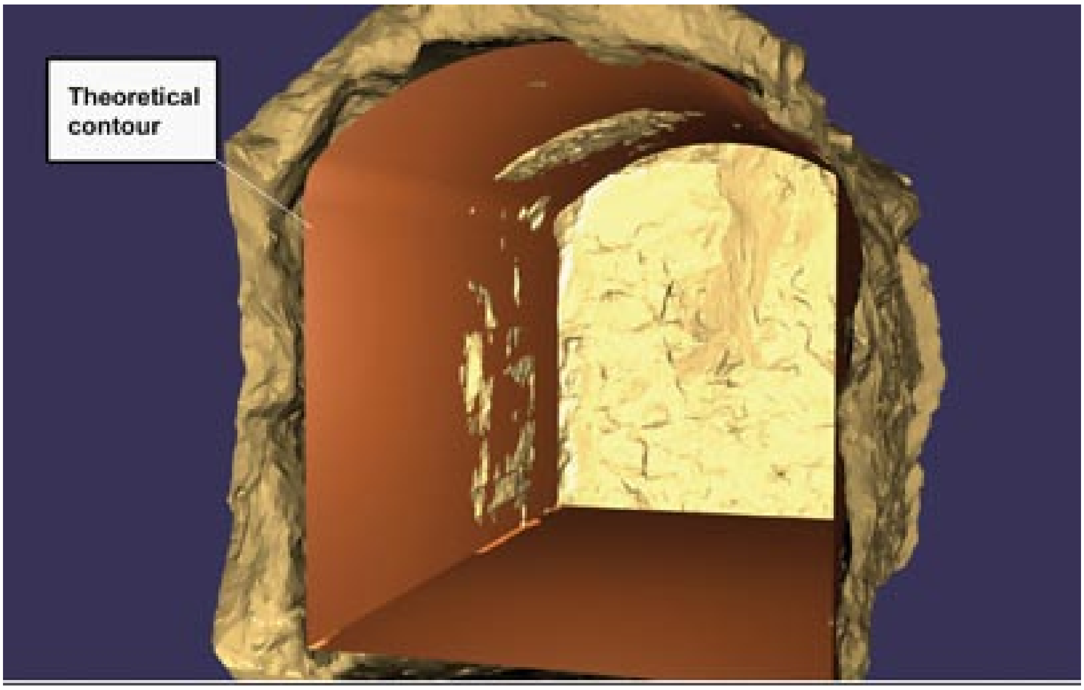

Figure 3-7. Scanned tunnel with theoretical contour (brown). The yellow parts have to be removed.

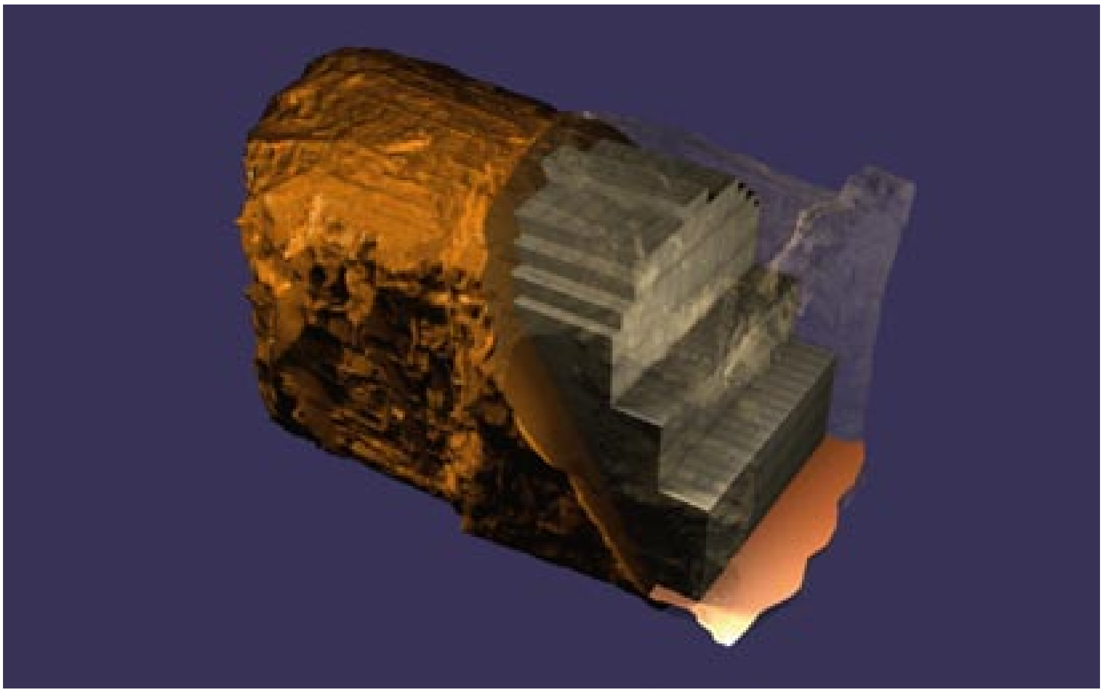

Figure 3-8. Picture showing a section of the modelled tunnel with the block masonry installed. On the left side a big rock block has fallen leaving a steep planar fracture exposed.

3.2.3 Adjustment of the rock contour

After completing the blasting and subsequent securing of the rock, which may require rinsing, bolting and shotcreting, the tunnel will be scanned by a suitable geophysical method. Protruding rock reaching inside the theoretical tunnel contour would then be removed. Larger cavities in the roof and walls could be filled with low-pH concrete anchored by bolts. Alternatively backfilling design could be locally adjusted to permit a larger quantity of block installation in such over-excavated regions.

Wire-sawing of the entire floor gives advantages in the form of evenness of the floor and no need of a temporary road bed for the block-placing and pellet-filling equipment. However, no decision has yet been taken of whether it will be tested or employed. Other alternative techniques have been proposed and will be assessed, like water-jetting or very careful blasting, or use of roadheaders. The ultimate choice of technique for preparing the floor depends on what is really required with respect to evenness, and what the impact is on the hydraulic performance of the excavation-disturbed zone (EDZ). Irrespective of the smoothness of the floor a foundation bed of clay granules must be constructed for allowing water to initially move along the floor without being drawn into the backfill with resulting softening, erosion and insufficient stability of the block assemblies. Cost will be an important factor in this context.

3.2.4 Excavation of ramps adjacent to deposition holes

In order to keep the height (and hence excavation volume) of the deposition tunnels as low as possible, the reference concept presumes cutting of recesses in the form of ramps adjacent to the deposition holes. This will provide sufficient space for rotating the canisters out from the transport vehicle and into the holes (Figure 3-9). The cutting of these ramps can be made by wire sawing /14/, a technique that is frequently used in stone quarries and has been successfully tested at the Äspö URL[9].

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[9] The cutting of the recesses may cause intensive fracturing because of the geometry and rock stresses and no final decision as to constructing them had yet been taken at the time of preparing this report.

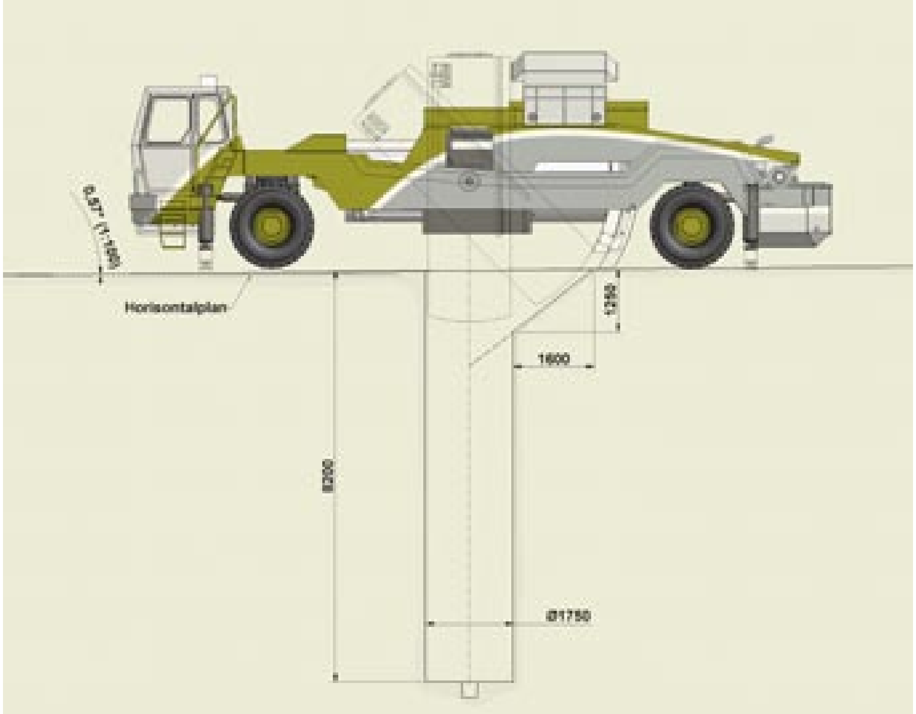

Figure 3-9.Cross section of deposition hole with the equipment for canister placement. *The ramp required for bringing it down is indicated.*

3.2.5 Need for drainage, performance of draining systems

Water flowing into backfilled parts of the deposition tunnels may cause piping and erosion that can jeopardize the backfilling operation by softening the latest applied clay materials. This process is particularly important at low backfilling rates, which means that great effort has to be made to perform the individual operations, i.e. completing the deposition holes, placing of blocks, and filling of pellets, without delay. The present study illustrates identified difficulties in doing the work and possibilities to minimize risks of malfunctioning and delay.

The degree to which non-uniform inflow of water from the walls and roof has an impact on the backfill depends on its absorbing ("buffering") capacity and on the distance from the points of inflow to the front of the backfilled part of the tunnel, and hence on the total length of the backfilled part of the tunnel. Questions have been raised concerning the importance of the rate of inflowing water and whether small channels formed by it merge and form larger flow paths with higher erosive capacity than the small channels. These matters, which determine the selection of backfill materials and placement techniques, are considered in the "Baclo" project.

The most important factor for obtaining a satisfactory backfill is the rate of inflowing water. The matter is being investigated in detail in the parallel SKB/POSIVA project "Baclo" /8/ but some preliminary estimates of maximum acceptable water inflow rates are already at hand. Experience from the Stripa Project indicates that an inflow of 1–2 l/day and meter of tunnel length causes no problems in backfilling of clay/sand mixtures /6/. Äspö experiments demonstrate that a daily inflow of about 500 l per meter of tunnel length makes backfilling impossible /15/. Experiments in less fracture-rich rock at Äspö showed that placement and compaction of clay/ballast fills at a daily inflow of 40–50 l per meter tunnel length gives satisfactory results. At the Stripa site the piezometric height was about 1 MPa and the hydraulic conductivity E-11 m/s in the undisturbed rock and E-8 m/s of the blast-damaged excavation-disturbed zone (EDZ). At Äspö the corresponding data were 1.5 MPa, E-11 to E-8 m/s, and E-10 to E-8 m/s. Both test sites were located at about 400 m depth. An inflow of 40–50 l per meter tunnel length corresponds to about 0.025 l per minute, which would hence be the inflow rate from one spot if the rock structure is such that there is one wet spot per 10 meter tunnel length, yielding 0.25 l per minute from this spot. For the Stripa case the inflow over this length was about 14 l/day corresponding to an inflow rate on the order of 0.001 l per minute and meter tunnel length. The test results from the BACLO project /8/ show that spotwise inflow of up to 0.5 l/min may be acceptable with respect to the erodability of the backfill. However, such high inflows will most probably require special means of discharging water and mud that reach the front. Today, there is no such technique but there are plans to work out methods for solving the problem. At present, spotwise inflow of more than 0.25 l/min can not be handled unless the rate of backfilling is higher than the rate of water migration in the backfill. The backfilling rate depends on the method employed for placing the materials.

Assuming that these results are representative of normal crystalline rock one would take an inflow of 0.5 to 1 liter per day per meter of tunnel as an upper limit for safe construction of the backfill in deposition tunnels. For a 100 m long tunnel the daily inflow would be 50 to 100 l and for a 300 m tunnel it would be 150 to 300 l per day. These amounts of water will flow from the rock via the EDZ to the deposition hole in front of the backfill being placed, which can cause very significant problems. The problem is basically that the successively hydrating and tightening backfill that has already been placed causes an increase in water pressure at the contact between rock and backfill, which redirects water to flow towards the less pressurized, outer end of the backfill via the EDZ. Here, successively more water hence flows from the rock and makes backfilling more difficult by causing softening, piping and erosion. The phenomenon of redirection of inflowing water along the EDZ was observed and recorded at the Stripa BMT experiment /6,12/ and in the Äspö URL /15/. The flow in the rock and in pellet fill hence depends on the rate of maturation of the pellet fill, together with the local rock conditions.

The practical experience of backfilling with respect to the impact of inflowing water is very limited and the transient change in water pressure and lack of information of how the inflow spots are distributed makes it difficult at present to define what the rate of backfilling needs to be in order to avoid unacceptable softening of the backfill, particularly of the pellet fill. In the inner parts of the Prototype and ZEDEX drifts at Äspö URL the inflow of water was so strong that the planned backfilling experiments could not be pursued without effective drainage of the inner ends of the drifts. They were intersected by fracture zones and had to be filled with coarse frictional material. Such artificial drainage, made by covering the wet rock surfaces by permeable geotextile that was drained by tubes extending through the backfill along the floor, cannot be arranged in a real repository. Instead, grouting will be required and a comprehensive R&D was initiated in the Stripa Project and continues in the Äspö URL /14/. A lot of work has also been done in co-operation within SKB, Posiva /18/.

The matter of inflowing water is complex, particularly because of the role of the EDZ. Thus, water flowing from the virgin rock towards the tunnel via a rather small number of flow paths is distributed in the blast-damaged rock and local sealing materials. Even by successful grouting there is a tendency to direct the water flow to adjacent, more permeable rock. The net effect of even comprehensive grouting, termed "hedge-hog" sealing in the Stripa Project /6,12/, using many short boreholes, may therefore be small. Grouting in advance of the tunnel excavation is much more effective and current systematic research for sealing not only wider fractures but also fine ones is presently conducted at the Äspö URL /14/. This activity also includes attempts to grout the EDZ after the tunnel excavation operation. Still, it may be necessary to apply other methods for reducing build-up of high water pressures and inflow of water. One possibility can be to bore some 5–10 more or less parallel holes around the tunnel to produce a hydraulic cage that preferentially takes up the water influx that would otherwise enter the emplacement tunnel. The 30–70 m long holes, which can be bored from a niche where a concrete plug can later be constructed, should be kept drained during a backfilling campaign comprising up to ten backfilling sequences, and can then be plugged by one of the clay-based techniques worked out by SKB /13/. If inflow of water is still too high to allow backfilling the holes can be used for freezing. After completion of the backfilling and the plug is moulded, freezing is stopped.

The assumptions for the backfilling will increase if degree of backfilling is higher than inflowing water from earlier backfilled sections. Inflow of water into the tunnel, causing piping, has to be stopped before backfilling starts.

4 Large-scale experiments

4.1 General

A comprehensive field study has been performed to show how the foundation bed, the block masonries and the pellet fillings can be constructed and what conditions are required for these operations. Three different backfilling methods worked out in the study will be described in the report: 1) the “Block”, 2) the “Robot”, and 3) the “Module” methods. They have two components in common, the foundation bed and the pellet filling around the block masonries, but make use of different types of blocks and methods for placing them. The outcome of the tests has been compared with the theoretical predictions referred to in the preceding chapter and has led to the conclusions and recommendations given in subsequent chapters. The tests were made in the Bentonite Laboratory on the ground surface at the Äspö URL. The preliminary work was largely done manually rather than through use of placement equipment but has given a good basis for future development of equipments for rational placement of the backfill components. This work has also shown the necessity of quality checking and regular supervision of all activities associated with backfilling. In this chapter the major results from the backfilling experiments are collected. Test set-ups and results are reported in greater detail in Appendix 4. Since the experiments were conducted under laboratory conditions and without impact of an EDZ and water flowing from the rock the results should be considered as preliminary.

4.2 Foundation bed

4.2.1 General

The bearing capacity and evenness of the foundation bed determine how the placement of blocks should be made and what the degree of block filling will be. The stability of the bed as a function of time and water inflow must be known for planning of the placement of blocks and pellets. The foundation bed must also be able to sorb some of the water that flows from the surrounding and already placed backfill in order to minimize outflow on the floor. If outflow is significant then there is a need to arrange drainage so as to minimize water interaction with the bed.

Ensuring that sufficient bearing capacity is present requires compaction of the material, for which a vibrating plate must be used. This has been investigated by conducting a series of loading experiments using concrete blocks of similar dimensions and density to backfill blocks. Levelling of the bed is shown in Figure 4-1.

A piece of equipment for constructing foundation beds has been outlined as indicated in Figure 4-2.

Material

Two types of commercially available granular smectitic materials were used: Minelco granular bentonite material, with somewhat varying granulometry, and Cebogel pellets, which originate from the same smectite-rich bentonite deposit, cf Appendix 4. Both have a content of smectite (montmorillonite) of about 80% weight percent, but have been processed in different ways giving different size distributions as shown in Figure 4-3.

Laboratory investigation by Clay Technology AB, Lund, has shown that loosely filled pellets have a bulk density of around 1,100 kg/m^3 (1,159 kg/m^3 bulk density and a dry density of 975 kg/m^3 for Minelco, and 1,121 kg/m^3 bulk and 943 kg/m3 dry density for Cebogel), cf Appendix 4.

Figure 4-1. Preparation of the bottom bed using Minelco granulate.

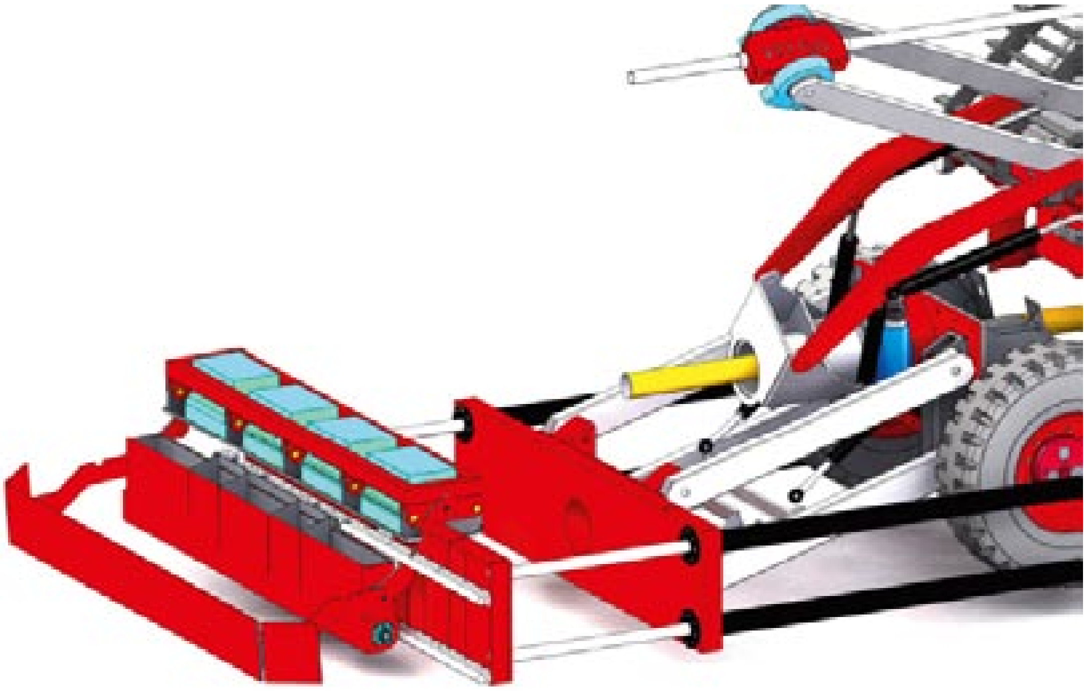

Figure 4-2. Machine for distribution and levelling of granular material in the bottom bed.

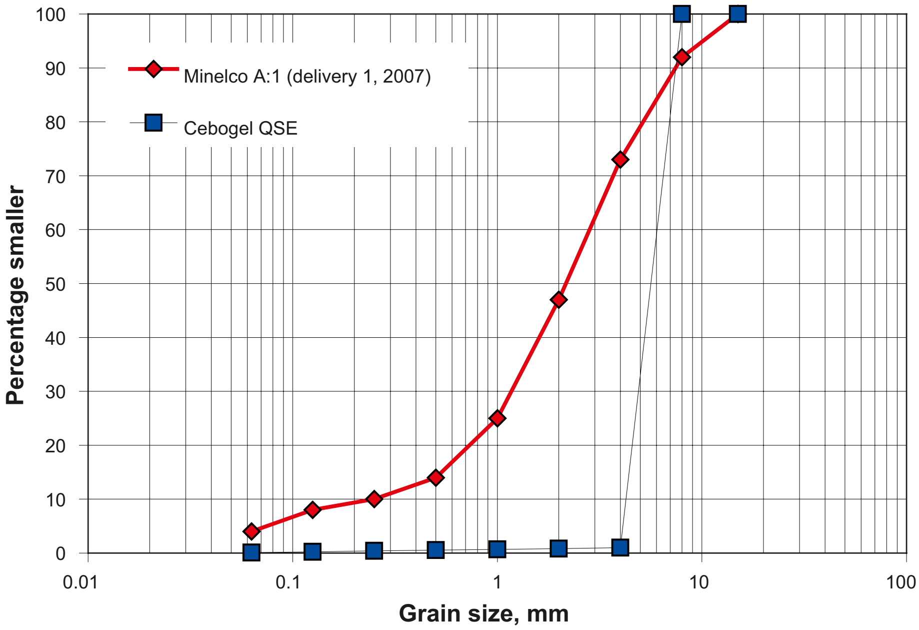

Figure 4-3. *Grain size distributions of the clay materials used for preparing and load testing of foundation beds.*

Tests

A testing program was worked out to determine how the deformation properties of the foundation bed affect the stability and strain of 100 blocks stacked on it. It comprised a study of how the type of vibrating plate and grain size distribution as well as layer thickness affect the compressibility (cf Appendix 4). The tests gave the bearing capacity and deformation mode of the beds with the purpose of investigating the impact of inflowing water from the original air-dry conditions (Figure 4-4).

The tests were intended to show:

- How different clay materials sorb water.
- How beds sorb water.
- How the evenness and density of the bed affect the stability of the block stack.
- How the beds react on spot-wise water inflow.
- How the beds are best designed for acceptable performance.

The dry density was about 1,250 kg/m^3 of the Minelco bed and about 1,150 kg/m^3 of the Cebogel bed after compaction. A major finding was that the Cebogel bed softened quicker and more than the Minelco bed, which led to the decision to use the Minelco in subsequent full-scale simulations of block placement. Some full-scale experiments with Cebogel pellets were made to confirm the superiority of the Minelco material in this respect.

In summary, none of the bed materials jeopardizes the stability of blocks stacks if it is placed before water flows in along the floor. A practical matter is that the bearing capacity of the Minelco bed at inflow of water is higher than for the Cebogel bed since it retains its stability for a longer time than the Cebogel material under wet conditions. It is concluded that additional testing and development of techniques for drying are required and that one needs to find a balance between good performance and rationality in the construction of foundation beds.

More detailed information on test arrangements and measurements are given in Appendices 1 and 4**.**

Figure 4-4. Examples of test arrangements for investigating of the impact of inflowing water on the settlement and bearing capacity of the foundation bed, as well as of the stability of block masonries.

4.3 Block filling

4.3.1 Tests

General

The study was practical and primarily aimed at showing how accurate block stacking could be accomplished in a full-scale version of the "idealized" tunnel (height 4.8 to 5.1 m, and width 4.2 to 4.8 m). It also gave an opportunity to determine joint apertures and displacements of placed blocks in conjunction with wetting of the foundation bed

Test principle

The block filling tests were planned to determine what accuracy and capacity in placing the blocks can be expected in practice. The experiments were constructed using concrete blocks since it was not possible to manufacture several hundred clay blocks of the required size. The material used to construct these simulated blocks was also not of importance as their geotechnical properties were of no importance. In a repository the clay blocks are planned to be handled using vacuum tools and tests with the concrete blocks of similar weight, size and surface smoothness indicated that this should be possible (Figure 4-5). Experiments with clay blocks by the company Creanova Teknik AB verified this for dry as well as wetted block surfaces but more tests are required, including establishing ways of certifying the block quality with respect to surface smoothness and surface evenness. For time and budget reasons no special vacuum tools were developed for these tests, instead fork trucks were used.

4.3.2 Test arrangement

The wooden simulated tunnel for investigating the placeability of clay blocks and pellets is shown in Figure 4-6. The photo illustrates a test with blocks stacked stepwise on a foundation bed of Minelco granules. Handling and placement of blocks in a repository requires preparation, handling and placement of block units of not yet decided type. Manual handling was commonly used in the tests while in practice the vacuum technique will be required. It is estimated that an extensive R&D program that includes preparation of thousands of real clay blocks will be needed to address all the issues associated with this technique and technology**.** As indicated by the description of the influence of joint widths in the block masonries and of different block arrangements this program must also include an accurate method for quality control of shape and texture of the blocks, cf Appendix 1.

The limited time and budget required the use of readily available building construction equipment for the tests, while a number of special tools have to be developed for future testing and full-scale application. Figure 4-7 gives examples of typical utilities.

Figure 4-5. *Vacuum plate for handling of concrete blocks.*

***Figure 4-6.** Stacking test with concrete blocks of relevant size and weight. Upper: Placement of blocks by use of the "Mecalac". Lower: Concrete block masonries constructed with simultaneous measurement of joint apertures and time for installation.*

***Figure 4-7.** Testing of candidate tools for full-scale tests in the Bentonite Laboratory at Äspö. Left: Block stacking tests with telescope-type truck. Right: The "Gradall", which is designed and used for ditching and other excavations.*

The objective of making realistic experiments led to the selection of a "Mecalac" unit, a digging machine, for moving and placing the blocks (Figure 4-8). It can remain in the same position while constructing a complete block masonry, the blocks being supplied from below the machine at the same rate as the blocks are placed. Figure 4-8 shows a stacking test performed by use of this equipment.

For the "Module" method, which makes use of coherent block assemblies for practical handling and placement of the blocks, special tests were made for investigation of how the blocks can and should be arranged to make the modules stable (Figure 4-9).

Several ideas for increasing the stability of block assemblies were discussed and tested, like the possibility of increasing the adhesion strength by wetting the surfaces of adjacent block before joining them. This raised the strength expressed in terms of the Coulomb friction angle from 31º to about 70º but the results were not consistent.

Figure 4-8. *The "Mecalac" at work in pilot tests.*

Figure 4-9. *Testing of the stability of a module. Notice the bigger bottom blocks and layers of differently placed and oriented blocks.*

4.3.3 Results

Block placement without using automatic or specially developed techniques puts strong demands on the operator. Tests at Äspö have shown that blocks can be placed at a rate of one block per minute with acceptable accuracy, i.e. with a volume of unfilled voids of about 1.5% of the total block volume. The rather ideal conditions for the experiments may explain the good results. The geometry of the stacked 100 blocks was recorded by point-wise laser measurement.

The experiments show that placing of blocks would be possible under repository conditions. Following the principle that was finally selected for the planning of the experiments, i.e. that 60% of the volume of the up to 300 m long blasted tunnels shall be filled with clay blocks, the experiments showed that this can be achieved even if the topography of the floor, walls and roof is rather irregular. The tests have shown that it will take about 60 seconds to pick up a block and place it accurately.

There is a risk that water flowing along the floor from earlier placed backfill can cause problems in the preparation of new beds and it is believed that a technique must be worked out for removing water from the construction area.

4.4 Pellet filling

4.4.1 General

While block placement is a relatively straight forward operation, pellet filling of the space between blocks and rock is much more challenging because of the geometrical restraint caused by the rough topography of the blasted walls and varying tunnel width, which gave limited access to the space for installation and measurements. The “Baclo” project /8/ will give information on the importance of piping and erosion, while the present study is confined to dealing with the placeability and degree of homogeneity of the pellet fill here.

4.4.2 Material

The selection of the pellet material Cebogel was based on laboratory tests for determining the hydraulic conductivity and swelling pressure as functions of its density. These properties will change as the density of the pellet fill increases due to the consolidation caused by the expanding block mass. The freshly filled pellets, saturated with Äspö water but not yet consolidated by the swelling pressure exerted by the block masonries, will have a density of about 1,600 kg/m^3 and a conductivity of about E-10 m/s and up to E-9 m/s for salter water. The swelling pressure will exceed 100 kPa for densities at saturation with salt water. A simple estimate referring to references /4,5/ shows that equilibrium after water saturation is reached when the swelling pressure of either substance is equal, which implies a dry density of the Friedland material of about 1,500 kg/m^3 and 1,190 kg/m^3 of the pellet fill for 3.5% $CaCl_2$ porewater (400 kPa). For this salinity the hydraulic conductivity of the pellet fill is E-11 m/s and that of the Friedland material E-10 m/s. One finds from this that even moderate compression of the pellet fill caused by the expanding tunnel blocks will make the firstmentioned less permeable than the block mass and provide the required support of the rock, cf Appendices 1 and 4.

4.4.3 Test arrangement

Several test series were conducted and the ones reported here represent the most promising techniques developed in the course of this study. Figure 4-10 shows a pilot experiment of pellet blowing using conventional equipment with a capacity of about 1 m^3/h, with water added at the nozzle, a method that led to a practically applicable way of blowing pellets with limited dusting.

Wooden tunnels of relevant size and shape were constructed for investigating how the homogeneity of filled pellets will be in practice (Figure 4-11). Irregularities in tunnel walls were simulated by attaching tetrahedrons of plywood to the walls resembling protruding rock that can serve as obstacles in the filling process. The larger part of these tunnels was occupied by a wooden construction representing block masonries.

Figure 4-10. *Blowing of pellets with a capacity of 1 m³/min as part of a study for finding a suitable technique for pellet filling.*

Figure 4-11. *The wooden test tunnel with stepwise stacked concrete blocks resting on the foundation bed and equipment for pellet blowing.*

Additional tests to investigate the behaviour of blown-in granulate were made in a steel tunnel that simulated a deposition tunnel on half scale (Figure 4-12). Both tunnels made it possible to simulate surface irregularities in a real tunnel in order to investigate the possibility of effectively placing the pellets along the walls and roof.

The simulated wooden tunnel for investigating placeability of clay blocks and pellets shown in Figure 4-11 was particularly useful for large-scale investigation of the homogeneity of pellet fills placed by blowing. It was equipped with windows for inspection of movements in the pellet fill. While the filling of pellets in one of the pilot test set ups was simply made by pouring and gentle compaction, blowing technique developed for dry concrete material was tested in the tunnel. The capacity of the latter technique was about 5 m³ per hour. Figure 4-13 shows the nozzle of the blowing tube, which had an outer diameter of 70 mm. An amount of 1% of water by mass was to be added at the nozzle to reduce dust under the installation.

***Figure 4-12.** Arrangements in steel tunnel for filling tests using Minelco granulate.*

***Figure 4-13.** The picture shows the nozzle of the tube for blowing pellets with holes for adding water for reducing generation of dust.*

4.4.4 Results

The intended density of the pellet fill was 1,000 kg/m³, which, for the Cebogel pellets with 16% water content, implies a dry density of about 975 kg/m³ and a density at water saturation of about 1,600 kg/m³. The actual dry density of the fill was, however, found to be only 907 kg/m³. This may at least partly be explained by the fact that the space immediately below some of the artificial rock outcrops was not filled. It was also concluded that although the pellet fill was in contact with the tunnel roof it will undergo some self-compaction leading to a gap that will remain open until the fill is contacted with water and it swells into any adjacent openings.

Figure 4-14 illustrates arrangements for watching the motion of the pellets in the course of the filling operation through windows in the walls. It was found that the fill was largely homogeneous but some smaller scale tests indicated stratification of the granular fills.

Figure 4-15 illustrates the filling process in the part of the simulated tunnel where its cross section was at minimum, i.e. where the theoretical distance to the block masonry was 100 mm.

The slope angle (angle of repose) of dry pellet fill was found to be 45º and ways of obtaining steeper orientation were tried and shown to be achievable by adding more water to the nozzle of the tube used for blowing the pellets (Figure 4-16). Since it is believed that the front of the pellet fill will have to be very steep in practice, further testing and development of a suitable technique are required.

Tests were also made with augers for placing pellets (Figure 4-17). This technique requires the augers to push the material and fill the space above them but the tests showed that the movement beyond the exit of the auger could hardly exceed about 400 mm and that the auger could not reach into all parts of the space to be filled. This limitation and the risk of heterogeneities in the placed fill suggest that the auger technique should be abandoned and focus instead be on the blowing technique.

***Figure 4-14.** Windows for watching motion of pellets and degree of pellet filling.*

Figure 4-15. Pellet filling in the most narrow tunnel section.

Figure 4-16. Steep front of pellet fill.

Figure 4-17. Pilot test using an auger for placing pellets.

5 Basis of selecting an optimal backfilling concept

5.1 Background

The backfilling experiments performed at Äspö give a good basis for selecting materials and design of the backfill by demonstrating possibilities and difficulties, and by showing that the margins to specified data and properties are often very small. Also, they indicate the need for rational and safe handling and placement of backfill components with respect to the limited time that will be available considering the impact of exposure to moist air and inflowing water. The latter issue has not been in focus in this study but sufficient information on the limitations caused by the conditions on site is at hand for realizing its importance.

The earliest attempts to fill the deposition tunnels by placing and compacting mixed clay and sand/gravel material or suitably graded Friedland clay by sideways filling and compaction were concluded to give acceptable results but the margins respecting hydraulic conductivity and swelling pressure were found to be too small. Certain attempts by Swiss and Japanese investigators to install pellets with and without subsequent compaction has given varying and not fully convincing results (dry densities of 1,400–1,600 kg/m^3), /13, 15/. Future development of full-scale adaptated methods for achieving high densities of blown, very dense pellets may provide alternative, simpler ways of backfilling.

According to ongoing synthesis and modelling of the integrated system of engineered barriers the margins for the criteria /5/ set for blocks compacted to 25 MPa are shown as percentages in Figure 5-1 for three clay types of which Asha 230 and Milos B are smectite-rich bentonites converted from the original Ca state to Na by soda treatment. These clay materials perform essentially identically to the American Wyoming bentonite MX-80 that has been studied extensively by SKB.

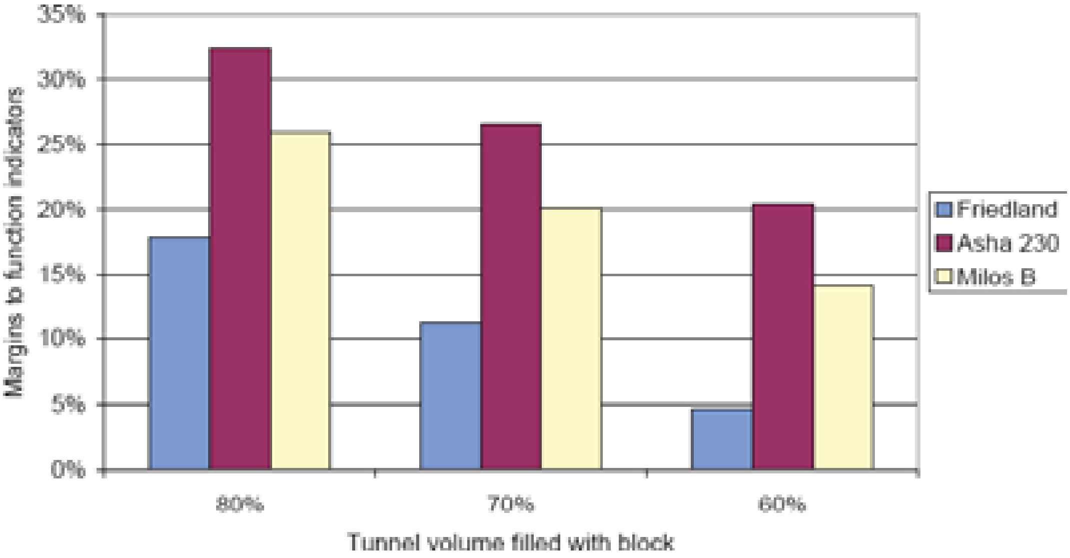

***Figure 5-1.** Margins to criteria set by SKB respecting the hydraulic conductivity for blocks compacted under 25 MPa pressure expressed in percent for three clay types.*

Additional margins are required to compensate for the expected deviation of 10–15% from planned densities caused by variations in compaction effort at installation of pellet fills, and the expected variations in composition of the clay materials. The fact that the properties of the clay must be sufficiently good for at least 100,000 years means that the impact of physical and chemical degradation of the clay must also be considered in the safety analysis, which has still not been made[10].

All these considerations mean that comparison and assessment of different backfilling methods must be made based on the entire series of activities in preparing and placing the backfill. Both practical issues related to construction of backfills and detailed understanding of the various processes in the maturation process and subsequently under transient temperature conditions need to be considered. A number of basic matters, especially concerning construction of the tunnels, are not yet well known. Furthermore, no decisions have yet been taken concerning the various stages in construction of backfills.

5.2 Backfilling with different degrees of block filling

The stacking of blocks can be made by applying a constant "static" pattern, or by using a flexible model (Figure 5-2). In both cases the placement of blocks must be made so that the space between blocks and rock is available for accurate filling of pellets at the specified rate, i.e. 6–8 m per day.

Use of Friedland clay blocks requires a degree of block filling degree of 80% of the space in order to meet the basic performance expectations for the backfilled tunnel. Blocks of more smectite-rich clay may not require more than 60% filling degree to achieve the same level of performance.

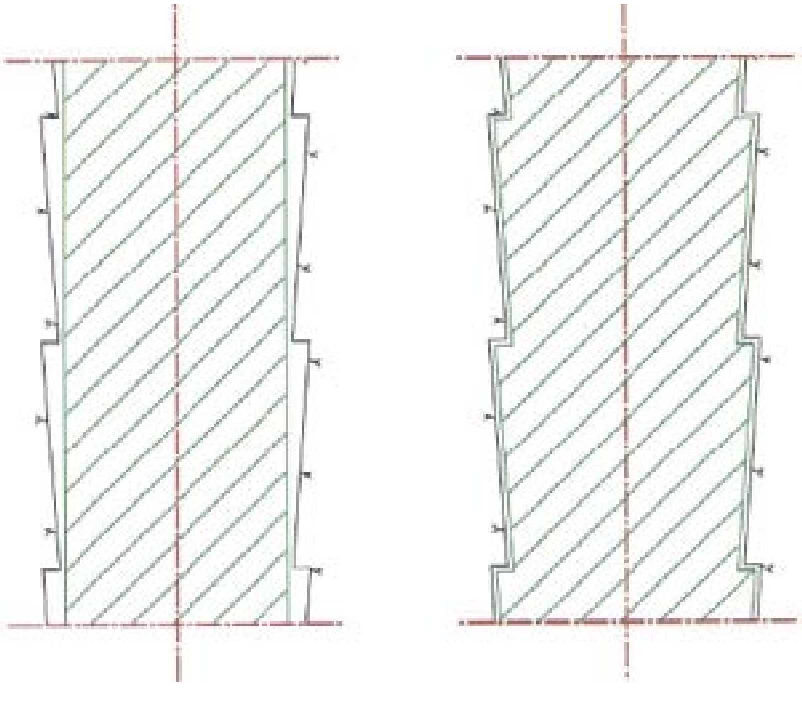

Figure 5-2. *Block stacking. Left:"Static" system with plane boundaries. Right: System adaptated to the rock contour "flexible stacking" (contour-adaptated).*

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[10] An often asked question is whether conversion of "bentonite" from Ca to Na state by soda treatment has any negative impact on the mineralogical stability. It does not, the only effect of such treatment is cation exchange from calcium to sodium and some slight increase in calcite content.

The acceptable amount of over-excavated rock in the tunnel roof is determined by the contour of the block masonry and the outlook of the blasting holes. For the tunnel sides the acceptable 30% over-excavation means that there will be differences in density of the matured backfill in the axial direction of the tunnel. Preliminary results from the 3D modelling of the shape of the TASS tunnel in the Äspö URL indicate that the average degree of block filling per blast-round would be about 73%. The deviation from the 60% required would hence be 13 percent units, which allows for a substantial variation in average density per meter tunnel length per blast-round. Since the density criterion is 1,250 kg/m^3 and the limit 60% degree of block filling settled for the backfilling (corresponding to the dry density 1,420 kg/m^3) there is in fact an additional margin of 14%.

The margin is determined by three variables: 1) the degree of block filling, 2) Unfilled spaces in the backfill (the voids between the blocks in the block masonry and unfilled spaces in the pellet fill) and 3) the dry density of the pellet filling. Figures 5-3 to 5-5 illustrate the influence of these variables on the average dry density of the backfill. Figure 5-3 shows the influence of the degree of block filling. Figure 5-4 shows the influence of unfilled space in the backfill. Figure 5-5 illustrates how the average dry density of the backfill is related to the dry density of the pellet filling. The basic assumptions are: ρ_d = 1,730 of the blocks, 2% slots between the blocks, ρ_d = 1,000 of the pellets filling and 73% block-filling degree. The figures show that the margin to the density criterion 1,250 kg/m^3 is very large. The degree of block filling may locally be as low as 40% without jeopardizing the density criterion.

The safety-controlling parameters are mutually independent but the demand for a certain maximum void space and dry density of the pellet fill is determined by the degree of block filling. It is important to realize that the use of a more smectite-rich clay than Friedland clay for preparation of the blocks increases the safety margin. Thus, while the degree of block fill for this clay type needs to be about 80% for fulfilling the criterion of no more than 2% unfilled space and 1,000 kg/m^3 dry density of the pellet fill, a significantly lower block-filling degree – down to slightly more than 60% – will be required for smectite-rich blocks.

The advantage of using such clay is exemplified by the fact that a block-filling degree of 73% for Milos B bentonite would raise the fraction of unfilled space to 11.5% (Figure 5-4) provided that the dry density of the pellet fill is 1,000 kg/m^3. Similarly, for a block-filling degree of 73% for Milos B bentonite, the dry density of the pellet fill can be reduced to 630 kg/m^3 (Figure 5-5).

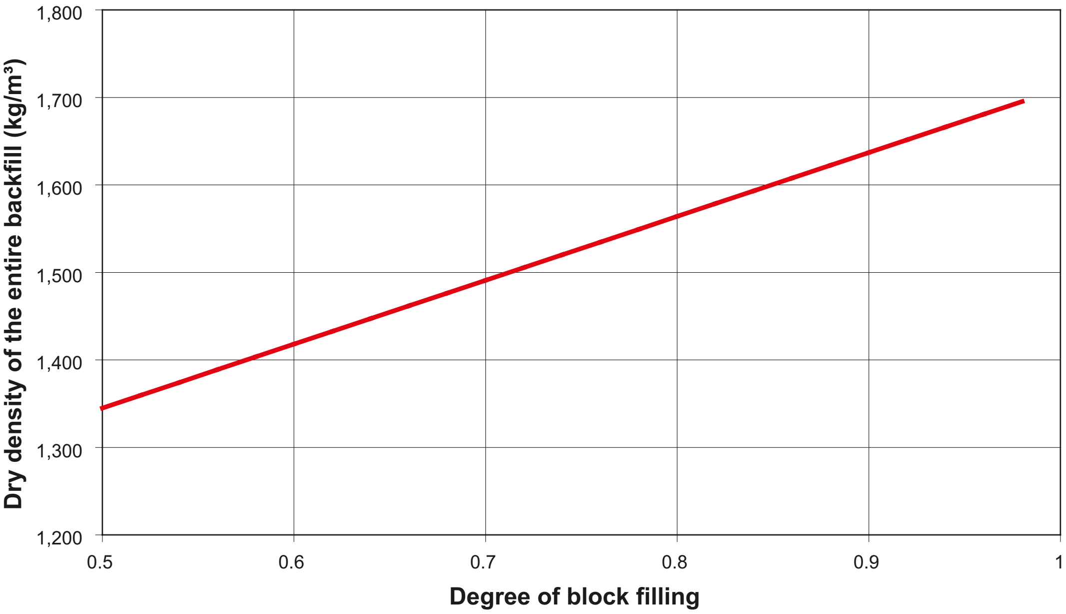


Figure 5-3. *Influence of degree of block filling. The dry density of the entire backfill is plotted as function of the degree of block filling. 2% slots between the blocks, □d = 1,730 of the blocks and □d = 1,000 of the pellets filling.*

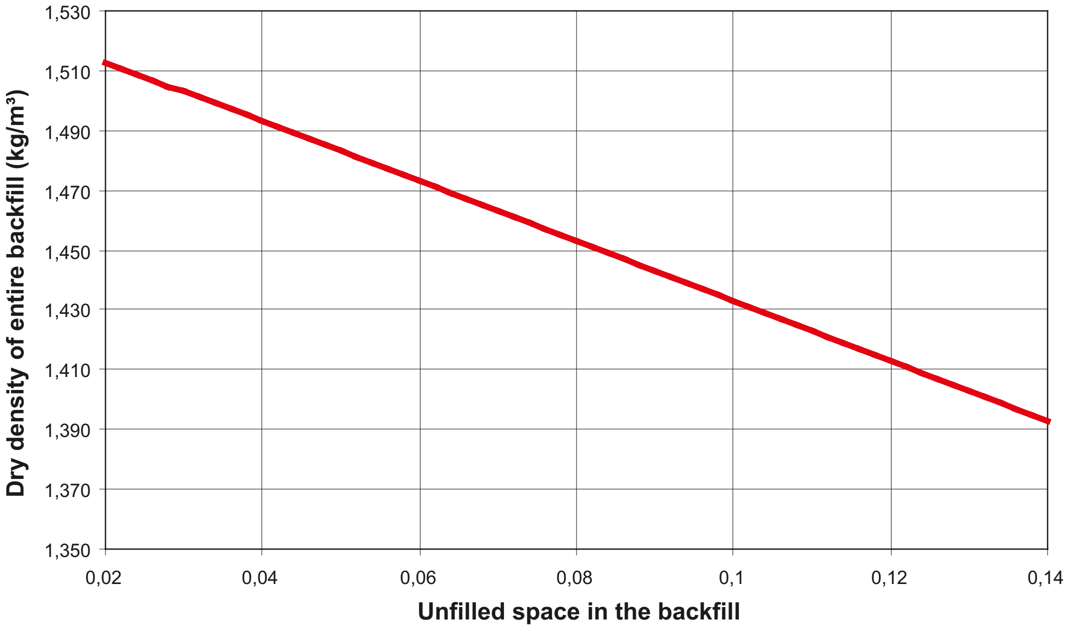


Figure 5-4. *Influence of the voids between the blocks in the block masonry ("unfilled space"). The dry density of the entire backfill is plotted as function of the portion of slots between blocks. 73% degree of block filling, ρd = 1,730 of the blocks and ρd = 1,000 kg/m^3 of the pellet fill.*

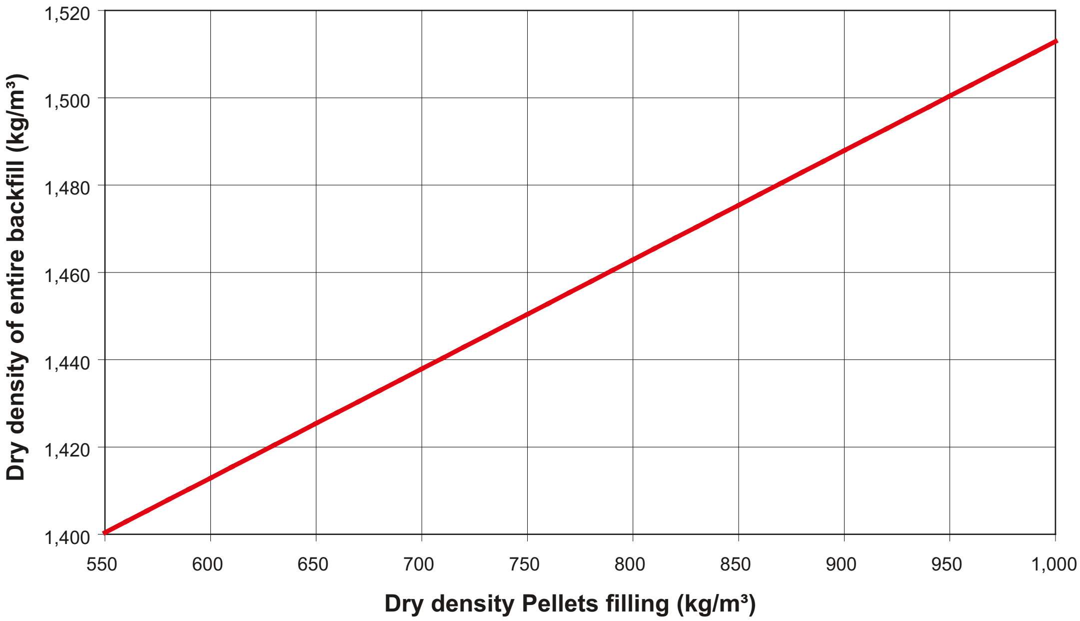


Figure 5-5. *Influence of the dry density of the pellet fill on the dry density of the entire backfill assuming 2% unfilled space, 73% degree of block filling, and ρd = 1,730 kg/m^3 of the blocks.*

5.2.1 "Flexible" stacking with at least 80% degree of block filling

For fulfilling the density criterion and a minimum degree of block filling of 80% a more flexible (contour-adaptated) stacking model is required for blocks prepared by using Friedland clay. In order to place the blocks according to the "static" mode (Figure 5-2) fulfilling the criterion of 80% filling degree of Friedland blocks, the amount of over-excavated rock must not exceed 10%, which is unrealistic. This has led to examination of various other stacking principles, taking also the entire series of activities, from block compression, placement techniques, tunnel contour variations, and logistics into consideration. An example of a flexible model is shown in Figure 5-6.

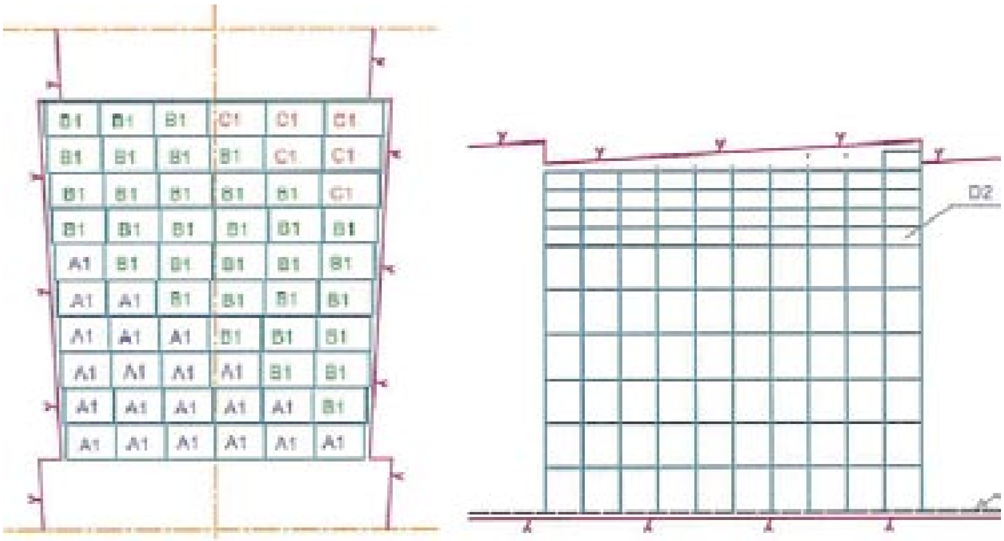


Figure 5-6. *Block masonry of flexible stacking type.*

Several attempts were made to find an optimal block pattern. The pattern that used four different block types gave the best fitting to the idealized shape of the blasted tunnel. It assumes stacking with vertical, continuous joints without providing self-locking effects yielding sufficient stability, especially if the front is stepped. A better coherence of the blocks would be valuable for getting good stability but it would involve difficulties in placing them and a poorer degree of filling of joints at the "breakpoints" i.e. the discontinuities where the walls meet the roof.

However, this and any other regular stacking model is not adaptated to the shape of the blasted floor, which calls for constructing the aforementioned foundation bed of compacted clay pellets or granules with a thickness that varies linearly along the individual blasted rounds. The use of three different block widths would give optimal fit to the walls. In practice, the blasted contour always gives a lower degree of block filling than the idealized tunnel shape shown in Figure 5-6.

The flexibility of this model is limited by the need for filling with pellets so that no unfilled space is left. It is believed that the maximum horizontal distance to the toe of previously placed pellet slope is about 2 meters for making homogeneous filling of the space possible. The natural slope angle for dry pellets will be about 45º thereby requiring a distance from the back end at the roof to the front of almost 7 meters before filling of the rear-most region is accomplished. A flexible stacking mode means that the tube for blowing pellets cannot reach to the end of the previously placed fill thereby requiring that each pellet fill sequence ends with a vertical front, which can be achieved in practice by adding water the pellets in the course of inatlling the fill. This type of pellet filling has been accomplished in the BACLO tests where the pellets were wetted as they were blown into place. These experiments were successful and demonstrate the practicality of the technique.

The layer of blocks between the "breakpoint" and the roof should have a height of 250 mm for acceptable adaptation to tunnel profile near the roof. The best technique of placing the blocks up to the roof is the "Module Method", which, however, requires very small look-outs for flexible stacking modes. The advantage of using flexible-type stacking of blocks compared to simple static-type stacking is that the block masonries can be better adaptated to the profile of blasted tunnels.

A number of calculations to estimate the impact of deviation from the idealized shape of the tunnel shape defined in Figure 5-6 have been completed and they have yielded the sets of data that are used to estimate the degree of block and pellet fillings. These results show the influence of blasted-induced widening of the tunnel space but not of the largely unknown effect of variations in surface topography of walls and roof caused by blasting. This can be demonstrated in that an increase in theoretical tunnel width by 1.5 cm means that the required amount of pellets increases by about 1%.

The results show that "flexible" models manage to produce the required degree of filling for different look-outs although with very small margins. By optimizing all parameters a theoretical filling degree of 88% can be obtained for each blast round but it requires a completely flat and smooth floor and it also yields difficult pellet filling conditions. Calculation of the maximum degree of block filling shows that in practice it should be possible to achieve approximately 84%, provided that the tunnel contour is smooth and that suitable blast-hole lengths have been selected.

A major advantage of flexible stacking models is that the look-outs and variation in topography of the tunnel walls do not affect the degree of backfilling. It is suspected, however, that the resulting margin of 4% can not be achieved when the impact of the rock structure is considered and that it is not compatible with the robustness required in the construction of a HLW repository. For the roof and floor over-excavation is a determinant of the block-filling degree. In order to reach a sufficiently low hydraulic conductivity and the required swelling pressure of the backfill the density of the backfill must be sufficiently high and it primarily depends on the geometry of the tunnel and therefore on the tunnel excavation method. The following possibilities have been identified:

- Maintaining the present concept but increasing the density of the blocks by using compression pressures of 100–200 MPa instead of 25 MPa. This would yield dry densities of at least 2,100 kg/m^3 and a hydraulic conductivity of less than E-11 m/s and a swelling pressure of at least 1 MPa for Friedland blocks.
- Smoothing of the tunnel contour by use of road headers or contour blasting.
- Constructing the tunnels by blasting according to the principle described in this report and accepting a lower degree of block filling (down to 60%) but use of more smectite-rich clay for preparing the blocks. This would make it possible to retain the principle of backfilling described in this report but provide better robustness and conditions for placing the backfill components.

5.2.2 "Static" stacking with at least 60% degree of block filling

The reference case of block stacking described below implies block-filling degrees down to 60% and use of smectite-rich clay in the blocks. It represents the "static" type, i.e. with straight, continuous joints between the blocks without adaptating to the actual rock contour. Figure 5-7 illustrates how single block masonries would appear at the beginning and end of 4.5 m long blasting rounds assuming plane tunnel boundaries.

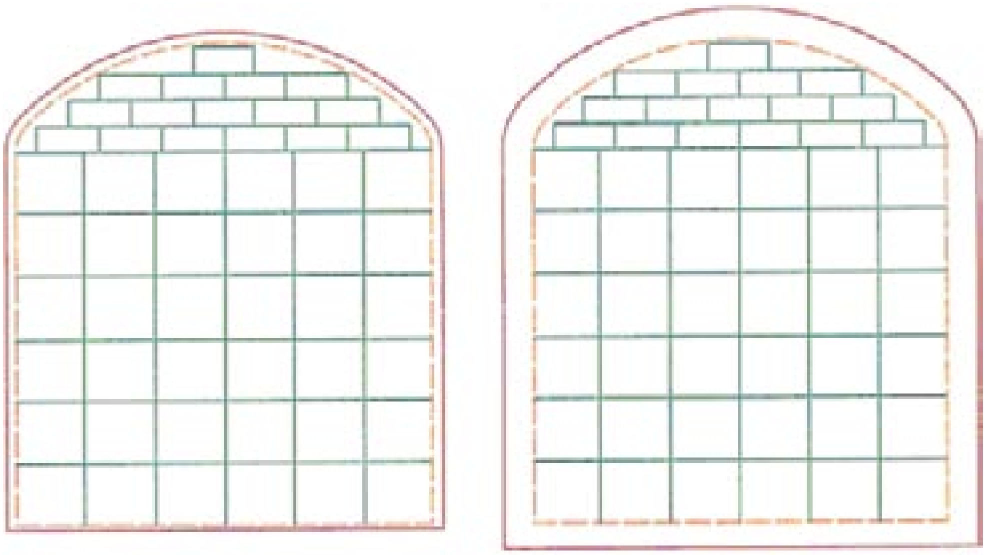


Figure 5-7. Cross sections of tunnels with "static" stacking with as low as 60% average degree of block filling.

The required average hydraulic conductivity of a block masonry occupying no less than 60% of the tunnel space can be reached by using bentonite like Milos B for preparing blocks and pellets. Following the criterion that the total unfilled space in the tunnel must not exceed 2%. The theoretical cross section area of the tunnel is 18.9 m^2 while those of the block masonries and pellet-filled space are 16.8 m^2 and 2.1 m^2, respectively. Table 5-1 and Figure 5-7 serve to illustrate this concept.

The maximum percentage of over-excavation of rock is set at 30% with respect to the earlier defined theoretical tunnel section, which according to Table 5-1 gives a block-filling degree of 67%. For 20% over-excavation it increases to 73%, improving the net bulk clay density and reducing the demands of precision block fitting and high degree of pellet filling.

Table 5-1. Impact of rock excavation on the degree of block filling.

1. *A = Degree of block filling (16,68 m²) for theoretical tunnel section (18,9 m²).*
2. *B* = Degree of pellet filling.
3. C = Acceptable average cross section along a blast-round (m²).
4. D = Acceptable unfilled area after block-filling (m²).
5. E = Acceptable over-excavated cross section compared to the theoretical section (m²).
6. F = (%), Acceptable over-excavated cross section compared to the theoretical section.
7. G = Margin for irregularities and deviations for 300 mm look out (%).
8. H = Margin for irregularities and deviations for 300 mm look out (mm).

A	B	C	D	E	F	G	H
80%	20%	20,850	4,170	1,898	10,01%	-3,99%	*
79%	21%	21,114	4,434	2,162	11,41%	-2,60%	-
78%	22%	21,385	4,705	2,433	12,84%	-1,17%	-
77%	23%	21,662	4,982	2,710	14,30%	0,29%	7
76%	24%	21,947	5,267	2,995	15,81%	1,80%	23
75%	25%	22,240	5,560	3,288	17,35%	3,34%	39
74%	26%	22,541	5,861	3,589	18,93%	4,93%	57
73,34%	26,66%	22,742	6,062	3,790	20,00%	5,99%	68
73%	27%	22,849	6,169	3,897	20,56%	6,56%	74
72%	28%	23,167	6,487	4,215	22,24%	8,23%	92
71%	29%	23,493	6,813	4,541	23,96%	9,95%	111
70%	30%	23,829	7,149	4,877	25,73%	11,72%	130
69%	31%	24,174	7,494	5,222	27,55%	13,54%	149
68%	32%	24,529	7,849	5,577	29,43%	15,42%	169
67,70%	32,30%	24,638	7,958	5,686	30,00%	15,99%	175
67,19%	32,82%	24,827	8,147	5,875	31,00%	16,99%	185
67%	33%	24,896	8,216	5,944	31,36%	17,35%	190
66%	34%	25,273	8,593	6,321	33,35%	19,34%	211
65%	35%	25,662	8,982	6,710	35,40%	21,39%	233
64%	36%	26,063	9,383	7,111	37,52%	23,51%	256
63%	37%	26,476	9,796	7,524	39,70%	25,69%	279
62%	38%	26,903	10,223	7,951	41,95%	27,95%	303
61%	39%	27,344	10,664	8,392	44,28%	30,27%	328
60,28%	39,72%	27,669	10,989	8,717	46,00%	31,99%	346
60%	40%	27,800	11,120	8,848	46,69%	32,68%	355
59,47%	40,53%	28,048	11,368	9,096	48,00%	33,99%	368

*** 300 mm "sticking" is 14,01% or 2,655 m² rel. to theoretical section**

*** Equal increase in all four directions related to theoretical sections**

Using a smectite-rich clay comparable to MX-80, like Cebogel or Milos B bentonite, for the block production would be required for accepting 60% degree of block filling as an average over the length of one blast-round, which means that about 38% of the tunnel space must be filled with pellets. Also, 60% degree of block filling would allow for an excess amount of excavated rock per blasting round compared to the theoretical section of 46%, provided that the unfilled space does not exceed 2% of the total volume that the dry density of the pellet fill is not lower than 1,000 kg/m³. If the over-excavated rock percentage is below 20% the block-filling degree would be increased. As mentioned earlier in the report the benefit of using a more smectite-rich clay for the block production is that the margins respecting allowed unfilled space and the dry density of the pellet fill increase and that the techniques for placement of the backfill components hence become more production-friendly for the 73% block filling degree that is foreseeable.

6 Methods for backfilling of deposition tunnels

6.1 General

6.1.1 Three backfilling methods

In this chapter we will examine and assess the three techniques for placing blocks and pellets outlined in considerable detail based on the experience from the backfilling tests and the theoretical considerations. The three alternative techniques for placing blocks are:

- The “Block” method – placement of block by block.
- The “Robot” method – placement of block by block.
- The “Modul” method – placement of units of blocks.

For installing pellets between blocks and rock two methods have been investigated:

- Auger feeding,
- shotcreting (blowing) technique.

The descriptions below refer to the present reference design with “static” stacking of blocks of smectite-rich clay like Milos B or similar. The most suitable method is not necessarily one that leads to the most precise stacking but that fits most accurately in the entire series of backfilling activities.

6.1.2 Material

While the geotechnical properties of the clay materials used for preparation of blocks and pellets in the full-scale experiments at Äspö were not of particular importance because of the dry conditions present during their placement in the simulations, they will be of fundamental importance for the performance in a repository. It has been demonstrated that the density determines the hydraulic conductivity and swelling pressure for any mineralogical composition of the clay material and that the type of clay minerals plays an important role for the physical performance. The two material parameters, density and mineral composition, determine the quality of the clay blocks and thereby the longterm safety margins of the major functional indicators.

6.1.3 The foundation bed

The foundation bed is the same for all the block and pellet placing methods, and that it consists of in situ compacted Minelco granules. In practice, it will be exposed to a range of conditions with respect to inflowing water since the size of the foundation units will depend on the duration of the respective block placement process. This matter will be discussed later in the report.

Optimal compactability is obtained by sieving the Minelco granules to generate a material that contains 7% powder finer than 0.125 mm and no grains larger than 30 mm. The layer thickness should be at least 5 times the maximum granule diameter, i.e. about 150 mm. Compaction should be made by 4 runs of a 150 kg vibrating plate but the thickness can be increased if heavier compaction equipment is used. However, the need for easily handleable units makes a 150 kg plate optimal. Some water may have to be sprayed on the material to avoid dust generation. The final surface should be parallel to the tunnel floor, i.e. inclined by about 1% towards its outer end, and fitted to the upper surface of previously placed beds (Figure 6-1). The bed has to be prepared rapidly in 2 m long units in order to minimize problems with inflowing water that can cause softening. The range of the block- and pellet-placing equipment available is of course the primary determining factor related to the length of foundation bed. Further details related to equipment options are given in Appendix 1.

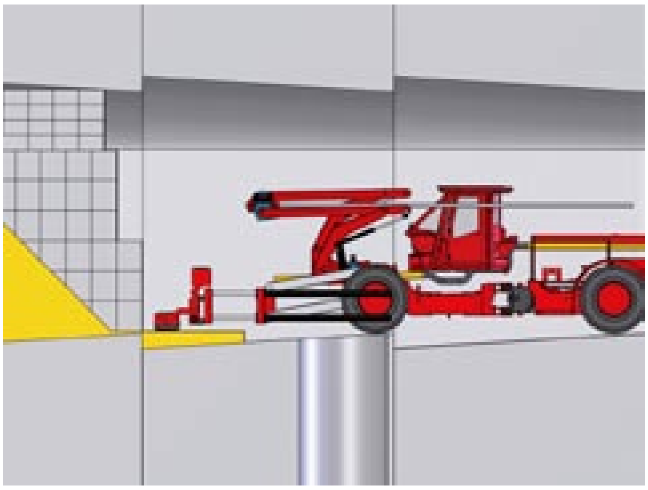


Figure 6-1. Compaction of the foundation bed.

The ramp leading into the deposition hole is backfilled immediately after installing the pellets around the buffer blocks using the same equipment for both purposes. In practice, the top buffer block will be placed in conjunction with installing the backfill in the ramp, which complicates this work and also the construction of the foundation bed.

6.2 The "Block" method

6.2.1 General

The major features of the "Block" method are described here while more detailed information on the evolution of this method is provided in Appendix 1.

6.2.2 Conditions and demands

The "Block" method implies placement of precompacted blocks of backfill clay to fill the majority of the tunnel volume. The blocks can come as close as 100 mm to the theoretical tunnel profile where the width and height of the tunnel profile are smallest. The space between these masonries and the rock determines how closely the block-placing tool can follow the tunnel contour, and the possibility of installing fill pellets in a controlled way. It must be noted that small blocks reduce the placement capacity and increases the frequency of voids between them, hence raising the average porosity of the block masonry.

From the foundation bed up to the breakpoint (Figure 2-14) the blocks have the dimensions 667 mm by 700 mm with 510 mm height. Above this level they are 600 mm wide, 700 mm long and 250 mm high (Figure 6-2). The blocks, between the breakpoint and the roof, should be laterally offset 300 mm from the lower blocks in order to stabilize the masonry and prevent the front from leaning out.

The block sizes ultimately selected for use will depend on the final design and the capacity of the block compression device. The required number of blocks fitted in the tunnel section is 58, based on the dimensions described above. In order to achieve a backfilling rate of 6.3 meters per day about 520 blocks have to be placed daily. This means that each block placement must be made in 60 seconds, excluding associated activities like quality checking and evaluation of aperture of the gaps between the blocks. The placement must go on as a continuous operation with no stoppage for other work in the tunnel or deposition holes and with supply of blocks at the required rate by means of transport vehicles. This matter is discussed in the subsequent treatment of the "Robot" method, which is more demanding respecting quick and regular block delivery.

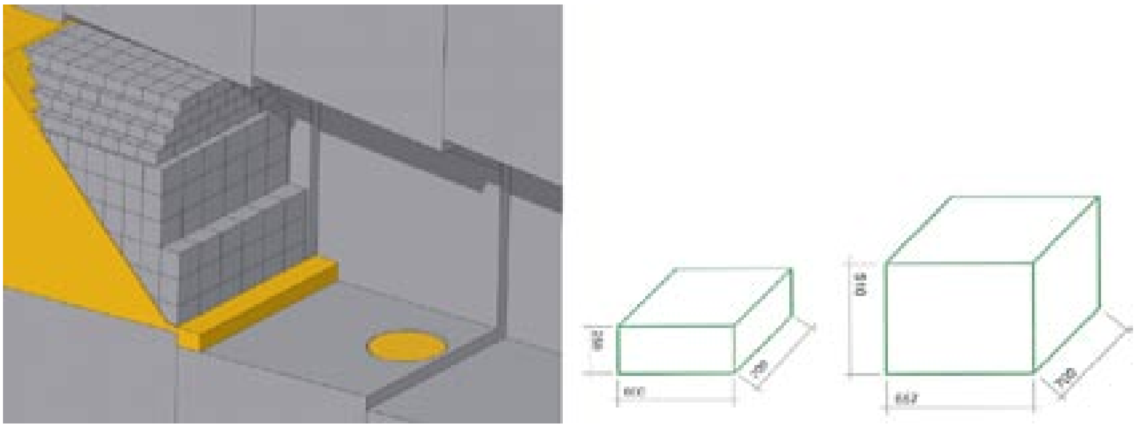
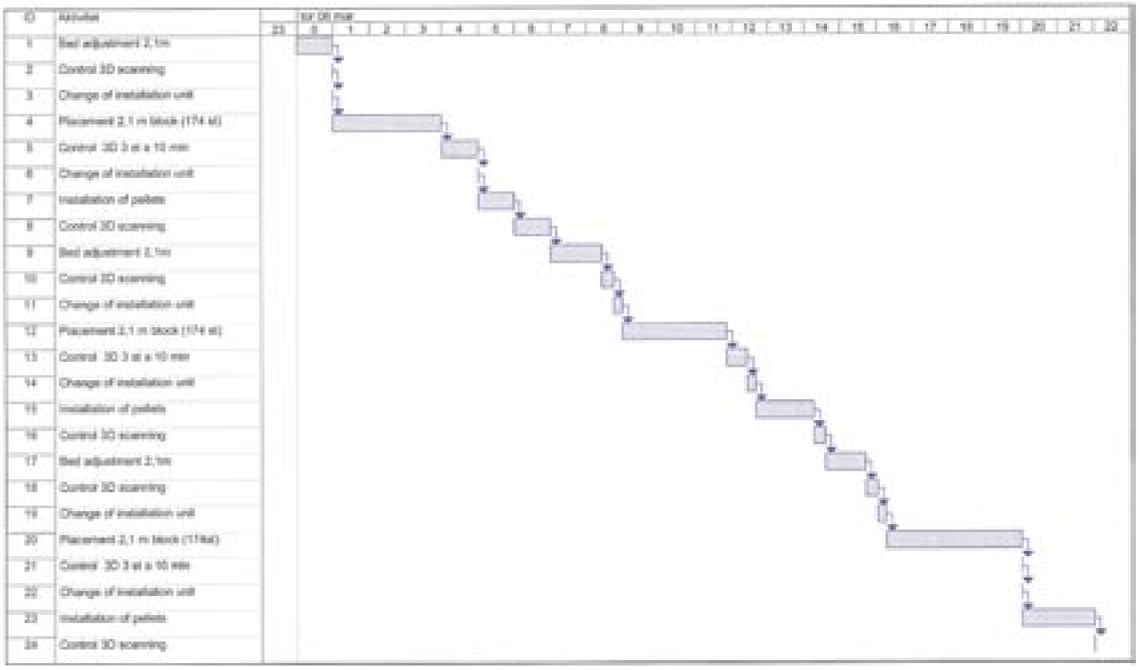


Figure 6-2. Stepped front of the block masonry resting on the foundation bed. The dimensions of the blocks shown are deemed suitable from practical points of view.

Difficulties beyond the placement rate requirement are caused by the pellet filling following the block placement. For "static" stacking with plane, continuous joints, air dry Cebogel pellets can be placed to form a slope of about 45 º but the maximum depth to which the pellet-filling tube can reach is only 5 m, which makes the filling to around block masonries of 4–5 m length somewhat heterogeneous. A vertical front of the applied pellets would be advantageous but it requires adding more water at the nozzle of the tube to induce pellet adhesion as they are blown into place. This technology has been successfully tested but which requires further technical development to improve the homogeneity of the placed materials.

The general time schedule for backfilling is illustrated in Table 6-1.

Table 6-1. Time schedule for backfilling, using the "Block" method. Any stoppage related to parallel activities in the deposition holes is not considered.



ID	Aktivitet
1	Bed adjustment 2,1m
2	Control 3D scanning
3	Change of installation unit
4	Placement 2,1 m block (174 st)
5	Control 3D 3 st a 10 min
6	Change of installation unit
7	Installation of pellets
8	Control 3D scanning
9	Bed adjustment 2,1m
10	Control 3D scanning
11	Change of installation unit
12	Placement 2,1 m block (174 st)
13	Control 3D 3 st a 10 min
14	Change of installation unit
15	Installation of pellets
16	Control 3D scanning
17	Bed adjustment 2,1m
18	Control 3D scanning
19	Change of installation unit
20	Placement 2,1 m block (174st)
21	Control 3D 3 st a 10 min
22	Change of installation unit
23	Installation of pellets
24	Control 3D scanning

6.2.3 Equipment for the "Block" method

For the backfilling the following three units are required:

- Block-placing equipment.
- Equipment for construction of the foundation bed and filling of pellets in the tunnel.
- Vehicle for transporting and delivering materials.

A detailed description of the various types of equipment is given in Appendix 1.

6.2.4 The backfilling process according to the "Block" method

The first activity is to fill pellets in the deposition hole that is located in the tunnel segment to be backfilled with pellets after pulling out the buffer protection sheet, The hole and associated ramp are then filled with pellets[11] up to the tunnel floor followed by construction of a foundation bed for placing blocks on it to form masonries around which further pellets are placed. These activities take place in one and the same tunnel or in parallel campaigns in two tunnels if the time schedule is too tight. Parallel operations may turn out to be necessary depending on the number of different pieces of equipment that have to be moved in and out of the tunnel for constructing the foundation bed and for placing blocks and filling pellets. Halts caused by removal of buffer protection sheets, drainage and alarm systems and filling of pellets in the deposition holes also call for parallel work in two tunnels. The backfill components, blocks and pellets are brought to the construction site by transport vehicles from which they are moved to predetermined positions for completing the 2.1 m long block masonry units (Figure 6-3).

Quality assurance during operations is obtained by measuring the front area of the masonry from the foundation bed to the tunnel roof after stacking the blocks. Knowing the tunnel cross sectional area, the front surface area of the block masonry and the weight of the vertical block layer allows its density to be calculated and compared with the required density.

After careful checking of the geometry and physical stability of the block masonry unit the equipment for block placement is moved out of the tunnel and the unit for pellet filling brought in. The pellet filling equipment is the same as was used for construction of the foundation bed and onto which a tool for pellet-blowing is attached (Figure 6-4).

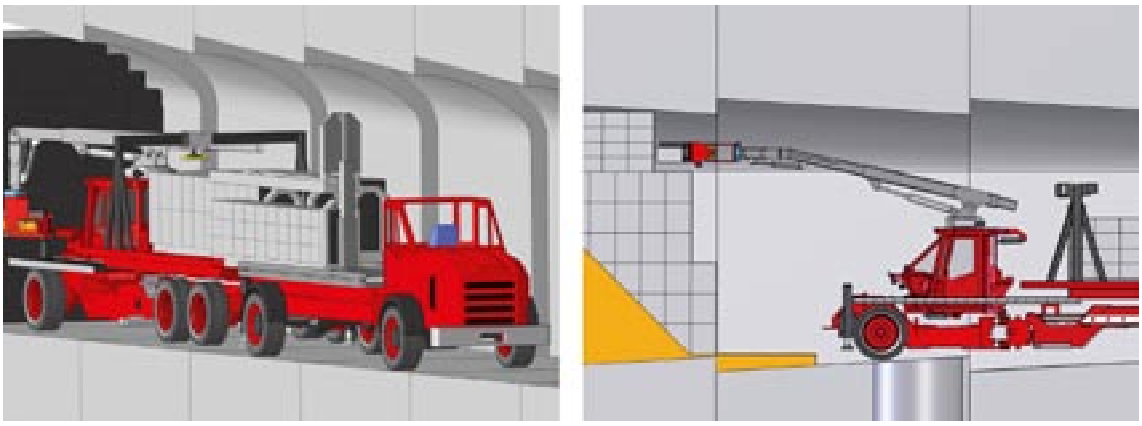


Figure 6-3. *Block placement. Left: Semi-automatic block-placing unit, supplied by blocks from the delivery unit. The delivery unit has a navigation tool to find its way in the tunnel. The block-placing unit is equipped with a sufficiently large store of blocks to allow for one hour of work. Additional blocks are delivered without disturbing the ongoing placement. Right: Placement of individual blocks requiring high precision.*

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[11] There is still no decision of whether pellets or compacted blocks will be placed in the ramps but the reference concept is the provisionally proposed way is to fill in pellets.

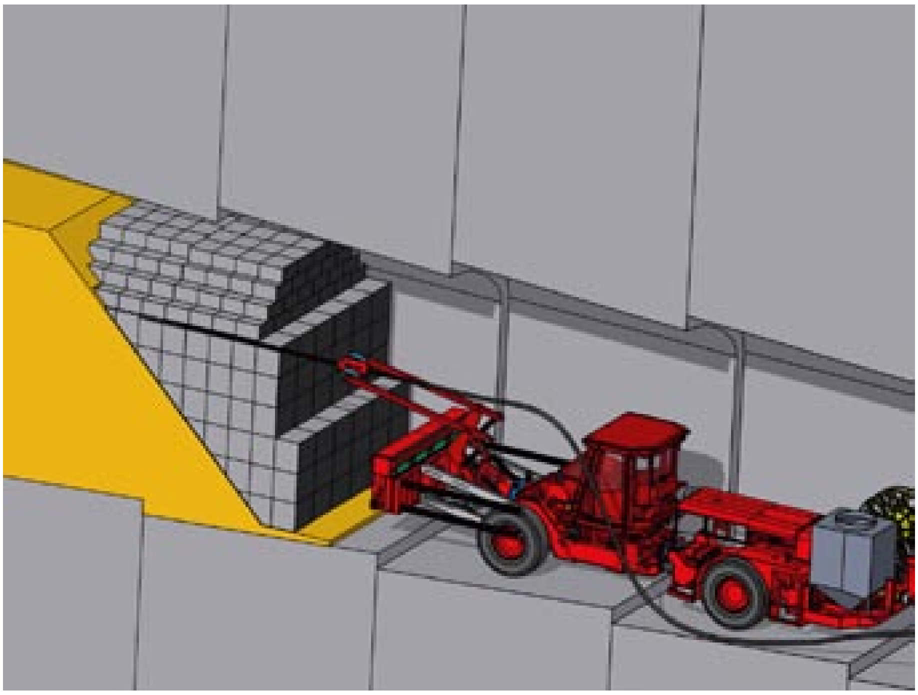


Figure 6-4. *Pellet filling by blowing.*

The tube for blowing pellets is moved around in the space between the block masonry and the rock and has a placement capacity of about 5 m^3 per hour. The pellet fill serves to support the block masonry and to tighten the confinement of the block masonries. It will be saturated by taking up water from the rock, a process that can take a few days or weeks where large volumes of water flows to the tunnel, to hundreds of years in very tight rock. Its initial density is not very high but when the block masonry starts to hydrate and expand, the pellet fill will undergo consolidation to a higher density. Depending on the rate and distribution of the water taken up by the pellet fill the front slope of the pellet fill can be a 45^o slope (for dry material) or be steep (nearly vertical) by adding more water during placement. The amount of pellets installed per unit volume of gap is determined by weighing of the pellets and calculation of the void volume based on survey information. The backfilling process is described in detail in Appendices 1 to 3.

6.2.5 Tentative assessment

The following conclusions have been drawn with respect to the possibility of applying the "Block" method:

- The required daily high rate of backfilling implies small margins for this method and may require parallel work in two tunnels. The method is very much dependent on equipment providing technical assistance to the operator for fulfilling the required precision criteria.
- For stepped block fronts there is a risk that blown-in pellets may fall on horizontal block surfaces requiring constant and careful cleaning before interrupted placement of blocks can continue.
- Comprehensive advantages can be obtained with respect to logistics and time saving if the block-placing unit can be integrated with the tool intended for construction of the foundation bed instead of being part of the equipment for pellet filling. The design work done so far did not lead to a practical solution of integrating these tools but further attempts are recommended.
- Of particular concern is checking of the aperture of the vertical joints between the placed blocks. The gaps must be measured and checked with respect to the specified maximal aperture of the joints set for the respective block pattern. This requires careful and quick measurement, and evaluation.

- The homogeneity, density and smoothness of the foundation bed determine the stability of the block masonries and of the possibility to minimize the joint aperture to fit required data.
- A way of improving the method may be to accept more unfilled space than 2%. This can be achieved by using a higher degree of block filling, i.e. up to about 75%, implying that geometrical criteria can be fulfilled with less difficulty.
- The filling of pellets is judged to be possible but there is no possibility to identify heterogeneities and increase the density if the finally obtained value would be too low. Experiments with pellet filling are somewhat discouraging in this respect: for the Cebogel pellets the evaluated dry density is around 910 kg/m^3, while the required value is 1,000 kg/m^3. It may be possible to increase the density by using a graded size distribution but there is an obvious risk that grain separation in the course of the blowing can cause changes in void size distribution and hence heterogeneities. Use of denser pellets would be a possibility as well for reaching a higher net density of the fill. Placement of pellet materials to a higher and more uniform density and increase of the pellet density are therefore topics that require further evaluation.

It is estimated that the "Block method" can be developed and tested before the end of year 2020. This technique is believed to require more careful handling for placement of the blocks than the other methods, and more technical support to the operator.

6.3 The "Robot" method

The major features of the "Robot" method are described here while more detailed information on the evolution of this method is given in Appendix 2.

6.3.1 Conditions and demands

This method of backfilling, like the "Block" method discussed in Section 6.2, involves placement of precompacted blocks to fill the majority of the tunnel volume. As for the "Block" method it is deemed possible to place the blocks to within 100 mm off the theoretical tunnel profile. In this approach only one block size is planned, for example 308x500 mm with 300 mm height (Figure 6-5).

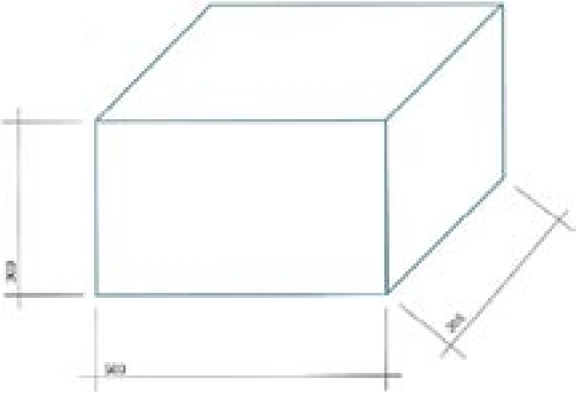


Figure 6-5. *Standard block for placement using the "Robot" method.*

6.3.2 The backfilling process according to the “Robot” method

As specified for the “Block” method, the first activity is to fill pellets in the deposition hole with pellets after pulling out the buffer protection sheet, The hole and associated ramp are then filled up to the tunnel floor followed by construction of a foundation bed for placing blocks on it to form masonries around which further pellets are placed. These activities take place in one and the same tunnel or in parallel campaigns in two tunnels if the time schedule is too tight. Parallel operations may turn out to be necessary depending on the number of different equipment that have to be moved in and out of the tunnel for constructing the foundation bed and for placing blocks and filling pellets. Halts caused by removal of buffer protection sheets, drainage and alarm systems, and filling of pellets in the deposition holes also call for parallel work in two tunnels.

The block size selected is believed to provide an optimal combination of the need for high quality respecting edge shape and mechanical strength and to provide enough space for attaching the vacuum-operated lifting tool. Bigger blocks would require fewer lifting operations but being larger they are less easily moved by the handling equipment. Two individually operating rather small robots would be more suitable than one with high load capacity. At present, robots that can handle at least 1,000 kg loads are commercially available but their range of motion is limited.

Figure 6-6 shows a schematic cross section of a deposition tunnel filled with “standard” blocks oriented with their long axes parallel to the tunnel axis. One steep layer of 0.5 m thickness comprising 184 blocks is required to occupy the cross section area of the tunnel. The stacking is made in three steps, each implying mutual displacement of the block layers for improving the stability of the masonries (Figure 6-7).

Deviations from the theoretical orientation of the various series of blocks will affect the aperture of the joints, which must not exceed 1 mm. The “Robot” method requires more blocks than the “Block” method, which means that the number of vertical joints will be higher. This requires that the aperture of the vertical joints between blocks must not exceed 1 mm as an average. Displacement along these joints can widen them and cause an unacceptably large amount of unfilled space in the backfill.

A backfilling rate of 6 meter per day implies daily placement of 2,208 blocks, for which two robots are suitable. Each block placement must be completed in 30 seconds, which is deemed possible with due respect to all associated activities, especially measurements and visual inspection.

No placement trials have been made because no suitable robot tools were available and the time schedule for backfilling therefore had to be estimated based on experience from various industrial projects. It is illustrated in Table 6-2. Assuming 30 seconds for each block placement the schedule implies that there will be 2 hours spare time per day. This is a necessary safety margin considering the uncertainty in estimating the required time for the respective activities.

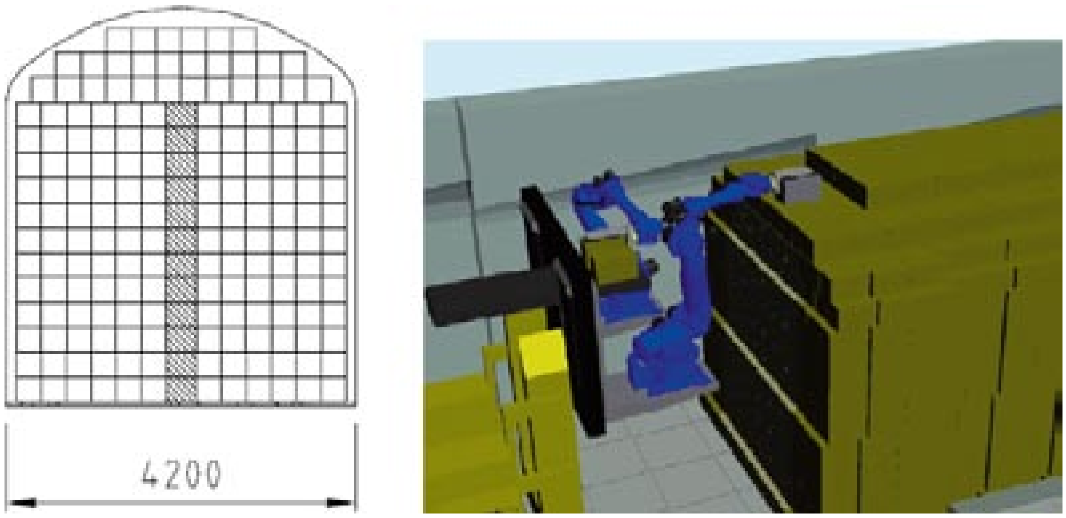


Figure 6-6. *Cross section of deposition tunnel filled with “standardized” blocks placed by use of the “Robot” method.*

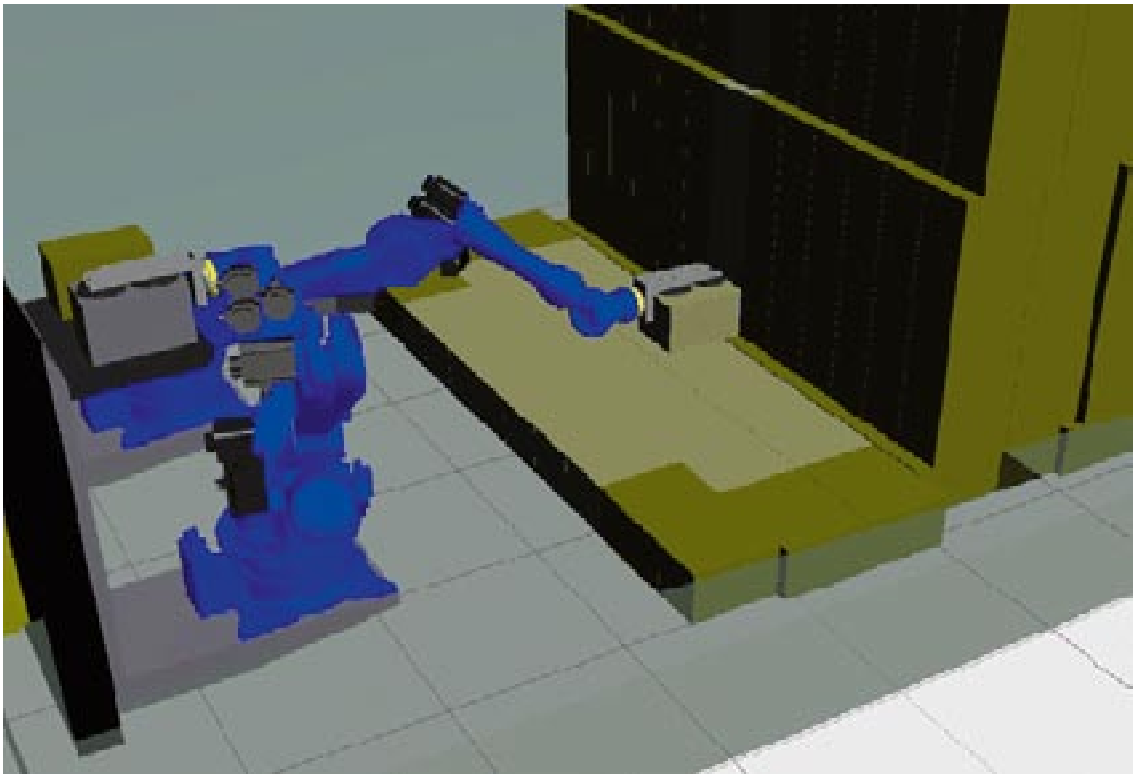
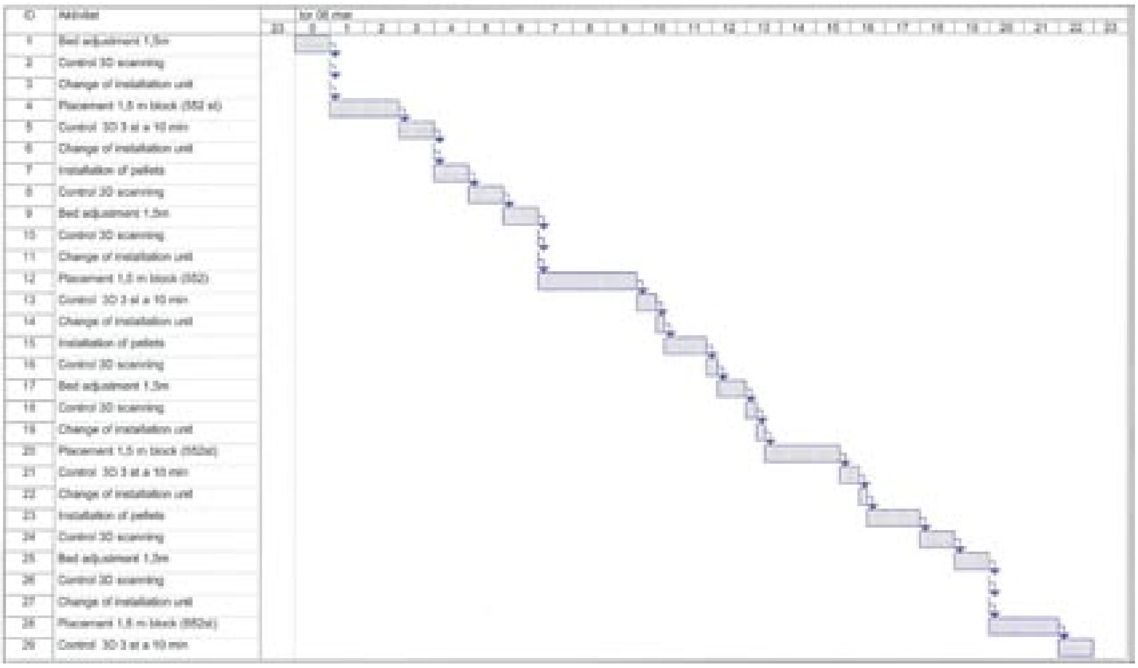


Figure 6-7. Principle for creating a stepped front of block masonries using the "Robot" method.

Table 6-2. Time schedule for backfilling, using the "Robot" method. Any stoppage related to parallel activities in the deposition holes is not considered.



ID	Aktivitet
1	Bed adjustment 1,5m
2	Control 3D scanning
3	Change of installation unit
4	Placement 1,5 m block (552 st)
5	Control 3D 3 st a 10 min
6	Change of installation unit
7	Installation of pellets
8	Control 3D scanning
9	Bed adjustment 1,5m
10	Control 3D scanning
11	Change of installation unit
12	Placement 1,5 m block (552)
13	Control 3D 3 st a 10 min
14	Change of installation unit
15	Installation of pellets
16	Control 3D scanning
17	Bed adjustment 1,5m
18	Control 3D scanning
19	Change of installation unit
20	Placement 1,5 m block (552st)
21	Control 3D 3 st a 10 min
22	Change of installation unit
23	Installation of pellets
24	Control 3D scanning
25	Bed adjustment 1,5m
26	Control 3D scanning
27	Change of installation unit
28	Placement 1,5 m block (552st)
29	Control 3D 3 st a 10 min

6.3.3 Robot equipment

Block placement according to the "Robot" method makes use of three units of which two are identical to those required for the "Block" method, i.e. the equipment for preparing the foundation bed and the vehicles for transport, while the third is the key tool, the robot unit. It is a two-armed robot tool of the type used in industry for quick handling with high precision of heavy objects. The equipments are hence:

- Robot-based block-placing equipment.
- Equipment for construction of the foundation bed and filling of pellets in the tunnel.
- Vehicle for transporting and delivering materials.

A detailed description of the various equipment involved in this type of operation is given in Appendix 2.

The robots should be capable of handling 200 kg loads over a distance of about 2,600 mm. The hardware and software needed for conducting the operations are shown schematically in Figure 6-8. Vacuum tools are attached to the robot arms and each of the arms is equipped with a 2D laser scanner that can determine the tunnel contour and the front of the placed block masonries. A camera is attached to one of them for documentation of joints and clay debris on horizontal block surfaces.

Personnel must be prevented from entering the space in which the robots operate in the backfilling process and scanners mounted on the robot-equipped unit are used for inspecting and checking all activities within this space.

6.3.4 Description of the block placement

Prior to each backfilling sequence documentation of the tunnel space is made by use of 3D-laser scanning. In the future, camera technique for automatic evaluation of topographical features may turn out to be more practical. The subsequent steps are illustrated in Figures 6-9 and 6-10**.**

Placement of blocks according to the "Robot" method is not made by use of a co-ordinate system but the blocks are placed so as to fit already placed units. The position of these blocks must hence be determined to ensure that the assembly is centred in the tunnel.

Additional information is given in Appendix 2.

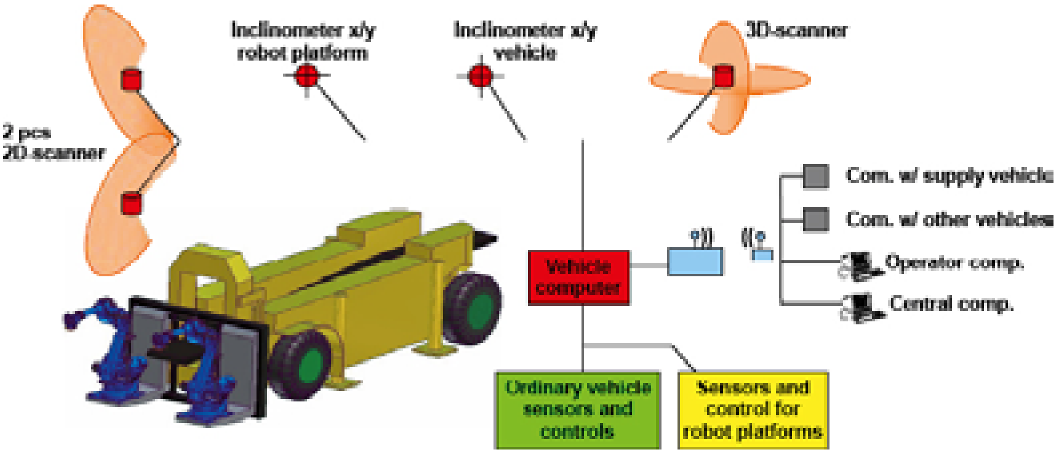


Figure 6-8. *Schematic hard- and soft-ware systems for placing blocks according to the "Robot" technique.*

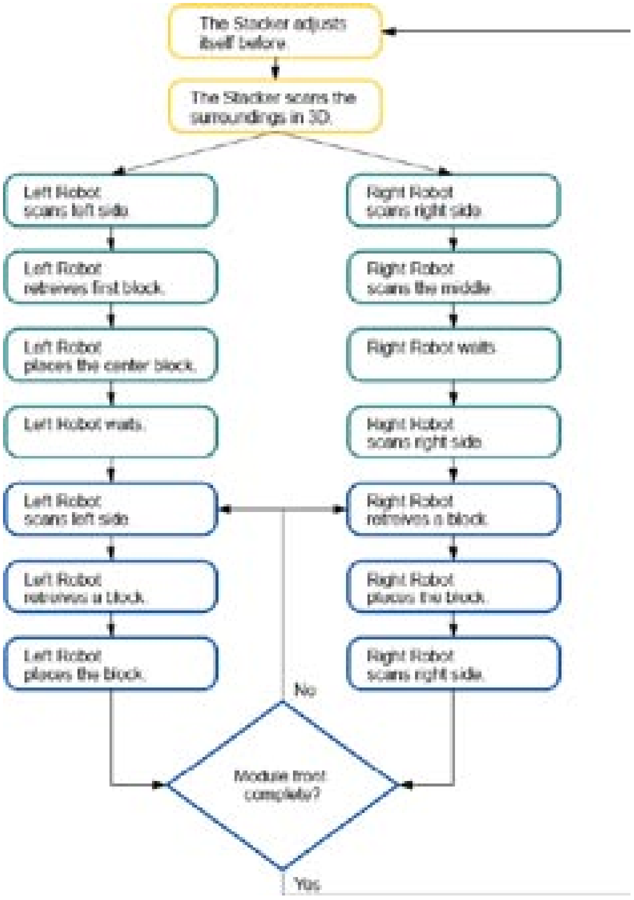


Figure 6-9. *Scheme of sequences of block placement according to the"Robot" method.*

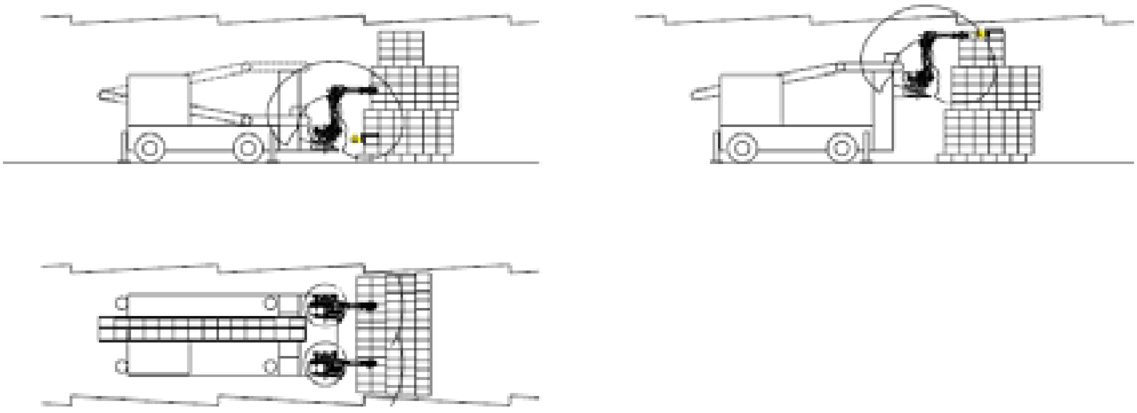


Figure 6-10. *Picture showing the principle of block placement.*

6.3.5 Tentative assessment

It is believed that the "Robot" method can be developed and refined but that this will require considerably resources. The major associated issues to be considered are:

- What will the aperture and volume of the joints be considering that the accuracy in placement of a single block will not be better than +/– 1 mm?
- How close to the robot-carrying unit can the robots place blocks in the lowest and highest layers?
- What is the required time for scanning and evaluating the positions of placed blocks?

- How frequently must the block positions be measured?
- What is the accuracy of the measurements of the block positions?
- How must the foundation of the robot-carrying unit be designed in order to providing required stability?
- How can clay debris on horizontal block surfaces be removed?
- How can the robots rearrange incorrectly placed blocks?
- Are the systems intended for operating the robots practical and sufficiently accurate?
- What will the actual capacity of block placement be?
- How does the tunnel environment (humidity, dust) affect the electronic and mechanical components of the robots?

For just placing blocks the Robot method is deemed suitable and it is therefore a strong candidate for installing blocks, particularly if two robot equipments are utilized in parallel for placing relatively small blocks. The longer their reach and the heavier the blocks the more practical is the method. Since the capacity of robots is presently limited the blocks can not be big, which requires many operations and short sequences implying risk of block damage and need for frequent checking of surfaces for placing the blocks. A major disadvantage is that the robot operations are not easily integrated in the construction and adjustment of the bottom bed. It is believed that development of the Robot method to become production-friendly until year 2020 is hardly possible.

6.4 The “Module” method

The major features of the “Module” method are described here while more detailed information on the evolution of this method is given in Appendix 3.

6.4.1 Conditions and demands

In contrast to the “Block” and “Robot” methods the “Module” method implies placement of pre-assembled coherent units of blocks as indicated in Figure 6-10. In principle, it should be possible to place them so that a minimum distance of 100 mm inside the theoretical profile is achieved.

Each bottom block consists of two parts, each with the edge lengths of 666 and 1,333 mm and a height of 500 mm. Each module hence has the edge lengths 1,332 and 1,333 mm and the height 1,500 mm. Each module weighs 5,200 kg, the average bulk density of the clay blocks being 2,000 kg/m^3 including the natural water content.

As shown by Figure 6-11 the number of plane steep joints are 3 in the longitudinal direction and this is also the number of continuous joints in the perpendicular direction, for which the spacing is 1,332 mm. The space between the modules must not exceed 9 mm in order to meet the requirements set for the maximum allowed unfilled space in the tunnel. Tests have been done using stacks with 4 bottom blocks; these modules are apparently stable although more thorough evaluation is still necessary.

The modules are stacked to form vertical faces in the backfilled tunnel, which is valuable from a practical point of view. It means that there will be no fragments or debris on horizontal surfaces as may occur for the other methods. A major advantage is that the handling of the modules is made using forklift tractors, meaning that the block units are hoisted from below and not lifted from above as required when using the vacuum technique (blocks in compression rather than tension during handling). It is also advantageous in that the modules are prepared on the surface and brought down, in pairs, by the skip. Common vehicles bring them from the central storage on the repository level to the deposition tunnels. The modules are transported in simple, detachable mesh protective containers of the type shown in Figure 6-12.

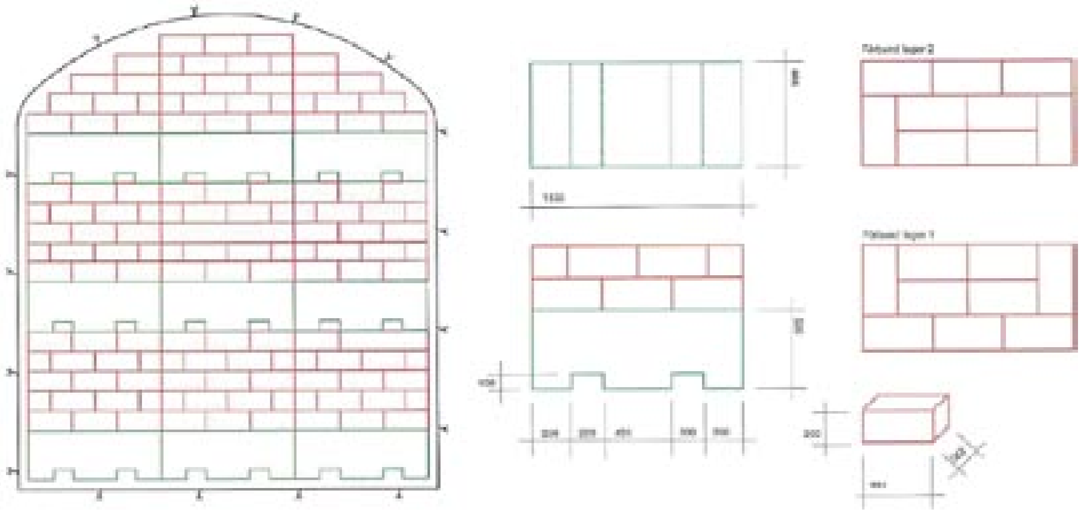


Figure 6-11. Stacking of modules consisting of blocks. The bottom blocks are big and serve as a base of smaller blocks of one size. The cross section represents the smallest cross section of the tunnel, i.e. the start of the respective blast-rounds.

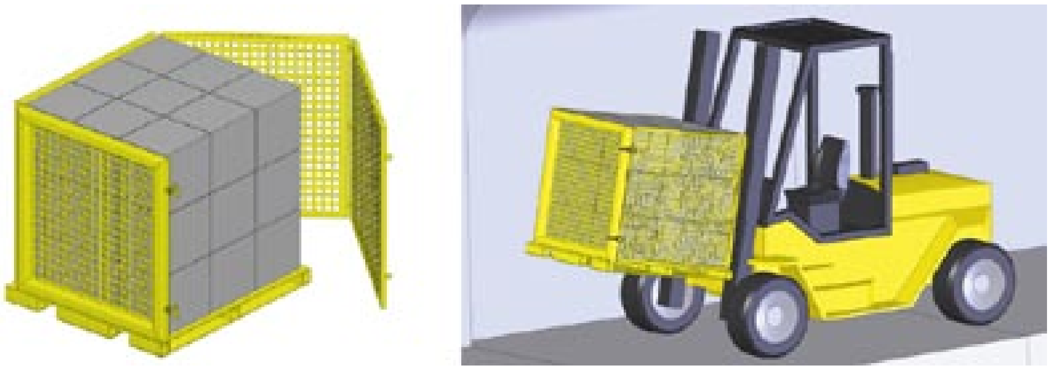


Figure 6-12. Transport container for modules.

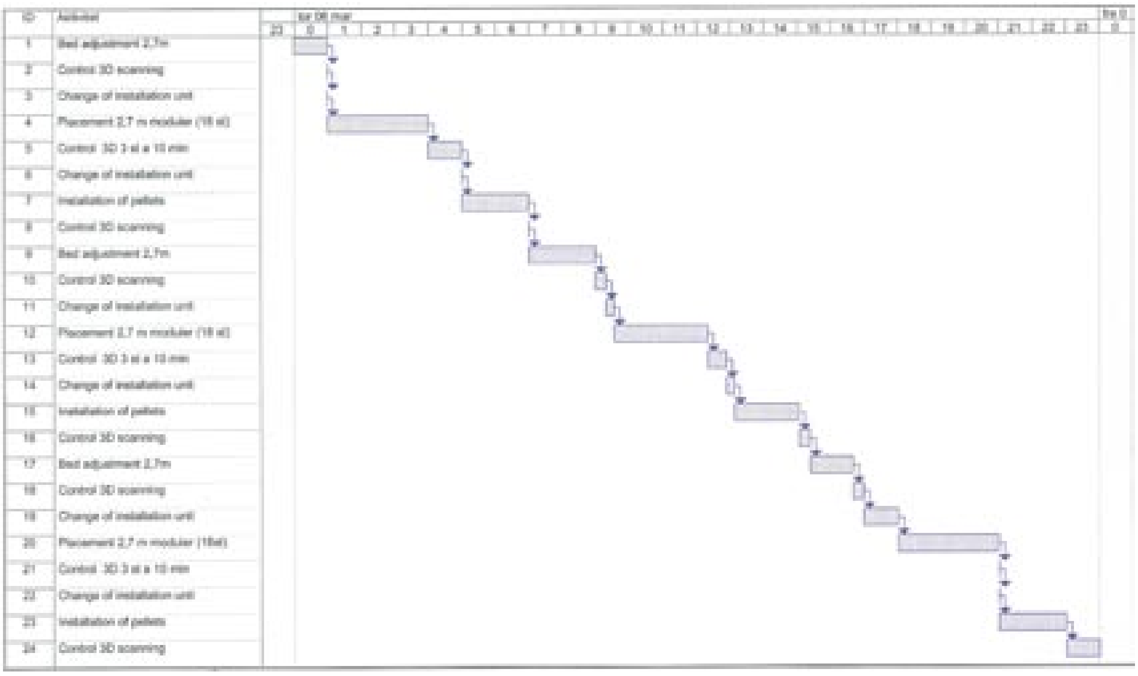
In order to achieve a backfilling rate of 7.2 meters per day, 54 modules must be placed each day, the time available for each placement is 10 minutes. If this time can be reduced to 5 minutes, which is deemed possible, the backfilling rate can be increased to about 10 meters per day.

As with the other methods the module placement must be continuous. No experiments have been made due to lack of suitable equipment but the estimated time schedule for backfilling is illustrated in Table 6-3.

6.4.2 The backfilling process according to the “Module” method

As specified for the “Block” and “Robot” methods, the first activity is to fill the voids remaining in the deposition hole with pellets after pulling out the buffer protection sheet. The hole and associated ramp are then filled up to the tunnel floor followed by construction of a foundation bed for placing blocks on it to form masonries, around which further pellets are placed. These activities take place in one and the same tunnel or in parallel campaigns in two tunnels if the time schedule is too tight. Parallel operations may turn out to be necessary depending on the number of different pieces of equipment that have to be moved in and out of the tunnel for constructing the foundation bed and for placing blocks and filling pellets. Halts caused by removal of buffer protection sheets, drainage and alarm systems, and filling of pellets in the deposition holes also call for parallel work in two tunnels.

Table 6-3. Time schedule for backfilling, using the "Module" method. Any stoppage related to parallel activities in the deposition holes is not considered.



6.4.3 Equipment

Block placement using the "Module" method requires three pieces of equipment, one of which is the previously described equipment for construction of the foundation bed and filling of pellets. Vehicles for transporting tools, modules and pellets represent the second unit, while the third is a very stable truck with fork loading system:

- Block-placing equipment (Fork truck).
- Equipment for construction of the foundation bed and filling of pellets in the tunnel.
- Vehicle for transporting and delivering materials.

Detailed descriptions of the various equipments are given in Appendix 3.

It is presently being investigated if the block-placing equipment and the tool for constructing the foundation beds can be combined. This change, which would greatly improve the technique and significantly reduce the time required for backfilling, is discussed in Appendix 3.

6.4.4 Description of the placement of modules

Placement of the modules is preceded by preparation of the foundation bed, which is made in the same way as for the "Block" and "Robot" methods.

The placement of the modules has been investigated in theoretical studies based on different presumptions concerning the way in which the modules are delivered from the central storage in the repository. Figure 6-13 shows a possible procedure. The holes in placed bottom blocks will be filled with pellets, which is feasible according to pilot tests.

The block-placing equipment is continuously supplied with modules either from vehicles or from a mobile store. It can be swung around together with the operator's cabin to provide unlimited viewing of the handling of module units. The equipment places modules from the foundation bed up to the tunnel roof, which makes up 9 module units per sequence, after which it is moved out by the thickness (depth) of one module and starts placing the next vertical layer of modules. Before this, quality control is made in the same way as for the "Block" and "Robot" methods.

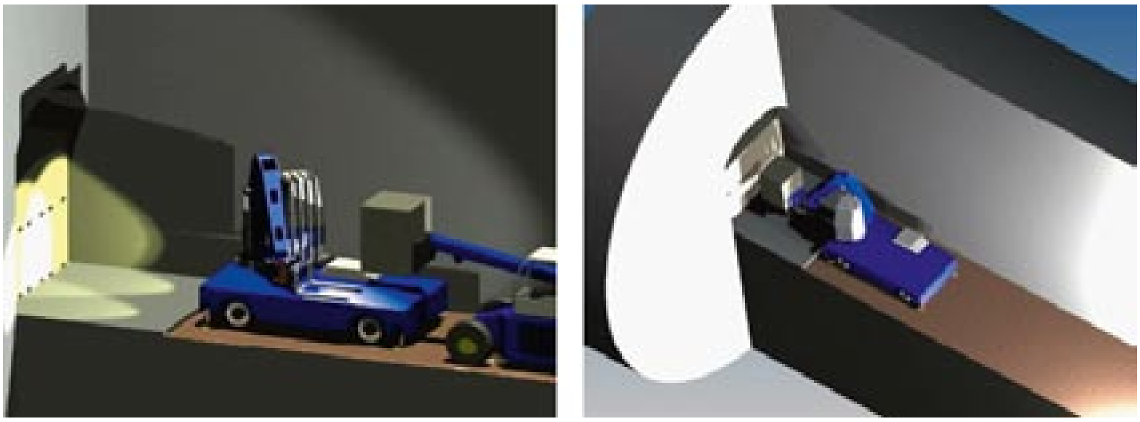


Figure 6-13. The forklift truck for handling modules. Left: A module is delivered. Right: The module is being placed.

The advantage of the placement equipment implemented in the “Module” method is that all employed techniques are available without significant development. However, the stability of the stacks of modules requires further investigation. Furthermore, the most cost-effective technique for preparing the big bottom blocks must be identified.

6.4.5 Pellet filling

Pellets will be filled by blowing as for the “Robot” method. For the “Module” method the unit for pellet filling is exchanged by the module-placing unit three times per day, providing less frequent changes in the backfilling routines than the other methods. In contrast to these methods the pellet filling is made from a steep block front, which is advantageous (Figure 6-14).

Filling of pellets to form a steep front is more accurate than creating a long slope since the operator is closer to the fill. Also, there is no risk of pellets accumulating on horizontal surfaces, which is a disturbing factor in block placement according to the other two methods. The biggest advantage is that it is easier to control the pellets installation, and that the reliability is higher.

Figure 6-14. Pellet filling with the equipment placed closed to the steep block front.

6.4.6 Tentative assessment

Tentatively, the "Module" method is superior to the other methods for the following reasons:

- It is much more rational than the other ones and more robust since it utilizes techniques that are very well known, like lifting and placing heavy objects with great accuracy, and it is characterized by simple logistics.
- Placement of modules is quicker than for block-by-block methods and hence makes the time schedule less tight.
- Big block units, representing large Modules imply simpler and less frequent checking of the geometry of the block masonries than the other methods.
- Large Modules makes adjustments of the construction bed simpler compared to the Block and Robot methods, which require great accuracy in the construction of the foundation bed.
- The low void ratio of the confined block units that make up the modules is advantageous. It is achieved by producing the units under factory-like conditions on the ground surface.
- The accumulation of clay debris on horizontal surfaces of stepped block masonries that may be required for the other methods is avoided by the steep front of the block masonry according to the "Module" method. A steep front also simplifies quality checking.

However, a few questions need to be answered of which the following are most important:

- Are the stacks of modules stable?
- Can one prepare bottom blocks of the proposed size?
- What is the role of the grooves in the bottom blocks respecting water flow in the construction phase and afterwards?

The stacking pattern of blocks in the respective module makes them sufficiently stable in the placement phase and afterwards but since the modules are separated by plane joints in the masonries they do not interact, which may affect the stability of the masonry. This can be advantageous since local settlement is not transferred to the entire masonry while it may also reduce the overall stability. These matters must be further investigated.

The matter of preparing big bottom blocks needs to be investigated and the size of the blocks may have to be somewhat reduced. Tests are presently being done to investigate the possibility of adapting the size of these blocks to fit forms for uniaxial compression, and to investigate the stability of module assemblies.

In conclusion, the "Module" method is deemed superior to the "Block" and "Robot" methods and worth more detailed investigations and full-scale testing. In the authors' opinion the weakest point of all three methods is the pellet filling. The homogeneity of the fills can not be sufficiently well checked and the intended net density may be too low. If the currently made calculation of the density of the pellet fill indicates that this is the case there is no way of improving it except perhaps by dynamic compaction. Previous trials that attempted to use dynamic compaction to densify pellet materials have not been particularly successful. It is unlikely that substantial improvement to the density achieved in the pellet-filled regions will be achievable. This may, however, cause displacement of blocks and large variations in density of the pellet fills.

7 Quality management and documentation

7.1 Quality control

The entire sequence of activities, starting from mining of the clay and further to processing including drying, soda activation, grinding and sieving, and ending with manufacturing of pellets and blocks and bringing them on site in the repository, must be controlled and checked to ensure that all criteria set are achieved. Figure 7-1 describes the various steps in the procedure at the repository, each of them requiring a detailed manual for the practical work and for the quality designation.

This chapter is a brief summary of proposed quality control measures that should be taken along the sequence of activities. The matter of demands and criteria is dealt with in detail in the SKB's "Production line reports" that are presently being prepared.

In this chapter we will consider clay materials, manufactured blocks, pellets and granulates, as well as the integrated backfill. For each of them it will specified what and when checking is required, what tests and accuracies are needed, and which steps that must be taken in case of deviations from specifications.

The specifications and recommendations given in this chapter may be changed in conjunction with further development of descriptions of materials, construction and quality checking of the backfill.

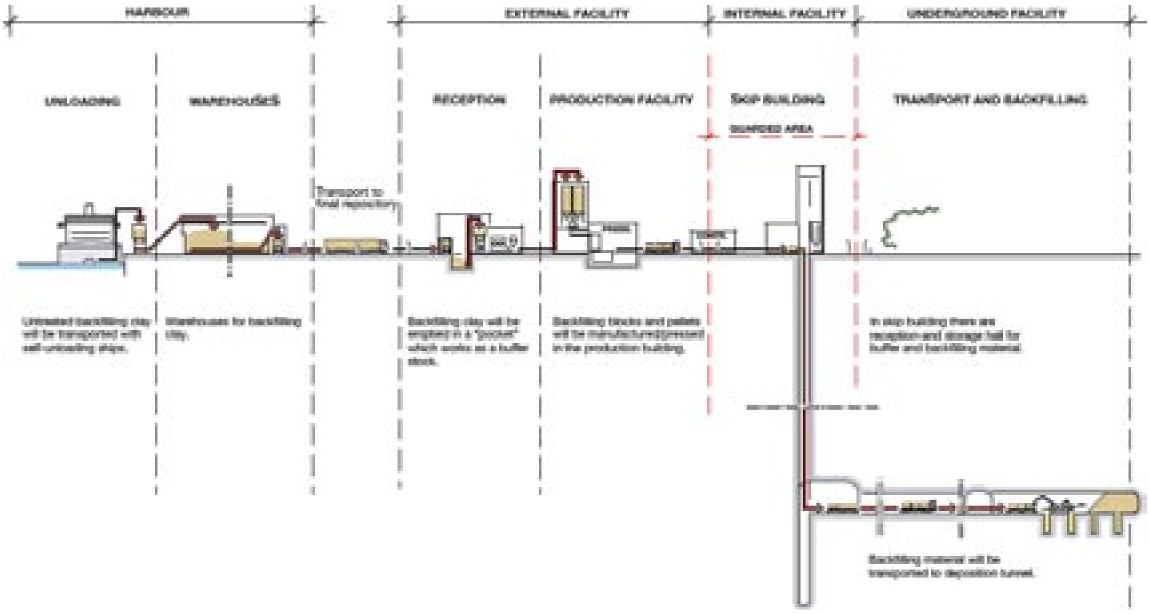


Figure 7-1. The sequence of activities at the repository.

7.1.1 Materials

The clay materials used for preparing blocks and the pellets delivered from a contracted mineral producer need to be checked with respect to important properties /7; Appendix 4/. They are specified as follows:

Test program

- Water content. The natural water content affects the rate of water saturation and the cost. It is determined by weighing material before and after heating to 105°C and evaluated according to a standard procedure /7/ both prior to delivery (by the manufacturer) and in conjunction with the construction work. Representative samples, one per 5 tons, should be tested. The recommended value and the acceptable interval are defined.
- Content of particles smaller than 2 µm. The "clay fraction" and the content of smectite determine the physical properties of the clay. The clay fraction is determined by dispersing material and evaluating the content according to a standard procedure /7/ both prior to delivery (by the manufacturer) and in conjunction with preparation of the buffer and backfill components. Representative samples, one per 5 tons, should be tested. The recommended value and the acceptable interval are defined.
- Content and type of smectite. The type and content of smectites and the "clay fraction" determine the physical properties of the clay. The smectite content is determined by dispersing material and performing tests according to a standard procedure /7/ both prior to delivery and in conjunction with preparation of the buffer and backfill. Representative samples, one per 50 tons, should be tested. The recommended value and the acceptable interval are defined.
- Content of other clay minerals and carbonates, sulphur- and potassium-bearing minerals and organic contaminants. The composition of these minerals is determined by a standard procedure /7/ both prior to delivery and in conjunction with preparation of the buffer and backfill. Representative samples, one per 50 tons, should be tested. The recommended value and the acceptable interval are defined.
- Expandability at water saturation. It determines the swelling pressure and the self-sealing capacity (cf Table 1-1). The swelling pressure is determined by conducting oedometer tests with defined solutions both prior to delivery and in conjunction with preparation of the buffer and backfill. Representative samples, one per 50 tons, should be tested. The recommended value and the acceptable interval are defined.
- Hydraulic conductivity at water saturation. It determines the tightness of the clay (cf Table 1-1). The conductivity is determined by conducting oedometer tests with defined solutions both prior to delivery and in conjunction with preparation of the buffer and backfill. Representative samples, one per 50 tons, should be tested /12/. The recommended value and the acceptable interval are defined.

The rate of testing proposed here is believed to be practical and sufficient. It has been applied, in principle, at the preparation of the clay-based engineered barriers in the repository for low- and intermediate radioactive waste at Forsmark, Sweden /7/.

7.1.2 Blocks

Quality issues in the preparation stage

The biggest block that can presently be manufactured by using available compression equipment has dimensions of 600 x 800 x 500 mm. The company contracted for this purpose is the German enterprise LAEIS GmbH, which can provide uniaxial compression under 30 MPa pressure /4/. Examples of blocks are shown in Figure 7-2.

***Figure** 7-2. Photo of blocks of Friedland clay.*

The compaction of blocks is a matter of quality and time. Uniaxial compression under a pressure of 100–200 MPa used for manufacturing buffer blocks can also be employed for preparing bottom blocks for the "Module" method. Buffer blocks with about 2,000 mm diameter and 500 mm height require a compression force of 30,000 tons to reach the desired dry density, 1,900–2,000 kg/m^3 (GEA Ecobraze AB Ystad) /Appendix 4/. Preparation of blocks for backfilling, particularly for manufacturing the big blocks for the "Module" method, requires sawing, which has been examined in earlier studies. /7,12/. For compaction of bottom blocks under 25 MPa pressure the required force is about 2,000 tons. The goal is to compact the bottom blocks without any requirement for later treatment of the blocks. The bearing capacity has been calculated but full-scale testing is required.

Isostatic compaction under the same pressures is also possible and the experience from both ways of producing large and dense blocks is sufficient for using them on an industrial scale. For the smaller blocks that turn out to be at optimum for the methods described in this report additional studies should be made for finding a suitable technical/economical block compaction procedure. These matters have been in focus in the evolution of block compaction techniques conducted by SKB since the eighties /7,12/ but they deserve to be further investigated in the future. The large-scale buffer test in the Stripa URL was made by use of isostatically compressed MX-80 powder yielding big clay columns from which blocks were sawn, some cheese-shaped and some rectangular. The experience is that sawing is rational and can be made with great precision but that the blade undergoes quick wearing /7/.

It is very important to use compaction machines and transport vehicles that operate safely with a minimum of maintenance and repair so that steady delivery of the clay products can be guaranteed.

Test program

According to the judgment of the present authors the blocks must be checked with respect to the following properties:

- The density. It determines the expandability and hydraulic conductivity. It is determined by measuring the dimensions and weighing the blocks. All the blocks must be examined and their density determined. The value must not deviate by more than of the intended value.
- The size and shape of the blocks. They determine the volume and density of the block masonries as well as the degree of block filling. The size of the blocks is determined by direct measurement of the dimensions. They must not deviate by more than 1 mm from the intended values for minimizing negative impact on the quality of the backfill. The procedure is repeated in conjunction with labelling immediately before placing the blocks.

- The mechanical strength of the blocks. It determines their stability when being handled, transported and placed. Samples are core-drilled from 1% of the total number of blocks for uniaxial compression, the values must be at least 90% of the intended value.
- Absence of damage. Fractures are not accepted since they imply risk of breakage at handling and placing. Damaged edges add to the void volume in the block masonries. Identification of possible damage is made by visual inspection and expressed in terms of volume of missing material.

Investigations for working out specifications for measurements and checkings are planned to be made in year 2009.

7.1.3 Pellets and granulates

Materials – pellets

The KBS-3V concept implies that pellets are required for 1) filling the gap between the buffer blocks and the rock in the deposition holes, and 2) as a component in the backfill. The pellets are smectite-rich highly compacted tablets of MX-80 clay or similar.

Materials – granulates

Granulates of smectite-rich clay material are crushed and sieved fragments (0–30 mm) of dense clay that are proposed for use in the backfilling of deposition tunnels, for placement in the ramps cut at the deposition holes, and for preparing the foundation beds. They are commercially available from various mineral-producing companies.

Test program

The quality control of the pellets and granulates is the same as for the blocks. The materials must be kept in tight bulk-bags or in RH-controlled silos for minimizing water uptake, and be transported to the central storage at depth. The water content is checked before the bags are emptied.

7.1.4 Entire backfill

General

As specified in the description of the investigated methods for backfilling a number of measurements have to be made for getting data on the volume of the tunnels space to be filled and of the block masonries and pellet fills, as well as on the weight of the placed backfill components. The aim of the checking after completing the respective backfill unit is primarily to make sure that the degree of block filling is the intended one.

Using Milos B or Asha bentonite for the blocks the criteria representing functional indicators are:

- The block-filling degree must be 60% at minimum.
- Pellets must not occupy more than 40% of the tunnel space.
- Unfilled space must not exceed 2% of the tunnel space.

Geometrical issues

Achievable accuracy respecting dimensions depend on the size of the object. It has been preliminarily estimated for the various stages, i.e. from compaction to placement of the blocks and it will be updated according to the experience gained in future work. Uncertainties and summed deviations from theoretical models will be compensated by increasing the degree of block filling.

A first and major item is the determination of tunnel volume. The basic method referred to in the report is scanning, which is a well known and accurate technique (cf Figure 7-3). The question is, however, how close to the actual volume that calculations based on the various techniques can lead, and what accuracy the decision-makers will require. In the future the accuracy is believed to be around +/– 0.5%. The quality of the instruments are expected to be improved in the future but the impact of various disturbing factors like temperature, vibrations, tunnel convergence and movements of shallow rock blocks will always play an important role and make volume calculations only slightly more correct and reliable than today.

The same problems remain with respect to accurately determining the volume of the components installed in the tunnel. An important matter is that blocks may move irregularly in the axial direction of the tunnel as indicated in Figure 7-4. This makes calculation of the degree of block filling somewhat uncertain.

Taking the “Block” method as an example the specified joint width between placed blocks must not exceed 2 mm horizontally and 4 mm vertically for 60% block-filling degree, and checking of these apertures requires that the block front is scanned and the results evaluated by theoretical models, which automatically provide area data. The resolution of such scans may be insufficient, since the block contour may not be very distinct. In combination with the difficulties in checking the density this matter makes it hard to evaluate the homogeneity of the pellet fill. Principles for specifying tolerances and evaluating deviations from required properties etc in the control program are planned to be made in year 2009.

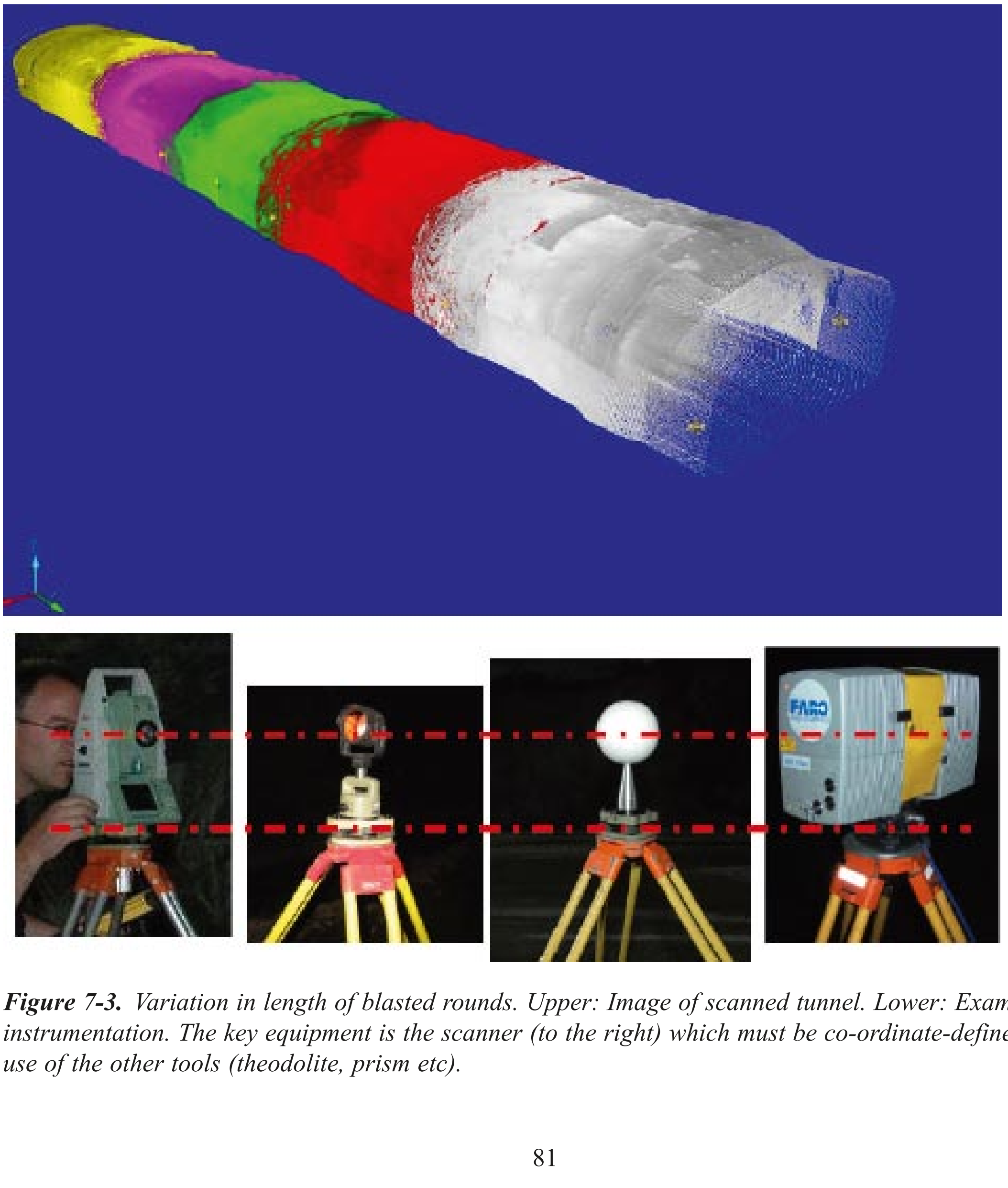


Figure 7-3. *Variation in length of blasted rounds. Upper: Image of scanned tunnel. Lower: Example of instrumentation. The key equipment is the scanner (to the right) which must be co-ordinate-defined by use of the other tools (theodolite, prism etc).*

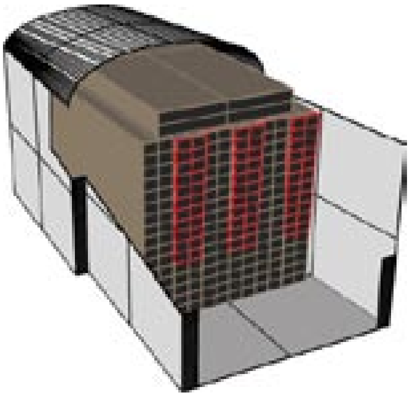


Figure 7-4. Deviation from intended positions of blocks or masonries of blocks forming regular patterns with straight joints. It is revealed by the scanning and reported to the operator and the control room.

7.1.5 Foundation bed

Quality issues in the construction stage

Before the bed is constructed the tunnel floor of the planned work is scanned, the topography evaluated and the volume to the theoretical floor level calculated using available computer technique. After compaction and levelling with respect to the required inclination and evenness, the surface of the bed is scanned and the weight and volume of the placed material determined, giving the average density of the bed. The previously mentioned criterion that there must not be water on the floor must be fulfilled.

Accuracy

Evaluation of the volume to be filled with clay material, (the theoretical volume of the foundation bed), should be made with great accuracy. The actual volume of the placed bed should be determined with the same accuracy. The same is valid for the weighing of the placed bed materials. The calculated actual density of the bed is compared with the specified minimum density for acceptance or rejection.

7.1.6 Block placement

Quality issues in the construction stage

The parameters are:

- Degree of block filling.
- Density of the block masonry.

The degree of block filling is calculated as the ratio of the volume occupied by the block masonry and that of the tunnel. The latter is calculated on the basis of the rock surface scanning and the measurement of the exact position of the prepared foundation bed. The volume of the block masonry is determined on the basis of the known level of the surface of the bottom bed, the measured width of the masonry, the level of its upper surface, and the scanned front surface.

The density of the block masonries is calculated on the basis of their volume and the weight of the blocks, which is determined in the course of the placement procedure.

Accuracy

The required accuracy of the calculated block filling degree is preliminarily estimated at 2%, meaning that it can be allowed to vary from 60–62% for 60% intended filling degree. For plane block fronts, like those obtained by using the "Module" method, this procedure is relatively simple and the required accuracy achievable, while stepped block masonries require great care to fulfil the requirements.

The evaluation of the density of the block masonries is made on the basis of the total weight of the blocks and the previously determined total volume of the masonries, yielding an accuracy of the average density of +/– 2%. This means that the actual average density may deviate from the calculated density by around +/– 40 kg/m^3. A pilot study for working out a practical procedure for the quality control is ongoing. Additional work remains to optimize the "control method".

A remaining problem is to define what the practical remedial measures would be if the actual degree of block filling is lower than the planned one. Partial or complete removal of already placed backfill would be very difficult or even impossible. It is therefore recommended to perform a study of how to compensate local low block filling degrees by installation of pellets with higher dry density in the respective section.

7.1.7 Pellet filling

Quality issues in the construction stage

The parameters are:

- Degree of pellet filling.
- Density of the pellet filling.

The average degree of pellet filling is calculated as the ratio of the volume occupied by pellets and the space in which they are placed, i.e. the space between rock and block. The latter is calculated based on the volume of the block-filled region and that of the tunnel. The average density of the pellet mass is calculated using the measured pellet weight, which is determined in the course of the filling procedure, and the pellet volume.

Accuracy

The required average degree of pellet filling depends on the degree of block filling. For 60% block filling degree, which is the lowest allowed percentage, the unfilled space remaining after pellet filling can be up to 2% of the total tunnel volume. Variations in filling degree are expected but quantification is difficult.

For sloping pellet fills determination of the degree of pellet filling will be more uncertain than for steep pellet fronts. This is because the slope reaches the tunnel roof at a large distance, up to 5 m from the front. A steep front of the pellet fill is desired and in fact required but it remains to find out if it can be obtained to the required density of the fill.

The actual average dry density may deviate from the calculated value because of variations in water content and volume determinations. A pilot study to work out a practical procedure for the quality control of the pellet filling is ongoing.

A remaining problem is to define what the practical measures would be if the actual degree of pellet filling and its density are lower than planned. As for the blocks removal of already placed backfill would be nearly impossible if the deposition holes have not been sealed beforehand. It is therefore recommended that a study be undertaken that examines the possibility of compensating for local deficiencies in density and filling degrees by increasing the planned densities.

7.2 Documentation

All scannings and calculations of achieved density and degree of filling must be instantly available to the operator and control room for permission to continue the backfilling. The data are documented in current reports and stored in temporary and permanent data bases according to the routines worked out. They are currently used for evaluation of the section-wise obtained data of density and degrees of filling, and of the quality of the entire placed backfill.

8 Proposed further work for improving the concepts

8.1 Major issues

The preceding chapters describe the outcome of the study of three different methods for backfilling of deposition tunnels of KBS-3V type and they are all applicable from both construction and performance points of view. Further work is however required, in order to improve the overall state-of-knowledge regarding their implementation so that a fair comparison can be made of them. The present chapter deals with this matter, starting with some general aspects and issues related to the constructability of backfills and their performance. That discussion is followed by examination of some vital issues like the tunnel profile and properties of clay materials. Finally, the experience gained from the tests is summarized with respect to what the in focus in future work should be and conclusions regarding further examination of alternative methods are provided.

The major issues in constructing backfills are:

- The parallel-process nature of the work in the deposition holes may cause difficulties in backfilling operations. This is in part due to the need to stop backfill installation in order to remove the buffer protection sheets, fill the deposition holes with pellets, as well as to compact pellets into the ramps associated with the deposition holes. These interruptions may cause softening of the foundation bed and of the pellets installed between blocks and the rock. This matter has great significance to system performance and construction and needs to be investigated as part of an ongoing development program.
- Ramps at the upper end of the deposition holes will cause practical difficulties by delaying preparation of the foundation bed. Their presence will require that the pellets occupying a larger proportion of the floor area must be effectively densified to limitwater seepage into the deposition holes. The variation in thickness of the ramp fill also increases the risk of uneven settling of the block masonries located both over the ramps and the rest of the tunnel floor.
- One needs to consider that concurrent construction elsewhere in the repository may alter the piezometric conditions at the site where backfilling is occurring. The flow of water into tunnels being backfilled can increase and require remedial measures to allow completion of the work (e.g. drilling of a large number of boreholes around the tunnel for drainage, grouting, or installing equipment for freezing).
- The ergonomic and environmental conditions in the tunnels must be investigated and assessed with respect to practicality and risk in conjunction with arranging ventilation and water drainage. Problems with dust and diesel combustion gases need to be solved and there must sufficient capacity to discharge water that flows into the tunnels. If softening of the backfill by sudden inflow of water is extensive, the floor will be covered by very slippery clay mud that has to be removed.
- Power breakdown must not cause stoppages in backfilling operations, which means that reserve power must be readily available. If not there is a risk of unstable conditions of placed backfills developing because of inflow of water to the deposition tunnels.
- Block compaction, logistics and storage need to be considered in detail. For backfilling 6–8 meters of tunnel per day the block compaction capacity must be about 800 blocks per day and storage of blocks for at least 2 days placement will be required. All the transport and handling must be such that the blocks are not exposed to water or high humidity not to drying conditions to a practically important extent.

- A possible risk is that inhomogeneous parts of the pellet fill between blocks and tunnel roof may remain undetected. Identification of such regions is believed to be difficult and so will replacing or adjusting poorly placed fills be. The main factor of importance in this respect is the tunnel contour; the more irregular it is the greater is the risk of occurrence of unfilled space.
- The risk of piping and erosion of the placed backfill remains and needs further investigation.
- Stepped block fronts are believed to cause more operational difficulties and poorer as-placed quality than steep ones. Firstly, blown pellets may fall on the top surface of previously placed blocks and require cleaning. Secondly, channels in blocks caused by eroding water entering from previously backfilled regions can flow into the region where operations are ongoing and possibly result in a need to exchange blocks already installed at the front of the masonries.

The preceding list of issues is not directly related to long-term safety, but affect efficiency and costs in the backfilling work. They are of importance with regards to the installation sequence and related activities and serve to illustrate what the focus should be in future work.

9 Alternative concepts

9.1 General

Any alternative backfilling concept must fulfil the basic criteria of providing an average hydraulic conductivity of the backfill of no more than E-10 m/s and a swelling pressure of at least 100 kPa. Also, the compression of the backfill caused by the upward expanding buffer must not cause reduction of the buffer density to be less than 1,950 kg/m^3. This can be offered by very dense moderately expansive clay, or moderately dense clay that is very expansive /7/. Although the basic case of blocks of Friedland clay blocks and Cebogel pellets fulfil the criteria for a block filling degree of 80%, it is obvious that it can not be applied without very considerable difficulties in placing the blocks and filling of pellets. A concept implying at least 60% block filling degree has therefore been taken as a specific demand.

9.2 Methods assuming sealed deposition holes

A deposition tunnel with sealed deposition holes would eliminate the interruption in backfilling caused by detachment of the buffer protection sheet and filling of pellets in the deposition holes, and hence make the entire backfilling operation more continuous. Still, after each campaign of placing the blocks in the tunnel, the pellet filling in the tunnel will cause temporary stops in further block placement during which the foundation bed for the next masonry unit is exposed to inflowing water. Temporary plugging ("sealing") of the holes requires considerable development of techniques and performance analysis.

9.3 "Sideways"[12] placement and compaction

The most simple and straight forward method for backfilling tunnels is by layered placing and compaction of slopes of granular clay. This method was initially tested in SKB's development of methods for backfilling of tunnels using i.a. granular Friedland clay but compaction with relatively light vibratory plates gave slightly lower density than was required to meet the hydraulic conductivity specification.

More effective compaction can most probably be obtained by using heavy compaction tools like the 1 t dynamic machines that have previously been used in Germany for construction of highways. This is believed to capable of producing materials with dry densities of at least 1,600 kg/m^3 but this needs to be demonstrated. A pilot study is recommended for constructing a large mobile press. Using Friedland clay, which is more easily compacted than other more smectite-rich clay, the dry density would have to be at least 1,415 kg/m^3, which is believed to be achievable by applying dynamic compaction. Testing of the density on site by using radiophysical methods is required and sampling for determining both density and hydraulic conductivity and swelling pressure must be made as well. Further investigation and development are required for assessing candidate materials and techniques. Involvement of experienced construction companies would offer a possibility to develop practically useful compaction tools with high capacity paying special attention to the role of inflowing water.

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[12] cf Figure 1-4.

9.4 Backfilling of deposition tunnels with smooth, regular contour

Simpler conditions for quick block-filling would be offered by tunnels with perfect or nearly perfectly circular contour obtained by TBM-boring or very careful contour blasting, especially for application of the "Module" method with just one or two block types. Considering just back-filling, placement of block units and blown-in pellets would be simple and probably make the fill more homogeneous than for blasted tunnels because of the smooth and regular tunnel shape. Depending on the excavation technique and repository layout the tunnels can be backfilled from one or both ends.

Deposition tunnels with smooth, regular contour have been considered to determine the potential of backfilling the tunnels block by block with a large number of blocks (Figure 9-1) without adding pellets. A general feasibility study has been made with respect to conditions and possibilities of backfilling of TBM tunnels (Figure 9-1).

The study has shown that the "Module" method is preferable for the backfilling of TBM-bored tunnels (Figure 9-2).

The unit shown in Figure 9-2 can perform all installation operations of blocks and pellets and is continuously served with modules.

The study shows that also backfilling of TBM-bored or contour-blasted tunnels is not unproblematic. A general request is therefore that all the activities involved in backfilling, i.e. placement of buffer and canister as well as the materials in the tunnels, must be feasible for any of the tunnel construction alternatives that can be considered.

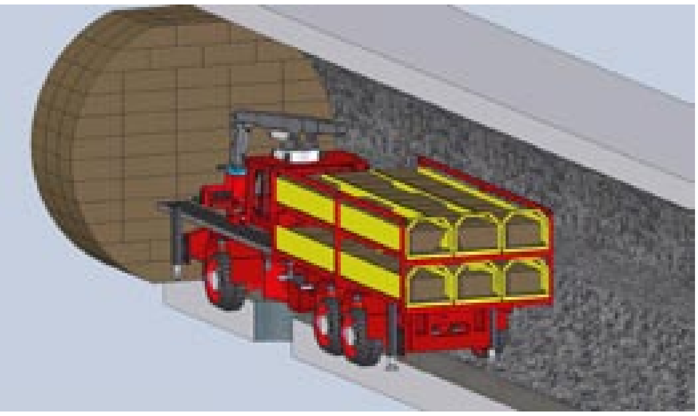

Figure 9-1. *Backfilling of TBM-bored tunnels, block by block.*

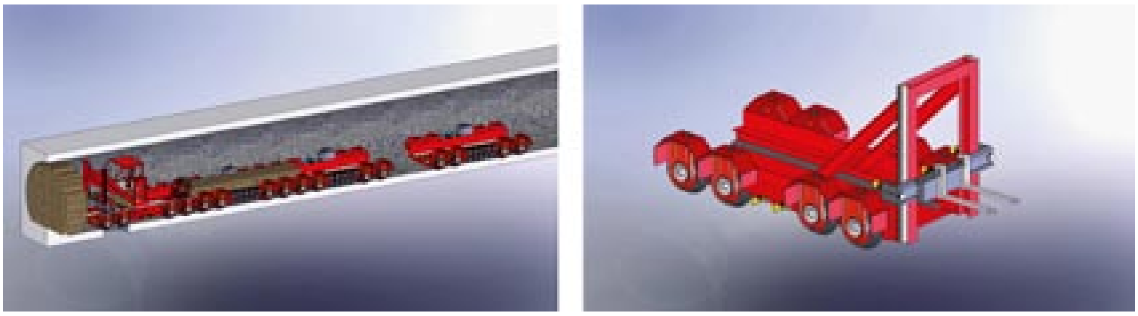

Figure 9-2. *Backfilling of TBM-bored tunnels with"Module"method. Left: Set-out machines with magazine and delivery units. Right: Set.out machines (without cabin)*

9.5 Use of muds instead of pellets assuming sealed deposition holes

The obvious difficulties in using pellets for filling the remaining space of the deposition tunnels after placing the blocks suggest use of some other material and thixotropic clay muds of the types used in deep borings may offer a solution. The idea is to pump in a slurry of smectitic clay mud that also penetrates the joints between the blocks and speeds up the maturation of the whole backfill. Smectitic muds with a density of 1,100–1,300 kg/m^3 are pumpable using dynamic injection technique but this technique requires that temporary or permanent plugs have been constructed or prepared prior to the backfilling operation /1/. The technique has been demonstrated in the Stripa Project /6,12/. The net density of the integrated backfill of TBM tunnels would be sufficient provided that the block filling degree and smectite content of the blocks and mud are high enough. It is estimated that Friedland clay blocks may represent optimal conditions and performance.

The mud technique requires that the space is kept drained until the mud is pumped in from below through perforated pipes and that pipes are placed at the crown of the tunnel for letting air out (Figure 9-3). The pipes can easily be sealed, section-wise, by applying a suitable borehole plugging technique. The figure illustrates application of the mud technique to TBM tunnels.

The evolution of the block/mud system involves a number of processes that are not fully analyzed. In principle, the blocks will sorb water from the consolidating mud, which is supplied with water from the rock. The outer part of the mud fill will remain wet and homogeneous while the mud adjacent to the blocks will undergo consolidation parallel to the expansion of the blocks. It may therefore undergo some temporary desiccation. Pipes for injection of the mud and for discharging air are left in the tunnels filled with mud and since they would be of copper no unwanted chemical reactions would be expected.

It is obvious that the whole backfilling operation including construction of plugs for creating closed regimes for making mud injection possible requires careful planning and performance analysis before it can be considered as a candidate method. The advantage of using a high degree of block filling is that the placement of blocks is not dependent on filling of the remaining space.

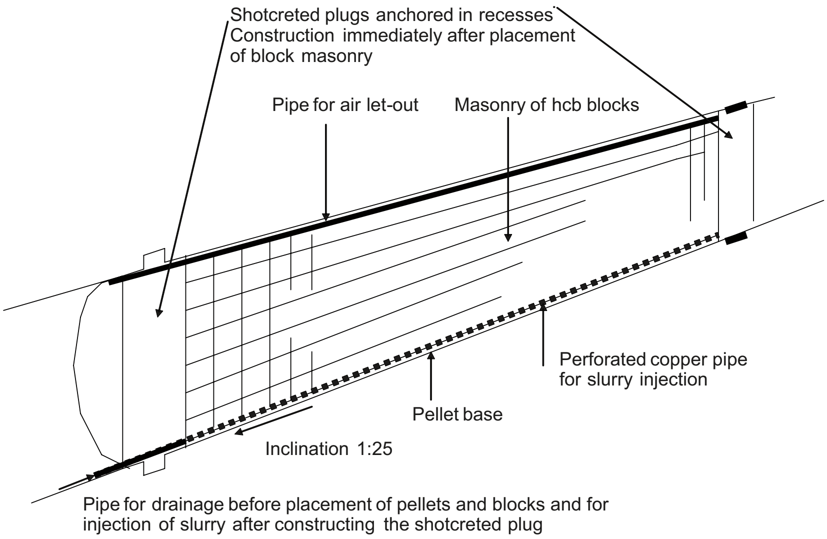

***Figure 9-3.** Principle of constructing a block masonry in a KBS-3V tunnel segment under drained conditions and subsequent injection of clay mud. The deposition holes are not shown*

10 Discussion and recommendations

10.1 Contour of the floor of blasted tunnels

The impact of the irregular shape of the tunnel floor of blasted deposition tunnels on backfill installation makes wire sawing of the floor an interesting option. However, a bed of pellet or granular material is needed irrespective of the rock excavation method since the sawn floor is not expected to be sufficiently smooth to allow for blocks to be placed directly on it. A further comment regarding this concept is that wire sawing is expected to be an expensive and time-consuming activity.

10.2 Clay materials

The large numbers of similar clay materials that are commercially available provide an opportunity to select an optimal type. Cost will be a major factor in the search for major candidates but the physical properties are naturally of greatest importance. The experience from earlier applications, like backfilling of the 1.5 m wide gap between the 50 m high concrete silo and the rock in the SFR at Forsmark with 7,000 t of smectite clay, showed that significant variations in composition and hence physical properties of the clay have to be expected in the course of material delivery. The material data specifications that are defined for the delivered clay must therefore include a margin that allows for deviation from the reference values without compromising the system performance.

10.3 Conclusions from tests performed with respect to the backfilling techniques investigated

10.3.1 General

- The experiments and concepts described and evaluated in this report are focused on possible means of bringing well-defined blocks into place in the deposition tunnels of a repository. Three techniques have been defined and discussed: the “Block” method with individual handling of blocks of different sizes; the “Robot” method which involves placement of identically-sized blocks and is more readily defined in terms of operational requirements and the “Module” method for placing pre-assembled packages (modules) of blocks and that is judged to be even more practical and more robust than the preceding options.
- The study has included an examination of the logistics from production facility of clay materials to placement of them in the repository via a series of refining processes. This has provided practical examples of; how backfilling can be done as parallel operations in two tunnels; demonstrated the accuracy in block placement that is required; and pointed out the difficulties in achieving acceptable backfilling results with respect to density and homogeneity of the backfill. The primary controlling factor in the backfilling process is time because the ongoing inflow of water will soften the clay and make any delay difficult to recover from.
- The practical testing described in this document has shown that accurate block placement is difficult. This is primarily because the preparation of the tunnel floor prior to block placement involves use of smectite clay and this material reacts with water (swells and softens) and that compresses under the weight of the block masonries, leading to a time-dependent growth of the gap between the blocks. The tests performed have shown that the stability of the block masonries was good even at point-inflows of water of 1 l/min, a necessary prerequisite being that that the foundation bed is even and dense. The tests, which did not include the effect of an EDZ are described in detail in Appendix 4.

- At present, inflow of water that causes piping and erosion and flow to the front of the block masonries at a rate faster than backfilling by 4 m per day, can not be handled. In general, even moderate inflow of water, particularly in the floor, makes it challenging to install backfills even if removal of buffer protection sheets and pellet installation in the deposition hole run smoothly.
- In order to fulfil the criteria set for the backfilling rates and performance in the tunnels development of a number of operational techniques is required. This concerns construction of the foundation bed and installation of tunnel blocks and surrounding pellets. Ways of controlling and checking the quality of the backfill respecting the various filling degrees and bulk densities also require development. Construction of foundation beds appears to be the most challenging item with pellet filling being the second-most difficult process.
- Alternative II for the selection of sequences, i.e. parallel activities in several deposition tunnels, is an approach that minimizes risks and increases the margins for adequate deposition and backfilling rates. The problems related to inflowing water to the construction site and on placed backfill still remain in whatever alternative is selected. This alternative also implies that the entire series of activities from canister installation to block and pellet filling of the tunnels run without interruption.
- The filling with pellets of the tunnels is judged to be possible but there is limited potential for effective identification of heterogeneities and increase of the installed density.

10.3.2 Specific aspects on the investigated backfilling methods

“Block” method

The following major conclusions have been drawn with respect to the possibility of applying the “Block” method:

- The method is deemed applicable but is unlikely to be able to achieve a backfilling rate of more than 6 m per day in one tunnel.
- The method requires uninterrupted access to 600 blocks per day.
- The method assumes that the blocks can be handled from above without damaging them. To accomplish this a vacuum technique is needed and that technology must be further developed for use under the difficult conditions that prevail underground.
- The method requires that the operator has comprehensive technical assistance available. This approach also requires an ability to foresee and address malfunction of the equipment with the associated risk of low quality where unforeseen quick wetting of foundation bed and blocks takes place because of interrupted block installation.

“Robot” method

This method features an improvement in speed and accuracy, but raises questions, primarily concerning:

- Location and capacity of the robot for accurate placement of blocks in the lowest and highest layers may be problematic. Rearrangement of incorrectly placed blocks needs to be tested.
- It will be necessary to develop precision systems for navigation of the robots to install the blocks in correct positions without using and checking position coordinates. Frequent checking of block positions and joints between the blocks might be needed.

Further work is needed before the potential for improvement of the “Block” method with robot techniques can be evaluated

“Module” method

The ”Module” method is judged to possess a good potential to achieve the desired combination of high backfilling rate with stable quality in the emplaced block mass due to its practicality and robust nature. It utilizes techniques that are well known, like lifting and placing heavy objects with great accuracy and it is characterized by simple logistics. It is also expected to cause less damage to the blocks by fracturing and fragmentation since the block assemblies are prepared under factory-like conditions on the ground surface.

Still, the following issues remain to be investigated in greater detail:

- The stability of the stacks of modules.
- The potential to prepare the large bottom blocks of the proposed size and shape.

10.4 Final comments

The authors conclude that the investigated techniques can probably all be applied in order to produce acceptably performing backfills although one can expect practical difficulties to be encountered as process development advances, especially for the “Block” and “Robot” methods. The most promising technique is believed to be offered by the “Module” method for block placement. Quality control of the backfill placement process is essential and the presently outlined procedures need to be validated through field demonstration. The sequencing of parallel activities requires further development as they still need to be made production-friendly in order to minimize disturbances and risks.

The authors also strongly recommend that additional alternative backfilling techniques be considered, especially the method of backfilling tunnels by placing and compaction of granular clay layers using heavy dynamic compaction tools. It is recommended that continued research and development of the conceptual design and techniques for construction of backfills, in particular placement of compacted blocks and on-site compaction of layers of granular material, be made.

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Appendix 1

Backfilling of deposition tunnels – the “Block” method

Svensk Kärnbränslehantering AB

Geodevelopment International AB/SWECO

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Contents – Appendix 1

1 Introduction

The Block method implies that the blocks are placed one by one in the deposition tunnels. Pellets are used to occupy the remaining tunnel space.

The conditions for constructing the repository are very special and the demands for acceptable performance strong. Common and well known techniques for construction should be used but for certain purposes SKB will have to develop new, partly unique methods. Certain equipment used for backfilling will be exposed to harsh conditions and undergo wearing, which requires maintenance and access to reserve units. Fully automatic handling of backfill components with great precision would be ideal but safety and reliability require robust and simple methods and tools, and several compromises therefore have to be made.

A pilot study has been made for assessing the practicality of the "Block" method with respect to its suitability for backfilling of deposition tunnels, and for making the investigators acquainted with the conditions for placing backfills, especially respecting identification of possible difficulties. The major results of these activities are reported here and in the main text of the report.

The following sequence comprises the main steps in backfilling using the "Block" method:

- Construction of foundation bed,
- Placement of blocks,
- Filling of pellets,
- Checking of geometry in 3D and acceptance of the backfilled part.

1.1 Conditions and demands

All the activities in the backfilling process take place under special conditions, i.e. relatively low temperature and inflow of water that can be locally very strong. Despite this variation the quality of the backfill components must be in agreement with the defined criteria concerning the hydraulic conductivity and the potential to create a tight contact with the rock, and also to exert a sufficiently high pressure on the rock to avoid flow along the contact, and for supporting it. The possibility of constructing well performing, long-lasting major components, i.e. the masonries of compacted clay blocks[1], the surrounding pellet fillings and the foundation bed for them is discussed in this report.

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[1] The term "masonry" is used here as in various reports and books as a synonym of "block assembly" referring to walls of very well fitting blocks without use of mortar ("Kallmur" in Swedish terminology).

A most important implication described in the main text of this report is that the backfilling is delayed by 6 hours per day by decommissioning activities. They include removal of drainage systems, alarms and buffer protection sheets; filling of pellets in the space between buffer blocks and rock and in the ramps at the upper ends of the deposition holes. The consequences of these matters are mentioned in the report, which also describes ways of avoiding or minimizing these difficulties.

2 Design principle

2.1 Basic stacking pattern

The basic principle is that the blocks shall be placed so that the distance between the stacks of blocks, i.e. the block masonries, and the theoretical rock contour is at least 100 mm (Figure 2-1).

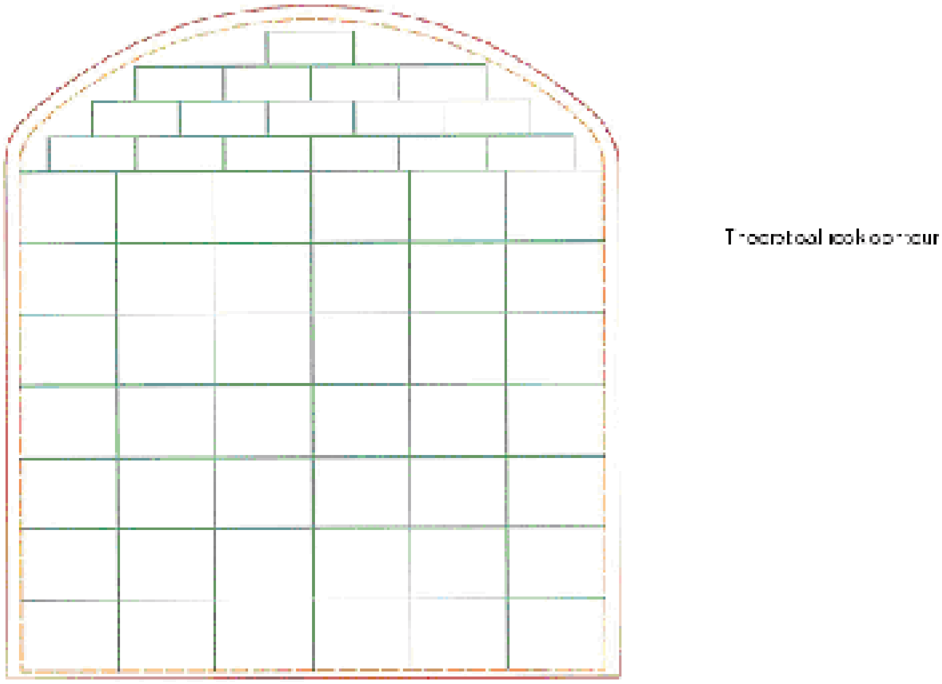

Figure 2-1. The blocks placed in the idealized tunnel cross section.

The block size and tunnel profile determine the conditions for arriving at the required block filling degree, which must not be less than 60%. For the assumed block sizes the theoretical cross section can be filled by 89% but the actual percentage is determined by the real tunnel profile. Theoretically, small blocks make it possible to follow the theoretical contour better than larger blocks and hence give a higher degree of block filling, but the higher number of unfilled joints reduces the average density of the block mass. In this context it is important to realize the impact of the evenness of the foundation of the block masonries on the straightness and width of vertical joints. Thus, for a foundation surface with small undulations the stacking of large blocks is not significantly affected, while stacks of small blocks will have wider joints with larger variations in aperture.

2.2 Size and shape of blocks

The issue of finding suitable dimensions and size distribution of the blocks has been investigated in detail, primarily with respect to the space and shape of the deposition tunnels, but also considering practical conditions at the placement. An additional factor has been the capacity of the block compaction equipment, although it may well be higher than at present respecting both size of blocks and pressure required to reach the specified minimum density. Comprehensive work has been made to find suitable block dimensions keeping in mind how they can be placed and stacked to form stable masonries. The most suitable stacking pattern is determined by the size of the blocks and the backfilling capacity, particularly the reach of the block-placing unit, and also by the required stability of the front part of the block masonry. The selected technique must be practical and simple, implying that the front shall be as steep as possible. At present, the stability of the masonries is believed to be sufficient for a water inflow into the foundation bed below them of 1.0 l/min. The presently favoured stacking mode is shown in Figure 2-2.

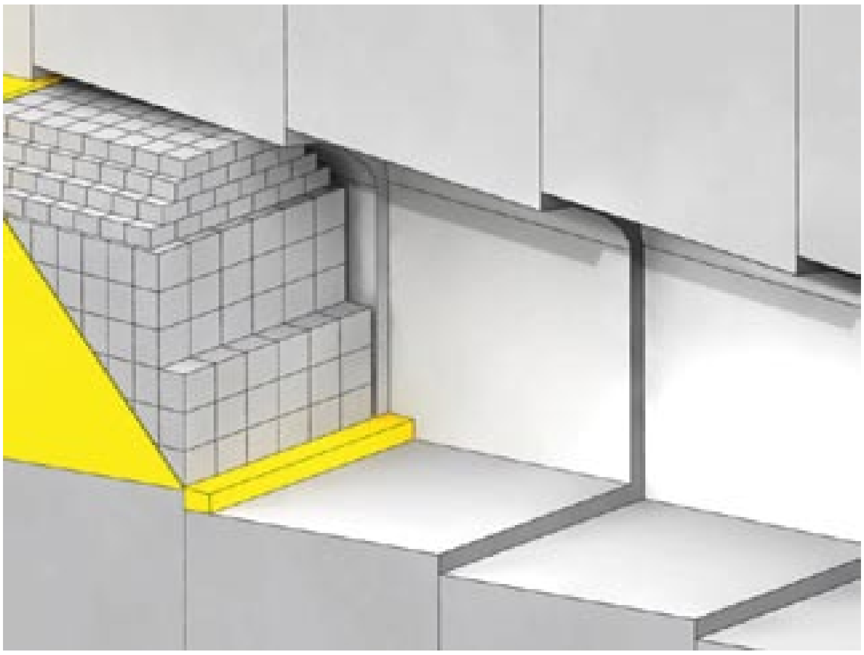

Figure 2-2. *Stepped front of a block masonry. The upper and lower boundaries as well as the front dip outwards by 1 %. Hence, the upper end of the front is about 5 cm further out than its lower end.*

The block size is determined by the capacity of the uniaxial compaction device to give products of high quality. Larger blocks are favourable because the handling and placing is quicker and the number of joints smaller than for small blocks.

The following block dimensions have been selected for the first block layer based on theoretical and practical estimates are (Figure 2-3):

- Width (lateral) 667 mm.
- Length (in axial direction) 700 mm.
- Height 510 mm.

The actual measures will not deviate from the theoretically defined measures by more than a few tenths of a mm(2).

The blocks, which have a weight of about 490 kg, should be stacked so that sufficient stability is reached. This is achieved by lateral offset of the blocks in the layers from the breakpoint to the roof by 300 mm in axial direction as indicated in Figure 2-2. The blocks placed from the breakpoint to the roof have 600 mm width, 700 mm length and 250 mm height.

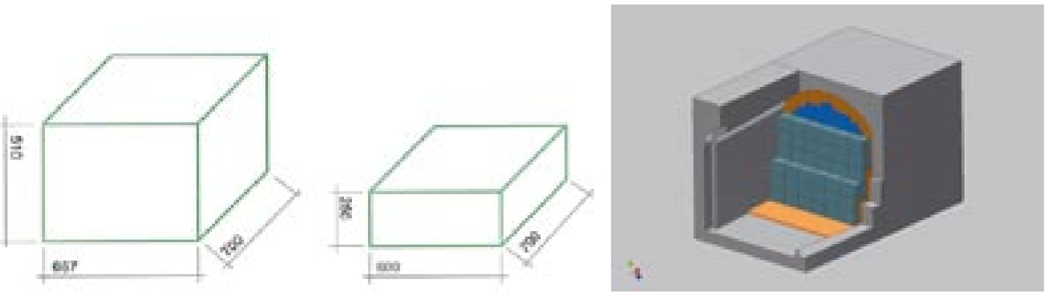

Figure 2-3. *Block dimensions. An example of offsetting of blocks is shown to the right.*

The average aperture of vertical joints should not exceed 4 mm while that of the horizontal joints should be smaller than 2 mm for fulfilling the criterion that the voids in the block masonry must not make up more than 1.5% of its volume. The blocks will be offset in the direction of the tunnel for stability reasons.

The number of blocks required to fill the theoretical tunnel cross section is 58. This means that the required rate of backfilling of 6.3 meters per day (24 hours) implies that 520 blocks must be placed daily and that each block placement, including fetching, gripping, turning and putting on site, must take no more than 60 seconds.

2.3 Foundation bed

2.3.1 Tests

The specification of a suitable bed-construction method is based on practical tests of the performance of foundation beds of Minelco and Cebogel materials. The dry density was about 1,250 kg/m^3 of the Minelco bed and about 1,150 kg/m^3 of the Cebogel bed after compaction.

The outcome of the tests is summarized as follows:

- Water flowing from the rock to the foundation beds follows its lower boundary until they become largely water saturated,
- Effective and uniform compaction makes the beds sustain spot-wise water inflow of 1 liter per minute without early collapse,
- The compacted beds sustain the load of block masonries without undergoing crushing,

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[2] Stated by U. Baltzar, SKB's responsible officer for blocks compaction

- The evenness of the surface and the density of the beds have a strong impact on the stability of block masonries placed on them under dry and wet conditions,

- Water flows readily on the upper surface of a bed of granulate (Minelco) and is slowly sucked up by the clay, while it flows slowly on a bed of pellets (Cebogel) and tends to soften the bed quicker,

- The backfilling must be associated and integrated with a suitable technique for collecting and discharging water that flows out from the previously constructed backfill,

- The conditions for taking care of water being accumulated at the front of the backfill are different for different materials; Cebogel sucks more water, softens more, and produces more fluid gel than a Minelco granule bed to, which is physically more stable and serves to let water through without forming much fluid gels. These differences are probably due to different densities of the clay species.

2.3.2 Recommended construction method

Construction of the bed is made in units with full width. It only has to be compacted to fit within the theoretical profile and over a length in the direction of the tunnel that depends on the inflow of water, the maximum length being 2.1 m. The technique employed for placing the blocks is also a determinant. No traffic will be allowed on the bed, which makes it necessary to plan the placement of blocks and pellets so that they can be safely handled with required precision by tools located outside the bed. The reach of the placing tool can hardly exceed 4.5 m from the outer end of the bed (cf. Figure 2-4.

A number of practical issues must be considered in planning and constructing the bed:

- The tunnel axis is inclined downwards by 1% towards the outer end of the tunnel and the foundation bed must have the same inclination. Its upper surface must be continuous and plane over the entire tunnel length for making the respective block layer in adjacent masonries fit.

- The foundation bed can be constructed on the irregular floor of blasted tunnels or on the plane floor obtained by wire-sawing. Water must be removed from the floor before construction starts. Irregular floor may have to be locally smoothened by use of silica concrete with a small amount of low-pH cement**.**

- Granular clay material used for the bed is most suitable since it provides a low-compressible foundation of the block masonries. Cebogel and Minelco granules, defined in the main report, have been tested and the lastmentioned material was found to be superior by being less compressible and reacting slower on wetting. The size distribution of the clay granules shall be such that the highest possible dry density for the applied compaction technique is obtained. Tests have shown that Minelco fill is preferable because water tends to flow along the contact with the rock underneath and not through it when loaded by blocks.

- The material to be compacted is filled and distributed by the equipment described under the heading “equipments”.
- The granular material should be compacted to a high degree of homogeneity and to a sufficiently high density in order to cause insignificant settlement of the block masonries that will be placed on the bed. This is best made by 4 runs of a 150 kg vibratory plate. Preliminary tests have indicated that more than 4 runs do not significantly increase the density when the placed fill is up to 150 mm thick. A series of full-scale tests need to be undertaken before the backfilling operation in the repository is started.
- Dust generation must be as small as possible, which may require intermittent spraying of water on the bed.
- Backfilling of the “ramp” cut out at the upper end of the deposition holes will be made by use of equipment, material and technique that are presently being considered.

2.4 Block masonries

2.4.1 Basic

The small blocks used in some experiments had been prepared by compaction of air-dry Friedland clay powder by the company Höganäs AB using a compaction pressure of 7 MPa while a pressure of 30 MPa had in fact been ordered. This discrepancy is of no importance for evaluating how the stacking and degree of block filling could evolve in a series of tests using a wooden, full-scale version of the “idealized” tunnel (height 4.8 to 5.1 m, and width 4.05 to 4.65 m). As outlined in the main text the required density of block masonries of Friedland clay is 1,950 kg/m^3, while only some 1,800 kg/m^3 is sufficient for providing a swelling pressure of 100 kPa. However, considering time-dependent degradation and conversion to less expandable clay minerals, necessary margins bring the figure for minimum density at water saturation up to around 2,050 kg/m^3 as concluded in the main text.

2.4.2 Construction of block masonries

The placement of blocks is made by use of equipment that lifts the block from a conveyor, which is served by the small block store in the back part of the machine. The lifting tool handles the blocks by vacuum and swings it to about 50 mm distance from the intended position (Figure 2-4). The operator then takes over the placement but the entire process can be semi- or fully automatic depending on the conditions and need for assistance of the operator. Great care and accuracy are required for getting the blocks sufficiently close to each others in order to reach the postulated maximum joint aperture, while at the same time, it is necessary to apply techniques that are as simple and robust as possible for practical reasons. An optimal solution has to be worked out on the basis of full-scale tests. The equipment and procedure for placing the blocks is described under Chapter 3 in this report.

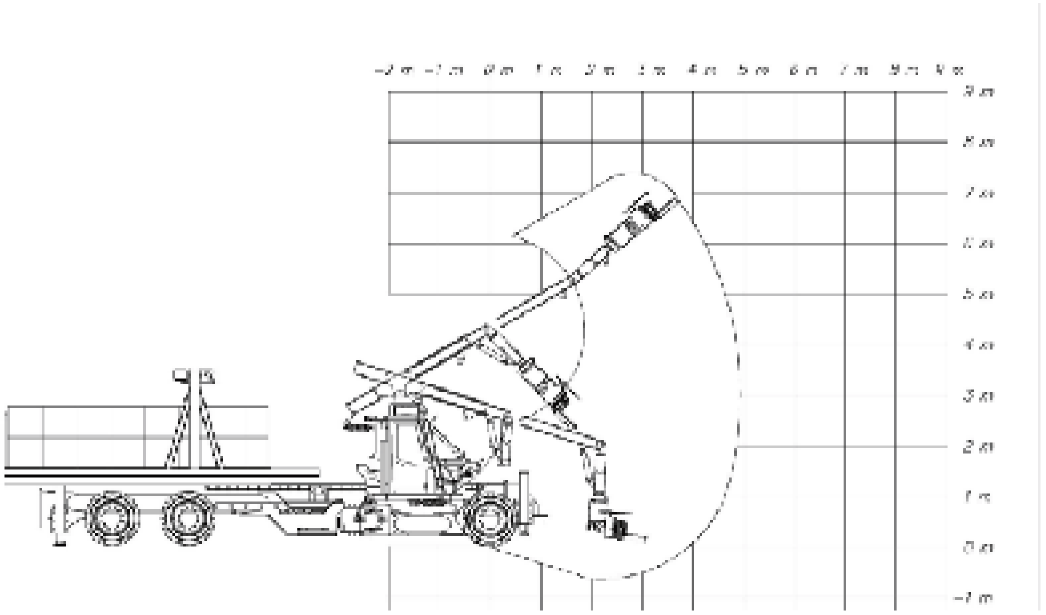

Figure 2-4. *The reach capacity of the block-placing equipment).*

2.5 Pellet filling

2.5.1 Material

The selection of pellet material was based on laboratory tests conducted for determining the hydraulic conductivity and swelling pressure as functions of the density. The swelling pressure will change from a low value at the moment of filling to a higher value due to the consolidation caused by the contacting expanding block mass. The preliminarily selected clay material, Cebogel, is a soda-activated bentonite with 80 % montmorillonite and 16% water content. It is a grey/green clay material delivered in the form of extruded cylindrical rods with 6.5 mm diameter and 5-20 mm length (Figure 2-5). After homogenization in a swelling pressure oedometer it becomes a homogeneous clay with a hydraulic conductivity of about E-10 m/s for a density at saturation with salt water (3.5 % $CaCl_2$) of about 1,650 kg/m^3, E-11 m/s for 1,750 kg/m^3, and E-12 for 1,900 kg/m^3 (cf. Table 1-1 in the main text). The just-filled pellets, saturated with water but not yet consolidated by the swelling pressure exerted by the block masonries will have a density of about 1,600 kg/m^3 and a conductivity of E-8 m/s or more. The swelling pressure will exceed 100 kPa for densities at saturation with salt water exceeding 1,600 kg/m^3. One finds from this that even moderate compression caused by the expanding blocks will make the pellet fill less permeable than the block fill, and provide the required support of the rock.

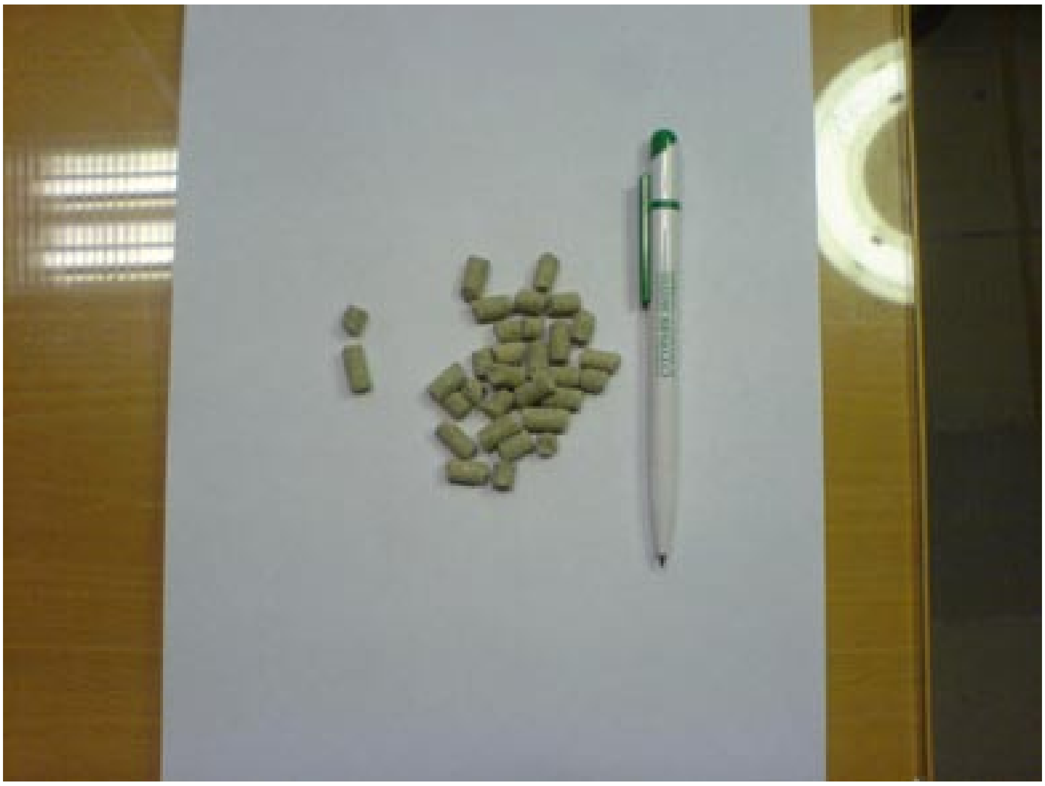

Figure 2-5. *Cebogel "pellets".*

2.5.2 Tests

A number of tests were made using augers and different types of tools for blowing granular material but the most promising method was found to be common equipment for concrete spraying (shotcreting). A program was worked out for systematic investigation of its practicality and capacity, starting with pilot tests with Cebogel and Minelco granulate as well as Friedland clay granules (5-8 mm). The firstmentioned caused less dusting and gave the highest filling degree. Its high gel-forming capacity is superior and makes this material a primary candidate for pellet filling.

3 Equipment

3.1 Specification of equipment for the various backfill operations

The following units are required for backfilling according to the “Block” method:

- Equipment for construction of the foundation bed and pellet filling.
- Block-placing equipment.
- Vehicle for transporting and delivering materials.

3.2 Equipment for construction of the foundation bed

The equipment intended for constructing the foundation bed is shown in Figure 3-1. The main purpose is to place the granular material and distribute it evenly on the tunnel floor in layers, with a thickness of up to 150 mm. It is then compacted by use of a vibrating plate (150 kg) moving it over the fill in four campaigns.

The smoothening bar at the front of the machine is moved so as to make the new layer fit the earlier placed one after compaction. All levellings are made automatically using the electronic control units of the machine. The operator running it selects the various functions.

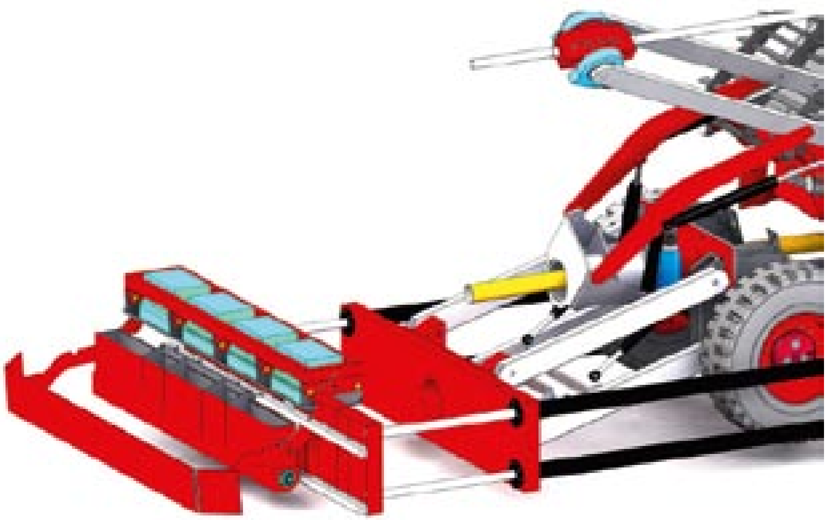

Figure 3-1. *Schematic picture of the equipment for constructing foundation beds.*

A pilot test, termed ”Full scale testing of block filling”, comprised pilot studies of equipments and techniques and gave photographic evidence of the outcome. The rock trimming unit JAMA 8000, manufactured by the company Industriteknik Nord AB in Skellefteå, was used as a basic unit (Figure 3-2). This picture is a relevant illustration of the nature of the tunnel floor in blasted tunnels, characterized by very rich fracturing that extends to at least 1 m below the floor. Smoothening of the floor requires careful planning of the blasting but evenness cannot be achieved. An important fact in this context is that the look-outs extend downwards to at least 300 mm depth at the inner end of each blast round, hence leaving an inwards inclined, irregular rock surface. In order to achieve a plane upper surface of the finally prepared bottom bed, dipping outwards by 1%, it has to be significantly thicker at its inner end than at the outer. This variation has an impact on the settlement of the heavy block masonry to be constructed upon the bed if the compaction has not given uniform and a sufficiently high density of the entire bed. Wire-sawing is being considered for achieving a plane and even tunnel floor but the rich fracturing and variations in rock strength as well as high rock stresses may cause topographical variations of the prepared surface.

Figure 3-2. *The Jama 8000 machine.*

3.3 Block-placing equipment

A suitable equipment for placing blocks is illustrated in Figure 3-3. It specifies the various features that are required for adequate handling of the blocks, which must be made with great precision, and for checking and watching the operations. The equipment makes use of advanced electronic technique, which normally operates without problems in ordinary room environment but which must be so designed that it can stand the tougher conditions in a deep repository.

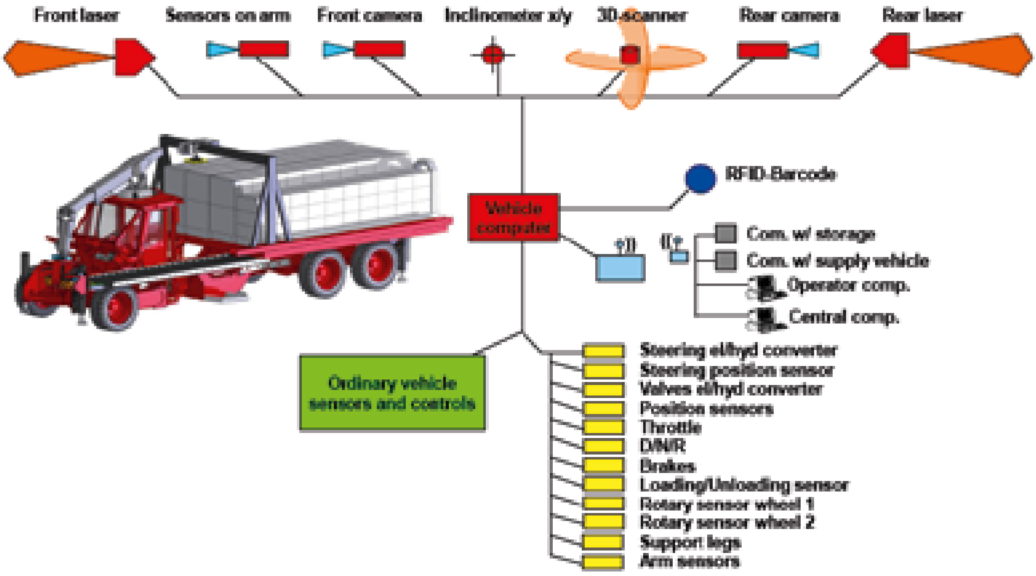

Figure 3-3. *Block-placing equipment.*

The basic part of the block-placing machine is a telescopic crane that takes care of the handling of the blocks, i.e. grasping, lifting and releasing them in exactly defined positions. A necessary prerequisite for carrying out these operations is to use vacuum technique. It must be possible to work with great flexibility, i.e. to move the gripping tool vertically and laterally and to rotate it, keeping in mind the significant weight of the blocks (Figure 3-4).

Figure 3-4. *Equipment for lifting and handling blocks using vacuum technique.*

3.4 Equipment for pellet filling

Filling pellets by pouring has been found to be inadequate since the homogeneity will not be satisfactory and some parts of the space may remain unfilled, like below rock asperities. Pellets should therefore be filled by blowing, using shotcreting technique. There will be some bouncing of pellets and a variation in homogeneity but the density is believed to be higher than by simple pouring. Still, tests made at Äspö have shown that the dry density of blown pellet fills placed by using tubes with 50 mm diameter and water added at the nozzle will be less than 1,000 kg/m^3, which is lower than requested. The problem of increasing the density sufficiently much is firstly that only direct impact will provide enough energy, and secondly that the resulting density may vary considerably. A possible way of increasing the dry density may be to mix two or more pellet size fractions but there is a risk that they could separate in the filling phase, leading to enrichment of coarser granules in the lowest part of the fill. The matter needs further consideration and full-scale testing.

The equipment for filling is the same as for constructing foundation beds but equipped with tubes for blowing the pellets and with a unit for providing compressed air (Figure 3-5).

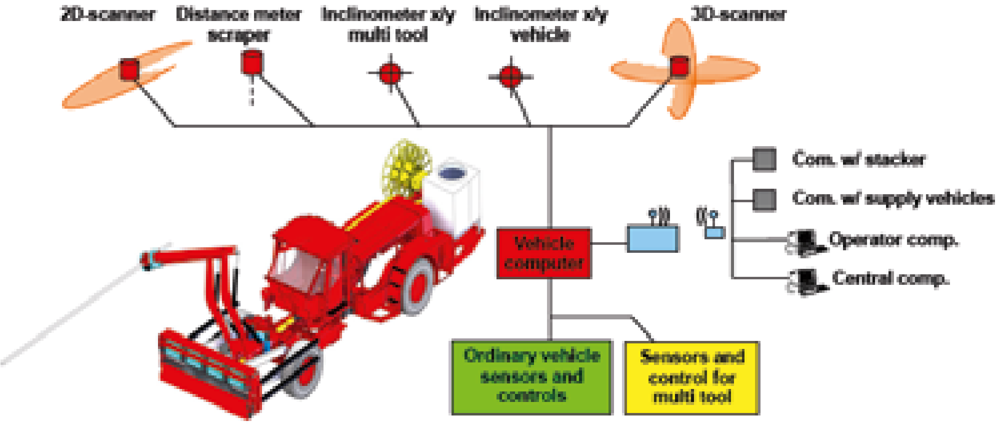

Figure 3-5. *Equipment for constructing foundation beds provided with shotcreting facilities for pellet blowing.*

3.5 Vehicles for transporting and delivering backfill components

A vehicle of the type shown in Figure 3-6 is required for supplying the blocks and the various backfilling components to the construction site. It must fit within the cross section of the tunnels and be so designed that blocks that are carried are not exposed to thrusts and blows while moving on the blasted floor from the central storage on the repository level to the deposition tunnels. The quality of the blocks determines how well they can be fitted in the masonries. Hence, damaged blocks makes placement difficult, requiring careful checking of the joint apertures and of the net density of the masonry. The transport rate is assumed to be 1.5 m per second.

If a temporary road with high bearing capacity and even surface is required to minimize the risk of block damage, it must be removed in conjunction with preparation of the foundation bed units. This will cause problems by reducing the rate at which blocks and pellets can be placed. The resulting delay will increase the amount of water that has entered the backfilling area, and this can cause significant difficulties. Construction and removal of a temporary road would require detailed planning with special consideration being given to effect on traffic required for bringing installation equipment and clay materials to the site. Assesment of the various transport activities in the deposition tunnels indicate that such arrangements are not suitable. Among other difficulties they would make it more difficult to seal off the deposition holes from inflowing water.

The current plan is to equip the vehicle with navigation tools that allow it to move automatically. Such automation would provide sufficient distance to the tunnel walls and prevent the wheels to move over the deposition holes. Scanners, coupled to the driving unit, would have to be mounted at the front and rear so that the vehicle is automatically halted if personnel approach too close to it.

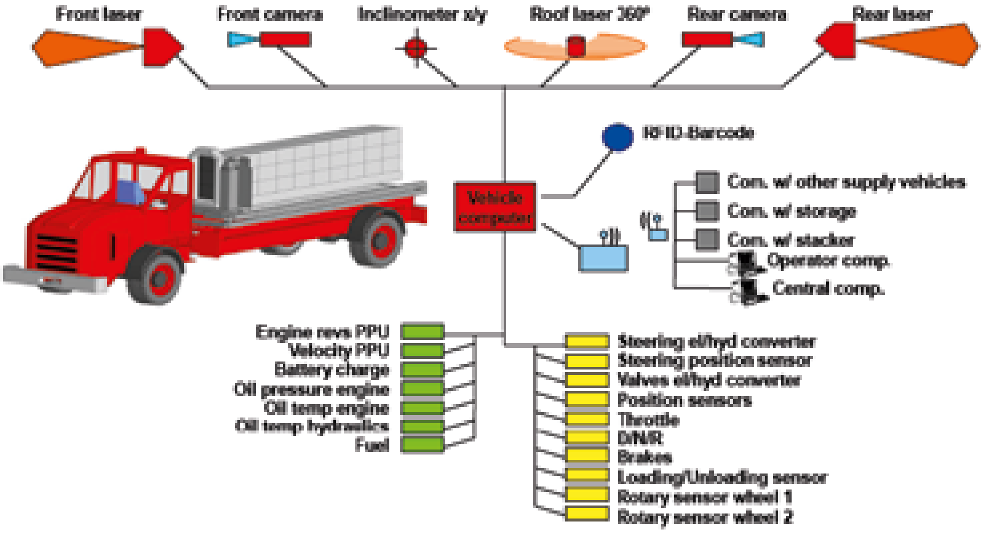

Figure 3-6. *Vehicle for transporting backfill components. The picture shows block delivery with the blocks placed in the order required for the installation work.*

The heavy vehicles are supposed to operate in the tunnel without passing over the deposition holes. The idea of locating the deposition holes asymmetrically in the tunnels is therefore not practical, since this will decrease the distance between operating vehicles and tunnel walls.

4 Construction of backfill

4.1 General

The subsequent description presumes that a first 50 m filling of the tunnel with blocks and pellets has been completed, Before any construction of the next 2.1 m long backfill unit is started, a scanning tool is employed for measuring the tunnel contour by recording the detailed topography of the walls and roof of the tunnel and of the front of the previously constructed block masonry. Such scanning tools are attached to the equipment used for preparing foundation beds and block placement. An important matter is that water flowing on the floor or into any space that is being backfilled, must be removed.

4.2 Foundation bed

The first activity is to bring the equipment for preparing the foundation bed to the required position. Its supporting legs are moved down to rest on the solid rock or on the temporary road and co-ordinates representing what is termed “global positions” of the equipment are measured by the laser-based navigation system. The scanning tool for measuring the tunnel profile records the topography of the walls and roof over the 2.1 m length that represents the next unit length, and of the earlier constructed foundation bed that protrudes by about 0.5 m from the previously placed block masonry. The computer code predetermines the level of the new foundation bed and calculates the need for adding material, making due corrections with respect to the forthcoming compaction. Water appearing on the floor is immediately removed.

A first levelling layer of clay granulate is placed, guided by the laser tools, and adjusted to the right level, followed by compaction by 4 runs of the vibratory plate for providing a plane surface of the dense bed. A second layer is then placed and compacted to reach a height of 150 mm and an inclination of 1.0% towards the outer end of the tunnel, followed by checking the level, which provides input to calculation of the density. All subsequent layers that are needed for bringing the upper surface of the bed to the required level are made in the same way and the finally obtained surface covered by a thin layer of granules with 0-4 mm diameter that is not compacted. The level and inclination of the finally obtained surface are measured by the 3D scanning equipment and recorded, after which the equipment retreats to the central storage at an expected rate of 1.5 m per second. The procedure is shown in Figure 4-1. All material is weighed and the density calculated based on the respective measured volume that it occupies.

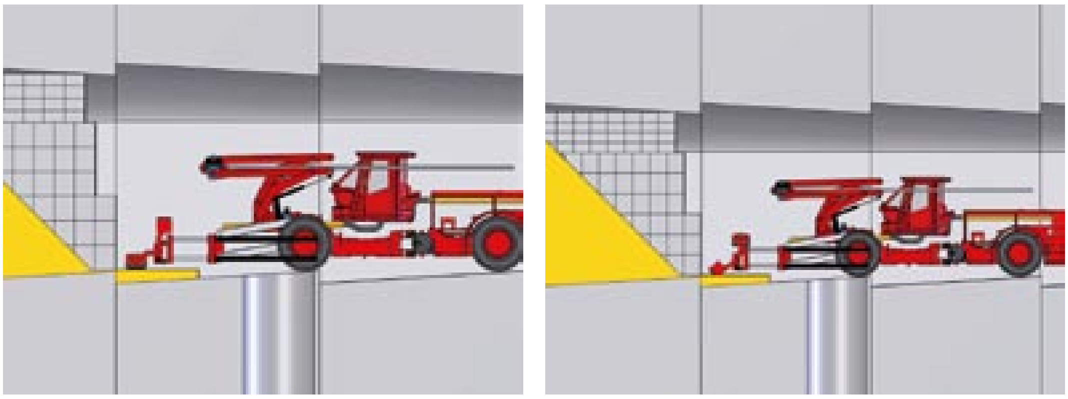

Figure 4-1. *Compaction of foundation bed (left), and adjustment and smoothening of its upper surface to the required inclination, followed by applying a very thin layer of fine granules.*

The recesses ("ramps") excavated at the upper ends of the deposition holes to make it possible to install the canisters in the deposition holes, will be backfilled but the material and technique for placement and compaction are not yet decided (Figure 4-2). Irrespective of what method will be used, the operation will cause delay of the entire backfilling work and require that more equipment is moved in and out of the deposition tunnel.

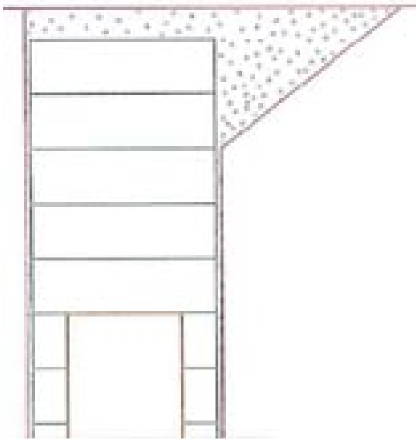

Figure 4-2. *Recess forming a ramp at the upper end of a deposition hole. The upper end of the buffer blocks may become located at the tunnel floor. The picture shows pellet filling of the ramp but compacted clay blocks may be an alternative.*

Backfilling of ramp will be performed directly after pellet installation in the respective deposition hole. With regards to logistic and technique, this is best done with the same unit that is used for installsing pellet in the deposition holes.

The two upper "buffer" blocks in the deposition hole are defined to be part of the backfill. Since the buffer density is not allowed to be lower than 1,950 kg/m³ the compressibility of the backfill, which is exposed to the swelling pressure of the buffer in the deposition holes, must be limited. The thickness of the foundation bed is not finally decided, but an approximate height of 100 mm is deemed acceptable. A further demand is that the uppermost buffer block must not extend above the tunnel floor and should therefore be installed parallel to the backfilling of the ramp. This will have consequences for the construction of the bed foundation since the tool for compaction has to follow the rounded contour of the buffer block.

4.3 Block placement

The equipment for placing blocks is moved in and its supporting legs moved down for providing stability and minimal movement of the machine in the block handling process. Its exact position is determined and recorded.

The computer code defines what block shall be delivered to the tool that handles and places the blocks and there will be continuous delivery of blocks according to the pre-determined schedule. Figure 4-3 illustrates this procedure.

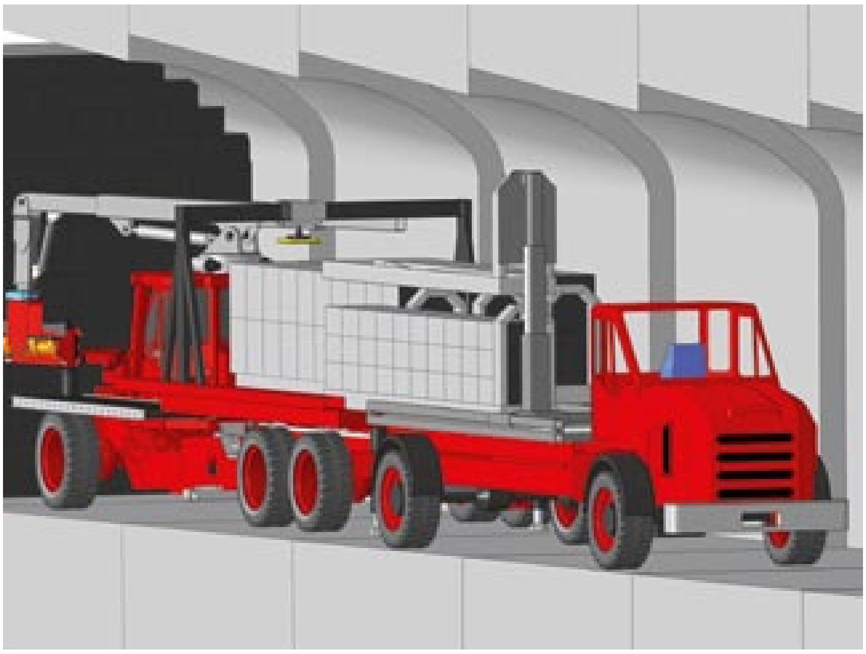

Figure 4-3. *Procedure of handling and placing blocks. The picture shows the moment when the vehicle delivering blocks is connected to the storage of the placing unit.*

The blocks are stacked stepwise, layer by layer from the left[3] to the right. For guiding the operator, the first block to the left is placed by use of a laser beam correlated with the theoretical cross section of the tunnel. All the blocks in the first row are placed in tight contact with the already placed blocks. The foundation bed is fully covered by blocks placed in the same careful way as in the subsequent stacking process, which leads to the desired stepped block profile (cf. Figures 2-2 and 4-1). By following this principle, problems with water flowing from earlier backfilled parts of the tunnel through the foundation bed will be minimized. Figure 4-4 illustrates that water flowing from previously placed backfill will pass the block masonry and needs to be removed.

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[3] All directions mentioned in this report refer to the viewer's impression when facing the latest placed part of the block masonries, i.e. opposite to the direction of the backfilling.

Figure 4-4. Examples of redirected water flow (cf. Appendix 4).

The first set of blocks is completed in one, continuous operation and scanning is made for determining its outer contour. The obtained data are assessed for deciding whether possible deviations from the theoretical block pattern respecting mass and density.are acceptable or not, If the contour of the front of the block masonry at any stage is found larger than allowable to achieve the specified minimum density or maximum void content, the blocks will have to be removed, which can ruin the entire backfilling operation because of the very tight time schedule. The scanning will also show if there is any debris on horizontal block surfaces. The various functions of the block-placing unit are semiautomatic and camera technique and geodetic equipment available for facilitating the operator's work.

Each block placing event starts by the operator commanding "fetch block". The equipment thereby grasps the block by its vacuum tool and moves it to the planned position where it is placed following the command "release block ". The movement is halted 50 mm from the desired position after which the operator takes over and puts the block on site. These operations are illustrated in Figure 4-5.

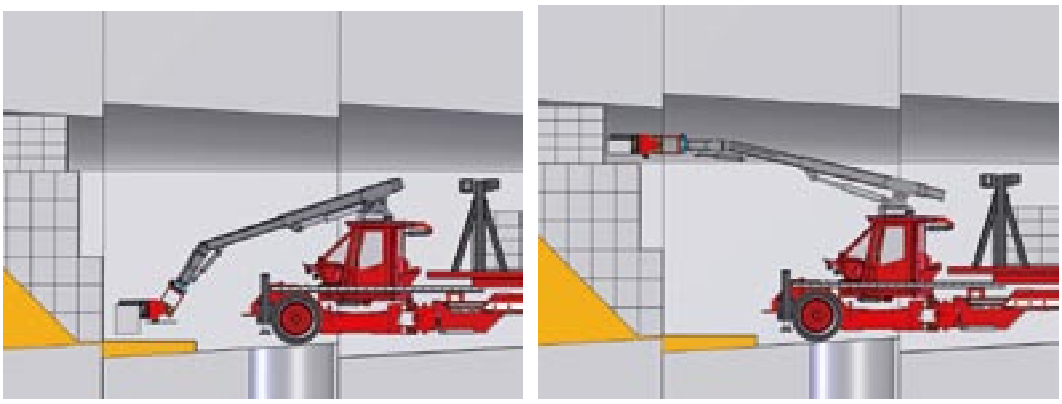
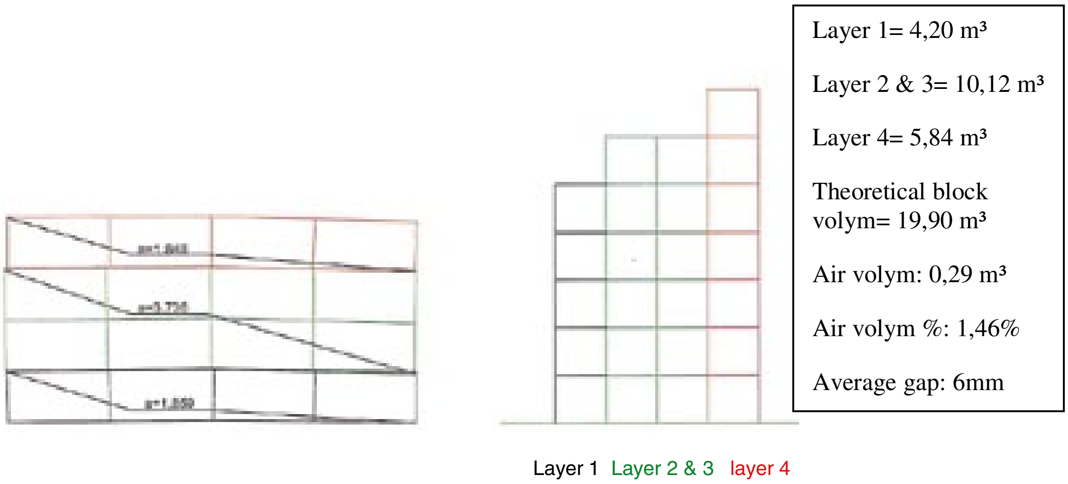


Figure 4-5. Block placement.

The placement proceeds until three rounds have been completed, the placing unit being continuously supplied with blocks by the conveyor belt from the block store in the back part of the machine. At the end of each sequence the block front is scanned and checked with respect to possible irregularities and presence of clay or rock fragments on horizontal surfaces. The density of the masonry is calculated based on the front area, the axial thickness of the block masonry unit, and the measured weight of these blocks.

Determination of the unfilled space is important and requires careful measurement. Figure 4-6 illustrates the result of such measurements.



Layer 1= 4,20 m³

Layer 2 & 3= 10,12 m³

Layer 4= 5,84 m³

Theoretical block volym= 19,90 m³

Air volym: 0,29 m³

Air volym %: 1,46%

Average gap: 6mm

Figure 4-6*. Example of result of the measurement of unfilled space in a block masonry.*

The most important outcome of the experiments is the comparison of predicted and actual block filling degrees. For future experiments and for backfilling of tunnels in a real repository the principle proposed is that at least 60% of the volume of the up to 300 m long blasted tunnels shall be filled with clay blocks. The experiments performed showed that this can be achieved considering even significantly rough floors, walls and roof. As an average a block-filling degree of somewhat higher than 70% is believed to be achievable.

The rate of block placement in the tests was estimated at about 60 seconds per block. The conclusion is that it will be possible to put the block on site before uptake of water from moist air or from inflow from the rock causes significant degradation, but it requires that the backfilling process is not interrupted.
A very important matter is the settlement of the stacks of blocks. It must be very small for avoiding the phenomenon indicated by Figure 4-7

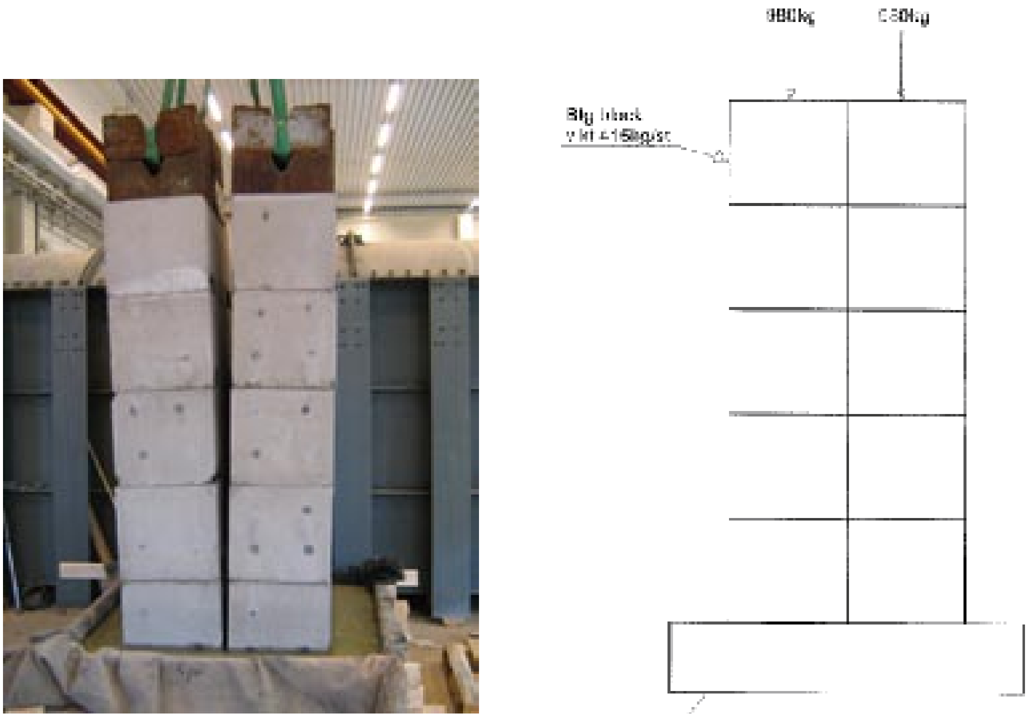


Figure 4-7. *Results from measurement of movements of stacks of blocks in tests at the Bentonite Laboratory at Äspö.*

4.4 Pellet filling

Figure 4-8 illustrates the pellet filling operation, which requires careful planning and checking. It is, in fact, the most difficult and least accurate operation in the backfilling process, as indicated by the following notions:

- The criterion set by SKB is that no more than 2% of the backfilled tunnel volume may be left unfilled with a degree of 60% of blocks with Milos B clay. Experiments have shown that the voids representing joints between blocks will make up at least 1.5%, meaning that 0.5% can be the maximal allowed tunnel volume for pellet filling that would in fact not be filled. This equals 100 liters unfilled space per meter backfilled tunnel assuming 20% excess excavated rock compared to the theoretical tunnel section. With a higher block filling degree the margins of allowed unfilled space increases.

- For 80% degree of block filling the pellets must be filled in campaigns corresponding to the length of the blast rounds since the front of the blocks will hinder insertion of the tube for bringing the pellets to reach all the way to the earlier filled pellets. This would be required if Friedland clay blocks are used but if a more smectite-rich clay like Milos B bentonite is used for the block production the conditions are less demanding. Thus, the calculated minimum degree of block filling would be 60% of each blast round giving more space for moving the pellet-filling tube. The filling process will not depend on the length of the blast rounds.

- Filling pellets so that a slope is formed means that many blocks will be exposed to humid air before the pellet fill embeds and supports the block masonries, which may therefore undergo some hydration and expansion. Sloping pellet fills mean that the toe of an earlier formed slope will be located far behind the latest placed block masonry, implying that it will be difficult to define and determine the geometry of the fills considering the varying topography of the tunnel walls and roof. Parts of the filled slopes may in fact escape inspection and scanning.

- The pellets between blocks and rock along the tunnel walls must be placed before the blocks start moving under their own weight or by possible yield of the foundation bed. If movements are identified, part of the block masonry and foundation bed may have to be removed and reconstructed.

- Dusting can be very significant and water should be added to the nozzle of the tube used for blowing the pellets. It has been demonstrated that the required amount of water is 1.0-0.5% of the weight of air-dry pellets.

- Pellets may accumulate on horizontal block surfaces, which must be checked and cleaned before additional blocks are placed.

- The tests performed show that the tunnel space can be filled acceptably well with the possible exception for those parts where significant rock fall from the roof has taken place. There is a risk that the operator's estimate of how much of the uppermost tunnel space that has been filled is not correct and that unfilled space may remain. In contrast to checking of the installation of the foundation bed and block masonry units, the evaluation of the volume and density of pellet fills with 45^{o} slope angle is not very accurate. However, the risk of significant errors in the calculation of the density will be considerably smaller if the front of the pellet fill is steep. It requires addition of more water at the placement resulting in some reduction of the dry density of the fill.

- The pellets can be allowed to form a slope with 45° angle, or placed to form a steep front wall at the end of each campaign, which can be achieved by adding more water to the nozzle of the tube than is needed for minimizing dust generation.

A number of pellet filling tests have been performed in the Bentonite Laboratory at Äspö to investigate the risk of dust generation and to find out whether pellets can be blown to form a steep wall by adding water at the nozzle. These tests were positive but systematic investigations are required for development of practical procedures.

***Figure 4-8.** Pellet filling by using shotcreting technique.*

<u>Procedure</u>

The filling of voids is done by using the shotcreting machine mounted on the equipment for construction of the foundation bed. Right behind it stands a truck loaded with pellets for supplying the machine, the required amount of pellets being predicted by the computer code. The calculation is based on the scannings made of the tunnel contour and the placed block masonry. The front of the blown pellets can be steep or inclined by down to 45° depending on water inflow. The procedure is shown in Figure 4-9.

The tube for blowing the pellets is inserted between the block masonry and the rock, no less than 1 meter from the earlier front. The pellets are blown in while adding water to the nozzle. The feed-rate of pellets and water (which must be of low-electrolyte type, i.e. tap water) is continuously recorded by weighing the pellets and water used. The operator moves the tube systematically, aided by cameras and strong illumination. The length of the fill in the axial direction of the tunnel can be about 5 meters including the 45° slope. It is formed while successively moving the nozzle outwards. Where only little water flows from the rock the filling is complete when the toe of the slope has reached the outermost blocks but where the foundation bed tends to become wetted and affect the lower blocks it is preferable to create a steep front of the pellet fill leaving drier material behind. The procedure has not yet been worked out.

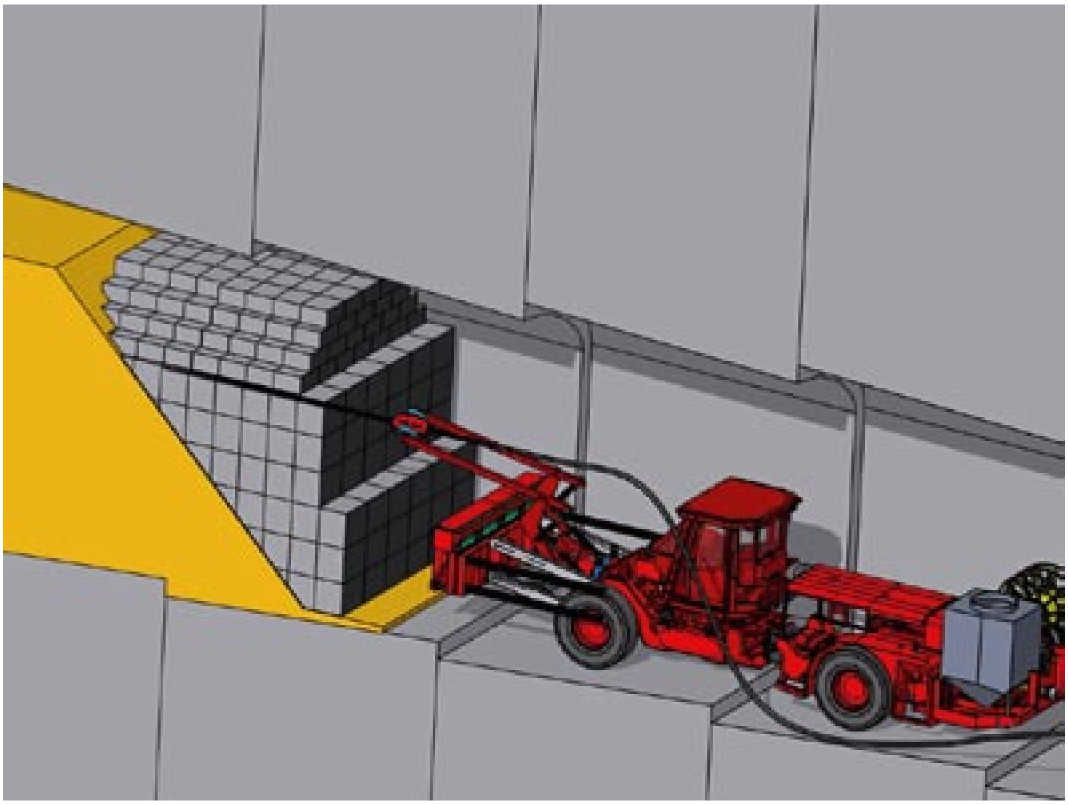


***Figure 4-9.** The equipments used for pellet filling, i.e. basically the machine for construction foundation beds, and the attached aggregate for pellet blowing. Notice the sloping pellet filling reaching to the front of the foundation bed.*

When a backfill unit is complete the pellet front is scanned and the positions determined. These data form the basis of the calculation of the amount of filled pellets using the computer code. It also gives the average density of the pellet fill and since the weight and volume of the placed blocks have also been determined, the density of both blocks and pellets can be calculated. This makes it possible to estimate the average hydraulic conductivity and swelling pressure of the entire backfill once it has been fully water saturated and matured. If the density of the pellet fill is significantly lower than anticipated it may be possible to use compaction tools to increase it although this may cause significant variations in density and be of limited effectiveness.

Once a backfill unit has been approved, work on the next 2.1 m long unit is started, beginning with the foundation bed. Construction of the individual backfill units would ideally take about 7 hours, which is estimated to yield a backfilling rate of 6, 3 meter in 24 hours under suitable conditions.

4.5 Time schedule

Time is the most important factor because inflowing water starts hydrating and softening the clay components as soon as they have been placed. This means that any delay in the activities that precede the construction of the next backfill unit can cause problems and require removal of unacceptable parts and replacement of those materials. The present study therefore comprised detailed time planning based on estimations and experience from completed tests. The major outcome of this was that each block installation cycle, including fetching, moving and placing the respective blocks and moving the equipment back for the next cycle, must be made in 60 seconds. This gives a margin of 3 hours per day, illustrating the tight schedule and the fact that there is practically no room for pauses and mishaps. In preparing the construction of a backfill unit volume in a real repository the following activities must be planned and defined and the required time for each of them estimated:

- 3D scanning of the tunnel.
- Construction of foundation bed including completion of the deposition holes (placement of canisters, buffer blocks and pellets).
- Installation of the equipment for block placing, arrangement of block supply.
- Placement of blocks in first layer.
- Checking of geometry in 3D.
- Placement of remaining block series.
- Checking of geometry in 3D.
- Retreat of the block placing equipment.
- Installation of the equipment for constructing the foundation bed, prepared for pellet filling.
- Filling of pellets.
- Checking of geometry in 3D.
- Extension of foundation bed.
- Checking of geometry in 3D.
- Retreat of the equipment for constructing foundation beds.
- Installation of the equipment for block placing, arrangement of block supply.

Start of next round:

- 3D scanning of the tunnel.
- Construction of foundation bed including completion of the deposition holes (placement of canisters, buffer blocks and pellets).

Etc etc

As for the other backfilling methods it should be noted that delay in carrying out preparative work in and around the deposition holes has not been included in the time schedule. According to the present plans the backfilling process has to be stopped for removal of the buffer protection sheet, for pellet installation in the respective deposition hole, and for filling of the ramp at its upper end. This suggests that backfilling is made in two tunnels at a time, an issue that is discussed in the main text of the report.

The planned routine implies that the backfilling operations shall cease once per 24 hours for removal of the buffer protection sheet, drainage and alarm installation from the respective deposition hole when it is reached by the front of the backfill. These activities are followed by completing the buffer pellets, and by filling the recesses at the upper ends of the deposition holes. The time for doing all this is estimated at 6 hours per day during which water will flow from the rock into the backfilled part as well as in the open part outside the backfill.

It is the authors' opinion that several of the activities preceding the start of each backfilling sequence need to be reconsidered and simplified to make backfilling according to this method possible. It is suggested that the ramps at the upper ends of the deposition holes be deleted and that the buffer protection sheets and possibly also the buffer pellets be eliminated or placed so that the backfilling operations are not affected.

5 Tests and development of techniques

It has not been possible to test the applicability of the ”Block” method since the required special equipment have not yet been manufactured. However, certain attempts have been made for getting an impression of whether it is feasible and they have involved use of conventional equipments, like fork tractors. The general impression from these attempts is that a comprehensive R&D program is required for assessing the possibility to conduct the various filling operations. It is of special importance to investigate the function of the tools utilizing vacuum with focus on the risk of dropping blocks, and for checking that placed backfill fulfils the requirements. A dropped block may cause operational delay for cleanup of debris and replacement of the damaged block. This causes hydration and softening of earlier placed blocks and pellet fills.

The following issues that need further examination and development are:

- Examination of the required resources, strategy, and time for development of equipments and tools.
- Specification of demands and criteria.
- Performance of tests for verification of the applicability of the respective methods, and for identification of controlling parameters as well as for identification of parameters, and ways of recording adequate data.
- Development of conceptual and detailed technical design of equipments.
- Development of drawings and descriptions for manufacturing of equipments.
- Contracting of consulting work and manufacturing of equipments.
- Manufacturing of equipments.
- Description of required test program.
- Performance of tests.
- Assessment of the outcome of the tests and selection of ways for further development.

Parallel to this, a program for manufacturing blocks must be worked out. It should specifically deal with the compaction technique required for different raw materials for production of blocks. It has to be integrated with the final selection of clay materials and comprise an assessment of the impact of compaction on the physical properties of the block components and of the influence of higher swelling pressure of blocks on the density and properties of the pellet fill.

Considering the unavoidable risk of disturbances and mishaps one must be able to halt the backfilling operations at any time, for which construction of a temporary or permanent bulkhead is the only realistic method. In its simplest form it may comprise application of shotcrete in a few layers, the number and thickness of which are determined by the expected or desired delay in backfilling. For permanent bulkheads silica concrete with low-pH cement will be required as well as continued work on development of suitable cementitious material for shotcreting. The ideal condition would be to prepare niches for constructing such bulkheads, adaptated to the presence of fracture zones and identified water inflow spots.

6 Tentative judgement

Use of the ”Block” method requires a number of actions to support the operator, both since high precision is required for several operations, and since the time available for performing them is very limited. Some of the operations can probably be automatized and involve remote handling but such development must not jeopardize robustness, accuracy and capacity. It is of particular importance to realize that techniques and tools that can be sensitive to the special environment at depth should be avoided since any mishap or stop means that placed backfill becomes hydrated and changes shape, a worst scenario being that it turns fluid. The respective units should not be placed so that movements, lifting, swinging etc can cause displacement of it, which would require repeated measurement of their actual positions. One can identify a number of issues that affect the practicality and value of this method, like the flowing ones:

- A risk of fundamental importance is that shallow wetting of blocks by dripping water or moist atmosphere makes vacuum lifting uncertain or impossible. Dust or debris on the block surfaces can also cause mishaps.
- The most critical issue is the criterion stating that there must be no more than 2% unfilled space in the tunnel. It would be valuable to reconsider this measure by 1) using more expansive clay for the block preparation, 2) using higher block compaction pressure if Friedland clay is maintained, or 3) reaching a higher degree of block-filling.
- The possibility of increasing the rate of backfilling using the “Block” method is very limited. About 6 meters per day seems to be at maximum for an individual tunnel.
- The logistics have not been optimized. By reducing the number of block sizes to two, one can probably use the transport containers utilized on the ground surface also for providing the equipment in the deposition tunnels with blocks at the required rate. This would also minimize the risk of selecting and placing blocks of wrong size.
- The robustness of the “Block” method is not convincing; there are several operations that may have to be disrupted and repeated, associated with removal and re-installation of blocks and pellets. Where water flow from the rock, any delay in the backfilling operation can cause severe problems by wetting and softening and a considerable part of placed backfill may have to be removed.
- It would be advantageous if the equipment for constructing the foundation bed could be designed so that it can also place the blocks. Further R&D for reaching a practical solution is strongly recommended despite the expected difficulties.

Äspö 2008-08-04

Hans Wimelius	Roland Pusch
SKB, Äspö	Geodevelopment International AB

Appendix 2

Backfilling of deposition tunnels – the “Robot” method

Svensk Kärnbränslehantering AB

Geodevelopment International AB/SWECO

August 2008

Contents – Appendix 2

1 Introduction

The “Robot” method implies that the blocks are placed one by one in the deposition tunnels using robot technique. Pellets are used to occupy the remaining tunnel space.

The conditions for backfilling deposition tunnels by use of a robot technique are the same as for the “Block” method. The same principle of using well known techniques for construction will be followed but for certain purposes SKB will have to develop new, partly unique methods. As for the “Block” method the various pieces of equipment for handling and placing the blocks will be exposed to harsh conditions and undergo wearing, which requires maintenance and access to reserve units. More advanced techniques, such as computer-controlled robotic operation increase the risk of frequent stoppages and equipment failure and so may not provide the robust, simple methods and tools that are asked for. Robot-based techniques do, however, offer fully automatic handling of backfill components with great precision and so would be ideal provided that safety and reliability criteria are fulfilled.

A pilot study has been made to assess the practicality of the “Robot” method with respect to its suitability for backfilling of deposition tunnels and to acquaint investigators with the conditions present during backfill placement, especially respecting identification of possible difficulties. The major results of these activities are summarized in the main text of the report while this Appendix gives some additional information, especially concerning the evolution of the “Robot” method concept.

This study has focused on how the various activities in the construction phase can be pursued considering logistics and time scheduling but it has not included any physical experiments.

1.1 Conditions and demands

All the activities in the backfilling process are undertaken under potentially challenging conditions, i.e. relatively low temperature and inflow of water that can be locally very strong. Despite the potential range of conditions the backfill components must meet the criteria established regarding hydraulic conductivity and the need to create a tight contact with the rock while providing active support to the surrounding rock mass. These demands are defined and discussed in greater detail in the main report. The possibility of constructing the most important components, i.e. the masonries of compacted clay blocks and the surrounding pellet fillings, and the foundation bed for them, is the focus of this report.

2 Design principle

2.1 Basic stacking pattern

The basic principle is that the blocks be placed so that the distance between the stacks of blocks, i.e. the block masonries, and the theoretical rock contour is at least 100 mm (Figure 2-1).

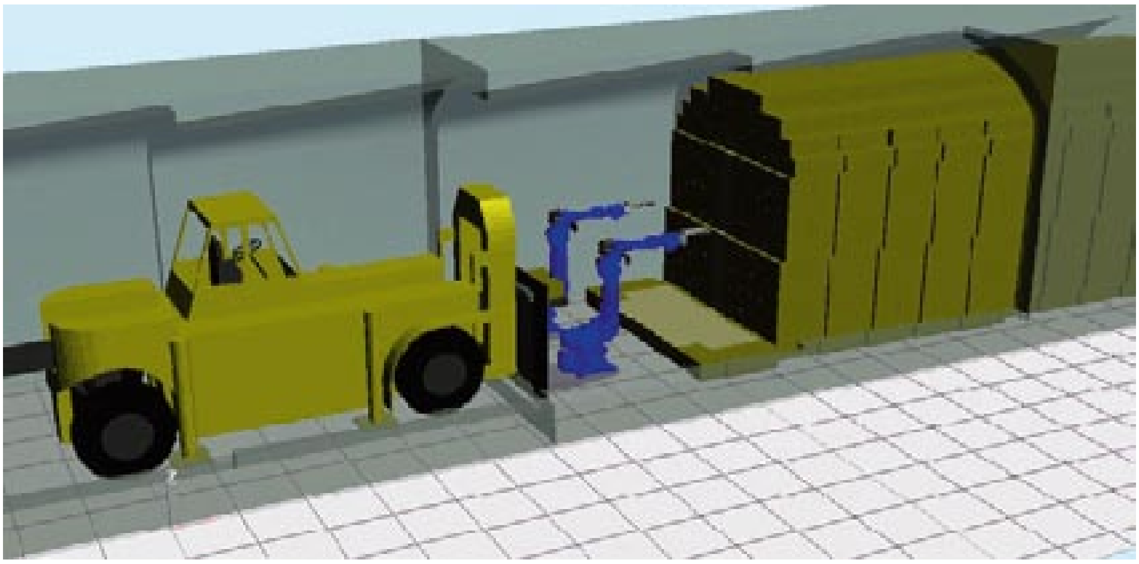


Figure 2-1. *Principle of placing blocks by use of robots.*

The tunnel profile and the block size determine the conditions needed to achieve the required block filling degree (at least 60%). Theoretically, small blocks make it possible to follow the tunnel contour better than larger blocks and hence give a higher degree of block filling, but the higher number of joints containing air, reduces the average density of the block mass. In this context it is important to recognize the impact of the evenness of the foundation of the block masonries on the straightness and width of vertical joints. Thus, for a foundation surface with small undulations the stacking of large blocks is not significantly affected, while stacks of small blocks will have wider joints with larger variations in aperture.

2.2 Size and shape of blocks

While the ”Block” method implies use of two block sizes and shapes the ”Robot” methods makes use of only one type of blocks. They have a width of 308 mm, a length (in the axial direction of the tunnel) of 500 mm, and a height of 300 mm. These dimensions, which must not deviate from the theoretically defined measures by more than a few tenths of a millimeter[1], were concluded to represent optimal conditions in preparing, handling and placing the blocks. The large horizontal surface of the individual blocks is suitable for using vacuum technique and even bigger blocks would

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[1] Stated by U. Baltzar, SKB’s responsible officer for blocks compaction

be handable but this would require larger and heavier robots. The maximum load is presently 1,000 kg. One can use two robot arms for handling two blocks at a time but this would require smaller blocks. Figure 2-2 illustrates the block arrangement.

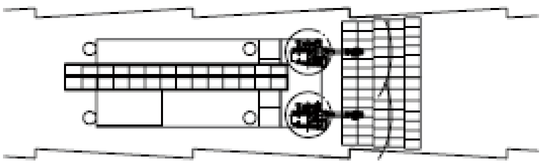

Figure 2-2. *Detailed mode of block stacking.*

For the “Robot” method the average aperture of vertical joints should not exceed 1 mm while the horizontal joints can be significantly smaller. The overall requirement is that the block masonries must not contain more than 2.0% unfilled space, for a block-filling degree of 60%. The larger part of this space is represented by the steep joints but also the horizontal joints may contain some air. As shown in Figure 2-2 the blocks will be mutually displaced in the direction of the tunnel and the amount of enclosed air will therefore depend on the displacement. Irregularities of the upper surface of the foundation bed will add somewhat to the amount of unfilled space. .

The number of blocks required to cover the cross section of the theoretical tunnel is 184, which means that the required rate of backfilling of 6 meters per day (24 hours) and that 2,208 blocks must be placed daily. Using two robots each of them must place 1,104 blocks per day. Each placement, including fetching, gripping, rotation and putting on site with due consideration of other activities, must take no longer than 30 seconds. This gives a very tight time schedule.

2.3 Foundation bed

As for the “Block” method, construction of the bed is made in units of full width, and with a length in the direction of the tunnel that depends on the inflow of water, and on the technique employed for placing the blocks. The foundation bed must not be loaded by vehicles or equipment, which means that each block placement sequence has to be adaptated to the reach of the tools used to place blocks and pellets. This sets the limit at 1.5 m for each sequence, corresponding to three vertical block layers, which is a little less than desired with respect to the impact of inflowing water.

The same practical implications are valid as for the “Block” method (cf. Appendix 1). Hence, the following issues must be considered in planning and constructing the bed:

- The tunnel axis is inclined downwards by 1.0% towards the outer end of the tunnel and the foundation bed must have the same inclination. Its upper surface must be continuous and smooth over the entire tunnel length to allow the respective block layer in adjacent masonries to fit adequately.

- The foundation bed is made 0.5 m longer than what is needed for hosting the block masonry. The reach of the block placement equipment must be at least 2 m in order to put the most distant blocks in the masonry on site.

- The foundation bed can be constructed on the irregular floor of blasted tunnels or on the plane floor obtained by wire-sawing. Water must be removed from the floor before construction starts. Irregular floors can be smoothed locally by use of silica concrete with a small amount of low-pH cement**.**

- The granular clay material used for the bed should provide a low-compressible foundation of the block masonries. Cebogel and Minelco granules have been tested and Minelco was found to be superior. The size distribution of the clay granules shall be such that the highest possible dry density for the applied compaction technique is obtained. Tests have shown that Minelco fill is preferable because water tends to flow along the contact between it and the underlying rock and not through it when loaded by blocks.

- The material to be compacted is placed and distributed by the equipment described in Appendix 1 ("Block" method).

- The granular material should be compacted to a high degree of homogeneity and a sufficiently high density to cause insignificant settlement of the block masonries that will be placed on the bed. This is suitably accomplished by 4 runs of a 150 kg vibratory plate over the surface of the bed. Preliminary tests have indicated that more than 4 runs do not significantly increase the density when the placed fill in about 150 mm thick layers. It will be necessary to conduct a series of full-scale tests before the details of the backfilling operation in the repository are formally defined.

- Dust generation must be as small as possible, which may require misting of water on the bed in the construction phase.

- Backfilling of ramps that extend from the tunnel floor down to the respective deposition hole will require use of equipment, material and techniques that are not yet specified or developed.

2.4 Block masonries

Figure 2-3 illustrates the stacking principle for the "Robot" method.

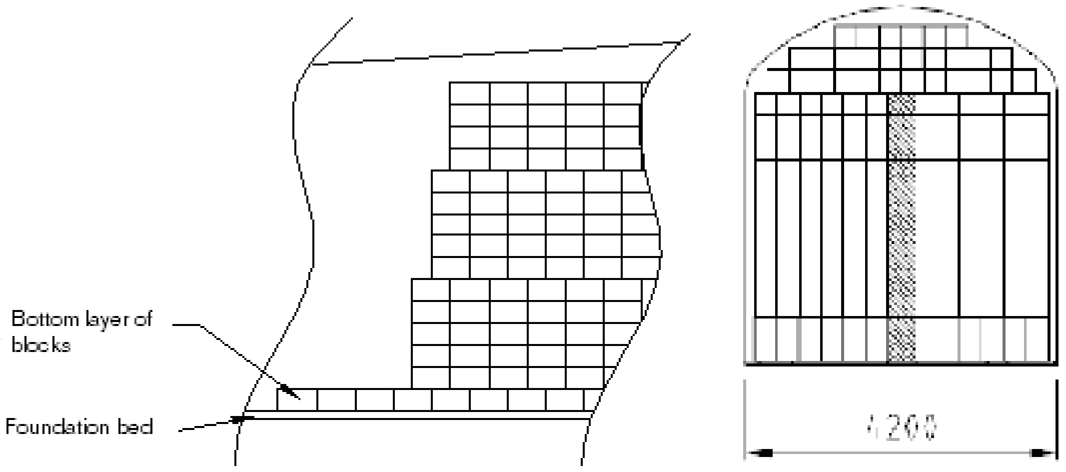

Figure 2-3. *Stacking mode for the "Robot" method.*

Deviations from the intended 1% inclination of the foundation bed affect the aperture of the horizontal joints in the block masonries and indirectly also of the vertical ones. The vertical joints should not be wider than 1 mm in order to fulfill the criterion that the maximal unfilled space in the masonry must not exceed 1.5%, assuming the block-filling degree to be 60%. The smaller size of the blocks means that the number of joints is higher for masonries constructed by application of the "Robot" methods, which hence means that this method is more sensitive for irregulars in the foundation bed than the ”Block" method.

For both the ”Block" and ”Robot" methods the geometrical pattern implying axial displacement of block means that there will be more unfilled space than for regular stacking with steep joints. Since the "Robot" method implies the highest number of blocks per cross section the numerous steep joints require more attention for fulfilling the criterion of maximum allowed unfilled space.

2.5 Pellet filling

Pilot tests have shown that pellets filled by simple pouring will not give a sufficiently high density and that unfilled parts of the space may remain. The problem of increasing the density sufficiently is firstly that only impact-type compaction will provide enough energy, and secondly that the resulting density may vary considerable. The shotcreting technique is preferable although a high degree of homogeneity of the fill may still not be achieved. Tests made at Äspö have shown that the dry density of pellet fills using tubes of 50 mm diameter and water added at the nozzle will be less than 1,000 kg/m^3. A possible way of increasing the dry density is to mix two or more pellet size fractions but experience from filling of granular material in other contexts, like the mining industry shows that there is a risk that they separate in the filling phase, leading to enrichment of coarser granules at the toe of pellet slopes. The matter needs further consideration and full-scale testing.

Placement of pellets in the space between the block masonries and the rock has several implications:

- The criterion set by SKB is that no more than 2% of the backfilled tunnel volume may be left unfilled with a degree of 60% of blocks made of Milos B clay. Experiments have shown that the voids representing joints between blocks will make up at least 1.5%, meaning that 0.5% can be the maximal allowed tunnel volume for pellet filling that can remain unfilled. This equals 100 liters unfilled space per meter backfilled tunnel assuming 20% over-excavated rock compared to the theoretical tunnel section. With a higher block filling degree the margins of allowed unfilled space increases.

- For 80% degree of block filling the pellets must be filled in campaigns corresponding to the length of the blast rounds since the front of the blocks will hinder insertion of the tube for blowing in the pellets to reach all the way to the earlier filled pellets. If a more smectite-rich clay like Milos B bentonite is used for the block production the conditions are less demanding. Thus, the calculated minimum degree of block filling would be 60% of each blast round giving more space for moving the pellet-filling tube. The filling process will not depend on the length of the blast rounds.

- Use of the more smectite-rich Milos B bentonite instead of Friedland clay for the block preparation means that the degree of block filling can be as low as 60% for each blast round. The pellet filling does not have to be adaptated to the blast rounds and the front can have the form of a slope. However, a steep front has advantages because better homogeneity of the fill will be obtained in the next filling sequence, and the checking of the installation can be made with better accuracy.

- The pellets can be allowed to form a slope with 45º angle, or be placed to form a steep front wall at the end of each campaign, which can be achieved by adding water to the nozzle of the tube,

- Dust generation can be very significant and water should be added to the nozzle of the tube used for blowing the pellets. Tests have shown that addition of 0.5-1.0% of tap water to the weight of air-dry pellets is sufficient for reduction of the dust production. This could be achieved by improving the nozzle used in the full scale experiments (Appendix 4).

Using the principle of stacking the blocks with smooth, continuous vertical joints the insertion of the pellet-filling tube is not hindered (Figure 2-4), and the pellets can be allowed to form a slope. The inclination will be 45º for Cebogel pellets. There are still some limitations, however. Thus, the tube should not be longer than about 5 m in order to achieve a pellet fill that is sufficiently homogeneous. In practice, there is no way of determining the degree of homogeneity.

The lower left picture in Figure 2-4 shows a flexible system that allows for a differently stepped front of the masonry, representing a very stable block arrangement with no risk of outward leaning with associated increase in void volume of the outermost block layer.

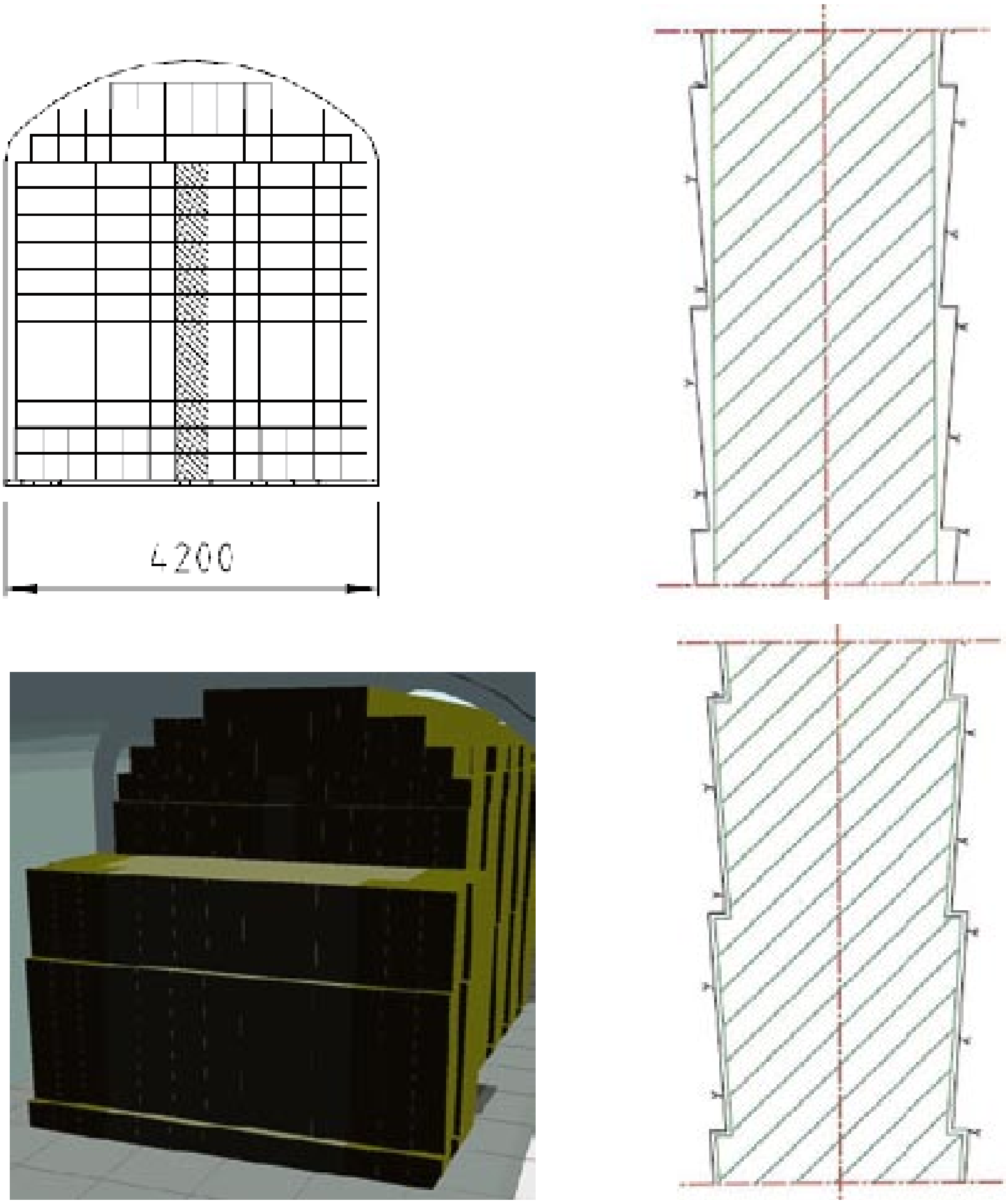

Figure 2-4. *Pictures of flexible stacking principles and their impact on the amount of pellet fill. The upper picture represents simple stacking with plane vertical joints.*

3 Equipment

3.1 Specification of equipment for the various backfill operations

The following three units are required for backfilling according to the “Robot” method:

- Equipment for construction of the foundation bed and pellet filling,
- Robot unit for placing blocks,
- Vehicle for transporting and delivering materials

3.2 Equipment for construction of the foundation bed

The equipment intended for constructing the foundation bed is the same as for the “Block” method, which is described in Appendix 1.

3.3 Robot unit for placing blocks

The robot unit serves to place the blocks and preliminary estimates have shown that two arms are preferable. Figure 3-1 illustrates the equipment.

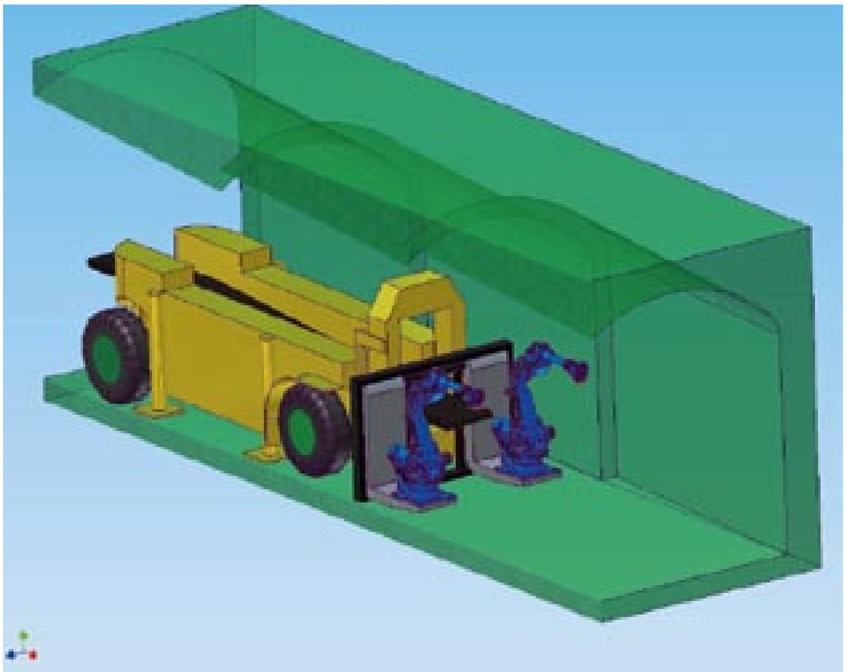

Figure 3-1. *Robot unit for block placement.*

As indicated in the figure a compartment for temporary storing of a limited number of blocks is coupled to the robot unit. The robot arms are individually supplied with blocks that are successively moved to the position where they are picked by the arms, which are equipped with vacuum-operated tools for lifting them.

Optimization with respect to easy handling, capacity and stability gave the design shown in Figure 3-2, implying use of robot with 200 kg lifting capacity and a reach of at least 2,700 (2,675) mm.

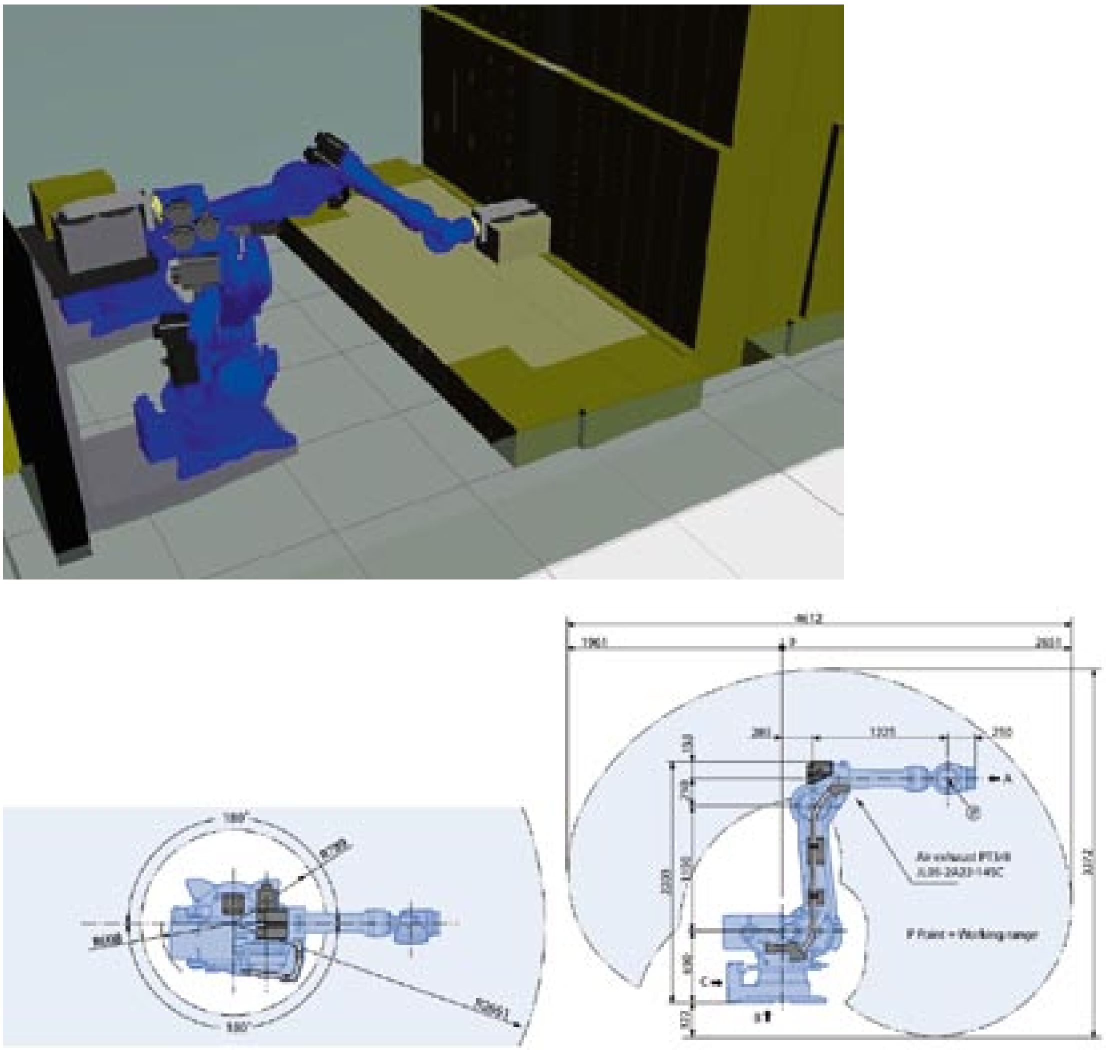

Figure 3-2. *Single-armed robot placing blocks. The lower two figures shows the working area of the robot.*

The decision to propose vacuum technique was based on the conclusion that block damage will be less extensive than would be caused by mechanical tools. It also means that the blocks are held from above, which makes placement with high precision possible. However, there are disadvantages as well, primarily that the space for the lifting tool is very limited and may require pushing of the uppermost blocks to get them in contact with the already placed blocks (Figure 3-3). Testing of proposed equipment under representative underground conditions is required and the need for maintenance estimated.

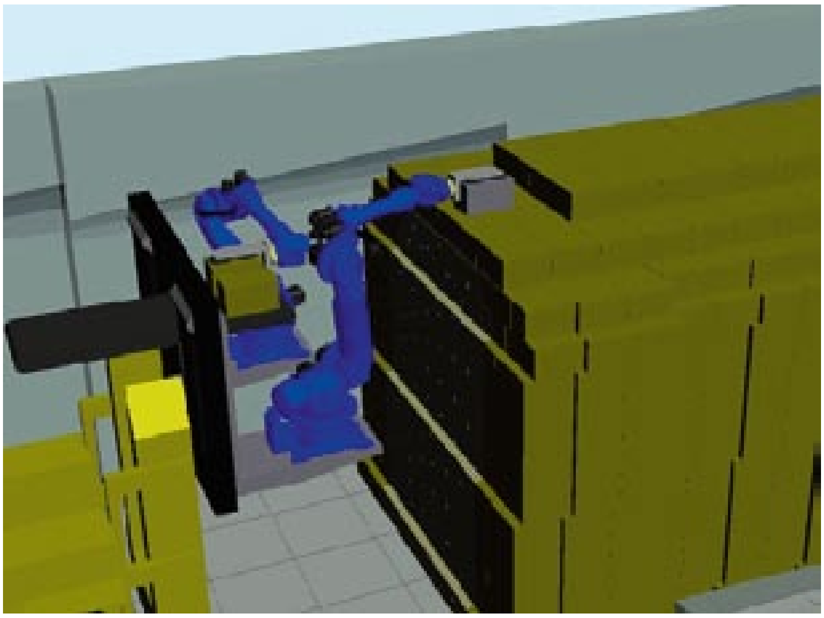

Figure 3-3. *Placement of the uppermost blocks where the tunnel height is at minimum.*

Operation of the robot unit will be computer-controlled implying an advanced technical solution that is sensitive to various disturbances, both externally and electronically. Any stoppage in the backfilling process will cause loss of time and problems like wetting and softening of placed backfill material. Figure 3-4 illustrates the computer-based system of operating the various units according to the “Robot” method. The most rational placing technique involves use of two robots as indicated in the figure.

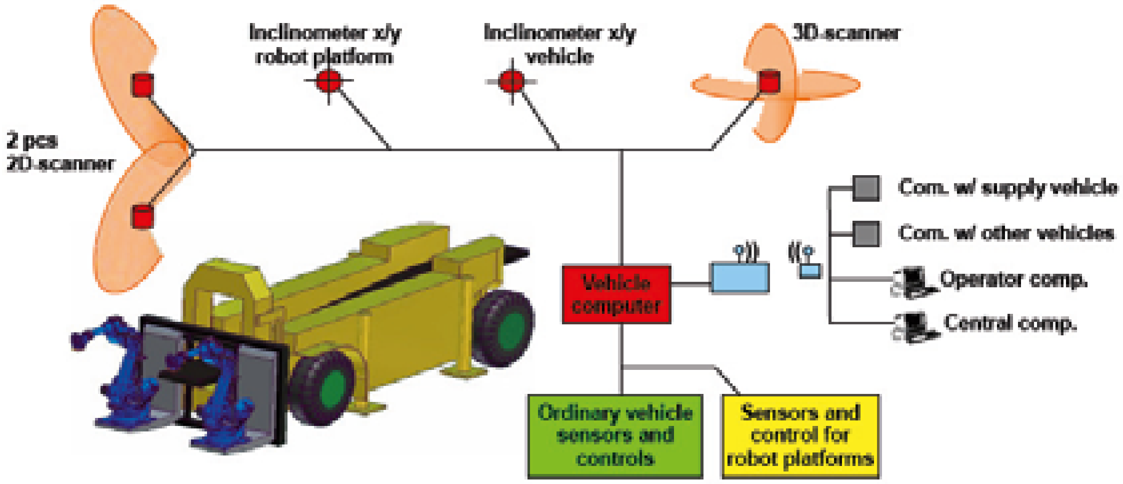

Figure 3-4. *System of two computer-controlled units of the ”Robot” methods.*

The working area of the robot arms must be fenced in and inspected during the block placing phase, for which two scanners are mounted on each side of the unit. A 3D scanner is placed on its top for measuring marks on the rock and block masonries. It determines the actual detailed (“global”) position of the unite expressed in x,y,z co-ordinates.

Each of the robot arms is equipped with a 2D laser scanner of type LMS400 to provide data on the tunnel contour and front of the block masonries taking the movement of the arms into consideration. The operator will also have access to advanced camera and geodetic techniques for precision measurement and for checking that there is no debris or block fragment left on horizontal block surfaces on which additional blocks will be placed.

It is estimated that the high precision of the systems for measuring positions of blocks and widths of joints would allow for placing the blocks with only millimeter-wide joints. This requires that the robot arms and block lifting tools can bring the blocks on site by exerting slight lateral pressure.

The most obvious difference between the use of robots for the presently described purpose and ordinary industrial use is that block placement requires movement of the entire robot unit to place blocks to fit earlier installed blocks while, in the industry, objects are mostly placed according to a predetermined program based on co-ordinate system.

3.4 Equipment for pellet filling

The equipment intended for constructing the foundation bed is the same as for the "Block" method, which is described in Appendix 1.

3.5 Vehicles for transporting and delivering backfill components

The vehicles intended for transporting and delivering backfill components is the same as for the "Block" method, which is described in Appendix 1.

4 Construction of backfill

4.1 General

For certifying that the criteria respecting joint aperture and that the degree of block filling are fulfilled the tunnel contour and geometrical features of the backfill must be regularly checked. This is more important for the "Robot" method than for the "Block" method since it will have more vertical joints due to the larger number of blocks per cross section and to the geometrical pattern of ½ block displacement. Comparison with other alternative measuring techniques has led to the proposal to use 3D- laser scanning techniques since it is estimated to provide tunnel volume data with an accuracy of about 99.5%. Camera techniques and automatic geodetic methods may turn out to be equally good or more competitive in a longer time perspective.

4.2 Foundation bed

The procedure is the same as described in Appendix 1 ("Block" method). It involves installation of the equipment for construction of the foundation bed with its supporting legs safely resting on the floor, and measurement of its co-ordinates, i.e. its "global positions". The scanning unit for measuring the tunnel profile records the topography of the walls and roof over the 1.5 m length that represents the next unit length, and of the earlier constructed foundation bed that extends by 0.5 m from the previous placed block masonry. The computer code calculates the level of the new foundation bed considering the possible need for adding material, and the impact of compaction. Once this has been made the material is distributed over the area and compacted.

4.3 Block placement

The Robot unit is installed in front of the previously constructed block masonry and its supporting legs are lowered to provide stability and minimal movement of the machine in the course of the block handling procedure. Its exact position is determined and recorded. The scanning unit for measuring the tunnel profile records the topography of the walls and roof over the 1.5 m length that represents the next unit length. It also checks the front of the previously constructed block masonry. Water flowing into the space between rock and earlier placed blocks is continuously discharged.

The various computer-controlled activities leading to completion of the block placement campaigns are shown in Figure 4-1.

The required rate of backfilling is 6-8 m. Thus, for backfilling of the tunnels at a rate of about 6 m per day, 2,208 blocks must be placed per day, each placement requiring 30 seconds with two parallel working robots. The backfilling rate can probably be further increased if the block-placing equipment can be combined with the unit for preparing foundation beds.

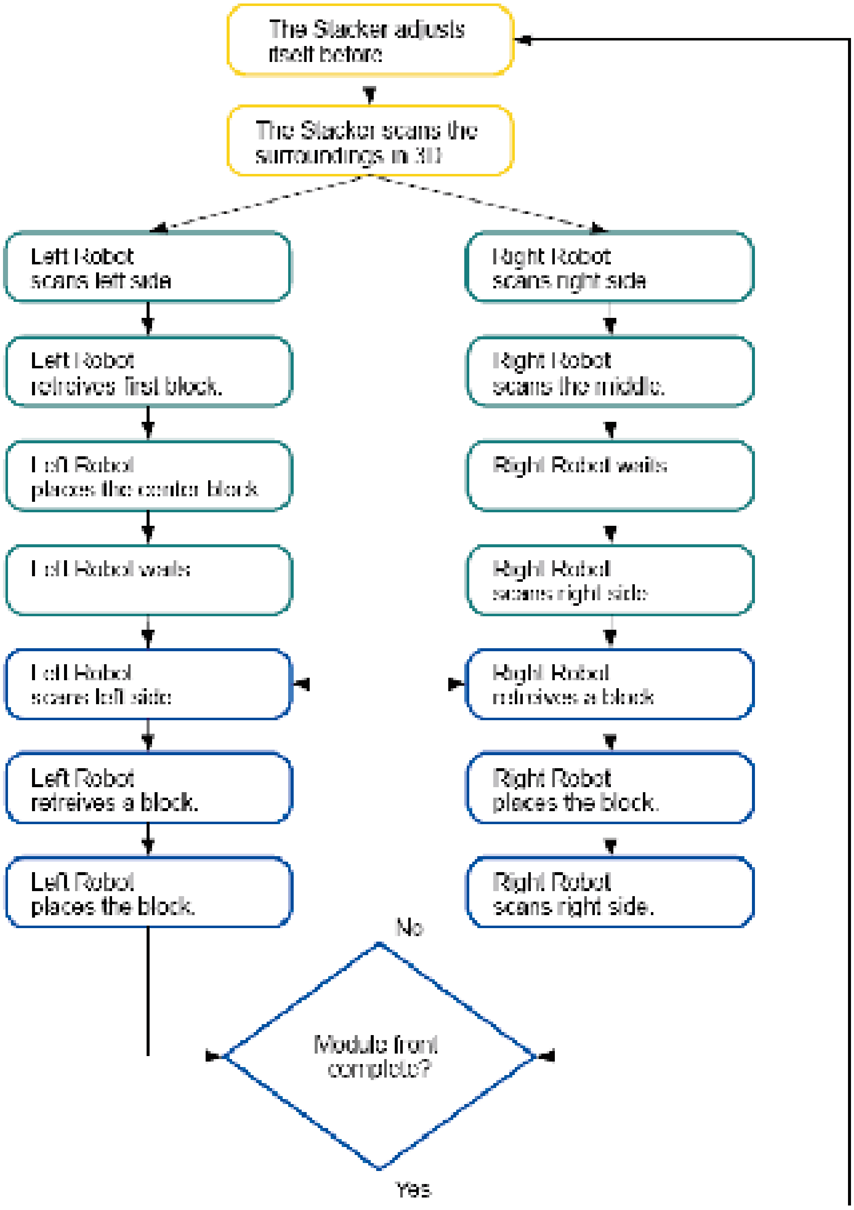

Figure 4-1. *Scheme of activities in scanning rock and block masonries and placing blocks.*

The block-placing starts by stacking blocks in the center and then sideways, one arm serving the left half and the other the right half. The placement is not made by following the co-ordinate system but simply placing the blocks as close as possible to each other. The exact position of the placed blocks is measured for comparison with the planned block pattern and for calculation of the total volume of the blocks. Significant deviation from the predicted geometry must be immediately identified and the placement of blocks stopped to allow removal of incorrectly installed blocks, and to adjust the masonry.

The stacking principle is shown in Figure 4-2. The lowest parts of the stepped units are placed to reach full width, length, and height before the second is started etc. At the end of each round the steep block front is scanned and checked.

***Figure 4-2.** Stacking of the equally sized blocks. Placement of blocks by use of both robot arms to form three stepped units mutually displaced by ½ block length. The total length of each unit is 1.5 m.*

4.4 Pellet filling

Filling pellets so that a slope is formed means that the blocks will be exposed to humid air before the fill surrounds and supports the block masonries, which may therefore undergo some hydration and expansion.. Sloping pellet fills mean that the toe of an earlier filled slope will be located far behind the most recently placed block masonry. The following limiting factors were identified:

- The pellets must be placed before the blocks start moving under their own weight or by a yielding foundation bed. If movements are identified, part of the block masonry and foundation bed may have to be removed and replaced,
- The pellet filling must not cause significant dust generation. If compressed air is used for placement, clay particles are released and stirred up causing problems if there is insufficient ventilation in the tunnel system,
- Pellets may accumulate on horizontal block surfaces, which must be examined and cleaned before additional blocks are placed. The robot unit is moved out of the tunnel and the facility employed for completing the backfill, i.e. the pellet blowing machine, moved to the front of the latest completed block masonry. This equipment and the pellet filling procedure are described in Appendix 1.

When the pellet filling is complete the front of the fill is scanned and geometrical data recorded. The amount of pellets is compared to the predictions and possible deviations evaluated for possible removal and reconstruction of the whole backfill unit. If the density of the pellet fill is significantly lower than anticipated it should be possible to use compaction tools for increasing it. The idea is to move a vibrating lance in and out in the pellet fill between rock and block masonry, which is believed to leave the latter unaffected. The compaction effort on the pellet fill may not be very important but the homogeneity is assumed to be raised except near the roof where some other tool, like a pneumatic hammer with moderate impact, may have to be used.

Once the backfill unit has been approved, work on the next 1.5 m long unit is started, beginning with the foundation bed. Construction of the individual backfill units ideally takes about 6 hours.

4.5 Time schedule

The time planning was based on estimations and experience from tests performed as part of this study. It was also assumed that each block installation cycle including fetching, moving and placing the respective blocks and moving the equipment back for the next cycle, must be made in 30 seconds. This gives a margin of 2 hours per day, a schedule that is even tighter than for the "Block" method. In preparing the construction of a backfill unit volume in a real repository using the "Robot" method the following activities must be planned and defined and the required time for each of them estimated:

- 3D scanning of the tunnel.
- Construction of foundation bed including completion of the deposition holes (placement of canisters, buffer blocks and pellets).
- 3D scanning of the foundation bed.
- Installation of the equipment for block placing, arrangement of block supply.
- Placement of blocks in first layer.
- Checking of geometry in 3D.
- Placement of remaining block series.
- Checking of geometry in 3D.
- Retreat of the block placing equipment.
- Installation of the equipment for constructing the foundation bed, prepared for pellet filling.
- Filling of pellets.
- Checking of geometry in 3D.
- Extension of foundation bed.
- Checking of geometry in 3D.
- Retreat of the equipment for constructing foundation beds.
- Installation of the equipment for block placing, arrangement of block supply.

Start of next round:

- 3D scanning of the tunnel.
- Construction of foundation bed including completion of the deposition holes (placement of canisters, buffer blocks and pellets).

Etc etc

As for the other backfilling methods it should be noted that delay in carrying out preparative work in and around the deposition holes has not been included in the time schedule. According to the present plans the backfilling process has to be stopped for removal of the buffer protection sheet, for pellet installation in the respective deposition hole, and for filling of the ramp at its upper end. This suggests that backfilling will need to be done in two tunnels at a time, an issue that is discussed in the main text of the report.

The planned routine implies that the backfilling operations shall cease once per 24 hours for removal of the buffer protection sheet, drainage and alarm installation from the respective deposition hole when it is reached by the front of the progressing backfill. These activities are followed by completing the canister deposition holes by placing the buffer pellets, and by filling the ramps at the upper ends of the deposition holes. The time for doing all this is estimated at 6 hours per day during which water will flow from the rock into the backfilled part as well as in the open part outside the backfill.

It is the authors' opinion that several of the activities preceding the start of each backfilling sequence need to be reconsidered and simplified to make adequate backfilling according this method possible. It is believed that the ramp at the upper ends of the deposition holes should be deleted and that the buffer protection sheets and possibly also the buffer pellets should be eliminated or made so that they do not hinder or jeopardize safe backfilling.

5 Tests and development of techniques

5.1 R&D program and general matters

The potential for developing the "Robot" method is considerable but it can hardly be expected that a sufficiently large and movable robot unit can be designed and manufactured within the next decade. It is realized that a comprehensive R&D program is required including comprehensive desk studies and construction of prototype versions for testing under representative conditions at depth.

The following issues that need closer examination and development are virtually the same as for the "Block" method, i.e:

- Examination of the required resources, strategy, and time for development of equipments and tools. Development of R&D program.
- Specification of demands.
- Performance of small-scale tests for verification of the applicability of the method (conditions for using vacuum and other techniques), and for identification of controlling parameters as well as for identification of parameters, and ways of recording adequate data.
- Development of conceptual and detailed technical design of equipments.
- Development of drawings and descriptions for manufacturing of equipments.
- Contracting of consulting work and manufacturing of equipments.
- Manufacturing of equipments.
- Description of required test program.
- Performance of tests.
- Assessment of the outcome of the tests and selection of ways for further development.

Parallel to this, a program for manufacturing blocks must be worked out. It should specifically deal with the compaction technique for preparing blocks using different clay materials, and should be integrated with the work required for selection final selection of clay materials. This work should show what the optimal density is of the blocks respecting hydraulic conductivity and swelling pressure and should show the impact of different block densities on the density and properties of the pellet fill.

5.2 Special studies

Applicability of the robot-based placement technique requires that a special program be worked out for development of the following components and investigation of the issues listed below:

- Lifting tool operating with elasticity; design and construction.

- Hardware, 2D-scanners mounted on robot arms and software for making them serve in the measurement of positions of marks and blocks.

- Study for finding out if there are commercially available industrial robots with larger load capacity and range than the presently proposed robot identified by the company Motoman Robotics Europe AB in Kalmar. This can lead to selection of other block sizes than are presently considered.

- Manufacturing of a simple prototype of the chassi of a robot unit. It shall be movable vertically and laterally and serve to carry a robot and be coupled to a simple equipment for bringing blocks.

- By use of this equipment tests should be made for providing answer to the following key questions:

    - What will the void space be between the blocks that are stacked on a very good foundation bed?

    - What will the void space be between the blocks that are stacked on a foundation bed that has been affected by water?

    - Demonstrate that the capacity of placing 1 block per 30 sek can be obtained considering required time for measurements.

    - How close to the first block row can the robot really place blocks considering the performance of the lifting tool and the height of the blocks? Can the tool put the blocks adequately on site with required precision where the tunnel height is at minimum?

    - How are incorrectly placed blocks removed and replaced?

    - How much debris and clay fragments are produced in the block handling?

    - How can the block placement equipment be designed and automized so that the blocks can be put in tight contact with earlier placed blocks?

When the tests have been conducted and the questions have been answered decision can be taken of whether a full-scale machine should be designed and manufactured.

6 Tentative judgement

It is believed that serious assessment of the ”Robot” method would require comprehensive continued investigation. A valuable property is that the method is much less dependent on operators than the ”Block” method and that the quality of the completed backfill can be very high. However, development of the technique is judged to be uncertain and it is recommended to do some preliminary studies, possibly in conjunction with a study also of the “Block” method. If this works out well the “Robot” method would be ranked higher than the “Block” method.

Once a decision has been taken to investigate the candidature of the “Robot” method one needs to consider the same issues as were listed for the “Block” method, i.e.:

- A risk of importance is that shallow wetting of blocks by dripping water or moist atmosphere makes vacuum lifting uncertain or impossible. Dust or debris on the block surfaces can also cause mishaps.
- The “Robot” method will make use of small blocks. With smaller blocks, a larger number of gaps will be formed, which means that extensive control with regards to position and density is required, which will have an influence on backfilling capacity.
- It is not decided how the robots shall handle removal of pellets from the upper side of the blocks, removal of blocks, rearrangement of blocks etc.
- The ”Robot” method has a small working range, which will cause a relatively low placing capacity.
- For fulfilling the criterion of backfilling 6 meters per 24 hours each block handling sequence must not require more than 30 seconds. The time schedule has no room for stops or mishaps. It is estimated that future R&D can yield robots that can handle bigger blocks. The presently estimated low backfilling rate, makes this method less promising than the “Block” method.
- It is estimated that the “Robot” method has a potential to be developed and improved parallel to the evolution of other techniques in the building and mining fields.
- Irrespective of the method employed for placing the blocks it would be advantageous to combine the equipment with the unit for constructing the foundation bed.
- It is estimated that the ”Robot” method has the lowest potential for development of a practically useful technique in a short time perspective. However,, if the reach and size of blocks can be increased, the potential of the “Robot” method will be of greater interest.

Äspö 2008-08-04

Hans Wimelius	Roland Pusch
SKB, Äspö	Geodevelopment International

Appendix 3

Backfilling of deposition tunnels – the “Module” method

Svensk Kärnbränslehantering AB

Geodevelopment International AB/SWECO

August 2008

Contents – Appendix 3

1 Introduction

The “Module” method implies that the blocks are handled and placed group-wise, forming “modules”. Pellets are used to occupy the remaining space.

The “Module” method is a rational way of placing blocks in deposition tunnels. It implies that the blocks are pre-assembled on the ground surface to form coherent units. This reduces the work in the deposition tunnels where the conditions for accurate handling and placing of the blocks are more challenging with respect to space and time. The method is straight-forward and the logistics appealing although there are some issues that need to be further examined, like the block size and some stability matters.

The basic conditions for backfilling deposition tunnels by use of the “Module” method are the same as for the “Block” and “Robot” methods. Thus, the same criterion of using well known techniques for construction will be applied but for certain purposes SKB will have to develop new methods. As for the other methods the various equipments for handling and placing the blocks will be exposed to harsh conditions and undergo wearing, which requires maintenance and access to spare parts.

A pilot study has been conducted for assessing the “Module” method with respect to its suitability for backfilling of deposition tunnels, with the specific intention to find a very simple technique for block placement. The major results of this activity are summarized in the main text of the report while this Appendix gives some additional information, focusing on practicalities and logistics and time scheduling. The conceptual modelling has formed the basis of a prediction of the structure and geometry of the backfill units for later evaluation of the expected performance.

1.1 Conditions and demands

All the activities in the backfilling process according to the “Module” method need to be planned in the same careful way as for the alternative techniques. Thus, the impact of inflow of water on the rate and accuracy of the placement of block units and pellets must be considered so that the basic requirement of a sufficiently low net hydraulic conductivity and a swelling pressure that is high enough are fulfilled. The special feature of the “Module” method to place groups of blocks has the potential of creating backfills of higher quality than the alternative methods. The weakest point is the same for all of them, i.e. the ability to determine the quality of the pellet fills. A further difficulty that is also common to all three methods is the construction of the foundation bed, which will be disturbed as the result of water inflow from the rock or from previously placed bed units.

2 Design principle

2.1 Basic stacking pattern

The principle to be followed is that the block units shall be placed so that the distance between these units and the theoretical tunnel contour is at least 100 mm. This distance can be obtained where the tunnel width and height are at their minimum, provided that the proposed handling of the modules is accurate enough. The stacking principle is shown in Figure 2-1. Three big bottom blocks with smaller blocks stacked over them form units termed "modules" that are held together during transport and placement. The units are kept stable by orienting some blocks so that they serve as binders. The stability of the stacks is significantly better than of the block assemblies of the alternative methods, because of the larger area of the block base. Still, the stability of the columns of modules, separated by steep, continuous joints, needs further study.

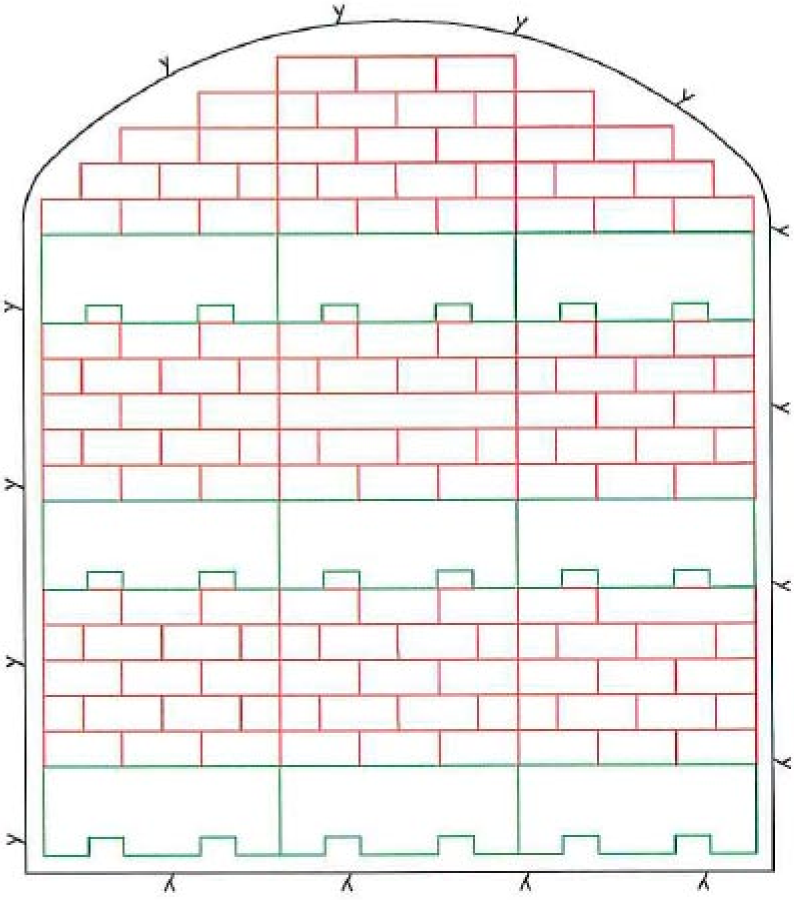

Figure 2- 1. *Schematic cross section of the tunnel with block module units consisting of a big bottom block on which tightly stacked smaller blocks rest.*

The potential for applying the "Module" design principle is determined by the required degree of block filling and the actual tunnel dimensions.

The bottom blocks are made in two halves having the dimensions 1,333 x 666 mm and a height of 500 mm. These blocks, forming the base of the modules, hence have the dimensions 1,333x1,332 mm in the horizontal plane. The height of the modules is adaptated to the tunnel height by using smaller blocks stacked on the bottom blocks as illustrated by Figure 2-1. Where the tunnel cross section is at minimum the modules will be designed and placed so as to follow the theoretical tunnel profile with a distance between rock and blocks of 100 mm. The modules in this part of the tunnel have the dimensions shown in Figure 2-2. Their weight is about 5.2 t.

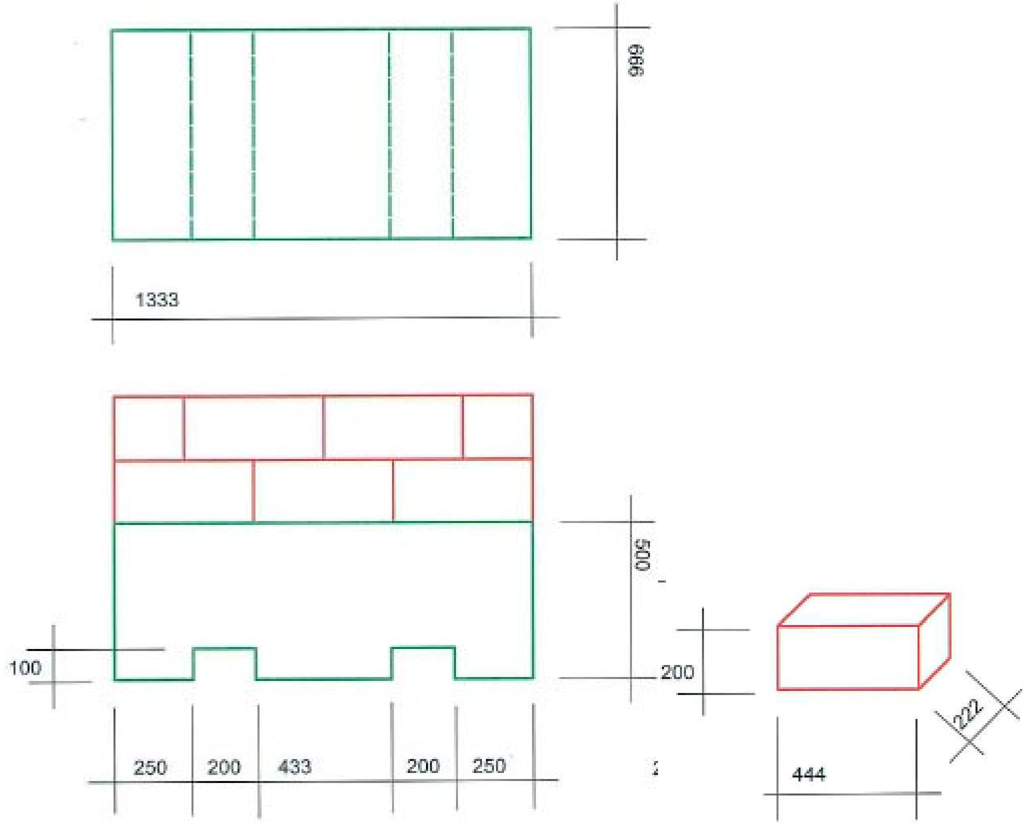

Figure 2-2. *Configuration of blocks where the tunnel height is at minimum.*

The required number of modules needed to fill the cross section of the tunnel is 9. This is believed to be optimal since a large number of smaller modules would cause practical difficulties and a lower filling rate. A smaller number of modules would make the modules too heavy.

Preparative tests and conceptual models have been used for finding optimal block arrangements in the modules with respect to stability and to block shape and size. The actual measures will not deviate from the theoretically defined measures by more than a few tenths of a millimeter[1]. This has yielded successively improved understanding of possibilities and limitations for manufacturing of blocks and construction of modules, especially concerning the bottom blocks. The work has continued throughout 2008 and will be reported later. The way of stacking the smaller blocks shown in Figure 2-3 has been tested on a full scale and found feasible.

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[1] Stated by U. Baltzar, SKB's responsible officer for blocks compaction

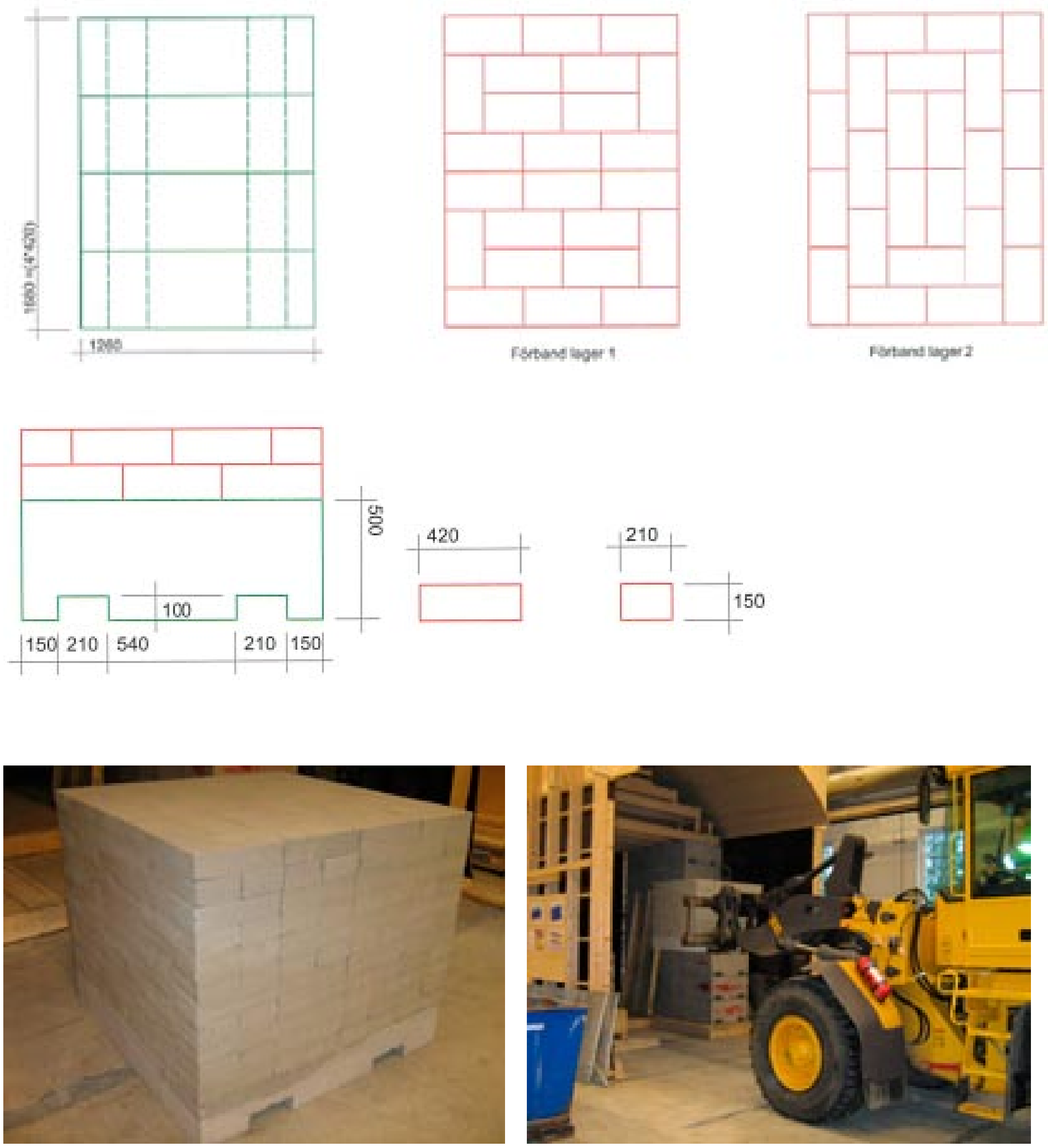

__Figure 2-3.__ Stacking of the smaller blocks. Upper: design principle. Lower: example of full-scale test.

2.2 Foundation bed

As for the "Block" and "Robot" methods construction of the bed is made in units covering the entire tunnel width but without compacting it within 100 mm distance from the theoretical rock profile because no modules will rest on this part of the bed. Each bed unit will have a length in the direction of the tunnel of 2-4 m depending on the inflow of water, and on the technique employed for placing the blocks.

The same practical implications are valid as for the other methods. Hence, the following issues must be considered in constructing the bed:

- The tunnel axis is inclined downwards by 1% towards the outer end of the tunnel and the foundation bed must have the same inclination. Its upper surface must be continuous and smooth over the entire tunnel length so that the respective block layer in contacting masonries fit.

- The foundation bed is prepared to correspond to the length of two modules (2.66 m). The block-placing tool has a maximum reach of slightly more than 4.5 m, which means that the bed can be constructed with a length of more than 2.66 m if the rate of inflowing water is small ("dry sections"). Where such conditions prevail the axial length of the bed can probably correspond to the length of three modules, i.e. about 4 m. This flexibility in "installation" length is an advantage compared to the "Block" and "Robot" methods.

- The foundation bed must be constructed on a dry base.

- The granular clay material used for the bed should be suitable, providing a low-compressible foundation of the block masonries. Cebogel and Minelco granules have been tested and the Minelco material was found to be superior. The size distribution of the clay granules shall be such that the highest possible dry density for the applied compaction technique is obtained.

- The material to be compacted is filled and distributed by equipment described in Appendix 1 ("Block" method). However, it seems possible also to mount the unit for bed construction on the module-placing equipment, which would make the whole backfilling sequence quicker. Hence, only two types of equipment would be required: one for bed construction and module-placing and the other for pellet filling. The latter can be placed close to the former reaching over it to perform the pellet filling. The time and cost saved by eliminating the transport in and out of several machines would be advantageous compared to the "Block" and "Robot" methods. Also, the backfilling would be safer because the time of exposure of the bed, blocks and pellets to water would be much shorter.

- The granular material should be compacted to become homogeneous and sufficiently dense to undergo only insignificant settlement of the block masonries that will be placed on the bed. This is suitably made by 4 runs of a 150 kg vibratory plate compactor for a layer thickness of up to 150 mm. A series of full-scale tests will be needed before the backfilling operation in the repository is formally defined.

- Dust generation must be as small as possible, which may require misting of water on the pellet bed in the construction phase.

- If the actual tunnel profile deviates significantly from the theoretical it may be necessary to construct the foundation bed with a stepped upper surface.

2.3 Block masonries

Like the “Block” method, the “Module” method requires use of more than one block size. The problems associated with individual placement of blocks that are evident in the application of the “Block” and “Robot” methods is solved by using units of blocks held together by a container during transport (Figure 2-4).

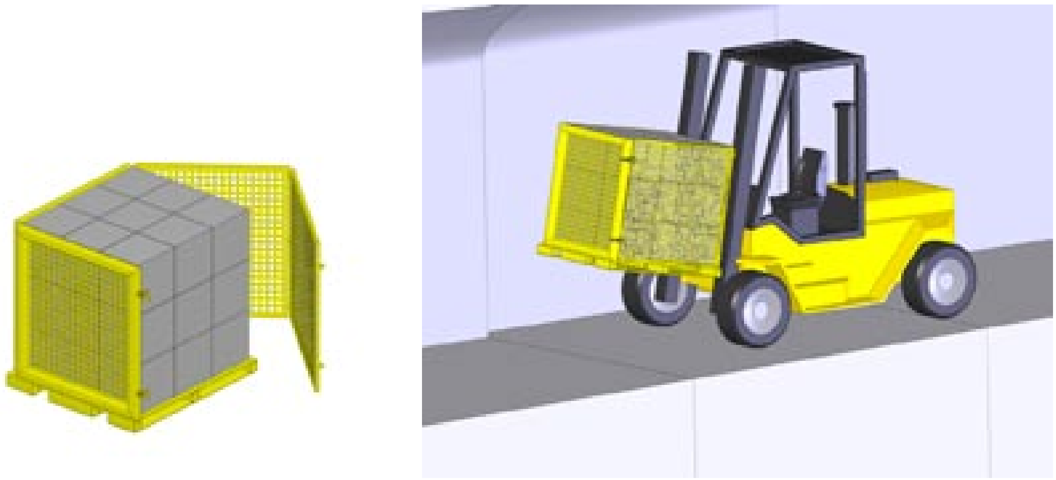

Figure 2-4. *Transport container for the modules, which will be plastic-coated until placement is made.*

The risk of dropping blocks when using vacuum technique for lifting the blocks as for the “Block” and “Robot” methods is avoided by using a fork truck. The larger size and weight of these units may cause difficulties in handling them with sufficient accuracy and care. The holes in the bottom blocks for the forks need to be filled with pellets or small blocks of compacted smectite-rich clay after placement. Preliminary tests have shown that such sealing can be made to a depth corresponding to at least the length of two modules (2.66 m).

The use of modules means that all front surfaces of the masonries are steep. The block size and internal stacking mode in preparing the modules determine the block filling degree, which may be as high as 89% of the theoretical tunnel section area for the case in Figure 1 but which may be reduced depending on the shape and volume of the tunnel.

The required rate of backfilling is 6-8 m but quicker placement is desired and possible. Thus, for backfilling of the tunnels at a rate of about 10.6 m per day, 72 modules must be placed per day, each placement requiring 5 minutes, which is deemed plausible. The backfilling rate can probably be further increased if the block-placing equipment can be combined with the unit for preparing foundation beds.

Figure 2-5 is a schematic longitudinal section of a masonry of modules with vertical front and joints reaching from foundation bed to roof. The impact on the construction of the foundation bed and pellet filling caused by the stepped rock profile at floor and roof is illustrated in this figure.

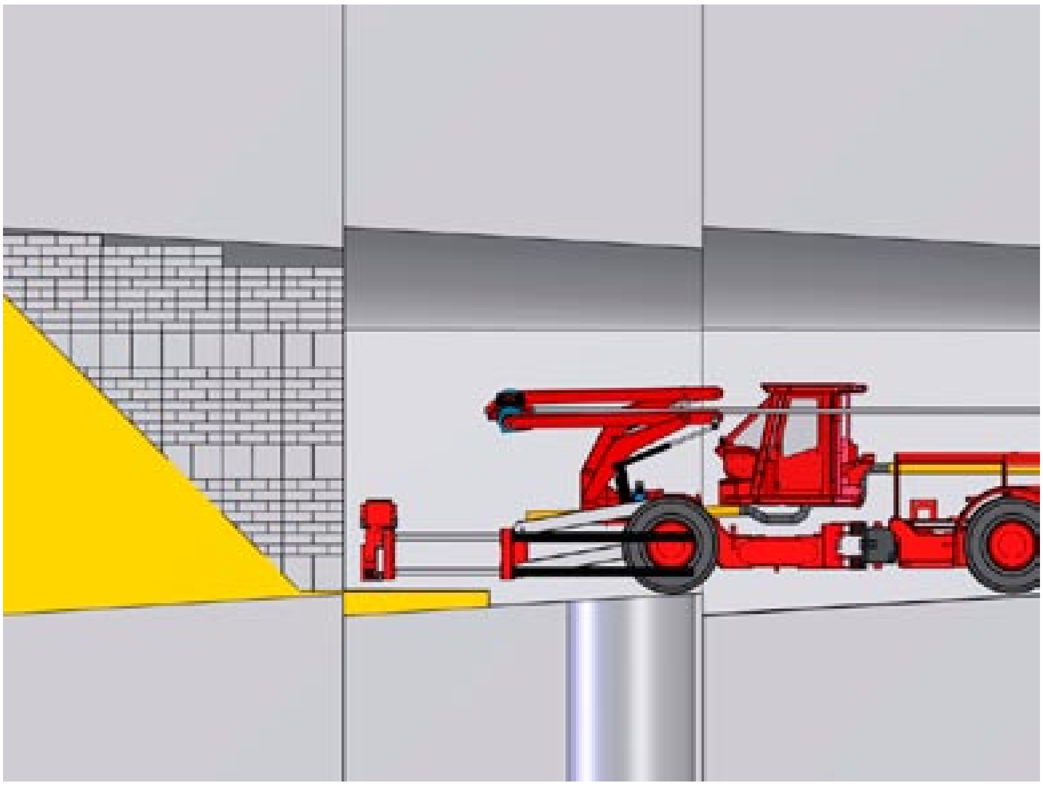

Figure 2-5. *Masonry of modules with steep joints*.

The stepped shape will be required if the look-out is larger than 200 mm, since the total height of the pellet-filled space at the roof would otherwise exceed the specified maximum value of 300 mm.

2.4 Pellet filling

The pellet filling process is the same as for the “Block” and “Robot” methods. It is made by employing shotcreting technique as summarized below:

- The criterion set by SKB is that no more than 2% of the backfilled tunnel volume may be left unfilled for a block-filling degree of 60% provided that the blocks are made of smectite-rich clay like Milos B bentonite.. Experiments have shown that the voids representing joints between blocks will make up at least 1.5%, meaning that 0.5% of the space intended to be filled with pellets can be left unfilled. This equals 100 liters unfilled space per meter backfilled tunnel assuming 20% over-excavated rock compared to the theoretical tunnel section. For a higher block filling degree the acceptable unfilled space increases.

- For 80% degree of block filling the pellets must be filled in campaigns corresponding to the length of the blast rounds since the steep front of the modules will hinder insertion of the pellet-filling tube to reach all the way to the earlier filled pellets. If a more smectite-rich clay like Milos B bentonite is used for the block production the conditions are less demanding. Thus, the calculated minimum degree of block filling would be 60% of each blast round, giving more space for moving the tube. The filling process will not depend on the length of the blast rounds.

- Dusting can be very significant and water should be added to the nozzle of the tube used for blowing the pellets. It has been demonstrated that the required amount of water is 1.0-0.5% of the weight of air-dry pellets.
- The pellets can be allowed to form a slope with 45º angle, or be placed to form a steep front wall at the outer end of each campaign, which can be achieved by adding water to the nozzle of the tube.
- The ”Module” method has two major advantages compared to the ”Block” and ”Robot” methods respecting the installation of pellets. One is that the determination of the volume of the filled mass and degree of pellet filling is easier and more accurately made because of the vertical front of masonry and pellet fill. A second one is that there is no need for checking and cleaning horizontal surfaces in the masonry construction phase. They simply do not exist.

3 Equipment

3.1 Specification of equipment for the various backfill operations

For backfilling according to the “Module” method the following three pieces of equipment are required:

- Equipment for construction of the foundation bed and pellet filling.
- Equipment for placing modules.
- Vehicle for transporting and delivering materials.

As indicated in the preceding text the planned development of the various equipments will include attempts to combine the units for block placement and bed construction.

3.2 Equipment for construction of the foundation bed

The equipment intended for constructing the foundation bed is the same as for the “Block” method, which is described in Appendix 1.

3.3 Equipment for placing modules

A very important part of the block handling using the “Module” method comprises lifting, handling and placing of the big units. It cannot be made with the high accuracy of the alternative methods because of the size and weight of the big block units but still with sufficient care**.** A prerequisite for considering application of the method is that the modules remain intact after placement, and that the average gap between them does not exceed about 9 mm. The equipment for placement has been preliminarily designed, leading to two alternatives that are shown in Figure 3-1. The left (blue) version with a capacity to rotate lifted objects by 180^o in the horizontal plane, is taken as a basis of the subsequent text. In contrast to the “Block” and “Robot” methods, the “Module” method only utilizes presently available techniques.

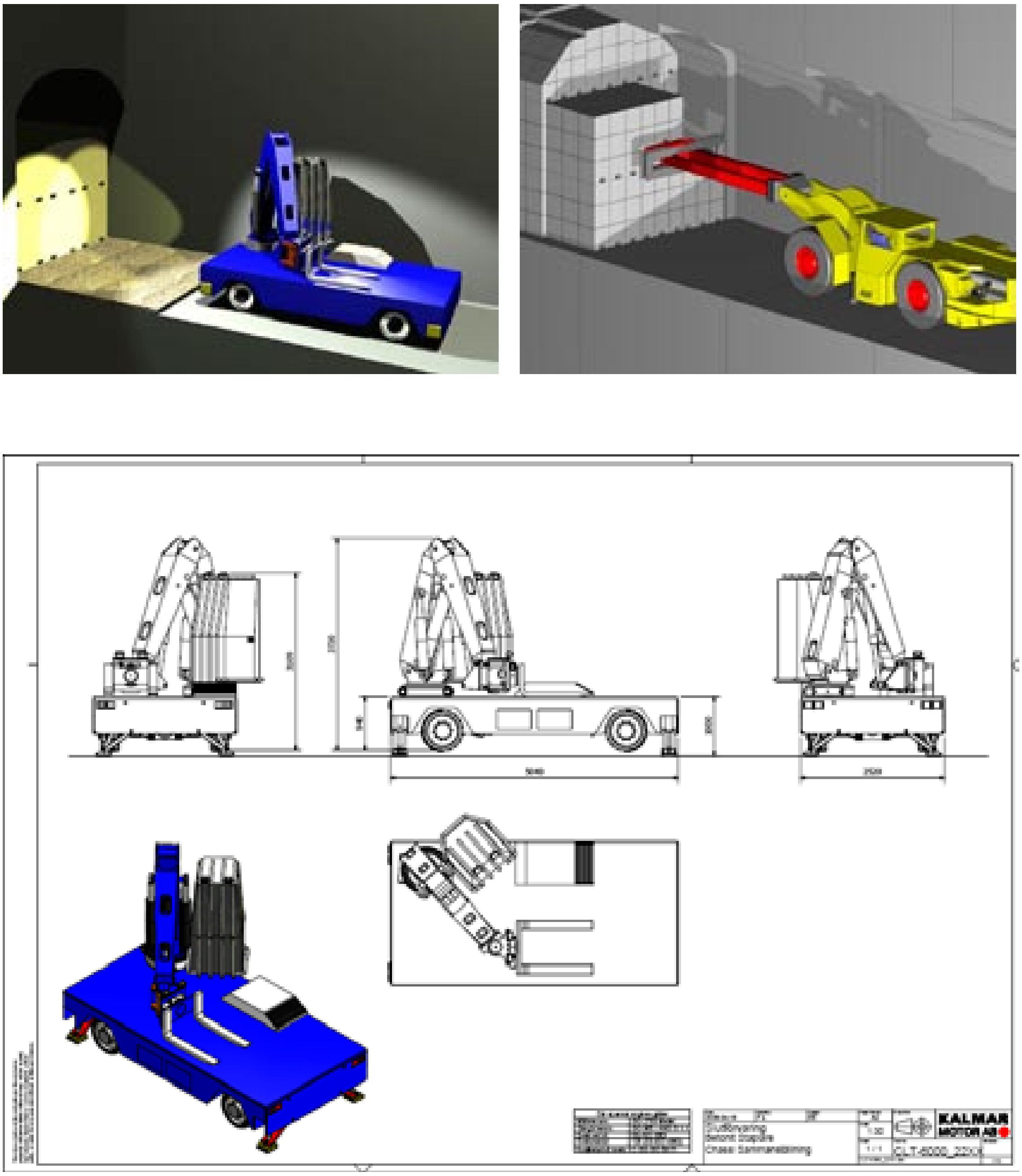

Figure 3-1. Proposed design of equipment for placing modules.

3.4 Equipment for pellet filling

The equipment intended for the pellet filling is the same as for the “Block” method, which is described in Appendix 1.

3.5 Vehicles for transporting and delivering backfill components

The modules can be transported either by use of lifting tools (cf. Figure 2-4), or by connecting a 9-module storage unit to the module-placing equipment located behind the placing unit, supplying it with modules for preparing one complete round. After emptying the store it is replaced by a new one, in parallel with relocation of the placing unit.

The rate of delivery of modules to the construction site may be a limiting factor for the time required for the entire backfilling process. The key parameter is the time needed for moving the module-carrying vehicles in and out of the tunnels. It is presently assumed that a vehicle with 9 modules would be docked to the module-placing equipment for providing it with a sufficient number of modules to complete a masonry unit. Removal of the vehicle and bringing in the next one with its 9 modules can be made in conjunction with checking and adjusting the front of the just completed masonry of modules.

The ”Module” method has the advantage of making use of block units that have been prepared on the ground surface and that can be brought down directly to the deposition tunnels without reloading and intermediate storage at depth.

4 Construction of backfill

4.1 General

As for the "Block" and "Robot" methods, fulfilling of the criteria respecting the degree of block filling, the tunnel contour and geometrical features of the backfill units must be regularly checked, for which 3D-laser scanning technique will be used. The data obtained will have an accuracy that is presently estimated at +/- 0.5% but that the matter requires further consideration. Camera techniques and automatic geodetic methods may turn out to be equally good or more competitive in a longer time perspective.

4.2 Foundation bed

The procedure is the same as described in Appendix 1 ("Block" method). It involves installation of the equipment for construction of the foundation bed with its supporting legs safely resting on the floor, and measurement of its co-ordinates ("global positions"). The scanning unit for measuring the tunnel contour records the topography of the walls and roof along the length of the next module placement sequence, i.e. 2.7 m, and the part of the previously constructed foundation bed that protrudes by 0.5 m from the completed masonry of modules. Using the computer code the level of the new foundation bed is calculated considering the possible need for adding material and the compaction process. Once this has been made the material is distributed over the construction area and compacted.

4.3 Modules, handling and placement

The equipment for placing the modules in the 2.7 m backfill unit is installed in front of the previously constructed masonry, the supporting legs lowered, and measurement made of its co-ordinates ("global positions"). Water flowing from regions that had previously been backfilled is collected and removed. Figure 4-1 illustrates a complete sequence of receival and placement of modules by the placing equipment. The modules are delivered by the loading unit in the order decided by the computer-aided operator and placed, from left to right, to form a vertical front all the way up to the roof. Each campaign hence forms a 1.33 m thick "wall" unit. The operator is guided by a laser beam that indicates the position of the first module on the left side as related to the theoretical tunnel section. The modules are stacked to form a masonry that is separated from the theoretical tunnel profile by 100 mm.

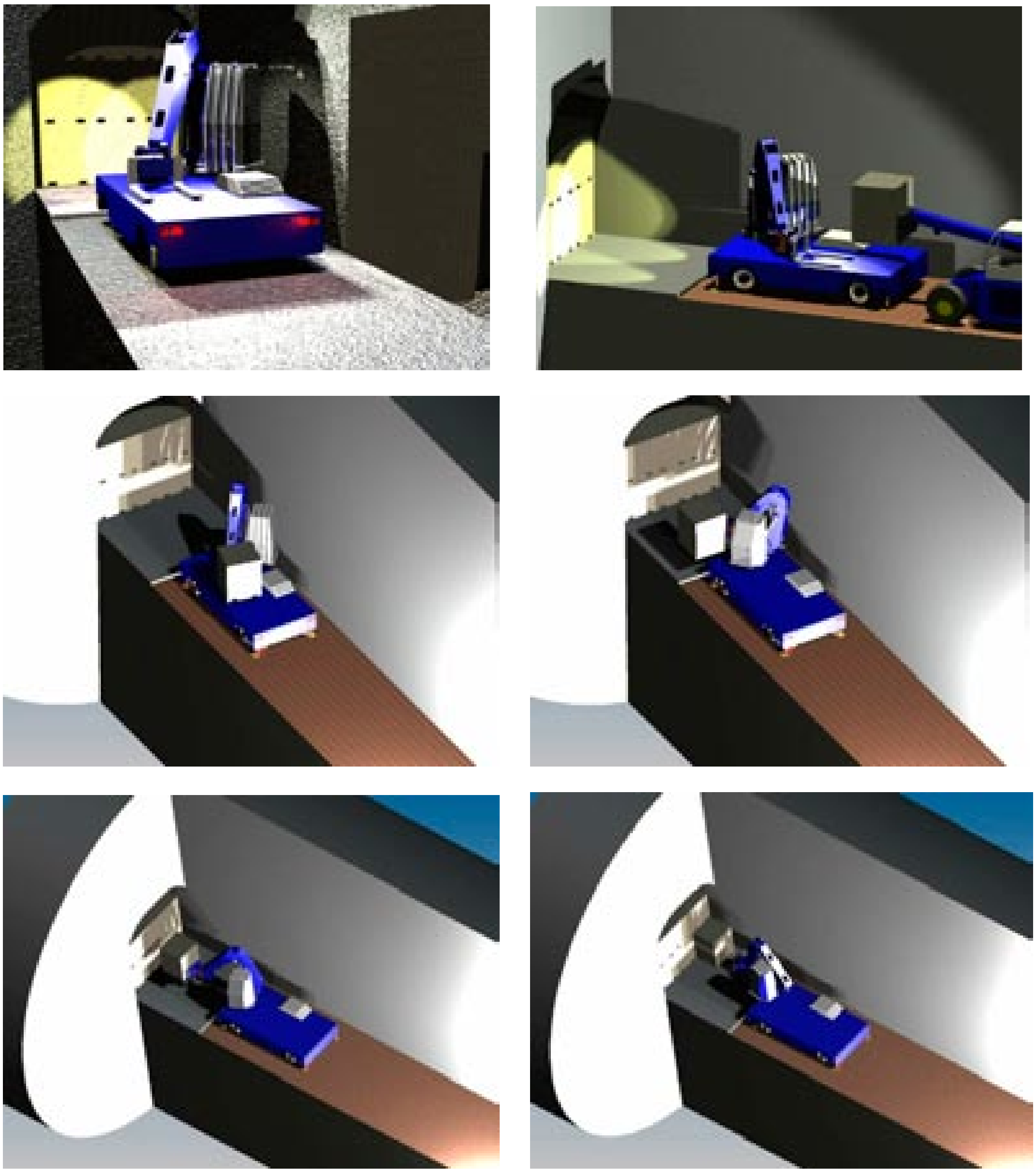

Figure 4-1. *Sequence of receival and placement of modules.*

After completing each module installation cycle, the front is scanned for determining the actual surface contour and comparing it with the planned, theoretical contour. Significant deviation from the latter may require removal and replacement of the modules. Since this is difficult and time-consuming because of their size and weight, the importance of accurate initial placement is high. It is planned to facilitate the operator's work by using semi-automatic techniques for placing the modules, and cameras and geodetical methods for checking their positions. The operator takes over the responsibility for placing the block units from the automatic system when the module is close to its intended position (Figure 4-1, lower left picture). The installation proceeds until two complete series of modules are on site extending from floor to roof, the placing unit being currently provided with new units without having to move. Before the module-placing units retreats from the tunnel for the subsequent pellet filling process the front of the placed masonry of modules is scanned and examined and the results compared to the planned contour of modules.

The stability of the individual stacks having varying orientation of the smaller blocks resting of bottom blocks, has been found to be quite satisfactory as illustrated by Figure 4-2.

Figure 4-2. *Test of the stability of a module.*

4.4 Pellet filling

This process is the same as described in Appendix 1 ("Block" method). It utilizes the equipment for preparation of the foundation bed that carries the facilities for blowing pellets (tube and nozzle for adding water). This machine is used for blowing the pellets supplied by the vehicle carrying the bulk pellets into the space between the masonries of modules and the rock, the pellets being supplied by the vehicle carrying bulk pellets. The previously made measurement of the shape of the tunnel contour and of the masonry of modules will provide computer-calculated data on the volume of the space to be filled and of the amount of pellets that are actually needed to achieve the required density in the fill. This is provided automatically by the computer. It is preferable to place the pellet fill so that it forms a steep front.

Depending on the inflow of water from the rock it may become necessary to add more water to the pellets in the filling phase in order to obtain a steep pellet front than would normally be required only for minimizing dust generation. In such a situation it would be possible to improve the degree of filling and to quickly stabilize the placed block units. Baclo studies do not find any discernible delay in outflow time as the result of wet pellet installation although there may have been redirection of flow to the rock-pellet boundary.

Figure 4-3 illustrates the pellet filling activity after completing the module masonry. The impact of the shape of the front of the modules on the quality of the pellet fills with special respect to the pellet filling degree has been investigated using different constellations of the modules, which are described as "static" or "flexible" models in the report.

The conclusion from these studies is that it will be easier to fill and evaluate the homogeneity of the filling between blocks and rock if the modules form a steep front and run straight through the entire tunnel independently of the look-outs. A vertical front of the masonry of modules will make both placement and checking of the quality of the pellet fill simpler and more accurate. The major reason for this is that the irregular topography of the walls and roof can lead to only partly filled space below protruding rock asperities and that this may escape identification, another being that the tube for blowing pellets may not be moved as desired in the space because of geometrical restraints (Figure 4-3). Additional advantages are that the availability of the space to be filled is better and that motion of the filling tube is simpler and more accurate when it can follow a steep front instead of a stepped contour, and also that the distance between the front and previously filled pellets is smaller. Checking of the degree of filling and homogeneity is also simpler although the accuracy may not be very high.

After completing the pellet filling and having carefully scanned the backfill to determine the shape of the front, preparation for the next backfill unit begins, involving removal of water for constructing the next foundation bed unit. The whole backfilling sequence, resulting in a 2.7 m long backfill unit being placed in about 7 hours, is then initiated, the required equipment already being on site.

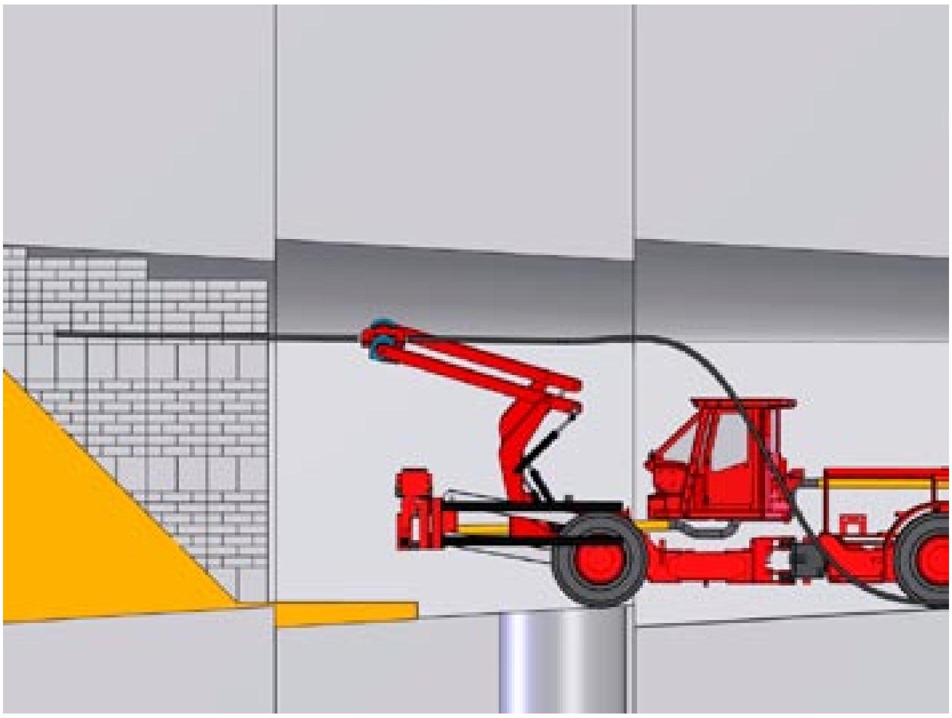

Figure 4-3. *The pellet filling process.*

Combination of the module-placing equipment and the unit for construction of foundation beds would greatly simplify the procedure of bringing the various units in and out of the tunnel. Similarly, creation of vertical masonry fronts would make the pellet filling simpler to install and more easily checked.

4.5 Time schedule

Backfilling using the “Module” method comprises three major activities: 1) preparation of the modules in a special factory on the ground surface with controlled environment, 2) construction of foundation beds and placement of the modules having been transported down to the repository, and 3) installation of pellet fills. The activities on ground can be made long before the modules are placed in the deposition tunnels. They are not described here.

Demands on backfilling rate are related to number of canisters deposited each year. In practice, the backfilling capacity is strongly dependent on water inflow in the tunnel. Backfilling can be performed in several tunnels in parallel campaigns for meeting the demand of 6 m per day, which is related to number of deposited canisters per year and the distance between the deposit holes. Because of water inflow in the tunnels it is an advantage to use a method with highest backfilling capacity as possible.

The time schedule is based on estimations and experience from simulations in order to estimate the duration of the entire module installation cycle, including fetching, grasping, moving and placing the modules and moving the equipment back for the next cycle. Provided that these operations take 10 minutes there would be a margin of 2 m backfilled tunnel length per 24 hours of normal operation where completing of 6 m of backfilling per day is expected. If the placement can be made in 5 minutes the margin would be 4 m backfilled tunnel per 24 hours. This illustrates that the schedule is less tight than for the “Block” and “Robot” methods. If the module-placing equipment can be combined with the unit for constructing foundation beds it would not have to be removed at the end of each sequence, hence yielding more rational production. The manufacturing of modules and transporting them to the construction site must be so planned and performed that they do not limit the backfilling rate.

For the underground activities the following steps shall be taken and the required time for each of them estimated:

- 3D scanning of the tunnel.
- Construction of foundation bed including completion of the deposition holes (removal of buffer protection sheet and installation of pellets in the deposition holes).
- 3D scanning of foundation bed (checking and documentation).
- Installation of the equipment for placing modules, arrangement of block supply.
- Placement of modules in first layer.
- Checking of geometry in 3D.
- Placement of modules in second layer of the masonry unit.

- Checking of geometry in 3D.
- Retreat of the module placing equipment.
- Installation of the equipment for constructing the foundation bed, prepared for pellet filling.
- Filling of pellets.
- Checking of geometry in 3D.
- Extension of foundation bed.
- Checking of geometry in 3D.
- Retreat of the equipment for constructing foundation beds.
- Installation of the equipment for block placing, arrangement of block supply.

Start of next round:

- 3D scanning of the tunnel.
- Construction of foundation bed including completion of the deposition holes (placement of canisters, buffer blocks and pellets).

Etc etc

As for the other backfilling methods it should be noted that delay for carrying out preparative work in and around the deposition holes has not been included in the time schedule. According to the present plans the backfilling process has to be stopped for removal of the buffer protection sheet, for pellet installation in the respective deposition hole, and for filling of the ramp at its upper end. This suggests that backfilling is made in two tunnels at a time, an issue that is discussed in the main text of the report.

5 Tests and development of techniques

The potential for developing the "Module" method is believed to be better than for the alternative methods and it is also estimated that relatively simple equipments have to be designed and tested compared to what the other methods require. The preparation of modules on the ground surface will not need very extensive R&D, nor does the transport of the "prefabricated" units require much planning.

However, the idea of preparing big "bottom" blocks must be worked on in detail and the matter of selecting the best technique and block density for preparing the blocks would need to be in focus. The presently used uniaxial compression technique for manufacturing buffer blocks would be one alternative. Another is represented by the high-isostatic powder compression technique used for preparing MX-80 blocks with a dry density of about 2,000 kg/m^3 for the Stripa BMT project. For the latter project, blocks were trimmed from columns with a diameter of 600 mm and a length of about 1,500 mm, corresponding, approximately, to the size of the proposed bottom blocks. Both techniques are available and hence represent considerable lower cost for block production than would be caused for developing new compression methods. Additional investigations will be performed throughout year 2008 with the aim of constructing stable modules with smaller bottom blocks.

It is realized that a relatively comprehensive R&D program is required including desk studies and construction of prototype versions of equipment for lifting and handling big block units, and for producing blocks of the finally selected clay material, as well as for testing the entire method under representative conditions at depth.

The following matters need to be considered:

- Examination of the required resources, strategy, and time for development of equipment and tools. Development of R&D program.
- Specification of demands respecting density and size of clay blocks making the modules as stable and handable as possible, and of demands respecting equipment for handling and placing blocks.
- Investigation of the possibilities and limitations of block compaction techniques.
- Performance of pilot full-scale tests for verification of the applicability of the proposed method for placing the modules as well as for identification of parameters, and ways of recording adequate data.
- Development of conceptual and detailed technical design of equipments for strapping of block units, and for handling and placement of them.
- Development of drawings and descriptions for manufacturing of equipments.
- Contracting of consulting work and manufacturing of equipments.
- Manufacturing of equipments.

- Description of required test program.
- Performance of tests.
- Assessment of the outcome of the tests and selection of ways for further development.

The “Module” method must include a program for manufacturing blocks of required size and density. It should specifically deal with the compaction technique for preparing blocks using different clay materials, and should be integrated with the work required for final selection of clay materials. This work should show what the optimal density is of the blocks respecting hydraulic conductivity and swelling pressure and should also show the impact of different block densities on the required density and properties of the pellet fill.

6 Tentative judgement

The “Module” method is the most attractive of the three proposed alternatives. Thus, the production and placement of coherent block units, the modules, are rational and time-saving, still keeping in mind that the placement must be made with precision and care.

Large modules give significant advantages, the major one being that the number of joints between the blocks is small. This means, in turn, that the rate of block placement is higher for the ”Module” method than for the methods. The higher capacity and less influence by water inflow make this method the strongest candidate.

Considering that all three methods comprise pellet filling, the technique for block placing is the main basis for comparing and assessing them. In this respect the authors consider the “Module” method to be superior to the “Block” and “Robot” methods and hence propose the “Module” method as primary candidate.

Äspö 2008-08-04

Hans Wimelius	Roland Pusch
SKB, Äspö	Geodevelopment International AB

Appendix 4

Engineered barrier system – large scale tests on feasibility

Svensk Kärnbränslehantering AB

Clay Technology AB

June 2008

Contents – Appendix 4

1 Introduction

The present plan for backfilling of a deposition drift includes emplacement and preparation of a bed made of bentonite pellets or granules. Specially made backfill blocks will then be piled on the prepared surface. The tests described in this report are aimed at investigating what techniques could be used to get a bed that fulfils the high demands required for this concept.

The objectives with the performed tests in this investigation were the following:

1. Investigate which technique that can be used for handling of the material i.e. machines, ladles and also how the surface can be adjusted by use of laser etc.
2. Perform tests with different vibrating plate compacters in order to achieve a stable bed on which the backfill blocks can be piled.
3. After optimizing the bed preparation, blocks were piled on the surface and possible movements (settlements) measured by time.
4. The influence of different water inflows on bed preparation and the following piling of blocks was also tested.
5. Study the influence of different bentonite materials (granules and pellets).

2 Test description and materials used

2.1 General

The investigations performed in this subproject belong to phase 3 of the BACLO project. The tests were made in the bentonite laboratory at Äspö Hard Rock Laboratory.

Tests were made in two different scales:

1. **Tests in medium scale**. This equipment was used in order to test different compaction devices, for piling of backfill blocks on a compacted surface in order to study possible movements and also for testing the influence of a water flow into the compacted bentonite. The equipment consists of a special made box (1.5 x 1.5 x 0.3 meter) manufactured in order to withstand high pressures.
2. **Tests in large scale**. Tests in large scale were made in an artificial part of a tunnel (5.6 x 4.05 (4.65) meter). In this equipment it also was possible to simulate different types of foundations i.e. blasted tunnel with a look-out angle but also a wire sawed floor which is very even.

The work was originally divided in five test series (A to E). In this report the results are presented in three chapters where the tests have been divided depending on test type i.e. Installation technique, Medium scale tests and Large scale tests.

2.2 Performed tests

Five test series have been performed:

Test series A. Introductory tests in large scale.

The introductory test series was divided in three steps:

1. **Handling of material**. A number of preliminary tests were performed in order to test machines and ladles. A first attempt to use a vibrating plate compactor was also done.
2. **Piling of blocks on a compacted bed**. Backfill blocks (concrete) were piled on a compacted bed of bentonite and possible movements were registered.
3. **Influence of a water inflow into the bentonite bed.** After preparation of the bentonite bed, backfill blocks were piled on the surface. A water inflow was then applied into the bed and the behavior of the piled blocks and the bed was studied.

Tests series B. Medium scale tests.

This test series was made in order to improve the technique for compaction of a bentonite bed. In addition, two tests with piled blocks and water inflow were performed. The test series was divided in two steps:

1. **Tests of different vibrating plate compactors**. Four different devices were tested in these tests (50, 70, 150 and 350 kg).
2. **Piling of backfill blocks on a compacted bentonite bed and studying the influence of a water inflow.** Two tests with different materials. The beds were prepared with the best available technique (150 kg vibrating plate compactor). After preparation, backfill blocks were piled on the compacted surface and a water inflow was applied into the bentonite. During the test time movements by and behavior of the blocks and bed was studied.

Test series C. Large scale tests including compaction of a bentonite bed, piling of blocks and studying the influence of water inflow.

Two large scale tests were performed simulating different foundations:

1. Test number one simulated a blasted tunnel with a look-out angle of 100-350 mm.
2. Test number two simulated a blasted tunnel where the floor was wire sawed i.e. the floor was very even.

Test series D. Medium and large scale tests with a new material.

This test series was divided in two steps:

1. Tests of different vibrating plate compactors. Three different compactors were used in these tests: 50, 70 and 350 kg. (Medium scale).
2. Two tests that included compaction of a pellet surface, piling of backfill blocks and then testing the influence of a water inflow into the pellet bed. The two tests were performed with different water inflow rates. (Large scale).

Test series E. New large scale test with higher water inflow rates.

A new large scale test with Minelco granules was performed in order to study the influence of higher water inflow rates.

2.3 Materials and water used in the tests

2.3.1 Bentonite material

Two different materials have been used in the tests. Both materials are considered as future candidates as backfill materials:

- **Minelco**: The material was very inhomogeneous in granule size. Dry bulk density is about 975 kg/m^3. This material was delivered at different times and the difference in grain size for the different deliveries was very strong, see Figure 2-1, which of course influenced the properties of the material.

1. **Minelco A:1**. Delivery 1, 2007. This material contained a lot more fines than the other two deliveries of this material. The material was used in test series A and in test B:1, B:2-1 and C-1.
2. **Minelco A:2**. Delivery 2, 2007. The grain size distribution of this material was very similar to the one delivered in 2001 (Minelco B, see below). This material was used in Test series E and in test C-2.
3. **Minelco B**. This material was delivered in 2001 and was used in some of the field tests. The material was used in test B:2-2.

- **Cebogel QSE pellets**. This is a commercial bentonite pellets with a montmorillonite content of about 80%. Extruded cylindrical rods with a diameter of 6.5 mm and a length of 5-20 mm. The origin of the material is Milos, Greece. The pellets are delivered by Cebo Holland BV. Dry bulk density about 943 kg/m^3. (Test series D).

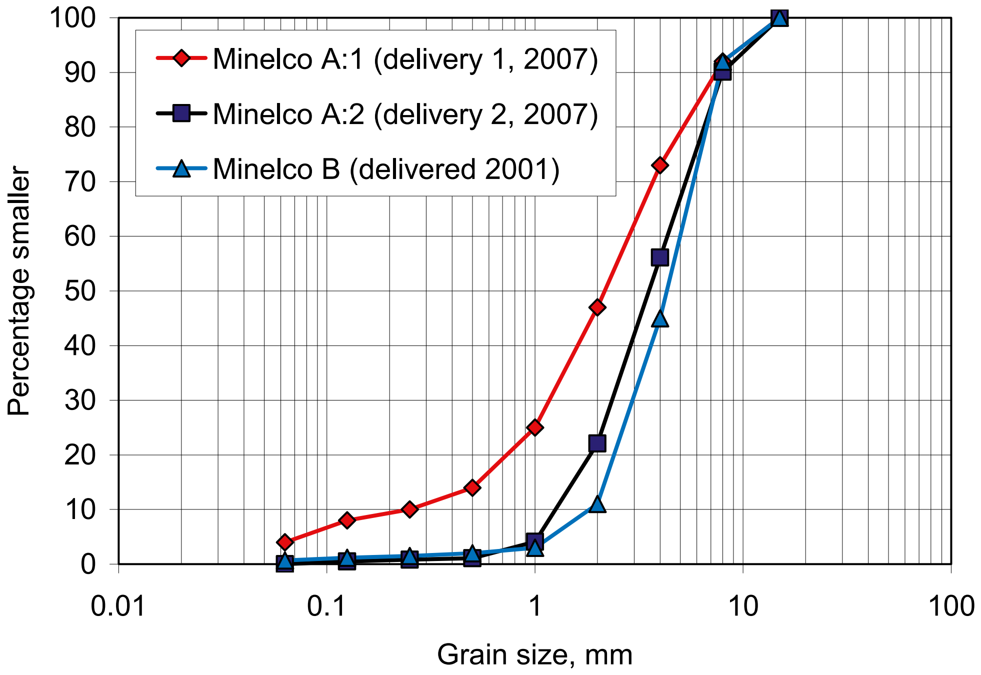

__Figure 2-1__ Diagram showing the grain size distribution for the three deliveries of Minelco material.

2.3.2 Water

In all tests water with a salinity of 1% total dissolved solids was used (50/50 NaCl/$CaCl_2$).

3 Installation technique

3.1 General

The initial tests were performed at large scale. An artificial part of a tunnel had been build in the laboratory (Length=5.6 meter and Width=4.05-4.65 meter), see Figure 3-1, and this was used to test the handling of the material, the technique for leveling of the surface and also for a first compaction test.

In order to test the compaction properties of the different materials, a number of tests have been performed in the medium scale (a special made box, 1.5 x 1.5 x 0.3 meter), see Figure 3-1. In this equipment a number of different vibrating plate compactors have been tested and the achieved density measured.

Figure 3-1 Left*: An artificial tunnel part was built in the laboratory.* ***Right****: A special made box was used for testing of different compaction devices.*

3.2 Results

A compilation of the tests related to the installation technique and the results are provided in Table 3-1.

3.2.1 Introductory tests

A number of introductory tests were made in order to test the technique to get the pellets/granules into the tunnel and also to level the surface. These first tests were all performed using the Minelco A:1 material. The results from the opening tests are the following:

- **Ladles**. In the first test a special sand ladle was used with good results. The placement operation was controlled and the amount of dust limited. The capacity was estimated to about 900 kg/5 minutes. A disadvantage was that some of the larger granules stayed in the ladle but this can probably be avoided by an adjustment. (Test A-1:1).

- **Leveling of the surface**. The surface was adjusted by using a machine equipped with a dipper ladle and a laser. The evenness was measured in 24 points (+5 to -20 mm). The time for adjustment was about 30 seconds/m^2. (Test A-1:2).

- **Compaction**. A first attempt was done to compact the material. A 50 kg vibrating plate compactor was used (1 layer and 4 crossings). The result from this test was that the maximum settlement was up to 30 mm and the surface was rather wavy. The dust production during the compaction was rather high. The density was determined to 1,269 kg/m^3. (Test A-1:3).

3.2.2 Compaction tests

Compaction tests were made in a special box. In the tests different vibrating plate compactors were tested. The materials used were Minelco A:1 and Cebogel pellets. The results from the tests are compiled in Table 3-1.

Some comments to the tests:

- **Minelco A:1 granules**. Five tests were performed with this material. In tests number one the material was just poured into the box with no additional compaction and in the following four tests were different compaction devices compared. The best result was achieved with the 150 kg compactor. All tests were performed with two layers of material each with a thickness of 150 mm. The surface was manually adjusted afterwards. The material was judged to be easy to compact. (Test B-1:1 to B-1:5)

- **Cebogel QSE pellets**. The material was very difficult to compact. Only two tests were performed. In the first test the material was just poured into the box with no additional compaction and in the next test were the pellets compacted with a vibrating plate compactor. There was an obvious increase in density after compaction but the compacted surface was very unstable. (Test D-1:1 and D-1:2)

Table 3-1 The table shows a compilation of the tests performed in order to study the installation technique of a bottom bed in a deposition drift.

Test	Description	Scale	Equipment	Material	Reached bulk density, kg/m3	Remark
A-1:1	Machine and ladle tests	5.6 x 4.05 (4.65) meter	Sand ladle	Minelco A:1	-	The equipment seems feasible. Capacity about 900 kg/5minutes, low dust production
A-1:2	Adjustment of surface with dipper ladle and laser.	5.6 x 4.05 (4.65) meter	Laser on machine	Minelco A:1	-	The surface is not even enough. Evenness determined in 24 points: +5 to -20 mm. Time about 30 sec/m^2
A-1:3	Compaction test, 4 crossings, 1 layer	5.6 x 4.05 (4.65) meter	50 kg vibrating plate compactor	Minelco A:1	1269	About 6-30 mm settlement, waves on the surface, makes a lot of dust
B-1:1	Compaction tests.	1.5 x 1.5 x 0.3 meter	Manual	Minelco A:1	1194	Pre-test where the material was poured into the box
B-1:2	Compaction tests.	1.5 x 1.5 x 0.3 meter	50 kg vibrating plate compactor	Minelco A:1	1212	Two layers x 0.15 m + adjustment
B-1:3	Compaction tests.	1.5 x 1.5 x 0.3 meter	85 kg vibrating plate compactor	Minelco A:1	1306	Two layers x 0.15 m + adjustment
B-1:4	Compaction tests.	1.5 x 1.5 x 0.3 meter	150 kg vibrating plate compactor	Minelco A:1	1416	Two layers x 0.15 m + adjustment
B-1:5	Compaction tests.	1.5 x 1.5 x 0.3 meter	250 kg vibrating plate compactor	Minelco A:1	1405	Two layers x 0.15 m + adjustment
D-1:1	Compaction tests.	1.5 x 1.5 x 0.3 meter	Manual	Cebogel QSE	1160	Pre-test where the material was poured into the box
D-1:2	Compaction tests.	1.5 x 1.5 x 0.3 meter	70 kg vibrating plate compactor	Cebogel QSE	1351	Two layers x 0.15 m + adjustment. The surface is not stable.

4 Medium scale tests

4.1 General

After the introductory tests in both medium and large scale, three more extensive tests were performed in the medium scale (special made box, 1.5 x 1.5 x 0.3 meter). The tests included the following steps:

1. **Compaction of the material**. Three materials were tested in this scale: Minelco A:1, Minelco B and Cebogel QSE. The materials were compacted in two layers with a thickness of 0.15 m a layer.
2. **Piling of blocks**. Backfill blocks (1 x 0.5 x 0.5 meter) made of concrete were piled on the compacted surface. Two blocks were used in each layer and in total 5 layers were positioned. Each of the blocks weighed 415 kg and an additional 2,000 kg was then placed on the top. The total weight of blocks and extra weight corresponds to a pressure of 60 kPa on the pellet flooring.
3. **Water inflow**. After finishing construction of the pile, water inflow at a rate of 0.25 l/min was applied into the compacted bentonite. The point inflow was located in the center of the box.
4. **Measuring of the settlements**. The pile of blocks was measured before applying the water flow and also before finishing the test.
5. **Studying of how the water influences the compacted bed**.

4.2 Results

A compilation of the results from the tests performed in medium scale have been done in Table 4-1.

4.2.1 Test B-2:1

The material used in this test was Minelco A:1. The compacted surface was very stable. The achieved density was 1,413 kg/m^3 which correspond very well to the value achieved at the earlier installation tests.

There was almost no influence from the water inflow on the stability of the piled blocks. During the test time almost 300 l water was injected, see Figure 4-1. The water pressure varied between 40 and 140 kPa. The water found a way up along the side of the box and after reaching the surface, water uptake was largely limited to the upper surface rather than the overall pellet fill. The test was finished after about 21 hours and it could be seen that a large part of the bentonite was wet but there were still dry areas under the blocks, see Figure 4-2.

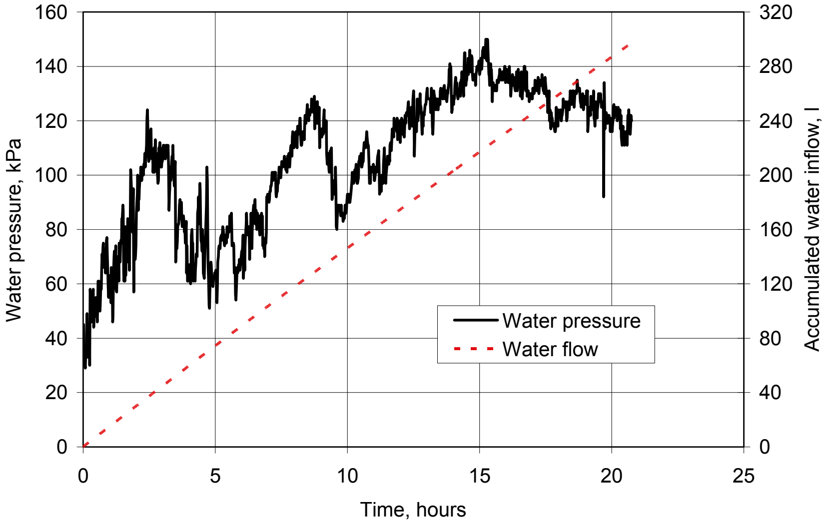

Figure 4-1 *Diagram showing the accumulated water inflow and the achieved water pressure plotted vs. time for Test B-2:1.*

Figure 4-2 Left*: Water from the injection point found a way up along the side and the continued saturation was done from the surface.* ***Right****: When finishing the test, dry areas were observed under the blocks. The surrounding bentonite had swelled up to a loose gel.*

4.2.2 Test B-2:2

The material used in this test was Minelco B. The density after compaction was much lower than in the earlier test (B-2:1) which is probably the results of the very low fines content of this material as can be seen in Figure 2-1.

The low density influenced the pile of blocks which were very unstable, see Figure 4-3. The settlement increased with time. After 24 hours a large part of the bentonite wetted (estimated to 70% of the volume). During the test water was standing on the surface, see Figure 4-4. The achieved water pressure was high in the beginning of the test but decreased after 1 hour to a level of about 40 kPa which then was rather constant during the test, see Figure 4-5.

Figure 4-3 *Picture showing the situation after 21 hours. The pile was very unstable and the gap between the blocks increased all the time.*

Figure 4-4 *Water was standing on the bentonite surface around the piled blocks.*

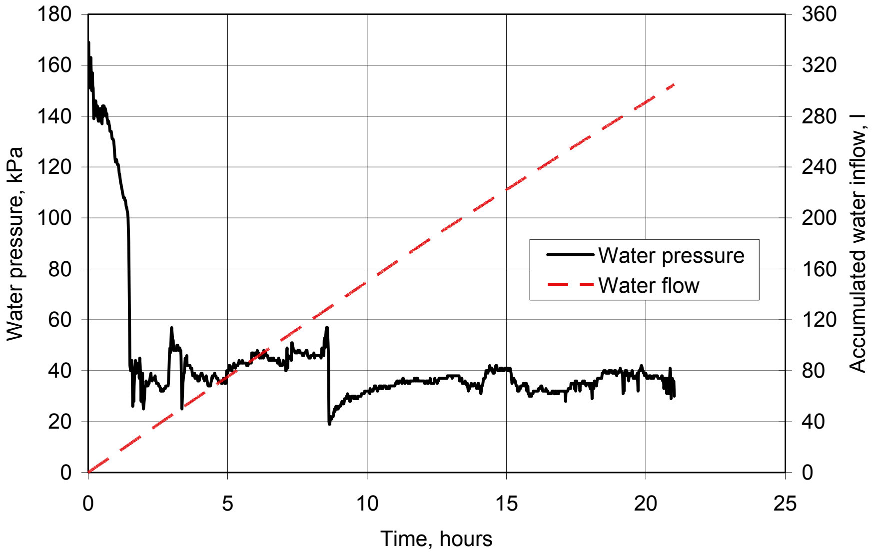

Figure 4-5 *Diagram showing the accumulated water inflow and the achieved water pressure plotted vs. time for Test B-2:2.*

4.2.3 Test D-1:2

The material used in this test was Cebogel QSE. The achieved density of the filling after compaction was rather high, about 1,351 kg/m3.

The behavior of the piled blocks was rather similar to Test B-2:2 i.e. the pile was very unstable.

The achieved water pressure was rather high in the beginning of the test, maximum 70 kPa, but decreased quickly to about 10 kPa, see Figure 4-6. When finishing the test after about 24 hours about 70% of the pellets were affected by water. The pellets had swelled up around the blocks, see Figure 4-7.

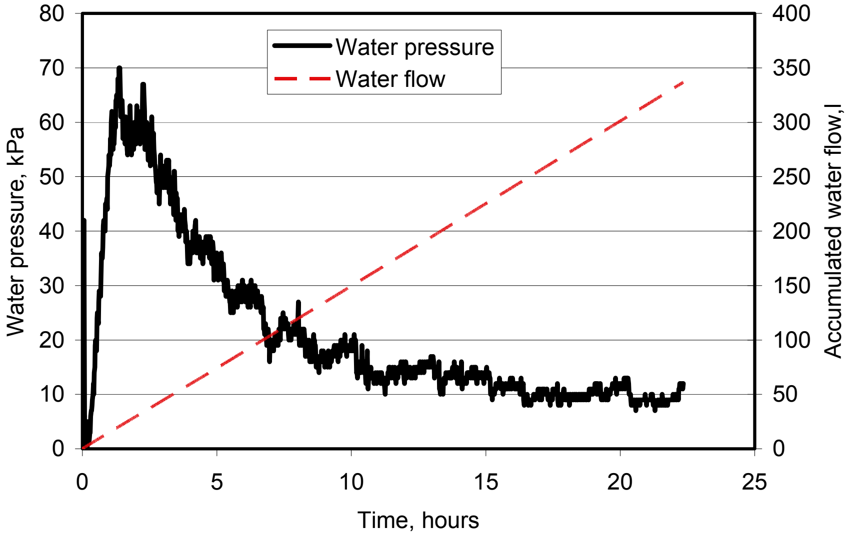

Figure 4-6 *Diagram showing the accumulated water inflow and the achieved water pressure plotted vs. time for D-1:2.*

Figure 4-7 *Picture showing the pellets after removal of the blocks. The pellets around the blocks had swelled quite a lot during the test time. Under the blocks there were large dry areas.*

Table 4-1 **The table shows a compilation of the tests performed in medium scale in order to investigate the stability of blocks piled on a compacted and levelled bentonite surface. The tests included that water was flowing during the installation time.**

Test	Description	Scale	Material	Compaction of material	Piled blocks	Water inflow	Results	
							Stability of blocks	Water leakage
B-2:1	Compaction test with following piling of blocks and water inflow.	1.5 x 1.5 x 0.3 meter	Minelco A:1	150 kg vibrating plate compactor. Two layers á 0.15m. Density 1413 kg/m^3.	2 x 5 block + 2 000 kg (60 kPa)	Point inflow in middle of one side. 0.25 l/min during 21 hours.	Very good! Surface was very hard and stable. Settlement of a few mm.	Water on surface around the blocks. Saturation from upper surface.
B-2:2	Compaction test with following piling of blocks and water inflow.	1.5 x 1.5 x 0.3 meter	Minelco B	140 kg vibrating plate compactor. Two layers á 0.15m. Density 1283 kg/m^3.	2 x 5 block + 2 000 kg (60 kPa)	Point inflow in middle of one side. 0.25 l/min during 21 hours.	Bad! Large movements! Probably depending on the low density!	About 70 % of the bentonite was influenced by water.
D-1:2	Compaction test with following piling of blocks and water inflow.	1.5 x 1.5 x 0.3 meter	Cebogel QSE	90 kg vibrating plate compactor. Two layers á 0.15m. Density 1351 kg/m^3.	2 x 5 block + 2 000 kg (60 kPa)	Point inflow in middle of one side. 0.25 l/min during 21 hours.	Bad! Pellets are swelling between the blocks and creating movements.	The pellets around the blocks is swelling fast. Great parts are affected by water (70%).

5 Large scale tests

5.1 General

A total of seven tests were performed at large scale. Six of the tests included a constant water flow that was applied in the beginning of the test i.e. the water was flowing both during emplacement of the bed material and during compaction and piling of the blocks.

In these tests three materials were used, two of the three different deliveries of Minelco granules and also two tests with Cebogel QSE pellets.

The artificial tunnel has a length of 5.6 meters and the width varies between 4.05 and 4.65 meters which simulates the look-out angle depending on the blasting technique. There is also a look-out angle on the floor with a height of 350 mm. Tests have been performed with both look-out angle on the floor, simulating a blasted tunnel but also with a levelled floor which simulates a wire sawed floor.

After preparation of the bed, full scale backfill blocks were piled as a stair case in the tunnel, see Figure 5-1. In total 100 blocks were used and the pressure they applied on the flooring materialranged between 33 kPa (in the front) and 66 kPa (at the back).

5.2 Results

A compilation of the results from the tests performed in large scale has been done in Table 5-1.

5.2.1 Test A-1:4

This was a pre-test and the preparation of the bed was not as good as it could have been. The material used was Minelco A:1. The achieved density was not measured but was obviously too low to get a stable surface. The low density was mainly due to the fact that the compactor used in this test was to light. In the later tests, A-1:5 and C-1, performed with the same material was the compaction made with a heavier device which resulted in a very stable surface. This test did not include water inflow.

The settlements were rather large, up to 30 mm, and the slots between the piled blocks varied between 20-60 mm.

Table 5-1 The table shows a compilation of the tests performed in large scale in order to investigate the stability of blocks piled on a compacted and levelled bentonite surface. The tests included that water was flowing during the installation time.

Test	Description	Scale	Material	Compaction of material	Piled blocks	Water inflow	Results	
							Stability of blocks	Water leakage
A-1:4	Piling of blocks on a compacted and even maked surface.	5.6 x 4.05 (4.65) meter	Minelco A:1	50 kg vibrating plate compactor. Four crossings, one layer. Density 1269 kg/m^3.	100 full scale blocks piled as a stair. (33-66 kPa)	No water in this test.	Bad! Pre-test with low density. Maximum settlement about 30 mm. Increasing vertical gaps between blocks.	No water in this test.
A-1:5	Piling of blocks on a compacted and even maked surface.Water inflow during installation.	5.6 x 4.05 (4.65) meter	Minelco A:1	70 kg vibrating plate compactor. One layer á 0.3m. Density was not determined.	100 full scale blocks piled as a stair. (33-66 kPa)	0.1 l/min (in the middle), 0.25 l/min (in the middle of the east side)	Rather good. Joints between blocks are increasing by time. Density probably low.	Great part of the bentonite was influenced by water.
C-1	The test is simulating a blasted tunnel with look-out angle. Water inflow during installation.	5.6 x 4.05 (4.65) meter	Minelco A:1	150 kg vibrating plate compactor. Two layers á 0.15m. Density 1382 kg/m^3.	100 full scale blocks piled as a stair. (33-66 kPa)	0.1 l/min (in the middle), 0.25 l/min (in the middle of the east side)	Very good! Only small movements.	Water was spread along the east side on the surface. Dry parts under the blocks. Wet below the block joints.
C-2	The test is simulating a blasted tunnel with wire sawed floor. Water inflow during installation.	5.6 x 4.05 (4.65) meter	Minelco A:2	150 kg vibrating plate compactor. One layers á 0.1m, 6 crossings. Density 1220 kg/m3	100 full scale blocks piled as a stair. (33-66 kPa)	0.1 l/min (in the middle), 0.25 l/min (in the middle of the east side)	Very good! Only small movements.	Water was spread along the east side on the surface. Dry parts under the blocks. Wet below the block joints.
D-2:1	The test is simulating a wire sawed floor. Water inflow during installation.	5.6 x 4.05 (4.65) meter	Cebogel QSE	90 kg vibrating plate compactor. One layer á 0.1 m. Density 1343 kg/m^3	100 full scale blocks piled as a stair. (33-66 kPa)	0.1 l/min (in the middle), 0.25 l/min (in the middle of the east side)	Very good! The pile is very stable. Small movements.	The pellets just below the block joints is wetted. The inflow can be taken care of.
D-2:2	The test is simulating a wire sawed floor. Water inflow during installation (increased).	5.6 x 4.05 (4.65) meter	Cebogel QSE	90 kg vibrating plate compactor. One layer á 0.1 m. Density 1343 kg/m^3 (unsure).	100 full scale blocks piled as a stair. (33-66 kPa)	1 l/min (in the middle), 0.25 l/min (in the middle of the east side)	Good! Only small movements. The pile is stable.	The surface in front of the pile is strongly affected of the high inflow. Dry areas under the blocks which makes the pile stable.
E-1	The test is simulating a wire sawed floor. Water inflow during installation (increased).	5.6 x 4.05 (4.65) meter	Minelco A:2	150 kg vibrating plate compactor. One layer á 0.1m, 4 crossings. Density 1220 kg/m^3 (unsure).	100 full scale blocks piled as a stair. (33-66 kPa)	1 l/min (in the middle), 0.25 l/min (in the middle of the east side)	Very good! Only small movements. Bentonite blocks under concrete blocks (one row) which did not affected the stability.	The surface in front of the pile is strongly affected of the high inflow. Dry areas under the blocks which makes the pile stable.

5.2.2 Test A-1:5

This test was similar to test A-1:4 but the bed was prepared in a better way and the test also included water inflows from two points, one in the middle of the look-out angle (0.1 l/min) and one in the middle of the east side (0.25 l/min). The achieved density of the bed was determined to 1,269 kg/m^3.

After 45 minutes water came up on the surface from the inflow point at the side and flow forward on the surface, see picture in Figure 5-1.

After 18 hours had the vertical slot widths at the middle of the front increased with about 30 mm and continued to widen at a rate of about 3 mm/h.

Figure 5-1 *Picture from the first performed large scale test, A-1:5, including water injection. Water from the injection point positioned in the middle of the right side have found a way up on the surface and was then flowing forward on the surface.*

After finishing of the test and having removed the blocks, large dry areas could be seen, see Figure 5-2. The water has however flowed in between the joints and saturated the bentonite there.

The results from this test showed that the compaction of the material and the following adjustment is very important for the stability of the piled blocks.

Figure 5-2 *After removal of the blocks large dry areas could be seen. Water had flowed between the joints and wet the bentonite.*

5.2.3 Test C-1

Test C-1 and C-2 were performed in order to study the influence of different tunnel floors i.e. a tunnel floor with a look-out angle (blasted tunnel) or a plane floor (wire sawed floor). Test C-1 simulated a blasted tunnel with a look-out angle on the floor of 350 mm. The compacted bed was made over this angle. The density after compaction was determined to 1,382 kg/m3 (Minelco A:1).

During the test there was a water pressure built up at the inflow point positioned at the side of about 120 kPa, see Figure 5-3. At the other inflow point, in the middle of the look-out angle, no increase of the water pressure was registered. Water came up on the surface from the water inlet on the side after about 10 minutes and was then spread along the east side, see Figure 5-4. After about 7 hours, water could be seen on the surface above the other inflow point.

The stability of the pile was very good. During the test only movement of a few mm could be registered. There was however a small upwards movement of the blocks in the middle of the front row.

After finishing the test it was observed that there were large dry parts under the blocks but water seemed to have wetted the bentonite just below the joints between the blocks, see Figure 5-4.

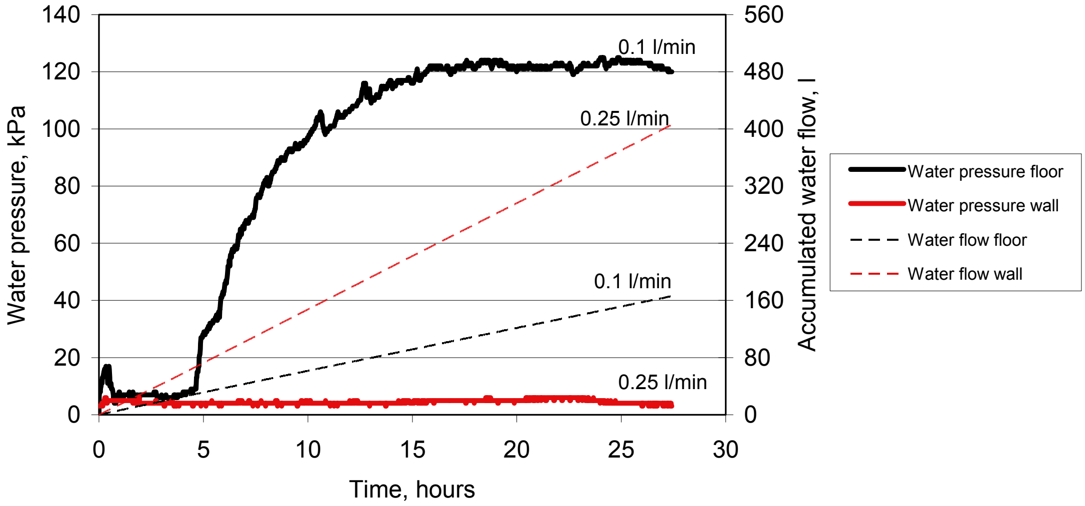

Figure 5-3 *Diagram showing the accumulated water inflow and the achieved water pressure plotted vs. time for test C-1.*

Figure 5-4 Left*: After 10 minutes water came up from the water inlet positioned on the east side (0.25 l/min).* ***Right****: After finishing the test it was observed that there were large dry parts under the blocks but the material under the joints was wetted.*

5.2.4 Test C-2

This test simulated a wire sawed floor i.e. the surface was very even. Only one layer with a thickness of 0.1 m was installed. The density was determined to 1,220 kg/m3 (Minelco A:2).

Very low water pressures were built up during the test time, see Figure 5-5. The difference in water pressure build up between this test and the earlier is likely the result of differences in the compacted density as well as the thickness of the bentonite bed.

In this test no increase of the water pressure was registered.

The stability of the pile in this test very good. During the test only movements of a few mm could be registered. Also in this test, large dry areas could be seen under the blocks after removal. The water had only affected the bentonite in the joints between the blocks.

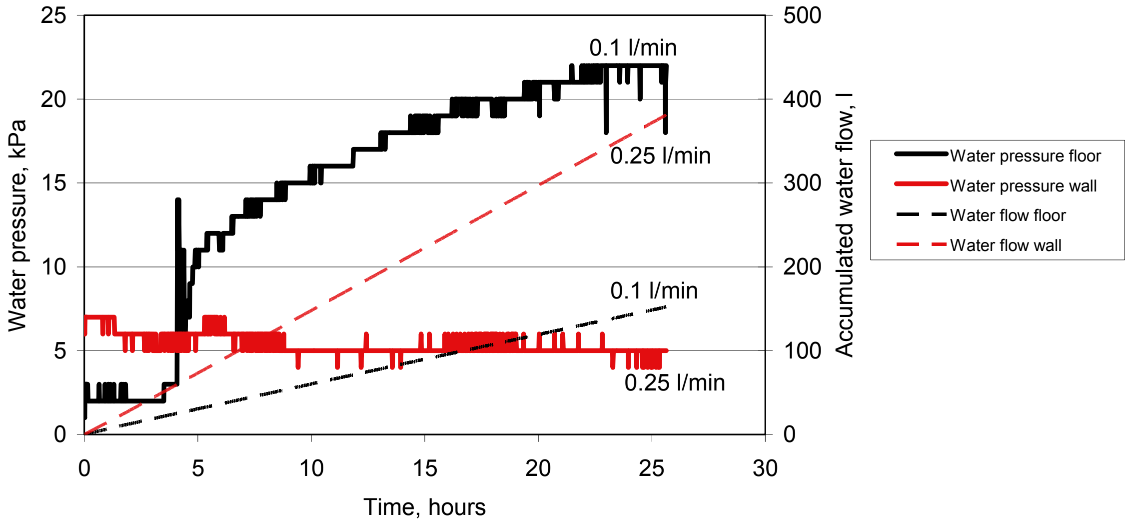

Figure 5-5 *Diagram showing the accumulated water inflow and the achieved water pressure plotted vs. time for test C-2.*

5.2.5 Test D-2:1

Test D-2:1 and D-2:2 were both made using Cebogel pellets. Both tests simulated a wire sawed tunnel floor). The difference between the tests was the water inflow rates which were 0.1 l/min in the middle and 0.25 l/min at the side for test D-2:1. In test D-2:2 the inflow rate in the middle was increased from 0.1 to 1 l/min.

During the time a small water pressure was built up at the inflow point positioned in the middle of the floor, reaching a maximum 60 kPa, see Figure 5-6. At the other inflow point no increase of the water pressure was registered. Water came up on the surface from the water inlet on the side after about 2 hours, see Figure 5-7. After an additional 5 hours water could also be seen on the surface above the other inflow point.

The stability of the pile was very good. During the time only movement of a few mm could be registered.

After finishing the test it was observed that there were large dry parts under the blocks but the water seemed to have wetted the bentonite just below the joints between the blocks, see Figure 5-7.

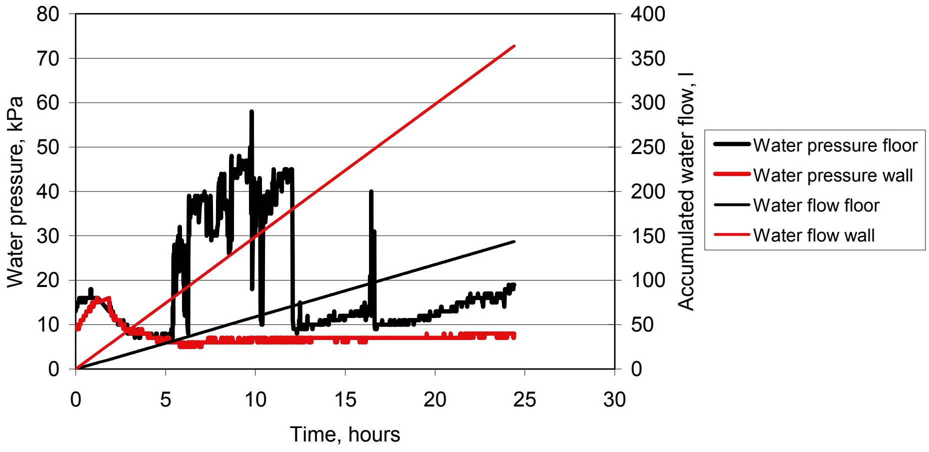

Figure 5-6 *Diagram showing the accumulated water inflow and the achieved water pressure plotted vs. time for Test D-2:1..*

Figure 5-7 Left*: After 10 minutes water came up from the water inlet positioned on the east side (0.25 l/min) and after additional 5 hours water could also be seen from the injection point in the middle.* ***Right****: After finishing the test it was observed that there were large dry parts under the blocks but the material under the joints was wetted.*

5.2.6 Test D-2:2

In this test the water inflow rate in the middle increased from 0.1 l/min to 1 l/min but the water inflow at the side was maintained at 0.25 l/min..

During the test there was a small water pressure registered at the inflow point positioned in the middle, maximum 30-40 kPa, see Figure 5-8. At the other inflow point no increase of the water pressure was registered. The bentonite surface in front of the pile was strongly affected by the high water inflow here (1 l/min), see Figure 5-9.

The stability of the pile was very good. During the test time only movement of a few mm could be registered.

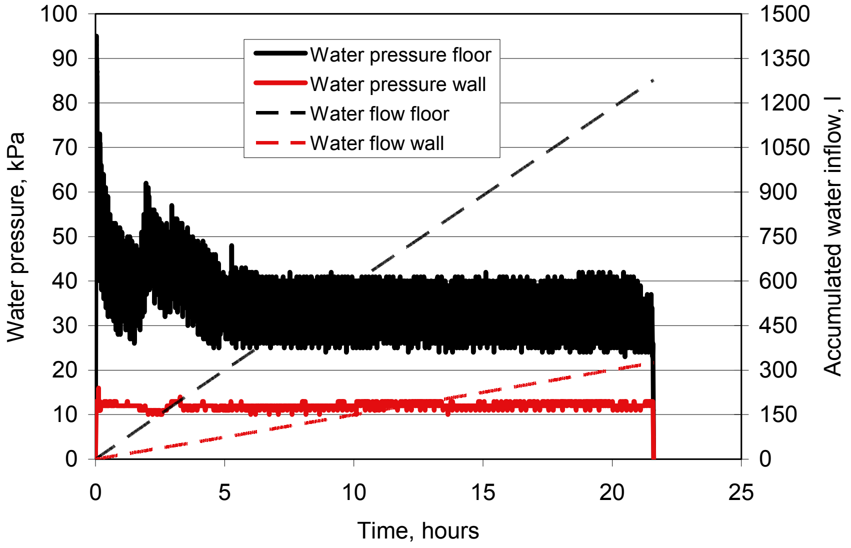

Figure 5-8 *Diagram showing the accumulated water inflow and the achieved water pressure plotted vs. time for Test D-2:2.*

Figure 5-9 Left*: Water from the injection point in the middle found a way up on the surface very soon.* ***Right****: The surface in front of the pile was strongly affected by the high water inflow (1 l/min). Also in this test dry areas could be found under the blocks.*

5.2.7 Test E-1

This test had the same layout as test C-2 (Minelco A-2), but the water inflow rate in the middle was increased from 0.1 to 1 l/min. Another difference was that under the front row with backfill blocks, one layer of bentonite blocks (Friedland clay) was positioned.

During the test there was a water pressure built up at the inflow point positioned in the middle of about 45 kPa, see Figure 5-10. At the other inflow point no increase of the water pressure was registered. During the installation time water started to flow up on the surface from both sides, see Figure 5-11.

The stability of the pile was very good. During the test time only movement of a few mm could be registered. The bentonite blocks under the front row did not affect the stability.

After finishing the test it was observed that there were large dry parts under the blocks but the water seemed to have wetted the bentonite just below the joints between the blocks, see Figure 5-11.

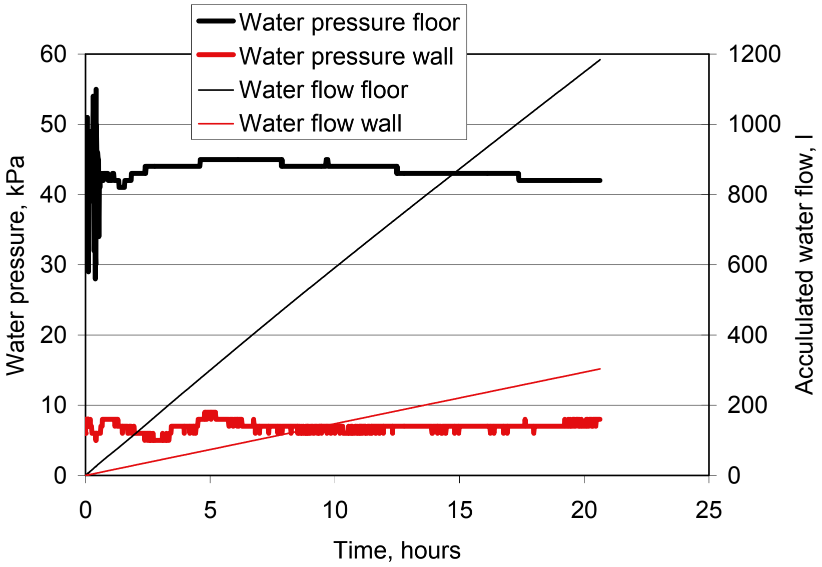

Figure 5-10 *Diagram showing the accumulated water inflow and the achieved water pressure plotted vs. time for Test E:1..*

Figure 5-11 Left*: During the installation of backfill blocks, water started to flow up on the surface from both sides of the tunnel.* ***Right****: After finishing the test it was observed that there were large dry parts under the blocks but the material under the joints was wetted. The bentonite blocks placed under the first row did not affect the stability.*

6 Summary of results and comments

6.1 General

The tests described in this report were aimed to investigate available technique for handling of the bentonite pellets/granules, compaction technique in order to get a stable bed, but also to test the performance of an installed bed i.e. when the bed was loaded with backfill blocks (settlements etc.) and there was a water flow from the rock.

This chapter summarizes the most interesting results from the tests.

6.2 Handling of the material and preparation of the bed

Some conclusions from the tests are:

- The material can be handled and placed using standard equipment. In the tests a sand ladle was used with good results. The placement capacity was estimated to be 900 kg/5 minutes which means that in a tunnel section with a length of 6 meters and a width of 4.5 meters (average) it will take about 1 hour to place the material if the final thickness of the layer after compaction should be 0.3 meter. The dust production was rather low with the tested equipment.

- Leveling of the material with a standard ladle equipped with laser was also tested. The surface should have an inclination of 1.5%. The time was estimated to about 30 sec/m2. The accuracy of the leveling was between +5 to -20 mm. The evenness of the surface must be better than this in order to pile backfill blocks in an acceptable way.

6.3 Stability of a compacted bentonite bed when exposed to load from backfill blocks and simultaneous water inflow

In the tests performed in the laboratory, that included piling of backfill blocks, it was necessary to do a last leveling of the compacted surface by hand. This technique must however be developed so it can be done in a more automatic way. Some conclusions from the tests are:

- The layout of the medium scale tests was very conservative with only two blocks on the bed and five blocks in height. It was observed in the large scale tests that the blocks could support each other and by that the pile became more stable.

- In all tests performed in large scale (except the pre-tests A-1:4 and A1:5, where the density of the compacted bed was too low and also rather uneven) the stability of the piled blocks was rather good.

- The tests have simulated a stoppage in emplacement for almost 1 day. According to the present design, it will take one day to install buffer and canister in one deposition hole and afterwards backfill 6 meter of the deposition tunnel. In order to avoid movements of the blocks, which mainly depends on water inflow that affects the bentonite bed, it will be necessary to continue the installation of blocks and also to fill the gap between blocks and rock walls with pellets as soon as possible.

- The choice of material for the bed is very important. It must be possible to compact the material to high density and to get an even and hard surface on which the blocks can be piled.

- Compaction of the Cebogel pellets, which are very even-grained, increases the density but the stability of the compacted surface is very bad if trying to walk on it etc. In spite of the instability of the surface the stability of the pile was very good in the large scale tests with this material.

- In the large scale tests, water inflows were simulated from two points, one at the middle of the east side (0.25 l/min in all tests) and one in the middle of the look-out angle (0.1 l/min in most tests and 1 l/min in two tests). In most of the tests, the water rose upwards through the bentonite (below the blocks against the not loaded surfaces) and then up on the surface, forward in front of the pile. This means that the main part of the wetting was done from above.

- The water pressure built up when applying a constant flow into the bed differed between the three tests. The highest pressure, 140 kPa, was achieved in test B-2:1 which also had the highest density.

- The layout of the tunnel floor, wire sawed or with look-out angle, did not influence the stability of the pile or the progress of the wetting.

- Irrespective of the choice of material in the bed, the buffering of water below the blocks was low which probably depends on the pressure from the backfill blocks, which makes the water go in other directions.

- The buffering of water in the pellets or granules is higher on the areas which are not loaded i.e. there are no blocks positioned. This means that the renewal of piling of blocks after a stoppage in backfilling operations can be problematic if the surface in front of the pile has swollen and become uneven.

- The granules seem to be more effective in limiting water uptake than the pellets. The water flows on the compacted surface and is slowly wetting the compacted material from above. This means that with granules there will be a shorter time before water is flowing on the surface, but pellet materials with their slightly slower hydration will be affected to a greater degree in terms of their ability to support the overlying blocks.

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Torbjörn Sandén	Hans Wimelius
Clay Technology AB	SKB, Äspö