Working Report 2008-88

Finite Element Modelling of Deformation of Unsaturated Backfill Due to Swelling of the Buffer

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April 2009

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ABSTRACT

Methods for backfilling and sealing of disposal tunnels in an underground repository for spent nuclear fuel are studied in cooperation between Finland (Posiva Oy) and Sweden (Svensk Kärnbränslehantering AB, SKB) in “BAckfilling and CLOsure of the deep repository” (Baclo) programme. Baclo phase III included modelling task force SP1: Finite element modelling of deformation of the backfill due to swelling of the buffer. The objective of the finite element modelling of the backfill was to study the interaction between the buffer and backfilling. The calculations aimed to find out how large deformations can happen in the buffer-backfill interface causing loosening of the buffer bentonite above the canister. The criterion used was that the dry density of the buffer right above the canister should be higher than 1.95 tn/m^3. This report presents the results of the VTT’s modelling calculations and comparison between different calculation approaches. The analytical and finite element calculations of ClayTechnology AB are reported separately.

The modelling calculations were conducted with SKB’s and Posiva’s deposition tunnel geometry. Posiva’s tunnel is clearly smaller than SKB’s and also the backfilling degrees may differ according to present design proposals. Based on current plans, 60…80% of the total volume of deposition tunnels will be backfilled with pre-compacted blocks and the remaining space will be filled with bentonite pellets. The basic assumption in these modelling was that the buffer is totally saturated generating swelling pressure up to 7 MPa and backfill is in unsaturated state. This was evaluated to present a “worst case scenario” with the highest risk to lead in decrease in dry density of the buffer. Most of the modellings were done using material properties determined for Friedland clay blocks, but also Asha case was tested. Besides these the boundary conditions of the problem were varied, like friction between tunnel wall and pellets and missing pellets or free spaces due to erosion. It was also planned to include some preliminary 3D studies into this work, but the Plaxis 3D proved to be unsuitable for that. Therefore most of the results gained were based on axisymmetric 2D calculations done with Plaxis 2D. The chosen material model was linear elastic continuum material. Some tests were done with elasto-plastic Mohr-Coulomb material model, but they failed due to the unrealistic stress concentrations in tunnel corner.

When the input assumptions and different calculation methods (2D, 3D and analytical calculations) are compared to each other it can be concluded that the vertical deformations in the interface between buffer and backfill vary between 80…120 mm for the SKB tunnel geometry. Based on 2D calculations for the Posiva geometry the vertical deformations in the interface are about 80 mm. The dry density requirement of 1.95 tn/m^3 will be exceeded if the loosening in the buffer is supposed to happen evenly. However, in reality the loosening is non-linear being highest near the interface. The 3D modelling of ABAQUS refer to the possibility that this requirement can be fulfilled meaning that the loosening of buffer right above canister will remain on acceptable level.

The modelling process should be an essential part of the tunnel backfill design. These modellings are preliminary and they include many assumptions and simplifications (like the deformations of block-block interfaces). In the future the modelling should include saturated backfill, 3D models, sophisticated material models and tunnel floor granules.

Keywords: Buffer, backfill, FEM, swelling

Puskurin aiheuttamat muodonmuutokset saturoitumattomalle täyteaineelle FEM-laskennan avulla

TIIVISTELMÄ

Posiva Oy ja Svensk Kärnbränslehantering AB (SKB) ovat yhdessä koordinoineet ydinjätteen loppusijoitustunnelin täyttö- ja sulkemisohjelmaa (Baclo). Ohjelman III vaihe on jaettu työtehtäviin, joihin sisältyy mallinnustehtävä SP1 'Modelling task Force'. Mallinnustehtävän tavoitteena oli arvioida loppusijoitustunnelin pystysuoran loppusijoitusreiän (KBS-3V) puskuribentoniitin ja täyteaineen välisen rajapinnan muodonmuutoksia erilaisissa kuormitustilanteissa. Kapselin päällä olevan puskurin kuivatilavuuden minimiarvoksi on asetettu 1,95 tn/m^3. Laskelmien tavoitteena on arvioida tämän vaikutusta tunnelin täyttömateriaalin ja täyttötavan valintaan. Tämä raportti sisältää VTT:n mallinnuslaskelmat ja niiden suuruusluokkavertailun suhteessa ClayTechnology AB:ssa suoritettuihin laskelmiin, jotka on raportoitu erikseen.

Työssä esitetyt laskelmat on tehty sekä SKB:n että Posivan tunneligeometrialle. Tunneligeometriat eroavat siten, että Posivan tunneli on selvästi pienempi. Nykyisten suunnitelmien perusteella sijoitustunneli tullaan täyttämään pääosin esipuristetuilla täyteainelohkoilla ja lopputila täytetään bentoniittipelleteillä. Näissä laskelmissa tunnelin blokkien täyttöastetta vaihdeltiin välillä 60 % ja 80 %. Laskelmien lähtöoletuksena oli täysin saturoitunut puskuri ja kuiva täyteaine, sillä se tapaus arvioitiin puskurin ja täyteaineen rajapinnan muodonmuutosten kannalta kriittisimmiksi. Kun puskuribentoniitti on täysin kyllästynyt, siihen on oletettu muodostuvan maksimissaan 7 MPa paisuntapaine. Täyteaineina tarkasteltiin pääsääntöisesti Friedland savea, mutta osa mallinuksista tehtiin myös Asha bentoniitti-tapaukselle. Laskelmissa vaihdeltiin myös muita reunaehtoja kuten kitkaa sekä tunnelin seinän että täytön välissä ja myös loppusijoitusreiän ja täyteaineen välillä. Tämän lisäksi tarkasteltiin erilaisia tilanteita, joissa pelletit olivat erodoituneet eri osista tunnelia. Työssä oli tarkoitus tehdä myös alustavia 3D laskentoja todellisella geometrialla, mutta Plaxis 3D osoittautui sopimattomaksi tähän tehtävään. Laskelmat on tehty Plaxis 2D ohjelmalla aksisymmetrisenä tarkasteluna. Materiaalimallina täyteaineelle käytettiin lineaarista elastista materiaalimallia, koska kimmo-plastisen (Mohr-Coulomb) materiaalimallin soveltaminen aiheutti epärealistisia jännityskertymiä. Täyttöaine mallinnettiin yhtenäisenä materiaalin, koska Plaxis 2D:llä ei voida mallintaa täyteainelohkoja.

Ottaen huomioon eri laskentatapojen erot ja materiaaliparametrien oletukset SKB:n tunnelin tapauksessa pystysuuntaiset muodonmuutokset puskurin ja täyteaineen rajapinnassa sijoittuvat kuivan täyteaineen tapauksessa välille 80…120 mm. Posivan tunneligeometrialle on tehty vain kaksiulotteisia Plaxis mallinnuksia. Niiden perusteella vastaava rajapinnan muodonmuutos olisi noin 80 mm. Jos oletetaan, että puskurin löytyminen tapahtuu tasaisesti, lasketut arvot ylittävät sallitun muodonmuutoksen puskurin löyhtyessä liikaa. Todellisuudessa löyhtyminen tapahtuu pääosin lähellä rajapintaa ja puskurin tilavuusvaatimus saattaa hyvinkin riittää kapselin yläpuolella, sillä pääosa tehdyistä 3D mallinnuksista viittaa tähän suuntaan.

Nämä mallinnuslaskelmat ovat alustavia ja ne sisältävät paljon oletuksia ja yksinkertaistuksia esimerkiksi täyteainelohkojen välisen muodonmuutoksen osalta. Jatkossa on tarpeen tehdä tarkasteluja myös eri saturaatioasteissa (saturoitunut täyttö). Edelleen erilaisien mallinnusmenetelmien (myös 3D) ja kehittyneempien materiaalimallien soveltaminen ovat tarpeen. Jatkon mallinnuslaskelmat tulevat olemaan oleellinen osa tunnelin täyttöratkaisujen suunnittelua.

Avainsanat: puskuri, tunnelitäyttö, FEM, paisuminen

TABLE OF CONTENTS

ABSTRACT

TIIVISTELMÄ

PREFACE

Posiva Oy (Posiva) and Swedish Nuclear Waste Management Company (SKB) coordinate the 3 phase programme of "BAckfilling and CLOsure of the deep repository" (Baclo). Baclo phase III includes modelling task force SP1: Finite element modelling of the swelling of the buffer against backfill in the deposition tunnel, functional studies. The objective of the finite element modelling of the backfill was to find out the interaction of the buffer and backfilling. The stress - deformation balance in this interaction area was studied to find out the most critical design cases and problems. Parallel modelling was performed at ClayTechnology AB and VTT for comparison of modelling tools and to verify previously done analytical calculations. This report presents the results of the VTT's modelling calculations and comparison between different calculation approaches. The results of analytical calculations of ClayTechnology AB have published earlier (Johannesson 2007) and their finite element calculations will be reported in a separate report.

The work performed at VTT's included three tasks. The first task was the parallel modelling of backfill studies. The modellings were done as axisymmetric calculations and Plaxis 2D program was used to do them. Both SKB's and Posiva's tunnel geometries were modeled. The modelling included different approaches to find out the effect of different boundary conditions and parameters. The second task was to compare different deformation calculations. The aim of this task was to compare the calculation methods and to find out the range of the results. The third task was to complete 2D calculations with some primary 3D element calculations. Unfortunately Plaxis 3D program proved to be unsuitable for this approach.

The work was done by Leena Korkiala-Tanttu. The analytical calculations were conducted by Lars-Erik Johannesson from ClayTechnology AB and 3D finite element calculations with ABAQUS by Lennart Börgesson (ClayTechnology). Paula Keto from Saanio & Riekkola, Johanna Hansen from Posiva and David Gunnarsson from SKB participated to the project management team.

Espoo, August 2008 VTT

1. BACKGROUND

One essential functional requirement for the deposition tunnel is that the backfill should be so stiff, that even if the buffer is swelling and compressing the backfill, the buffer density must not decrease substantially. The dry density requirement for the buffer is at least 1.95 t/m^3 right above the canister (1.5 m below the buffer-backfill interface for SKB and 2.0 m or 1.95 m for Posiva). The stress and displacement balance in the surface of the buffer changes depending on the saturation degree of the buffer and backfill. The most critical balance situations as the function of the material properties of backfill was modelled with finite element methods.

The modelling will be used to calculate the vertical displacement in the interface between buffer and backfill. The average density of the buffer above the canister can be calculated from the interface displacements and the results can be compared with the analytical calculations done earlier by Johannesson & Nilsson (2006) and Johannesson (2008). These results will be used in the backfill and buffer design to evaluate how the functional requirement can be achieved. They will be also needed for the long-term safety evaluations concerning the performance of backfill and buffer.

2. OBJECTIVES OF THE MODELLING TASKS

Finite element modelling of the backfill was done to find out the interaction of the buffer and backfilling and finding the dominating forces and their ratios. The stress - deformation balance in this interaction area was studied to find out the most critical design cases and problems. Parallel modelling has been performed at Claytech and VTT for comparison of modelling tools and to verify previously done analytical calculations. This report describes VTT's finite element calculations and the comparison of the modelling results of Claytech and VTT together with the earlier performed analytical calculations.

3. DESCRIPTION OF THE MODELLING METHOD

In these studies the backfill material was described as a continuum of material. The Plaxis 2D version 8.6 was used and the applied elements have been the 15 node triangle elements. The modelling simulated the same geometry which has been used in the analytical calculations performed in Baclo phase II and III by Johannsson & Nilsson (2006) and Johannesson (2008).

The modelling was done as an axisymmetric calculation. The radius and other measures of the model were defined so that they could be compared to the retangular 3D tunnel geometry (Figure 1). This kind of approach is a compromise between the true 3D geometry and the axisymmetric geometry with the real tunnel width (4.9 m). Yet, it probably underestimates somewhat the real displacements.

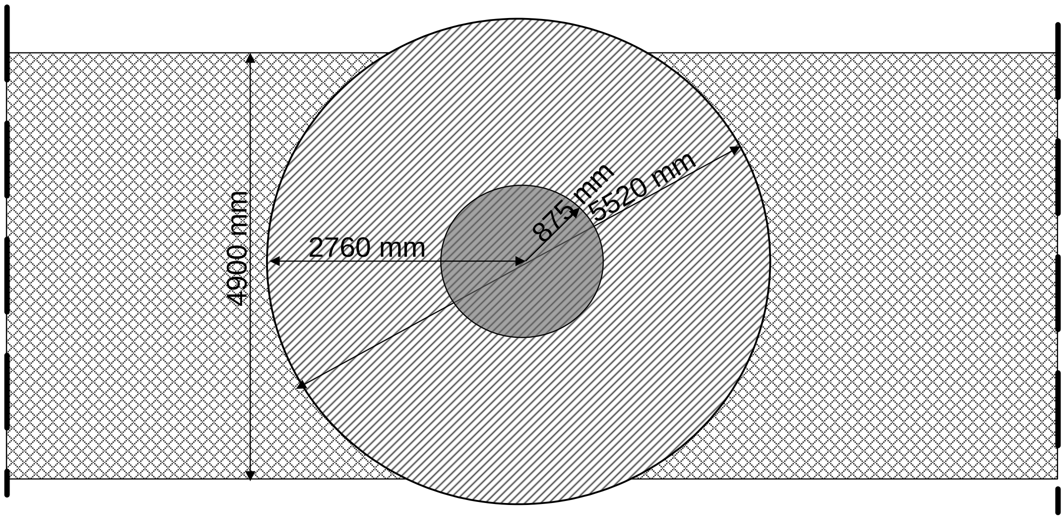


Figure 1. *The definition of the axisymmetric radius compared to the tunnel of SKB.*

Assumptions for the modelling were:

- Buffer bentonite was in fully saturated state, and backfill was in “dry” state (no increase in water content had occurred after installation).
- Buffer and backfill materials were modeled as continuum materials.
- The swelling pressure of buffer was described as an external loading up to 7 MPa.
- The friction angle between rock and buffer clay was 0° but some additional calculations were done with a friction angle of about 10° and with a rigid contact.
- Material model for backfill material: at first linear elastic-plastic material model (Mohr - Coulomb) was tested, but was changed to the linear elastic (LE) model.
- Material model for rock: linear elastic model.
- Buffer material was described as linear elastic material.

4. GEOMETRY AND FIXITIES

The modelling cases and input parameters were fixed mainly based on the assumptions made in Johannesson (2008) to gain comparable results. For the basic modelling case the geometry was chosen to be SKB’s deposition tunnel (Figure 2), but Posiva’s geometry was also used in some of the calculations to evaluate the effect of tunnel geometry on the results. The block filling degree chosen for the basic case was ~70%. In the 2D calculations, the materials (pellets and blocks) were modelled as continuum of materials. Otherwise the fixed assumptions were:

- Block materials: Friedland-clay & Asha 230. See the density data & mechanical parameters (Young’s modulus, Poisson’s ratio, densities etc.) from Tables 1 and 2. The parameters used were average values.
- Pellets: MX-80. See parameters from Tables 1 and 2.
- Same tunnel, buffer & backfill dimensions as in Claytech’s analytical calculations.
- The friction angle between the backfill and the rock was about 10°.
- The friction angle between rock and buffer clay was assumed to be 0°, but some additional calculations were done with a friction angle of about 10° and with a rigid contact.
- In the cases where the backfill material was modelled as a continuum, the thickness of the horizontal block-block interfaces between the blocks were supposed to be 4 mm each, and the amount of block layers was 9.

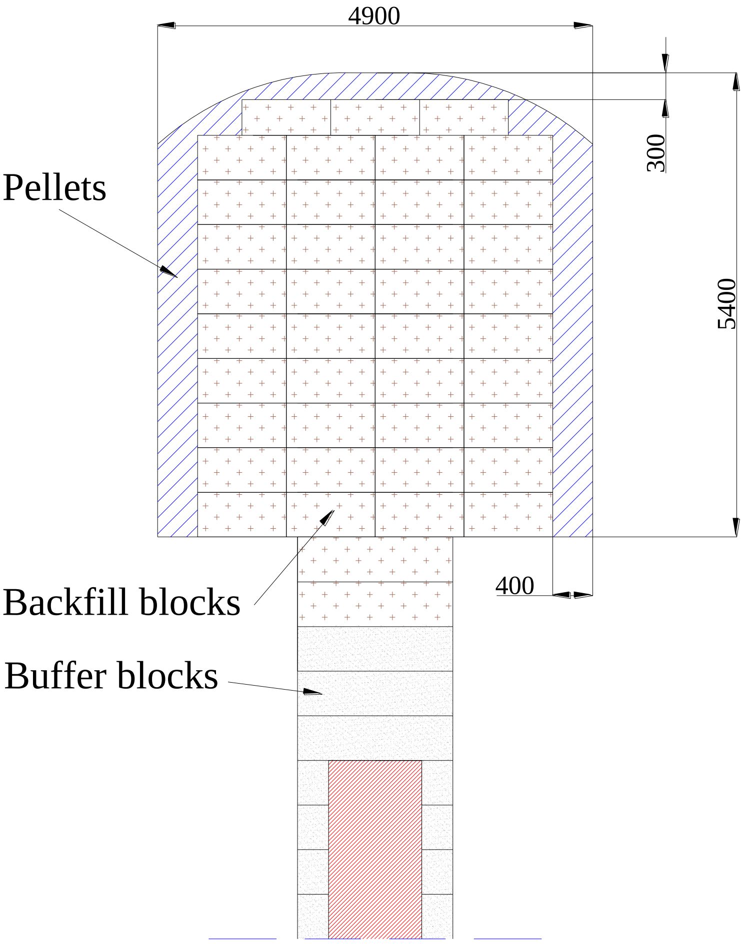


Figure 2. *The geometry of SKB depostion tunnel (KBS-3V).*

The axisymmetric modelling case of VTT is presented in Figure 4. The buffer material is on the bottom left hand side and rock on the bottom right hand side of the figure. The rock slice was needed to give support for the tunnel part of the backfilling. The total radius of the model was 2.76 m. The backfilling was surrounded by a pellet filled zone with width of 400 mm. In the interface between buffer and backfill there was an external loading, which described the swelling pressure of the buffer. In addition, there was a thin empty gap (15 mm) between rock and (deposition hole's) buffer and backfilling to model a case when there is no friction between the rock and the buffer.

In Plaxis the forces in the interface between two materials are described through R_{inter} parameter. R_{inter} parameter is a relative parameter, which indicates the friction between two materials (Equation 1 in page 9). If R_{inter} is 0.01, there is no friction between materials. The value of about 0.1 describes the situation where friction angle is near to 10°. The modelling also included interface elements between the horizontal interface of backfill and rock and between pellets and rock wall.

Two different boundary conditions (fixities in Plaxis) were varied for the top part of the model: free swelling upwards and a fixed roof. The modelling steps for the basic case were following (Figures 3 and 4):

1. initial state, when there is no external loading, only the gravity loading (weight) of the materials
2. the external load was added and it was let to increase to 160 kPa (about the weight of the material above)
3. the buffer material was removed, when the swelling pressure was about 160 kPa
4. the swelling pressure was increased to 2.5 MPa
5. the material properties of the backfill blocks in the deposition tunnel were changed to correspond to the stress state
6. the swelling pressure was increased to 4.5 MPa
7. the material properties of the backfill blocks in the deposition tunnel were changed to correspond to the stress state
8. the swelling pressure of the buffer was increased up to maximum loading of 7 MPa.

The step 3 was needed, because otherwise the deformations in the buffer backfill interface did not give realistic values. The swelling pressure of 160 kPa corresponds to the gravity loading of the backfill materials. The material properties of the backfill blocks in deposition tunnel were changed to correspond to the average stress level and to model the non-linearity of the backfill material. The hydrostatic stress levels in the tunnel backfilling stayed so low that there was no need to correct the material properties due to that.

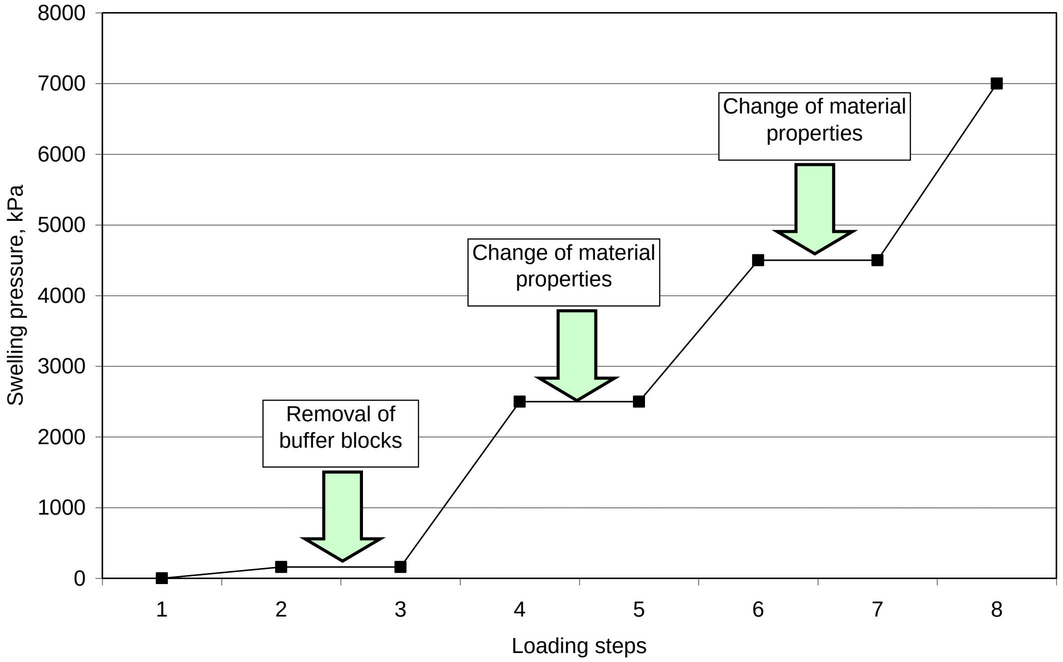
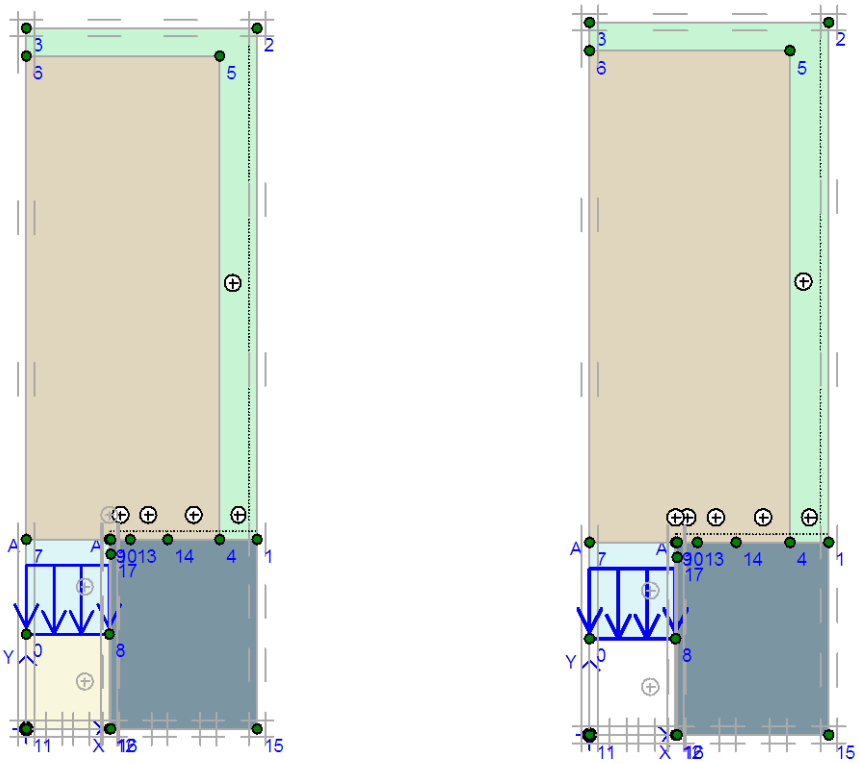
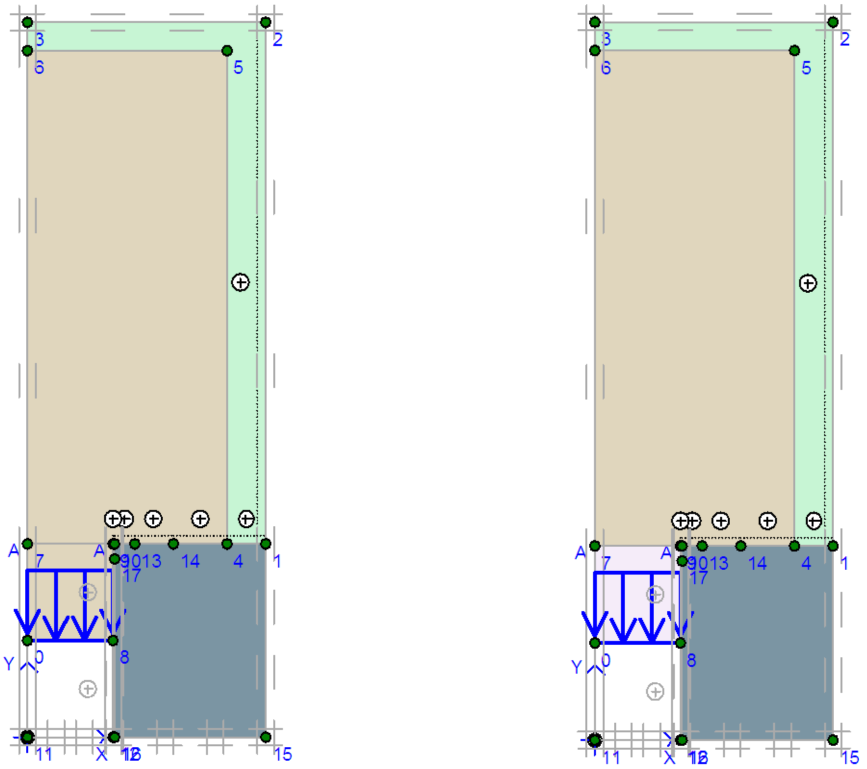


Figure 3. *The modelling steps.*



Step 1. Initial state.

Step 3. Removal of buffer blocks.



Step 5. Change of material properties in the upper part of the deposition hole.

Step 7. Change of material properties in the upper part of the deposition hole.

Figure 4. *The modelling steps.*

5. MODELLING PROCESS, MATERIAL MODELS AND THEIR PARAMETERS

The first attempt of the modelling was done with Mohr-Coulomb material model (MC) for pellets, backfill and buffer materials. Rock was modelled as a linear elastic material (LE). The parameters used are presented in Table 1.

Table 1. *Mohr-Coulomb material parameters for Friedland backfill material. The* γ_{unsat} *is the unsaturated bulk density and* γ_{sat} *saturated density*

material	**model**	γ_{unsat}, **kN/m³**	γ_{sat}, **kN/m³**	ν, **-**	**E, MPa**	**cohesion, kN/m²**	**friction angle, ϕ, °**	**R inter**
Backfill	MC	20	20	0.28	212*	3	24	0.2
Pellets	MC	16	16	0.12	20	40	27	0.01
Buffer	MC	21	21	0.28	300	2	25	0.01
Rock	LE	24	24	0.25	4 000	-	-	-

*E_{50} defined from the TUT triaxial tests (Kuula-Väisänen & Kolisoja 2008)

The material parameters were originally chosen based on the laboratory results presented in Kuula-Väisänen & Kolisoja (2008). In this report, the deformation moduli E_{50} for backfill materials determined with triaxial tests were defined from the deformations, which have been measured outside the loading frame. Because this measuring technique is very conservative i.e. underestimating the Young's modulus, a decision was made to use mainly the Young's moduli defined in Johannesson (2008), since they were supposed to be more realistic being somewhat higher than those defined from triaxial tests.

Mohr-Coulomb material model is an elasto-plastic material model, which combines linear elastic behaviour and the Mohr-Coulomb's failure criterion. By using a simpler LE model the numerical problems in the corner areas can be avoided. While the LE model does not have a failure criterion, it is possible that unrealistic stress concentrations can grow to some places and the deformations will then be underestimated. This can be partly restricted by the use of stress dependent Young's moduli.

Figure 5 illustrates the compression properties of unsaturated Friedland clay in one axial compression test (Johannesson 2008). The Young's Modulus E is defined from the linear part of the curve. Because the deformation - stress curve is notably non-linear the moduli have been defined for different stress level separately. In this case three different stress levels have been used. Table 2 presents the material parameters for linear elastic modelling case.

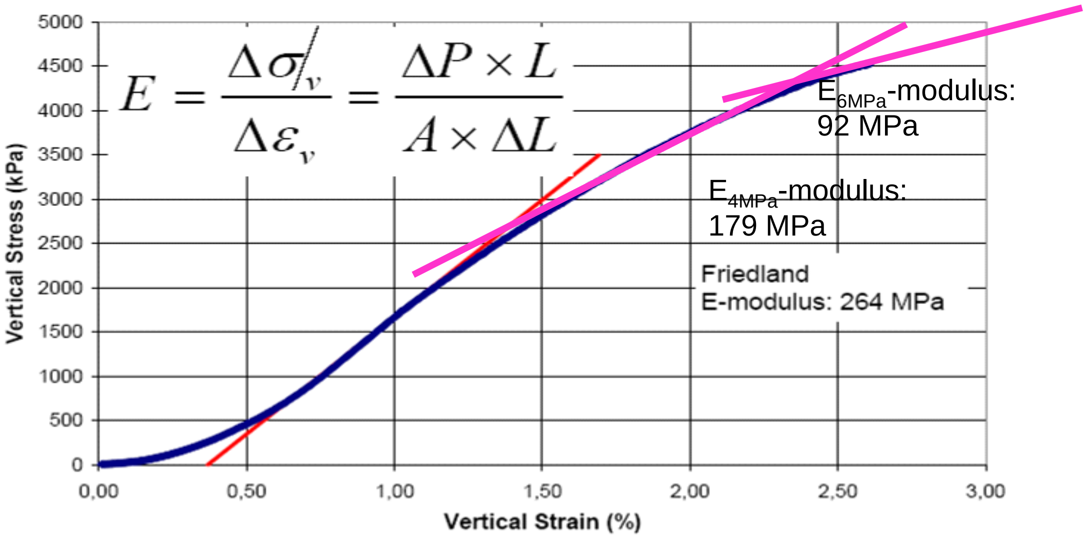


Figure 5. *The compression properties of unsaturated Friedland clay in one axial test.*

Table 2. *Linear elastic material parameters for Friedland backfill material.*

material	**stress level, kPa**	**model**	γ_{unsat}, **kN/m^3**	γ_{sat}, **kN/m^3**	**ν, -**	**E, MPa**	**R inter**
Backfill	0 - 2 500	LE	20	20	0.28	264	0.1
Backfill**	2 500 - 4 500	LE	20	20	0.28	179	0.1
Backfill**	4 500 - 7 000	LE	20	20	0.28	92	0.1
Pellets		LE	16	16	0.12	20*	0.1
Buffer		LE	21	21	0.28	300	0.1
Rock		LE	24	24	0.25	4 000	-

*triaxial test result E_{50} (Kuula-Väisänen & Kolisoja 2008)
** these models were only applied to the deposition hole

The interface between different material sets can be described with interface elements. The material properties of interface elements are described with parameter R_{inter}. The interface properties are calculated from the soil properties associated data set and the strength reduction factor by applying rules of Equations 1 and 2 for frictional materials. When R_{inter} has value 1, it means that there is no interface and the deformations of each material set are totally connected (Brinkgreve 2002).

$$c_i = R_{inter} \cdot c_{soil} \tag{1}$$

$$\tan\phi_i = R_{inter} \cdot \tan\phi_{soil} \tag{2}$$

where c_i is cohesion of interface, kPa
c_{soil} cohesion of soil, kPa
ϕ_i friction angle of interface
ϕ_{soil} friction angle of soil.

So, if ϕ_{soil} is 50° and R_{inter} is 0.1, ϕ_i corresponds to about 7° and R_{inter} is 0.2, ϕ_i about 13.4° respectively. Because the actual friction between wall and backfill in the repository is not known, the value of R_{inter} has been varied in the calculations. For the elastic materials both slipping and formation of gaps could be expected to occur. The magnitudes of these displacements are calculated after Equations 3 and 4.

$$s_{gap} = \frac{\sigma \cdot t_i}{E_{oed,i}} \tag{3}$$

$$s_{slip} = \frac{\tau \cdot t_i}{G_i} \tag{4}$$

$$\nu_i = 0.45$$

$$E_{oed,i} = 2G_i \frac{1-\nu_i}{1-2\nu_i} \tag{5}$$

$$G_i = R_{\text{inter}}{}^2 \cdot G_{soil} \le G_{soil} \tag{6}$$

where	$E_{oed,i}$	is one-dimensional compression modulus of the interface, MPa
	G_i	shear modulus of the interface, MPa
	s_{gap}	elastic gap displacement, m
	s_{slip}	elastic slip displacement, m
	t_i	virtual thickness of the interface, (is chosen automatically by the program)
	σ	normal stress perpendicular to the interface, kPa
	τ	shear stress perpendicular to the interface, kPa.

Equations 5 and 6 show, that the elastic parameters of the interface elements can be very small causing excessively large elastic displacements. This can cause numerical ill-conditioning. To avoid this, the automatically chose the virtual thickness of the interface can be changed in those cases (Brinkgreve 2002). In these calculations the virtual interface thickness was not changed.

6. MODELLING RESULTS

6.1 Results gained with the Mohr-Coulomb material model

The first calculations were done with the ideal elasto-plastic material model Mohr-Coulomb for the basic case assuming SKB:s tunnel dimensions, Frieland clay blocks and 70% block filling degree. Many different kind of geometries were tested near the corner of deposition hole and tunnel (see Figure 6). The problem with this area is that elasto-plastic models are not able to model this kind of corner areas properly. The stresses concentrate around the corner with very high peak values. The reason for this is that with plastic continuum materials, when the failure (or yielding) stress has been achieved, the stresses will be redistributed to the adjacent nodes. This process continues near the corner area. The high peak stress produces also unrealistic deformations around the corner. Thus the element mesh ‘breaks’ easily, especially if there are deformations to different directions. In this case the gravity presses backfill towards rock and swelling pressure pushes it upwards.

After several trials MC approach was rejected because the external loading (representing swelling pressure) could grow only up to the level of 400…500 kPa. The implementation of LE model does not take all phenomena in to account in realistic way. E.g. the phenomena in the vicinity of yield strength may lead to non-physical results. In this case LE model was used as the results were in region considered reasonable.

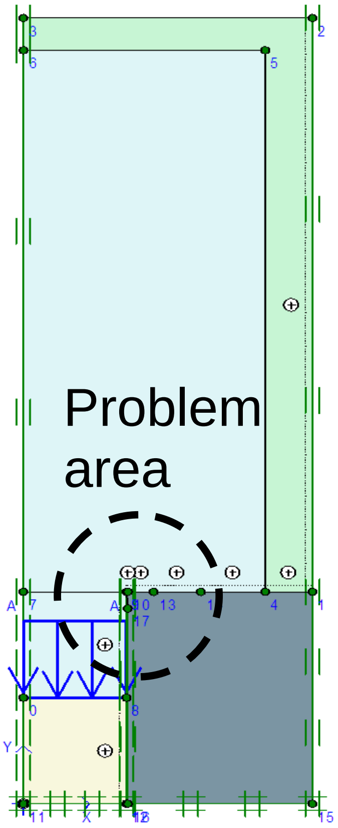


Figure 6. *The situation of the problem area near the hole corner.*

6.2 Results gained with a Linear -elastic material model

The results presented in this section are for the basic case assuming linear-elastic material model, SKB:s tunnel dimensions, Friedland clay blocks, block filling degree of 70% and assuming that the friction hole between the buffer and the deposition hole wall is 0°.

The calculation process for linear elastic model was mainly the same as for MC modelling, but two more steps were added where the Young's modulus for the whole backfill material was changed in the swelling pressure levels of 2 500 kPa and 4 500 kPa (corresponds to the material properties in Table 2). Because the stress level in the whole backfill material was considerably lower, this approach overestimated the deformations. The LE model was stable in the conditions described whereas the implementation on the MC model turned out to be unstable. With LE model the top swelling pressure level 7 MPa could be reached. Figure 7 presents the total displacements of the modelled structure. The extreme mean stresses occur near the hole corner.

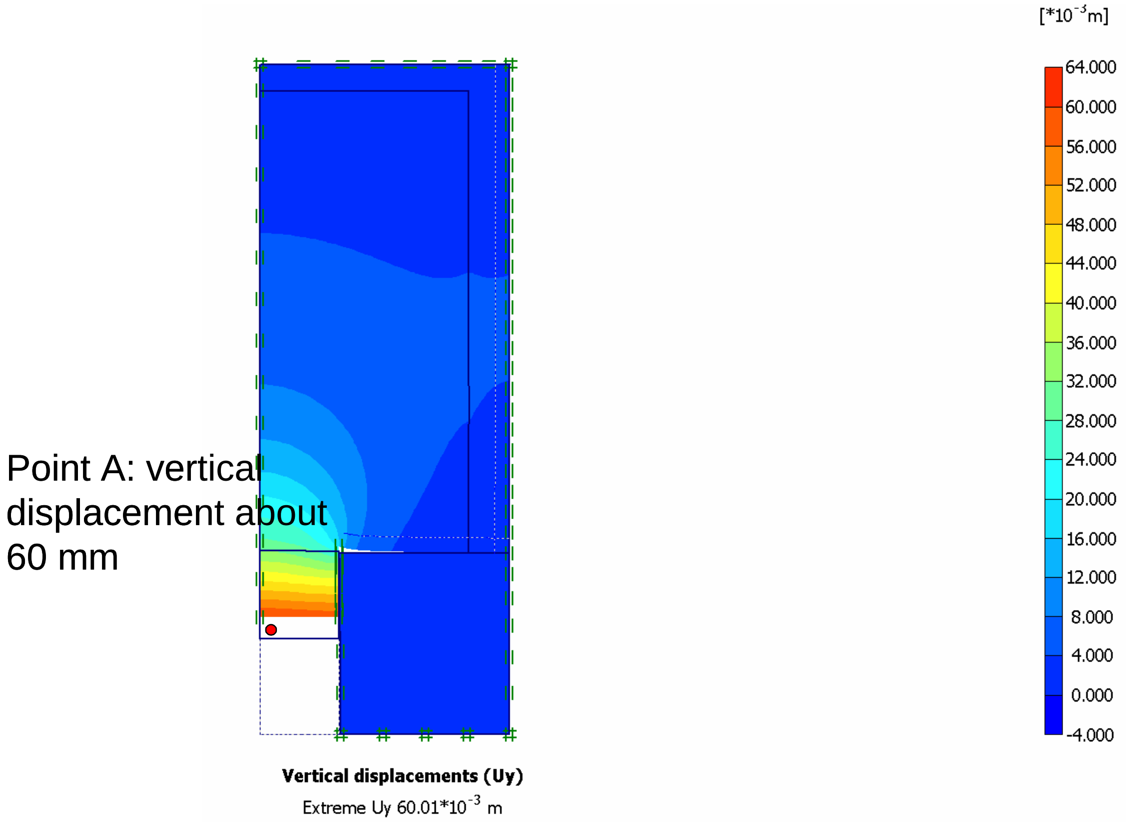

Point A: vertical displacement about 60 mm

Figure 7. *The total displacements of the linear elastic model.*

Few interface cases were tested for the tunnel floor and tunnel wall. Figure 8 presents the same modelling case as Figure7 focusing on the vertical displacements on the floor area. In this case R_{inter} has a value of 0.1 meaning that there is little friction between the tunnel floor and backfill, yet the swelling pressure is so high that the backfill moves upwards slightly in the floor area near deposition hole corner.

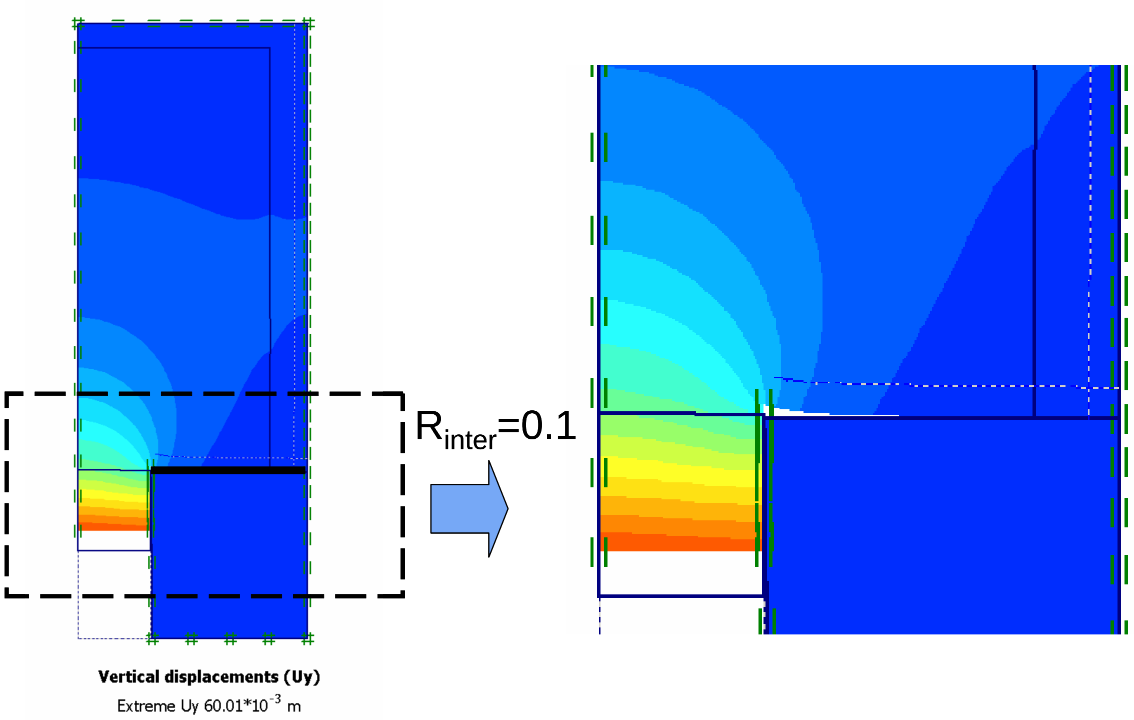
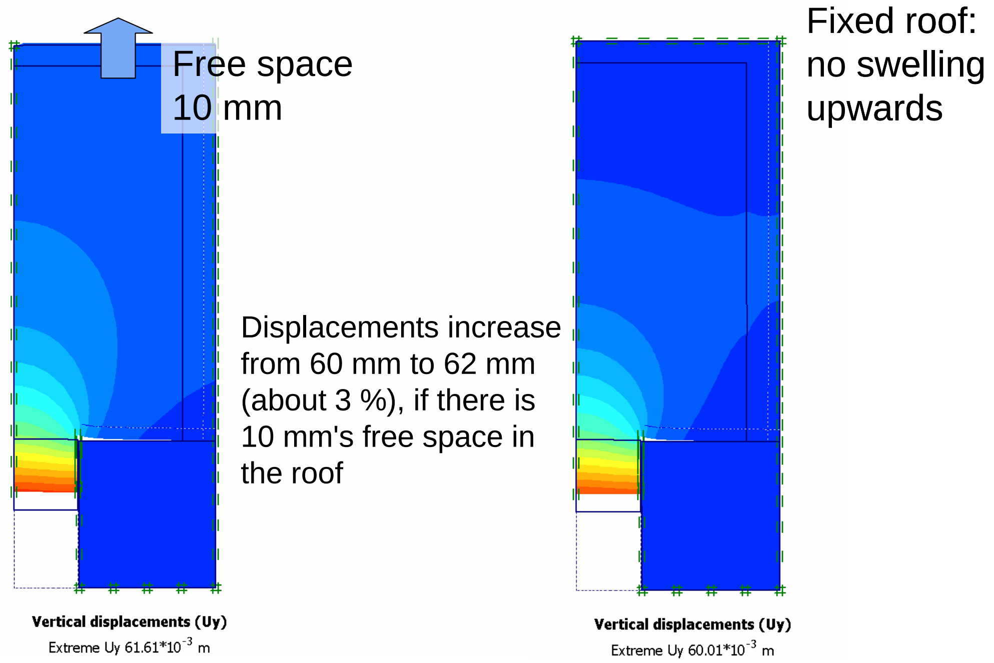


Figure 8. *Vertical displacements when R_{inter} is 0.1. A detail on the right side. Scaling as in Figure 7.*

The effect of boundary conditions (in Plaxis fixities) of the tunnel roof was tested in two different cases. The basic assumption was that the tunnel roof was fixed, meaning that there was a full contact between the pellets and tunnel roof. In the second calculation case it was assumed that some free space (a 10 mm thick air filled gap) had formed between the pellets and the tunnel roof due to settlement of the pellets by their own weight. Figure 9 compares the vertical displacements of these two modelling cases to each other. The vertical displacements in the interface increased only slightly if there was the free space of 10 mm in the roof. It is important to notice that the displacement and stress distributions for the free space case differ from the fixed roof case; in the fixed roof case the stresses distribute more to the wall side, while in the free space case the deformations will happen mainly upwards. Also Figure 10 illustrates this, showing the vertical displacements near the symmetry axis. For the free space case the vertical displacements concentrated near the symmetry axis being much larger near roof area. The vertical displacement in the roof for the free space case was about 7…8 mm. It means that the free space would practically be filled the pellets.

Figure 11 illustrates the effective mean stress (p’) as a function of height near the symmetry axis in the case of fixed roof. The effective mean stress is used as the non-linear material parameters have been defined for different swelling pressure levels. As Figure 11 shows the effective mean stress distributes quite quickly in the tunnel backfill.


Free space 10 mm

Fixed roof: no swelling upwards

Displacements increase from 60 mm to 62 mm (about 3 %), if there is 10 mm's free space in the roof

Figure 9. *Vertical displacements with 10 mm free space in the roof (left side) and fixed roof (right side).*

If it is assumed that there will be a free space (less than 10 mm) in the tunnel roof caused by the gravity loading of the blocks and deformation of the blocks and pellets then free swelling setup corresponds this case. If it is assumed, that the installation of the blocks and pellets will succeed well and there are no post installation deformations, then the restricted roof should correspond to this case. For the tunnel floor the assumption of the friction angle of about 10° seems quite reasonable. Modelling results indicate maximum expected vertical displacement of the backfill and pellets is about 60 mm, if the decrease in swelling pressure of the buffer due to decrease in buffer density is not considered.

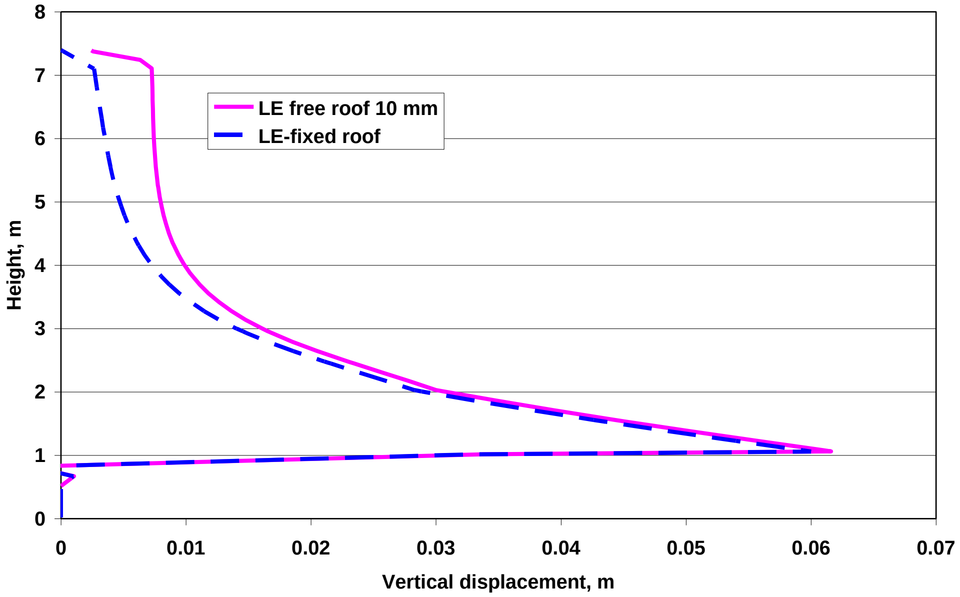


Figure 10. *Vertical displacements as a function of height near the symmetry axis.*

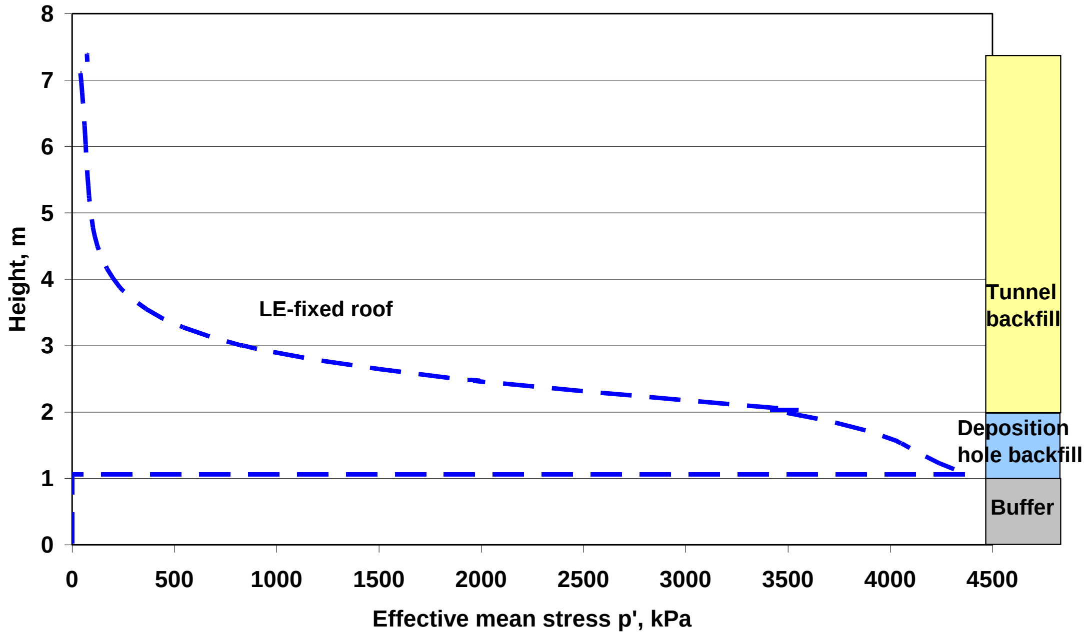


Figure 11. *Effective mean stress (p') as a function of height near the symmetry axis (fixed roof).*

6.3 Results gained varying the R_{inter} factor

The results presented in this chapter are for basic case using linear-elastic material model, Friedland clay blocks, 70% block filling degree and friction angle of 0° between the buffer and the deposition hole.

The fixed roof case has been tested with various friction values (R_{inter}) for the tunnel wall and tunnel floor besides the basic assumption of 0.1. The assumed R_{inter} value of 0.1 means that there is only a very small friction between tunnel wall and pellets. The varied R_{inter} values were 0.2, 0.3 and 1.0 (total rigid interface). Figure 12 illustrates the effective normal stress along the pellet material near tunnel wall in the case of different interface values. The change from interface value of 0.1 to 0.2 has clearly the biggest effect on vertical deformations and normal stresses. The change from 0.3 to 1.0 has only minor effect, which mainly happens in the lower part of the tunnel wall. Figure 13 illustrates the vertical displacements with different interface R_{inter} values. If R_{inter} has the value of 0.1, it means that connection between wall and pellets is very weak. When R_{inter} increases the connection forces will be larger. This also means that wall friction decreases the vertical deformations (see Figure 13). When R_{inter} is 0.1, vertical deformations will be 60 mm, if R_{inter} is 0.2 deformations are 56 mm and R_{inter} is 0.3 deformations are 53 mm. If the connection is totally rigid, the vertical deformation is about 52 mm.

The greater wall friction the more deformations are concentrated near to the buffer-backfill interface. The difference with respect to maximum deformations is 13 % (=(60 mm - 52 mm)/60 mm) and as a result is significant but with respect to the performance at entities deforming most has only a minor importance.

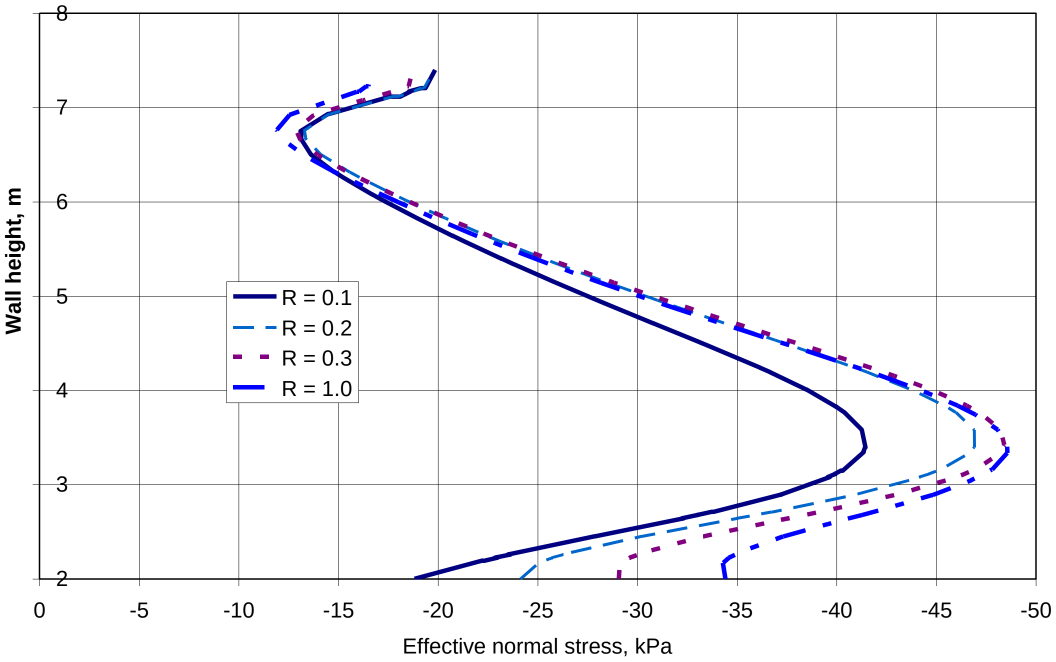


Figure 12. *Effective normal stress along the tunnel wall with different interface values.*

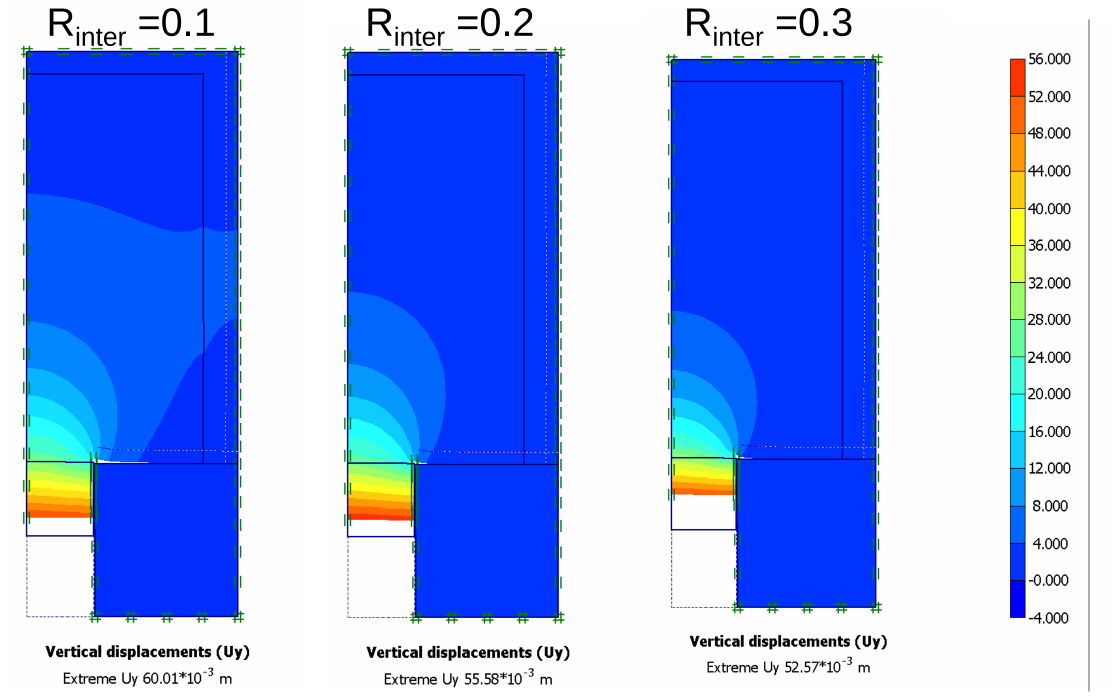


Figure 13. *Vertical deformations of Friedland backfill with different interface values* R_{inter}.

6.4 Results gained varying the friction between the materials and the deposition hole wall

The basic assumption in the previous calculations has been that there is not friction between deposition hole and buffer and backfill. The additional calculations were done for the basic case to test what would the consequences be if there is a weak connection (R_{inter} = 0.1) or rigid contact between deposition hole and buffer or backfill. The maximum vertical displacements were about the same in the case of weak friction (59 mm). However, the distribution of the vertical displacement along the buffer/backfill interface changed (Figure 14). The maximum vertical displacements were naturally near the symmetry axis. For frictional cases the displacements decreased clearly towards the wall. The maximum vertical displacement for the totally rigid case was much smaller (37 mm). The relative difference is considerable (~40 %) but the depth of the influence zone determines whether the effect is noteworthy: for one block of height of 0.4 m the decrease in density is 15 % and for five such blocks the decrease in density is 3 %.

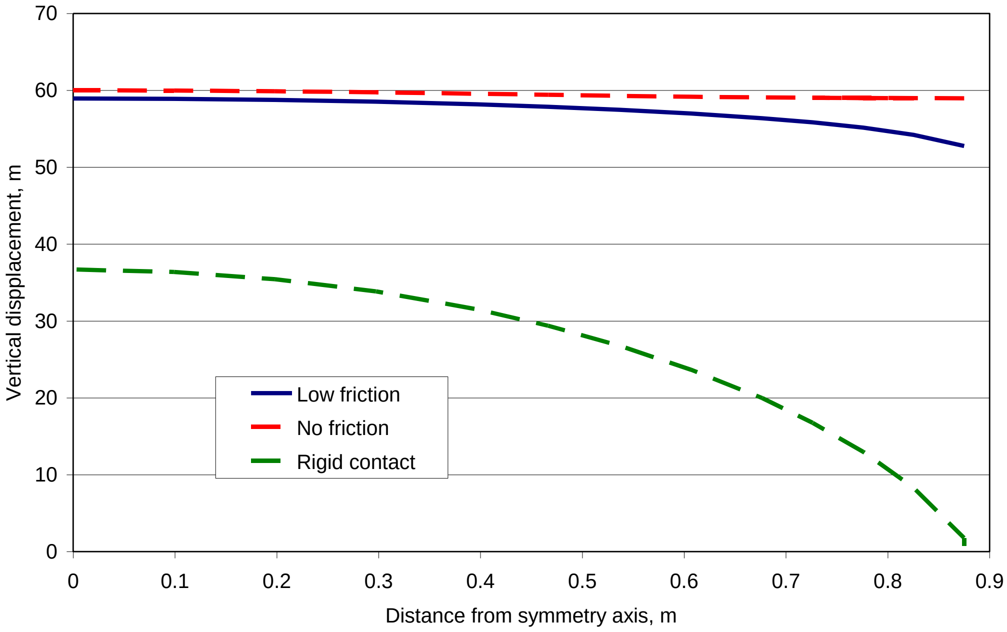


Figure 14. *Vertical displacements along buffer/backfill interface.*

6.5 Results gained with Asha 230

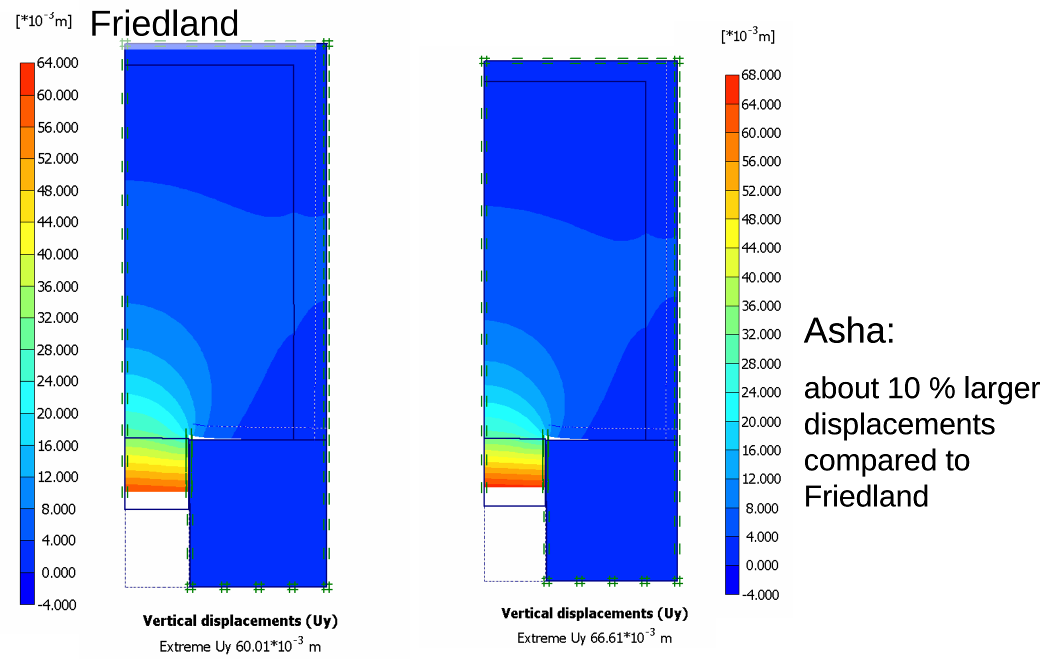
Calculations were also performed using Asha material parameters (Table 3) otherwise applying the same assumptions as in the basic case (SKB tunnel dimension, 70% block filling degree fixed roof and LE material model) (Figure 15).

Table 3. *Material parameters for Asha backfill material, different stress levels.*

material	**stress level, kPa**	**model**	**γ_{unsat}, kN/m^3**	**γ_{sat}, kN/m^3**	**ν, -**	**E, MPa**	**R_{inter}**
Backfill (hole)	0 - 4 000	LE	20	20	0.1	251	0.1
Backfill (hole)	4 000 - 7 000	LE	20	20	0.1	100	0.1
Pellets		LE	16	16	0.12	20*	0.1
Buffer		LE	21	21	0.28	300	0.1
Rock		LE	24	24	0.25	4 000	-

*triaxial test result E_{50}(Kuula-Väisänen & Kolisoja 2008)

In this case the vertical deformations were about 10...13% larger (max. 67 mm) than for corresponding Friedland clay (max. 60 mm). The most important factor for the bigger deformations of Asha is the fact that the compression modulus (M) defined for Asha from one axial compression test described in Johannesson (2008) was smaller than for Friedland clay. That is, Asha material is able to store less energy before it starts to move like rigid body.



Asha:

about 10 % larger displacements compared to Friedland

Figure 15. *Deformations of Friedland (left) and Asha (right) backfill.*

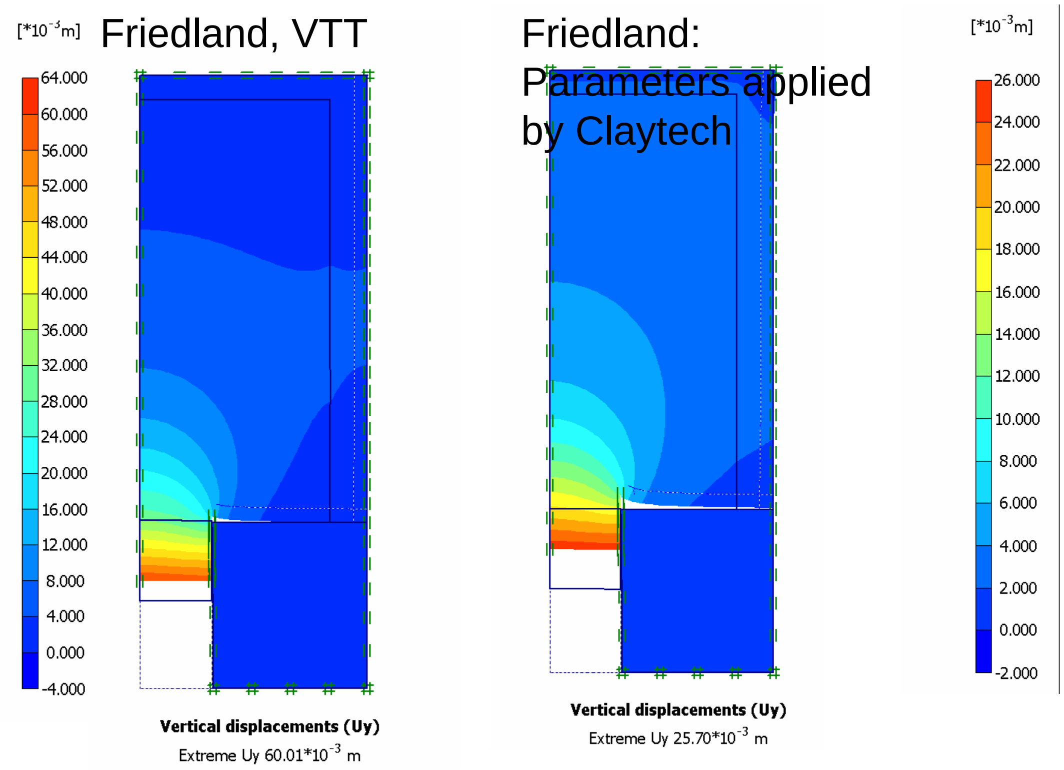


Figure 16. *Deformations of Friedland clay with VTT's material parameters (left) and Claytech's (right).*

The influence of changing backfill material parameters between the ones used for majority of calculation cases presented in this report and the ones used in the parallel modelling performed at Sweden (with ABAQUS) was also conducted. Figure 16 illustrates the results of the comparison. The Plaxis modelling on the left hand side of the figure was done with the parameters presented in Table 2, and the modelling on the right hand side with ABAQUS using parameters presented in Table 4. The backfill block's Young's modulus was much higher for the latter case, but on the other hand the modulus of the pellets was much lower. In the Plaxis approach the displacements occur mainly in the backfill block material instead of pellets. So the total displacements are considerably more sensitive to the changes in block's modulus than to pellet's modulus.

6.6 Results gained varying the block filling degree

The basic case was also recalculated varying the block filling degree. Figure 16 compares the vertical displacements assuming block filling degrees of 70% and 80%. There was only very small difference in the vertical displacements between these two cases (less than 0.5 mm corresponding to ~1%) even though the block filling degree was increased to 80% from original 70%. This result suggests that in these calculations only a small fraction of deformations occur in pellets.

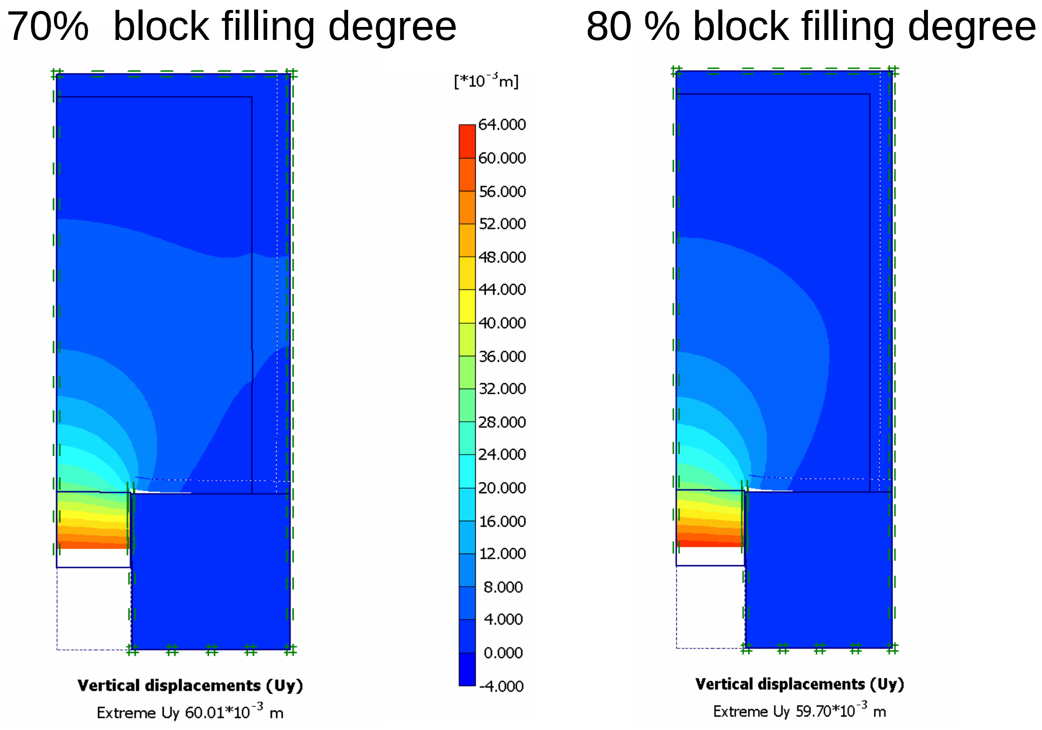


Figure 17. *Block filling degrees of 70% and 80%.*

6.7 Results gained with the Posiva geometry

A reference study with the Finnish tunnel geometry (the tunnel geometry used by CT in the analytical calculation was based on Swedish tunnel geometry) was also included into the study. The calculations were otherwise performed with the same parameters used for the basic case but with varying the tunnel geometry and also the block filling degree. The Finnish tunnel geometry is presented in Figure 18.

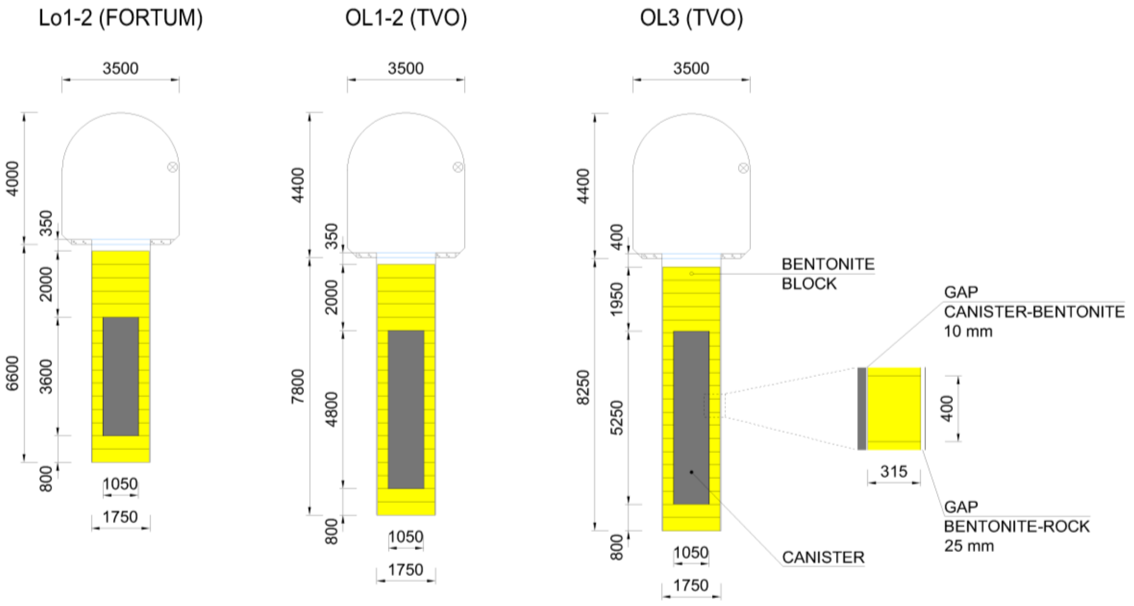
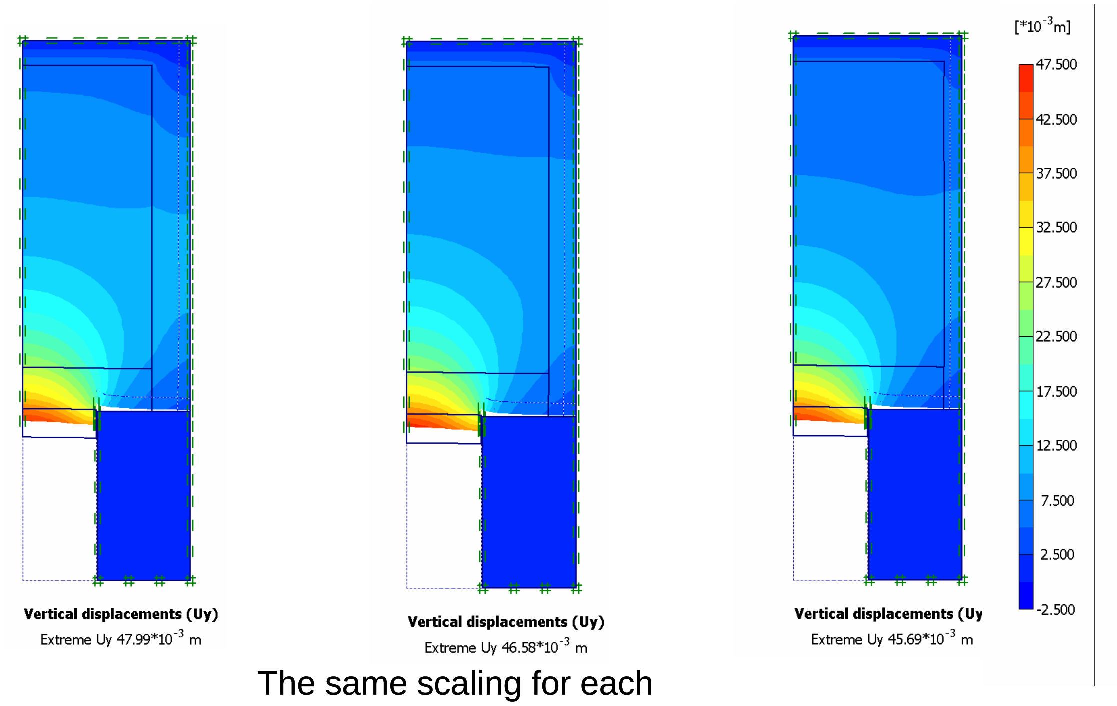


Figure 18. *The geometry of Posiva deposition tunnel (KBS-3V).*

Posiva's deposition tunnel cross section is clearly smaller than SKB's, yet the deposition hole has the same radius in both cases. However, in the Posiva case the thickness of the buffer above the canister is 2.0 m (for SKB 1.5 m) and the thickness of the backfill block in the uppermost part of the deposition hole is smaller (350 mm) compared to SKB's 1 000 mm. Otherwise, the same assumptions are previously were retained. In Posiva calculations three different backfilling degrees was tested: 60%, 70% and 80 %. The calculated vertical displacements are presented in Figure 19 for different block filling degrees. The maximum vertical displacements (Figure 20) as a function of swelling pressure (at the interface between buffer and backfill) for Posiva's tunnel and block filling degree of 60% are smaller (48 mm) than for the SKB's tunnel and 70% block filling degree (60 mm). When the backfilling degree in Posiva geometry is increased from 60% to 70%, the vertical deformation will be 47 mm. If the backfilling degree is yet increased up to 80% the displacement is 46 mm. Vertical deformations for Posiva case are smaller because the thicknesses of the block and pellet layers are smaller and on the other hand the thickness of the buffer is bigger. This is the case even though the tunnel width for Posiva is smaller and thus the stresses distribute to a smaller volume.



The same scaling for each

Figure 19. *Posiva: the vertical displacements for block filling degrees of 60% (left), 70% (middle) and 80% (right).*

The effect of a 20 mm thick gap between the pellets and the tunnel roof was also tested for two different block filling degrees of 60 and 80 (see. Figures 20, 21 and 22). In this case the effect of block filling degree makes a relatively small difference. For block filling degree of 60% a very small free space in the roof (representing the compression of the backfill after installation) increases vertical deformations from 48 mm up to 54 mm. For the 80% block filling degree the effect is smaller, from 46 mm up to 49 mm. The assumption of the 20 mm's free space can be considered to be representative, because the deformations in free space are less than 20 mm (about 14 mm for 80 % and 18 mm for 60 %).

These calculations show that the Posiva tunnel geometry will produce more than 10% smaller deformations than the SKB's tunnel geometry. One reason for this is the differences in buffer thicknesses. However, because Posiva's tunnel geometry is smaller it is more susceptible to the changes of block filling degree. Yet the effect of block filling degree was not so big, if the tunnel roof was fixed. But if there will be some free space on the tunnel roof, the effect of the block filling degree is more remarkable.

The load is transmitted from the deposition hole to the opposing (rigid) support i.e. the tunnel roof by the backfill blocks. Therefore, the filling degree of the sides is of lesser importance. In case there is free space at the region that provides the support to oppose swelling (roof), these calculations suggest a single-rigid-body like vertical displacement of the system comprising of the blocks and pellets.

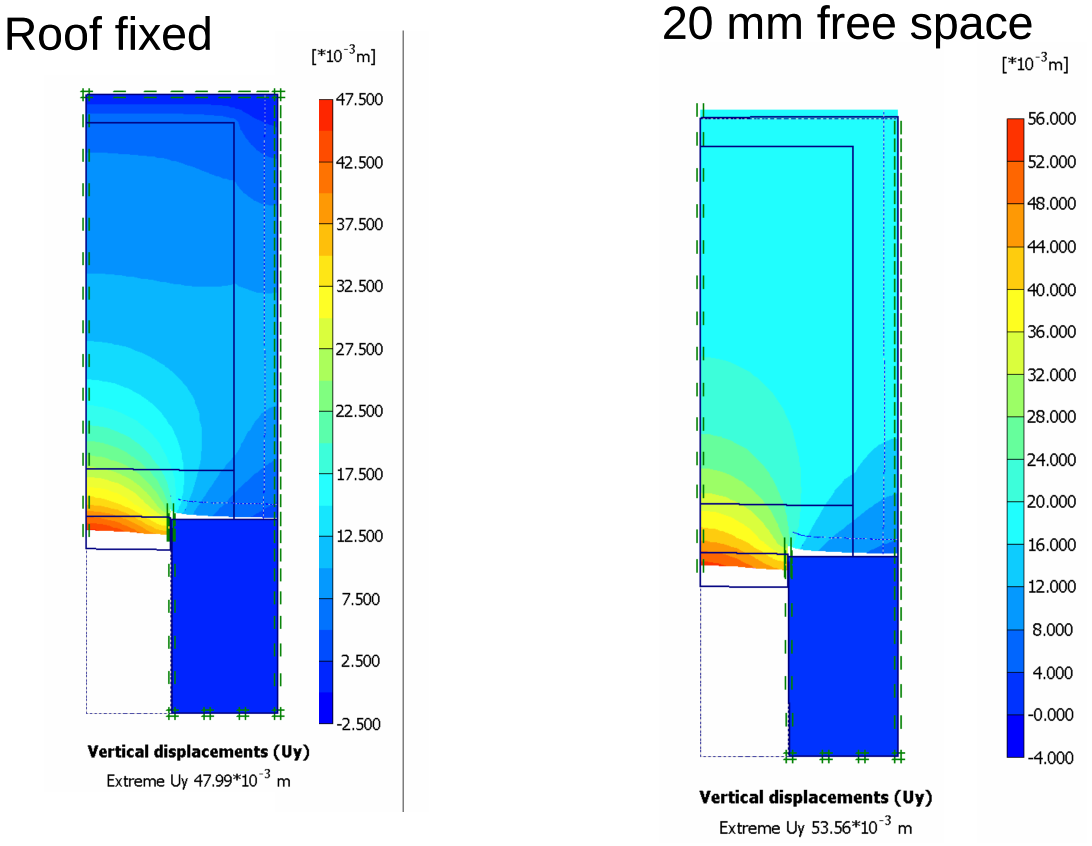


Figure 20. *Posiva: the vertical displacements for block filling degree of 60% with roof fixed and 20 mm's free space in the roof.*

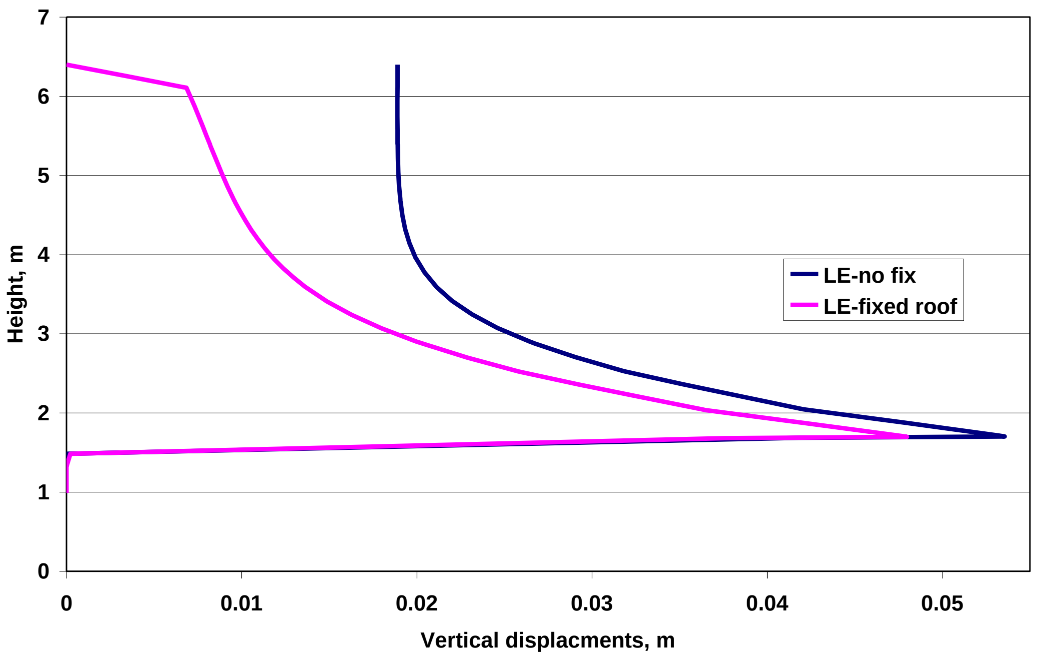


Figure 21. *Posiva: the vertical displacements for block filling degree of 60% with roof fixed and 20 mm's free space in the roof.*

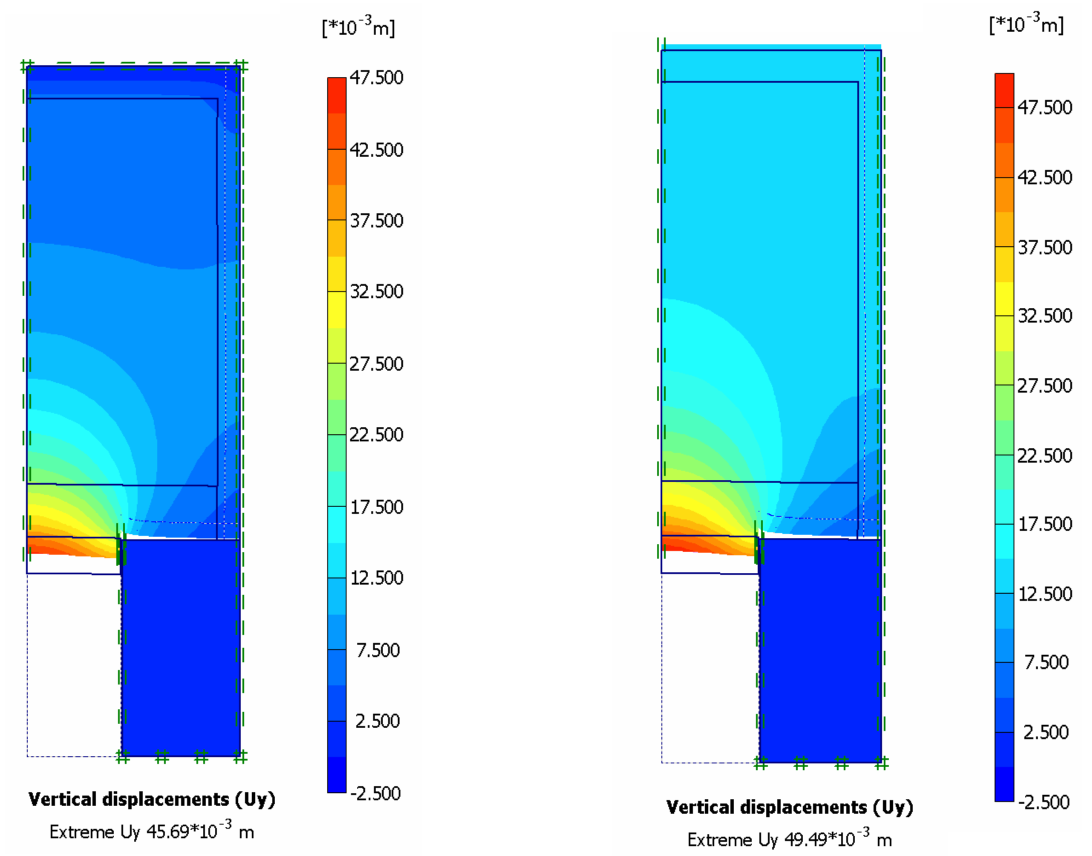
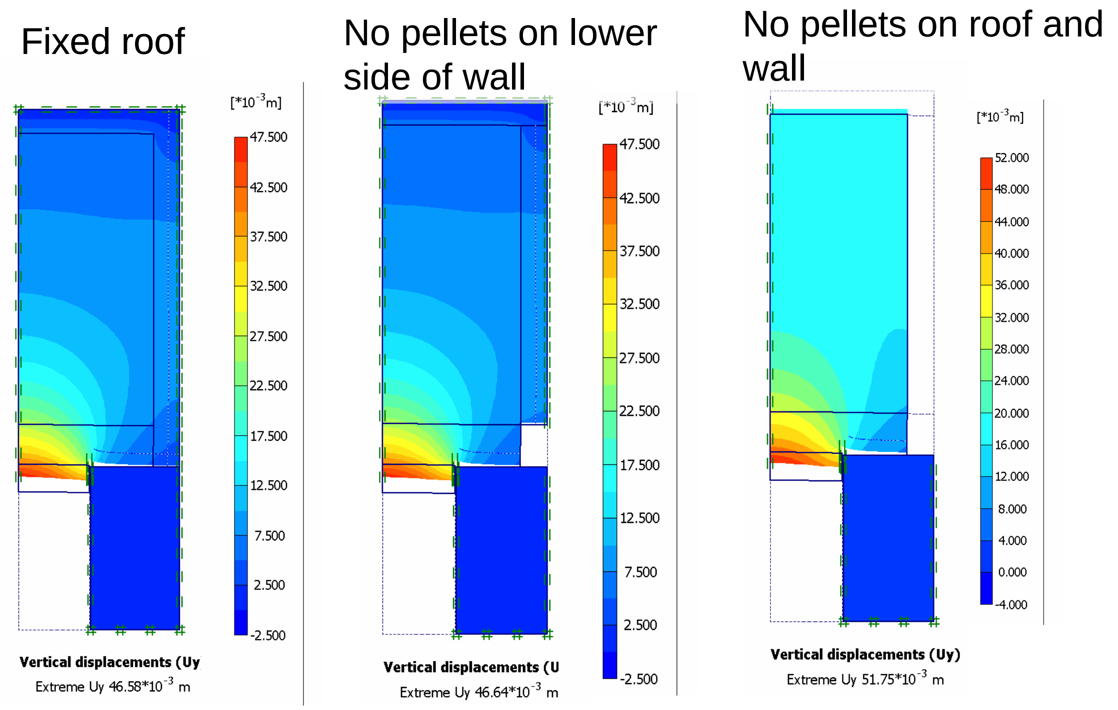


Figure 22. *Posiva: the vertical displacements for block filling degree of 80 % with roof fixed and 20 mm's free space in the roof.*

The calculations were done also for a case where pellets are missing from different parts of the structure with backfilling degree of 70%. This was done to simulate a situation where some of the pellet material has been washed away due to erosion. Three different cases were studied with missing pellets from (for comparison the deformation in the basic case was 46 mm):

- roof leading to max. vertical deformation of 51 mm
- roof and wall leading to max. vertical deformation of 52 mm and
- lower 500 mm part of tunnel wall leading to max. vertical deformation of 47 mm.

To model the effects of the missing pellets a couple of different modelling cases were conducted. The right hand side of figure 23 illustrates the ultimate case, when pellets are missing from walls and roof. In modelling pellets were removed in the step 3 (after the swelling pressure has reached 160 kPa). The most important difference is that the backfilling is now moving mainly upwards. Due to the modelling process there is some friction in the tunnel corner, which does not let the whole backfill to move upwards freely. The displacement is smaller than what was expected, because the free upheaval is restricted by the connection between backfill and the tunnel floor. Theoretically, if there is no friction in the tunnel wall and no roof, the backfill could rise up to 2.4 m. In practice the tunnel roof will restrict this kind of upheaval. An interesting feature is to notice that if the pellets are missing from the lower 500 mm part of the tunnel wall, the deformations are nearly the same as with pellets (47 mm), see Fig. 23 middle.



Fixed roof

No pellets on lower side of wall

No pellets on roof and wall

Figure 23. *Posiva: the vertical displacements for block filling degree of 70% with fixed roof (left), with no pellets on the lower part of the wall (middle) and with no pellets on wall and roof (right).*

7. COMPARISON OF THE MODELLING RESULTS, DRY BACKFILL CASE

VTT's and CT's results were compared to verify the calculation methods and to find out the range of the results. Table 4 presents the input parameters for ClayTech’s finite element calculations and Table 5 for analytical calculations. The Table 6 presents the calculation results of VTT’s finite element calculations and CT’s calculations for dry Friedland clay when the friction angle between buffer and rock is 8.7°. The analytical calculation results are presented in Figure 24 and more details can be found from Johannesson (2007). ClayTech’s finite element calculation with ABAQUS program will be presented in a separate working report. For the calculations, which do not take into account the swelling of the buffer (Claytech’s analytical and VTT’s Plaxis) Table 6 presents the deformations of the equilibrium pressures (see also Figures 24-26).

Table 4. *Modelling input parameters for ABAQUS calculations, backfill Friedland clay.*

material	**model**	**γ, kN/m^3**	**ν, -**	**E, MPa**	**Friction angle between materials**
Backfill block	linear elastic	20	0.2	500	-
Pellets	linear elastic	20	0.3	3.24	-
Buffer*	Drucker Prager	24	-	-	-
Steel	linear elastic	78.5	0.3	21 000	
Block-block interfaces (4 mm)	-	-	-	-	20°

*more specific definition in ClayTech’s working report

Table 5. *Modelling input parameters for ClayTechnology analytical calculations, backfill Friedland clay.*

material	**model**	**γ, kN/m^3**	**ν, -**	**E, MPa**
Backfill block	linear elastic	-	0.24	323
Pellets	linear elastic	-	-	21
Block-block interfaces (4 mm)	-	-	-	-

*more specific definition in Johannesson 2007

Table 6. *Compression (mm) of the Friedland backfill material due to swelling of the buffer for SKB geometry when the friction between buffer and rock is 0° and the swelling of the buffer is also taken into account.*

Deformation mm	**Claytech, analytical**	**VTT, element Plaxis***	**VTT, element Plaxis†**	**VTT, element Plaxis‡**	**Claytech, element ABAQUS***	**Claytech, element ABAQUS**	**Claytech, element ABAQUS**	**Claytech, element ABAQUS**
Backfill model	continuum	contin.	contin.	contin.	contin.	Large blocks	Small blocks	Small blocks, several elements
Equilibrium pressure, MPa	5,6	6,5	6,5	6,1				
Backfill blocks	44	38	25	46	103	122	89	90
Pellets at the roof	35							
Block-block interfaces	36	36	36	36	-	-	-	-
Total displacement (vertical), mm	115	74	61	82	103	122	89	90

* the same parameters as in ClayTechnology's analytical calculations (Table 5)

† the same parameters as in ClayTechnology's element calculations (Table 4)

‡the parameters from laboratory tests (Table 2)

Different calculation methods give vertical deformations that are relatively near to each other ranging from 61 mm to 122 mm (Table 6) for SKB tunnel geometry depending on the modelling method, material parameters and calculation assumptions. If it is assumed that the loosening of buffer is even, then the maximum allowable displacement can be calculated from Equation 8.

$$\Delta h = h_0 \left(\frac{\rho_0}{\rho_1} - 1 \right) \tag{7}$$

where Δh is vertical displacement, m
h_0 height of buffer, m (1,5 m)
ρ_0 bulk density of buffer in the beginning, kg/m^3 (2 011 kg/m^3)
ρ_1 bulk density of buffer after saturation, kg/m^3 (1 950 kg/m^3).

According to the equation 7 average vertical displacement should be smaller than 47 mm for the SKB tunnel geometry. Because the height of the buffer above the canister is 2.0 metre in Posiva's backfilling case, the allowed average vertical displacement is 63 mm.

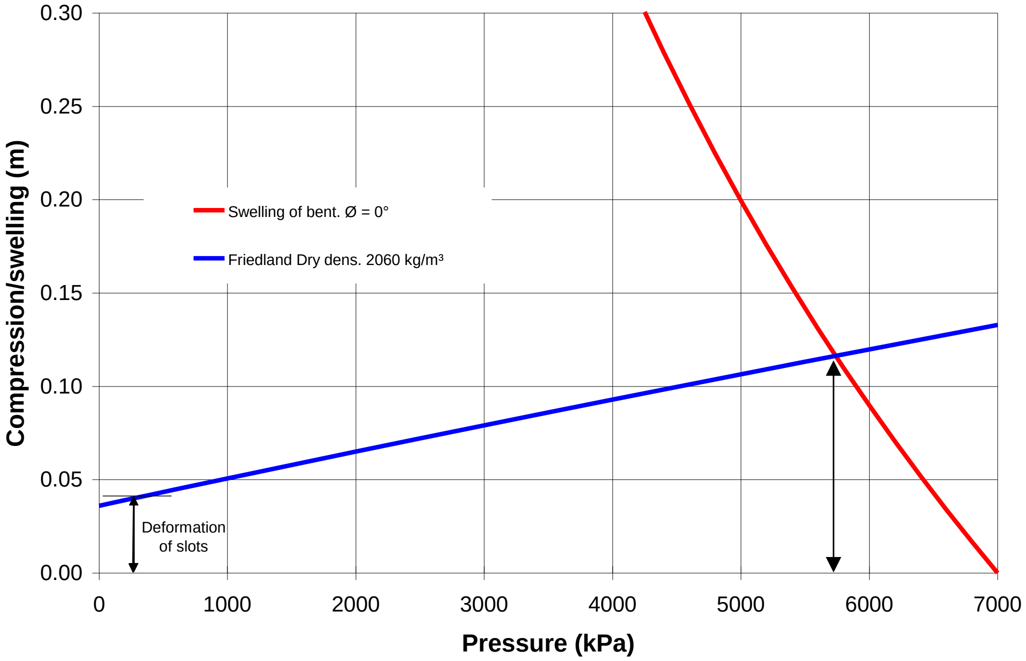


Figure 24. *The balance between deformations of buffer bentonite and backfill; Claytech analytical calculations (Johannessson 2007).*

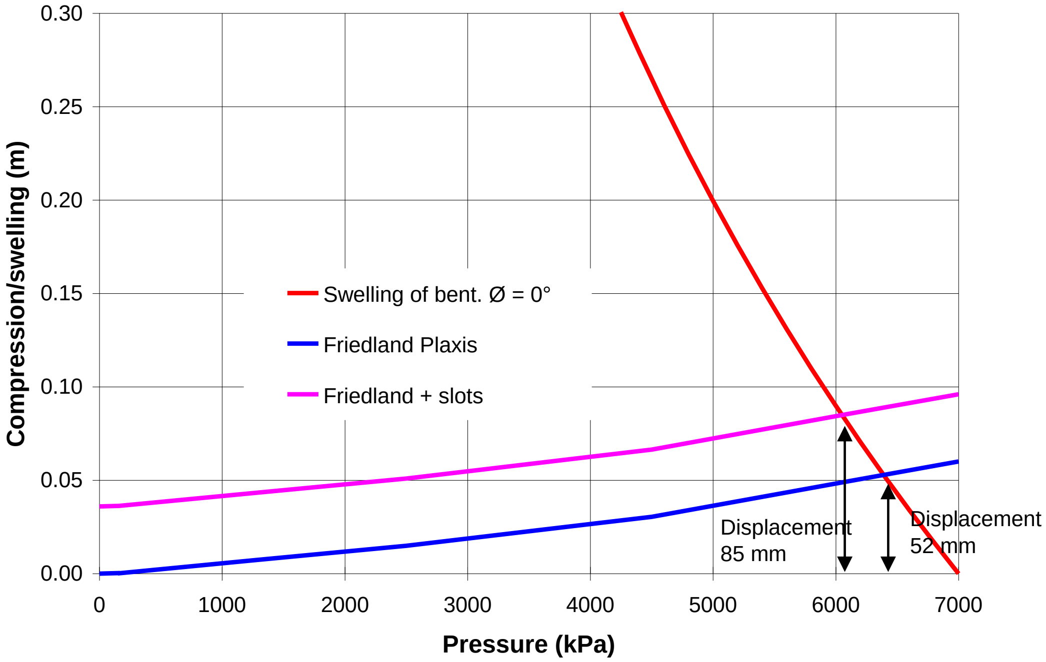


Figure 25. *The balance between deformations of buffer bentonite and backfill; SKB's geometry VTT’s finite element calculations (fixed roof).*

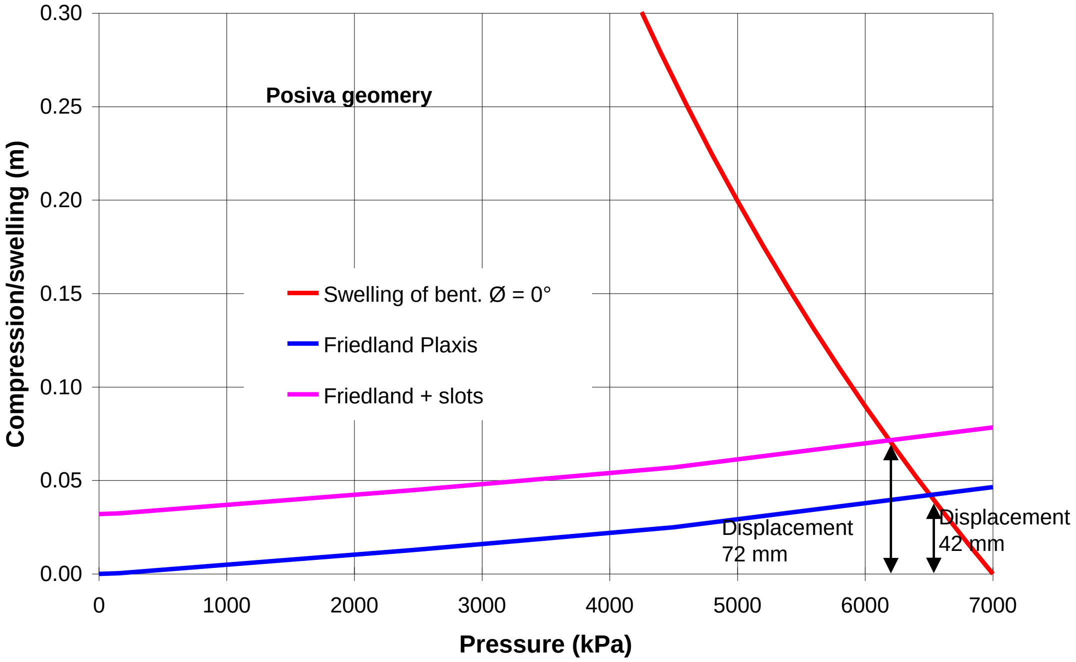


Figure 26. *The balance between deformations of buffer bentonite and backfill for Posiva geometry; VTT's element calculations (fixed roof).*

The results gained with Plaxis calculations using SKB's geometry have are summarized in Table 7. It can be concluded that the maximum vertical deformation of the dry backfill and pellets for SKB geometry is about 56…62 mm, in case the gradual decrease in swelling pressure of the buffer due to decreasing density is not taken into account. If the swelling of buffer is taken into account the maximum value of vertical deformation is about 52 mm. And if it assumed that each block-block interface will deform about 4 mm (total block-block interfaces 9), then the maximum vertical deformations in the interface of buffer and backfill is about 85 mm.

Table 7. *The maximum vertical displacements for SKB geometry with different calculation cases with the maximum swelling pressure of 7 MPa.*R_{inter} *see Equation1.*

Tunnel wall and floor, R_{inter}	**Deposition hole, R_{inter}**	**Tunnel roof**	**Backfill material**	**Block filling degree, %**	**Vertical displ.**
0.1	0	fixed	Friedland	70	60
0.1	0	10 mm gap	Friedland	70	62
0.2	0	fixed	Friedland	70	56
0.3	0	fixed	Friedland	70	53
1 (rigid contact)	0	fixed	Friedland	70	52
0.1	0.1	fixed	Friedland	70	59
0.1	1	fixed	Friedland	70	37
0.1	0	fixed	Asha	70	67
0.1	0	fixed	Friedland	80	59
0.1	0	fixed	Friedland*	70	26

* material parameters according to Table 4

The vertical deformations for Posiva tunnel seem to be smaller (48 mm) than for SKB tunnel (60 mm), because the thickness of the buffer in Posiva case is bigger than in SKB case and the deforming backfill is smaller. The test calculations for Posiva geometry indicated that the block filling degree had only small effect to the vertical deformations (Table 8). This was regardless of Posiva's tunnel being smaller it is also more sensitive towards changes in the boundary conditions, like tunnel roof fixities. With the changes in boundary conditions and block filling degrees the deformations varied from 46 mm to 48 mm, if the swelling of buffer is not taken into account. If the swelling is taken into account, but not the deformations between block-block interfaces, the vertical deformations on the buffer /backfill interface is about 42 mm (see Fig. 25). And if it assumed that each block-block interface will deform about 4 mm (total block-block interfaces 8), then the maximum vertical deformations in the interface of buffer and backfill is about 72 mm.

Table 8. *The maximum vertical displacements for Posiva geometry with different calculation cases with the maximum swelling pressure 7 MPa.* R_{inter} *see Equation1.*

Tunnel wall and floor, R_{inter}	Deposition hole, R_{inter}	Tunnel roof	Backfill material	Block filling degree, %	Vertical displ.
0.1	0	fixed	Friedland	60	48
0.1	0	20 mm	Friedland	60	54
0.1	0	fixed	Friedland	70	47
0.1	0	no pellets*	Friedland	70	48
0.1	0	fixed**	Friedland	70	47
0.1	0	no pellets	Friedland	70	52
0.1	0	fixed	Friedland	80	46
0.1	0	20 mm	Friedland	80	49

* No pellets on roof or wall

** No pellets on lower part of the wall

8. DISCUSSION AND FURTHER RESEARCH

Different calculation methods give vertical deformations that are relatively near to each other ranging from 61 mm to 122 mm (Table 6) for SKB tunnel geometry depending on the modelling method, material parameters and calculation assumptions. The analytical calculation method will probably overestimate the displacements, because it does not take into account the stress distribution in the tunnel. The Plaxis calculations with parameters used in analytical and ABAQUS calculations were made to get an idea of the material parameter’s sensitivity. The most reliable of the Plaxis calculations is the case using parameters presented in Table 2. The continuum approach used in these Plaxis calculations will probably underestimate slightly the final displacement. On the other hand ABAQUS calculations with blocks and vertical block lines will probably overestimate the displacements because in the ABAQUS's block modelling the most important factor is the interfaces between blocks. The block lines move upwards and most of the deformations take place in the roof pellets.

Because it is impossible to model real blocks in Plaxis axisymmteric 2D calculations the backfill was described as continuum material. The use of continuum material model is a simplification, which has two major implications. First, this approach does not include the block-block interfaces between the blocks, so the deformations occurring in horizontal block-block interfaces must be taken into account in some other way. In this case the vertical displacement between each block-block interface has been chosen to be constant (4 mm). While there is supposed to be 9 block-block interfaces the total deformation in block-block interfaces is 36 mm, which will be added to the backfill deformations. This assumption can be considered as slightly conservative. Second, the approach does not take into account the shearing which will take place between vertical block-block interfaces of blocks. If the blocks are installed such that there is no continuous block-block interface line from bottom to the top of tunnel, the shearing will be much smaller than in the case of continuous block line. This means that the assumption of continuum material somewhat underestimates the displacements due to the missing part of block shearing. The amount of the underestimation depends on the block installation model.

The swelling pressure was modelled as a pressure, because in the Plaxis there is no material model for the swelling material. The aim of the modelling was to assess the displacements in the buffer-backfill interface up to the maximum swelling pressure of 7 MPa. This approach overestimates the displacements, because the actual swelling pressure will decrease when the buffer swells upwards. A simple method to take this phenomenon into account is to estimate the displacements from the buffer swelling curve (see chapter 7). As the outcome from these assumptions it can be concluded that VTT’s approach somewhat underestimates the actual displacements. When constant deformations of the block-block interfaces are added to the interface displacements, the the results will be quite near the 3D block approach.

The aim of the case where there was a free space of 20 mm in the tunnel roof was to simulate a case when the blocks and block-block interfaces have been settled downwards for 20 mm. The vertical displacements increase slightly (in maximum 10% for the Posiva geometry) if there is the free space of 20 mm in the roof, but it affects more to the displacement distribution. In the fixed roof case stresses distribute more to the wall side, while in the free space case the deformations will occur mainly upwards. Other tested boundary conditions were friction along the tunnel and deposition hole walls and tunnel floor. Four different frictional assumptions were made for the tunnel wall and floor. In the basic case an interface element between tunnel wall and pellets and another between tunnel floor and backfill was assumed. The connection effect of the interface element (friction angle / R_{inter}) was varied from 0.1, 0.2, 0.3 and 1.0. The small values correspond to only a weak connection between materials while 1.0 corresponds to the total contact. Vertical displacements were smaller when contact was more tight decreasing from 60 mm down to 52 mm for the $R_{inter} = 1.0$ case. For the tunnel floor and wall in the dry case the assumption of the friction angle of about 10° (corresponds to $R_{inter} = 0.1…0.2$). seems quite reasonable according to the TUT's laboratory tests /Kuula-Väisänen et al. 2007/.

The effect of the deposition's hole wall friction was also tested. The basic assumption was that there is a gap between buffer and wall. Two different friction levels were tested: small friction ($R_{inter} = 0.1$) and total contact. The maximum vertical displacements were about the same in the case of weak friction (59 mm), but for the total contact case much smaller (37 mm). The change of the block filling degree from 70% to 80% had only a slight effect (about 1%) to the vertical deformations. The backfill material Asha gave bigger deformations than Friedland clay (60 mm Friedland 67 mm Asha). The main reason for this was that the deformation properties of Asha implemented in calculations from ClayTech's test were smaller than for Friedland clay.

Future calculations will include studies with homogenization and saturated backfill. Also the swelling of backfill should be taken into account. These calculations require availability of laboratory results on compression properties of saturated materials as well as laboratory test results on homogenisation. Some additional case studies should also be done for the cases where the tunnel floor is filled with bentonite granules. The assumptions concerning the deformations in block-block interfaces should also be validated with field tests.

These numerical assessments are preliminary and they include many assumptions and simplifications. The future modelling should include saturated backfill, other modelling methods (3D approach), more sophisticated material models for example buffer material and the effect of the tunnel floor granules. The modelling process should be an essential part of the tunnel backfill design.

9. CONCLUSIONS

The 2 D calculations showed that linear elastic material model for backfill material has to be used in the finite element calculations performed with the Plaxis programme, since the elasto-plastic models tend to generate unrealistic stress concentrations to the deposition hole/tunnel corner area. The basic assumption in calculations was that the tunnel roof is fixed, meaning that no deformations beyond this was allowed to happen.

The results show that the interface between buffer and backfill blocks for SKB geometry for the dry backfill case is deforming differently depending on the calculation method and tools. Table 6 summarises the results. The deformations varied from 81 to 122 mm. The 3D calculations performed for assemblage of blocks gave clearly higher deformation compared to the continuum of materials cases. The reason for this was that the block rows will deform upwards more easily than in the continuum material model. The governing factor was the vertical block-block interfaces that lead to a situation where the stresses do not redistribute to as wide area as in the continuum cases. The feasibility of the general assumptions used should be tested with pilot tests, like the deformation in block-block interfaces. The dimensioning criteria of the density of buffer after saturation around the canister should also be rechecked and the calculation results should be evaluated against these requirements. The modelling results can also be compared to the results that will be gained after dismantling the Prototype repository, although the backfill design considered today is different from what was assumed when the Prototype repository was installed.

According to the calculations, all vertical displacements in the buffer backfill interface will lie between 80…120 mm for SKB’s deposition tunnel geometry. For Posiva’s geometry there is only VTT’s calculations, which resulted in displacements around 80 mm if the block-block interface deformations (32 mm) are added to the backfill deformations. The dry density requirement of 1950 kg/m^3 will be undercutted if the loosening in the buffer is supposed to happen evenly. In reality the loosening will be non-linear being highest near the interface. The 3D modelling of ABAQUS refer to the possibility that this requirement can be fulfilled meaning that the loosening of buffer right above canister will be smaller.

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