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Finite element calculations of the upward swelling of the buffer against both dry and saturated backfill

Lennart Börgesson, Clay Technology AB

Jan Hernelind, 5T-Engineering 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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Abstract

The mechanical interaction between the buffer material in the deposition hole and the backfill material in the deposition tunnel is an important process in the safety assessment since the primary function of the backfill is to keep the buffer in place and not allow it to expand too much and thereby loose too much of its density and barrier properties.

In order to study the upwards swelling of the buffer and the subsequent density reduction a number of finite element calculations have been performed. The calculations have been done with the FE-program Abaqus with 3D-models of a deposition hole and the deposition tunnel. In order to refine the modelling only the two extreme cases of completely un-wetted (dry) and completely water saturated (wet) backfill have been modelled. For the wet case the influence of different factors has been studied while only one calculation of the dry case has been done.

The calculated upwards swelling of the buffer varied between 2 and 15 cm for the different wet cases while it was about 10 cm for the dry case. In the wet reference case the E-modulus of the block and pellets fillings was 50 MPa and 3.24 MPa respectively, the friction angle between the buffer and the rock and canister was 8.7° and there were no swelling pressure from the backfill.

Influence of friction angle between the buffer and the rock and canister

There is a strong influence of the friction angle on both the upwards swelling and the canister heave. The friction is important for preventing especially canister displacements. The unrealistic case of no friction yielded strong unacceptable influence on the buffer with an upwards swelling of 15 cm and a strong heave of 5 cm of the canister.

Influence of backfill stiffness

The influence of the backfill stiffness is as expected strong. Both buffer swelling and canister heave are twice as large at the E-modulus E = 25 MPa than at the E-modulus E = 100 MPa. The influence of the stiffness of the pellets filling is not strong since there are no pellets on the floor in the model used.

Influence of the swelling pressure in the backfill

The influence of the swelling pressure of the backfill is strong with both buffer swelling and canister heave reduced to less than 50% at the swelling pressure 1 MPa and to less than 25% at the swelling pressure 3 MPa compared to the corresponding case with no swelling pressure.

Influence of a dry backfill

The difference between this case and the reference case is small (9 and 10 cm heave respectively), which manly depends on that the average stiffness of the backfill seems to be similar for those cases and that no swelling pressure of the backfill was assumed for the reference case.

The calculations show that there are three parameters that are critical for the swelling, namely the friction angle between the buffer and its surroundings, the stiffness of the backfill and the swelling pressure of the backfill. For the case of wet backfill material only the combination of a low friction angle and a low swelling pressure (which is not a realistic case) can violate the density criterion. The wet case does thus not seem to be critical.

Additional studies and calculations of the dry case are desired.

Sammanfattning

Den mekaniska samverkan mellan buffertmaterialet i deponeringshålet och återfyllningsmaterialet i deponeringstunneln är en process som är viktig att beakta i säkerhetsanalysen eftersom återfyllningens viktigaste funktion är att hålla bufferten på plats och inte låta den svälla upp så mycket att den tappar i densitet och därmed förlorar för mycket av sina barriäregenskaper.

För att studera buffertens uppsvällning mot återfyllningen och den tillhörande densitetssänkningen av bufferten har ett antal finita elementberäkningar utförts. Beräkningarna har gjorts med FE-programmet Abaqus med 3D-modeller av deponeringshålet och deponeringstunneln. För att renodla beräkningarna har bara de två ytterlighetsfallen med helt torr (torra fallet) och helt vattenmättad (våta fallet) återfyllning modellerats. För det våta fallet har inverkan av olika faktorer på uppsvällningens studerats emedan endast ett torrt fall har modellerats.

Den beräknade uppsvällningen varierade mellan 5 och 15 cm för de våta fallen medan det torra fallet gav en uppsvällning på ca 10 cm. I det våta referensfallet var E-modulen för block- och pelletfyllningarna 50 MPa respektive 3,24 MPa, friktionsvinkeln mellan bufferten och berget och kapseln 8,7° och svälltrycket i återfyllningen noll.

Inverkan av friktionsvinkeln mellan bufferten och berget och kapseln

Friktionsvinkeln har stor inverkan på uppsvällningen och kapselns rörelse. Friktionen är särskilt viktig för att förhindra att kapseln rör sig uppåt. Det orealistiska fallet med ingen friktion och inget svälltryck gav ett oacceptabelt stor påverkan på bufferten med en uppåtsvällning av 15 cm och en hävning av kapseln med 5 cm.

Inverkan av återfyllningens styvhet

Inverkan av återfyllningens styvhet är som väntat stor. Både buffertuppsvällningen och kapselhävningen är dubbelt så stora vid en E-modul av 25 MPa för återfyllningen i jämförelse med en E-modul av 100 MPa. Inverkan av pelletfyllningens styvhet är liten eftersom modellen inte hade pellets på golvet.

Inverkan av svälltrycket i återfyllningen

Påverkan av återfyllningens svälltryck är stor med en buffertuppsvällning och en kapselhävning som halveras vid svälltrycket 1 MPa och blir mindre än 25 % vid svälltrycket 3 MPa jämfört med om inget svälltryck finns i återfyllningen.

Inverkan av torr återfyllning

Skillnaden mellan torr återfyllning och referensfallet för vattenmättad återfyllning blev liten (9 respektive 10 cm uppsvällning) i huvudsak beroende på att medelstyvheten hos återfyllningen blir ganska lika i de båda fallen och för att referensfallet antog att inget svälltryck fanns i återfyllningen.

Beräkningarna visar att det finns tre parametrar som är speciellt viktiga för uppsvällningen, nämligen friktionsvinkeln mellan buffert och berg, återfyllningens styvhet och återfyllningens svälltryck. För det våta fallet blev endast kombinationen av en låg friktionsvinkel och inget svälltryck i återfyllningen kritisk för bufferten. Det våta fallet tycks därför inte vara dimensionerande.

Däremot är det önskvärt med ytterligare studier och beräkningar av det torra fallet.

Contents

1 Introduction

The investigations described in this report is a part of the third phase of the joint SKB-Posiva project "*Backfilling and Closure of the Deep Repository, BACLO*". The overall objective of the BACLO project is to develop backfilling concept for the deep repository that can be configured to meet SKB's and Posiva's requirements in the chosen repository sites /1-1/. The project was divided into four phases, of which two have already been performed. The second phase of the BACLO project consisted of laboratory tests and deepened analyses of the investigated backfill materials and methods and resulted in recommendation to focus on the development and testing of the block placement concept with three alternative backfill materials /1-2/. The third phase investigations comprise of laboratory and large-scale experiments aiming at testing the engineering feasibility of the concept. In addition, the effect of site-specific constraints, backfilling method and materials on the long-term functions of the barriers are described and analysed in order to set design specifications for the backfill.

The third phase of the BACLO project is divided into several subprojects. The work described in this report belongs to subproject 1 concerning *processes during installation and saturation* of the backfill that may affect the long-term function of the bentonite buffer and the backfill itself.

The mechanical interaction between the buffer material in the deposition hole and the backfill material in the deposition tunnel is an important process in the safety assessment since the primary function of the backfill is to keep the buffer in place and not allow it to swell too much and thereby loose too much of its density and barrier properties. This process has been studied earlier in different contexts.

Most studies have been related to the earlier backfill concept with in situ compacted mixture of 30% bentonite and 70% crushed rock. Both analytical and numerical models were used (/1-3/, /1-4/ and /1-5/). Since the swelling pressure of this material is low and the degree of saturation is of minor importance for the compression properties and thus the results only the case with completely water saturated backfill was investigated.

Lately the concept has been changed to the present reference backfill concept with blocks of Milos backfill (IBECO-RWC-BF) piled in the tunnel and with the slots between the blocks and the rock filled with pellets of the same material. With this type of backfill the interactions gets more complicated on the following reasons:

- The swelling pressure can be significant and must be taken into account.
- The degree of saturation affects the results and must be taken into account.
- The backfill is inhomogeneous both at dry condition and after completed saturation.
- The properties change with increasing degree of saturation.

The extreme of these conditions (completely dry and completely saturated) have been investigated with simplified analytical calculations (/1-6/ and /1-7/) but more refined methods are desired in order to better understand the process and confirm the results from the analytical calculations. The latter reports also include laboratory tests, which are used to evaluate parameters needed for the modelling.

On these mentioned reasons a new finite element model has been made and a number of finite element calculations with different parameter values have been performed and are reported in this report.

2 Modelling philosophy

The actual interplay between the buffer material and the backfill material is as mentioned above very complicated. At installation both the buffer and the backfill consist of bentonite blocks with very high density and different degree of saturation and pellets filling of all remaining slots between the blocks and the rock surface. Then water enters the deposition hole and the tunnel with wetting and swelling of the blocks together with wetting and compression of the pellets filling. The rate of these processes depends on the rate and location of water inflow and the actual evolution of the saturation and homogenisation of the buffer and backfill. The corresponding interaction between the buffer and backfill materials is different in every deposition hole.

The complicated nature calls for simplifications in order to be able to model the process with moderate effort. The extreme cases are to assume either completely saturated (wet) or completely un-wetted (dry) conditions, which yield four cases:

1. Wet buffer and wet backfill
2. Wet buffer and dry backfill
3. Dry buffer and dry backfill (uninteresting)
4. Dry buffer and wet backfill

Case 3 is obviously not relevant but also case 4 is not of primary interest since there will be very little compression of the buffer blocks and rings and the uniaxial compression strength of the blocks and rings are 3 MPa and 4 MPa respectively, which is higher than the expected swelling pressure from the backfill. This case is also not expected to occur since it takes 100 years for the backfill to be completely water saturated.

Thus only cases 1 and 2 have been investigated. The wet materials are assumed to have been completely homogenised, while the dry backfill consists of blocks, pellets and slots between the blocks.

The geometry of the deposition hole and the tunnel with the buffer and backfill is shown in Figure 2-1. This geometry has been used for the calculations but is not in complete accordance with the reference geometry settled in the production line reports. The calculations will be updated in this respect.

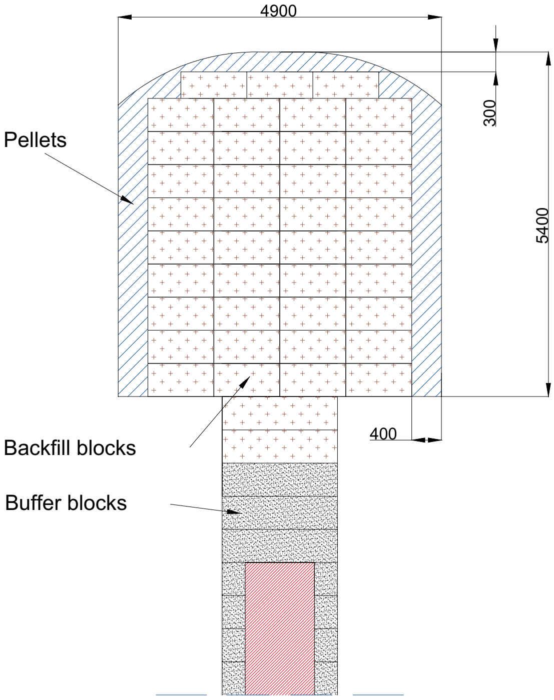

Figure 2-1. *Geometry of the tunnel and backfill used in the calculations.*

3 Finite element code

3.1 General

The finite element code ABAQUS was used for the calculations. ABAQUS contains a capability of modelling a large range of processes in many different materials as well as complicated three-dimensional geometry.

The code includes special material models for rock and soil and ability to model geological formations with infinite boundaries and in situ stresses by e.g. the own weight of the medium. It also includes capability to make substructures with completely different finite element meshes and mesh density without connecting all nodes. Detailed information of the available models, application of the code and the theoretical background is given in the Abaqus manuals /2-1/.

3.2 Hydro-mechanical analyses in ABAQUS

The hydro-mechanical model consists of porous medium and wetting fluid and is based on equilibrium, constitutive equations, energy balance and mass conservation using the effective stress theory.

Equilibrium

Equilibrium is expressed by writing the principle of virtual work for the volume under consideration in its current configuration at time *t*:

$$\int_V \boldsymbol{\sigma} : \delta\boldsymbol{\varepsilon}\, dV = \int_S \mathbf{t} \cdot \delta\mathbf{v}\, dS + \int_V \hat{\mathbf{f}} \cdot \delta\mathbf{v}\, dV \qquad (3\text{-}1)$$

where $\delta\mathbf{v}$ is a virtual velocity field, $\boldsymbol{\delta\varepsilon} \stackrel{def}{=} sym(\partial\delta\mathbf{v}/\partial\mathbf{x})$ is the virtual rate of deformation, $\boldsymbol{\sigma}$ is the true (Cauchy) stress, $\mathbf{t}$ are the surface tractions per unit area, and $\hat{\mathbf{f}}$ are body forces per unit volume. For our system, $\hat{\mathbf{f}}$ will often include the weight of the wetting liquid,

$$\mathbf{f}_w = S_r n \rho_w \mathbf{g} \qquad (3\text{-}2)$$

where S_r is the degree of saturation, n the porosity, ρ_w the density of the wetting liquid and $\mathbf{g}$ is the gravitational acceleration, which we assume to be constant and in a constant direction (so that, for example, the formulation cannot be applied directly to a centrifuge experiment unless the model in the machine is small enough that g can be treated as constant). For simplicity we consider this loading explicitly so that any other gravitational term in $\hat{\mathbf{f}}$ is only associated with the weight of the dry porous medium. Thus, we write the virtual work equation as

$$\int_V \boldsymbol{\sigma} : \delta\boldsymbol{\varepsilon} dV = \int_s \mathbf{t} \cdot \boldsymbol{\delta}\mathbf{v} dS + \int_V \mathbf{f} \cdot \boldsymbol{\delta}\mathbf{v} dV + \int_V S_r n \rho_w \mathbf{g} \cdot \boldsymbol{\delta}\mathbf{v} dV \qquad (3\text{-}3)$$

where $\mathbf{f}$ are all body forces except the weight of the wetting liquid.

The simplified equation used in ABAQUS for the effective stress is:

$$\overline{\boldsymbol{\sigma}}^* = \boldsymbol{\sigma} + \chi\, u_w \mathbf{I} \qquad (3\text{-}4)$$

where $\boldsymbol{\sigma}$ is the total stress, u_w is the pore water pressure, χ is a function of the degree of saturation (usual assumption $\chi = S_r$), and $\mathbf{I}$ the unitary matrix.

Energy balance

The conservation of energy implied by the first law of thermodynamics states that the time rate of change of kinetic energy and internal energy for a fixed body of material is equal to the sum of the rate of work done by the surface and body forces. This can be expressed as (not considering the thermal part, which is solved as uncoupled heat transfer):

$$\frac{\mathrm{d}}{\mathrm{dt}}\int_{\mathrm{V}}\left(\tfrac{1}{2}\rho\mathbf{v}\cdot\mathbf{v}+\rho\mathrm{U}\right)\mathrm{dV}=\int_{\mathrm{s}}\mathbf{v}\cdot\mathbf{t}\mathrm{dS}+\int_{\mathrm{V}}\mathbf{f}\cdot\mathbf{v}\mathrm{dV} \qquad (3\text{-}5)$$

where

ρ is the current density,

$\mathbf{v}$ is the velocity field vector,

U is the internal energy per unit mass,

$\mathbf{t}$ is the surface traction vector,

$\mathbf{f}$ is the body force vector,

V is the volume of the domain,

S is the area of the domain.

Constitutive equations

The constitutive equation for the solid is expressed as:

$$d\boldsymbol{\tau}^{\mathrm{c}}=\mathbf{H}:d\boldsymbol{\varepsilon}+\mathbf{g} \qquad (3\text{-}6)$$

where $d\boldsymbol{\tau}^{\mathrm{c}}$ is the stress increment, $\mathbf{H}$ the material stiffness, $d\boldsymbol{\varepsilon}$ the strain increment and $\mathbf{g}$ is any strain independent contribution (e.g. thermal expansion). $\mathbf{H}$ and $\mathbf{g}$ are defined in terms of the current state, direction for straining, etc, and of the kinematic assumptions used to form the generalised strains.

The constitutive equation for the liquid (static) in the porous medium is expressed as:

$$\frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{w}}^{0}}\approx 1+\frac{\mathrm{u}_{\mathrm{w}}}{\mathrm{K}_{\mathrm{w}}}-\varepsilon_{\mathrm{w}}^{\mathrm{th}} \qquad (3\text{-}7)$$

where ρ_w is the density of the liquid, ρ_{w}^{0} is its density in the reference configuration, $K_w(T)$ is the liquid's bulk modulus, and

$$\varepsilon_{w}^{th}=3\alpha_{w}(T-T_{w}^{0})-3\alpha_{w|T^{I}}(T^{I}-T_{w}^{0}) \qquad (3\text{-}8)$$

is the volumetric expansion of the liquid caused by temperature change. Here $\alpha_{\mathrm{w}}(T)$ is the liquid's thermal expansion coefficient, T is the current temperature, T^{I} is the initial temperature at this point in the medium, and T_{w}^{0} is the reference temperature for the thermal expansion. Both $\mathrm{u}_{\mathrm{w}}/\mathrm{K}_{\mathrm{w}}$ and $\varepsilon_{\mathrm{w}}^{\mathrm{th}}$ are assumed to be small.

Mass conservation

The mass continuity equation for the fluid combined with the divergence theorem implies the point wise equation:

$$\frac{1}{J}\frac{d}{dt}(J\rho_{\mathrm{w}}S_{r}n)+\frac{\partial}{\partial\mathbf{x}}\cdot(\rho_{\mathrm{w}}S_{r}n\mathbf{v}_{\mathrm{w}})=0 \qquad (3\text{-}9)$$

where J is the determinant of the Jacobian matrix of the skeleton motion and $\mathbf{x}$ is position. The constitutive behaviour for pore fluid is governed by Darcy's law, which is generally applicable to low fluid velocities. Darcy's law states that, under uniform conditions, the volumetric flow rate of the wetting liquid through a unit area of the medium, $S_r n\mathbf{v}_w$, is proportional to the negative of the gradient of the piezometric head:

$$S_r n \mathbf{v}_w = -\hat{\mathbf{k}} \frac{\partial \phi}{\partial \mathbf{x}} \tag{3-10}$$

where $\hat{\mathbf{k}}$ is the permeability of the medium and ϕ is the piezometric head, defined as:

$$\phi \overset{def}{=} z + \frac{u_w}{g\rho_w} \tag{3-11}$$

where z is the elevation above some datum and g is the magnitude of the gravitational acceleration, which acts in the direction opposite to z. $\hat{\mathbf{k}}$ can be anisotropic and is a function of the saturation and void ratio of the material. $\hat{\mathbf{k}}$ has units of velocity (length/time). [Some authors refer to $\hat{\mathbf{k}}$ as the hydraulic conductivity and define the permeability as

$$\hat{\mathbf{K}} = \frac{\nu}{g} \hat{\mathbf{k}} \tag{3-12}$$

where ν is the kinematic viscosity of the fluid.]

We assume that g is constant in magnitude and direction, so

$$\frac{\partial \phi}{\partial \mathbf{x}} = \frac{1}{g\rho_w} \left(\frac{\partial u_w}{\partial \mathbf{x}} - \rho_w \mathbf{g} \right) \tag{3-13}$$

3.3 Handling of buffer and backfill processes

Overviews of how Abaqus handles the THM-processes for buffer and backfill materials are given in other SKB reports (see e.g. /2-2/, /2-3/ and /2-4/).

4 Swelling against wet tunnel

4.1 General

In the calculations of the wet case material models simulating porous materials (both buffer and backfill) have been be used. Different cases with different degree of homogenisation and different properties have bee modelled. Since the buffer material is assumed water saturated from start the time scale will only include the time for the buffer to swell upwards. The canister has been modelled but only as a tube with very stiff material.

A 3D model has been used mainly because the block dimensions for the calculation of the dry case need to be made in 3D. The rock has been included in the model since there are contact elements at the rock surfaces in order to model the possible slip that may take place between the buffer/backfill and the rock.

Several cases of material properties have been modelled, but only the results from the reference case will be shown in this chapter. The overall compilation of results and comparisons between results are done in Chapter 6.

4.2 Material models

4.2.1 Buffer material

The buffer material model is identical to the model used for studying the buffer homogenisation after erosion /2-4/. The bentonite has been modelled as completely water saturated. The motivation for assuming full water saturation is manifold:

- The mechanical models of unsaturated bentonite are very complicated and not sufficiently good for modelling the strong swelling that may take place.
- The models for water saturated bentonite are much more reliable and well documented.
- The stress path and time schedule will differ if saturated instead of unsaturated bentonite is modelled but the final state will be very similar.

The mechanical models of water unsaturated bentonite materials are however successively improved and some calculations could later be done with those models for comparison reason.

The **mechanical model** of the buffer controlling the swelling and consolidation phase is identical to the models and properties derived for MX-80 by Börgesson et al /1-6/. This model is still considered to be sufficiently good for these types of calculations and has therefore also been used in this and similar calculations for SR-Site.

Porous Elasticity combined with *Drucker Prager Plasticity* has been used for the swelling/consolidation mechanisms, while *Darcy's law* is applied for the **water flux** and the *Effective Stress Theory* is applied for the **interaction pore water and structure**.

Mechanical properties

The *Porous Elastic Model* implies a logarithmic relation between the void ratio e and the average effective stress p according to Equation 4-1.

$$\Delta e = \kappa/(1+e_0)\Delta \ln p \tag{4-1}$$

where κ = porous bulk modulus, e_0 = initial void ratio

Poisson's ratio ν is also required.

Drucker Prager Plasticity model contains the following parameters:

β = friction angle in the *p*-*q* plane
d = cohesion in the *p*-*q* plane
ψ = dilation angle
$q = f(\varepsilon^d_{pl})$ = yield function

The yield function is the relation between Mises' stress q and the plastic deviatoric strain ε^d_p at a specified stress path. The dilation angle determines the volume change during shear.

The following data has been derived and used for the *Porous Elastic* model (valid for $e<1.5$):

$\kappa = 0.21$
$\nu = 0.4$

The following data has been derived for the *Drucker Prager Plasticity* model

$\beta = 17°$
$d = 100$ kPa
$\psi = 2°$

In some calculations the data for the *Drucker Prager Plasticity* model has been varied in order to study the influence of the friction angle, the cohesion and the dilation.

Hydraulic properties

The hydraulic conductivity is a function of the void ratio as shown in Table 4-2.

Table 4-1. Yield function.

q (kPa)	ε_{pl}
112	0
138	0.005
163	0.02
188	0.04
213	0.1

Table 4-2. Relation between hydraulic conductivity and void ratio.

e	K (m/s)
0.45	$1.0 \cdot 10^{-14}$
0.70	$8.0 \cdot 10^{-14}$
1.00	$4.0 \cdot 10^{-13}$
1.5	$2.0 \cdot 10^{-12}$
2.00	$1.0 \cdot 10^{-11}$
3.00	$2.0 \cdot 10^{-11}$
5.00	$7.0 \cdot 10^{-11}$
10.00	$3.0 \cdot 10^{-10}$
20.00	$1.5 \cdot 10^{-9}$

Interaction pore water and structure

The effective stress theory states that the effective stress (the total stress minus the pore pressure) determines all the mechanical properties. It is modelled by separating the function of the pore water and the function of the particles. The density ρ_w and bulk modulus B_w of the pore water as well as the density ρ_s and the bulk modulus of the solid particles B_s are required parameters. The following parameters are used for Na-bentonite:

Pore water

ρ_w = 1,000 kg/m^3 (density of water)

B_w = $2.1 \cdot 10^6$ kPa (bulk modulus of water)

Particles

ρ_s = 2,780 kg/m^3 (density of solids)

B_s = $2.1 \cdot 10^8$ kPa (bulk modulus of solids)

Initial conditions

All calculations were done with the same initial conditions of the buffer. The buffer is completely water saturated and is assumed to have an average density at saturation of ρ_m = 2,000 kg/m^3 or the void ratio e = 0.77 corresponding to the average density in the deposition hole. The pore pressure is set to u = –7 MPa in order to correspond to the effective average stress p = 7 MPa that yields zero total average stress. The required initial conditions of the buffer are thus:

u_0 = –7 MPa

p_0 = 7 MPa

e_0 = 0.77

4.2.2 Backfill

The backfill has been modelled as a linear elastic solid material mainly due to lack of data for a porous elastic model. When data is available it may be possible to formulate a porous elastic model of the same type as the buffer. The influence is considered small and the effect of the stiffness (E-modulus) is illustrated with a sensitivity analysis.

The following parameters are applied for the reference case:

Block section

E = 50 MPa
v = 0.3
Initial average stress p_0 = 0 MPa

Pellet section

E = 3.24 MPa
v = 0.3
Initial average stress p_0 = 0 MPa

4.2.3 Canister

The canister is modelled as a solid steel body and the following elastic parameters:

E = $2.1 \cdot 10^5$ MPa
v = 0.3

4.2.4 Rock

The rock is modelled as a rigid body.

4.2.5 Contact surfaces

The contact between *the buffer/backfill and the rock and between the buffer and the canister* has not been tied in order to allow slip. Instead interface properties with a specified friction have been applied between the different materials. The friction can be modelled with Mohr Coulomb's parameter friction angle ϕ and without cohesion c. The following basic value has been used:

$\phi = 8.69°$

This friction angle corresponds to $\beta = 17°$ in the Drucker Prager model. The value has been changed in some calculations in order to investigate the influence of the friction.

Since the friction angle ϕ against the rock is an uncertain parameter it has been varied between 0 and 17.4°.

The contact surfaces are made not to withstand tensile stress, which means that the contact may be lost and a gap formed between the surfaces.

Another property of the contact surface is the so called "slip tolerance", which describes the required slip to reach full friction. This parameter has been set to 1 mm. Below 1 mm slip the friction is proportional to the slip.

4.3 Element model

The geometry used for the model was shown in Figure 2-1. The element mesh for the calculation with wet backfill is shown in Figure 4-1.

It is a full 3D model of a quarter of a deposition hole and tunnel section with symmetry planes in three of the four vertical boundaries yielding a model of a long tunnel with deposition holes with 6 m distances. There are contact surfaces in all contacts between the rock and the buffer and backfill as well as between the buffer and the canister.

4.4 Boundary conditions

The following boundary conditions are applied:

Mechanical

The vertical planes except the one that partly coincide with the pellets filling (farther y-z plane in Figure 4-1) are free to move parallel with the plane and fixed perpendicular to the plane.

All other outer boundaries are fixed.

Hydraulic

Only the buffer is modelled hydraulically with pore pressure elements. The buffer boundaries to the rock have constant water pressure (u = 0 MPa), the boundaries to the canister are no flow boundaries and the vertical "inner" boundaries (x-y and y-z planes) are no flow boundaries.

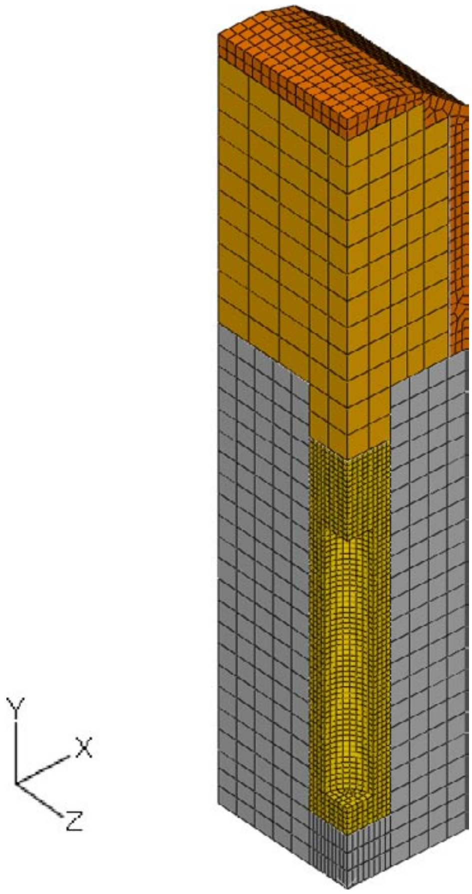

Figure 4-1. Element mesh for the calculation with wet backfill (the canister is excluded).

4.5 Calculation sequence

The calculations are coupled hydro-mechanical calculations. The pore water pressure in the hydraulic boundary of the buffer is stepwise increased from –7 MPa to 0 MPa during 1,000 seconds. Then the actual consolidation calculation is run until complete pore water pressure equilibrium with pore pressure 0 MPa is reached in the entire buffer.

4.6 Results

The results are illustrated with the "base case" simulation (named Baclo3b). The results of all the other variants are compiled and analysed in Chapter 6.

Figure 4-2 shows the displacement of three points in the buffer between the canister and the backfill bottom as function of time. The swelling of the interface between the buffer and backfill is slightly more than 10 cm and is completed after $0.6 \cdot 10^9$ s or 19 years. Although the time only includes the time for the swelling of the buffer and not for saturation or compression of the backfill it anyway shows that such large swelling is time consuming, especially in the final stage (since the final 5 mm takes half of that time). The canister at first heaves about 8 mm during the first two months and then settles about 3 mm to end with a final total heave of about 5 mm.

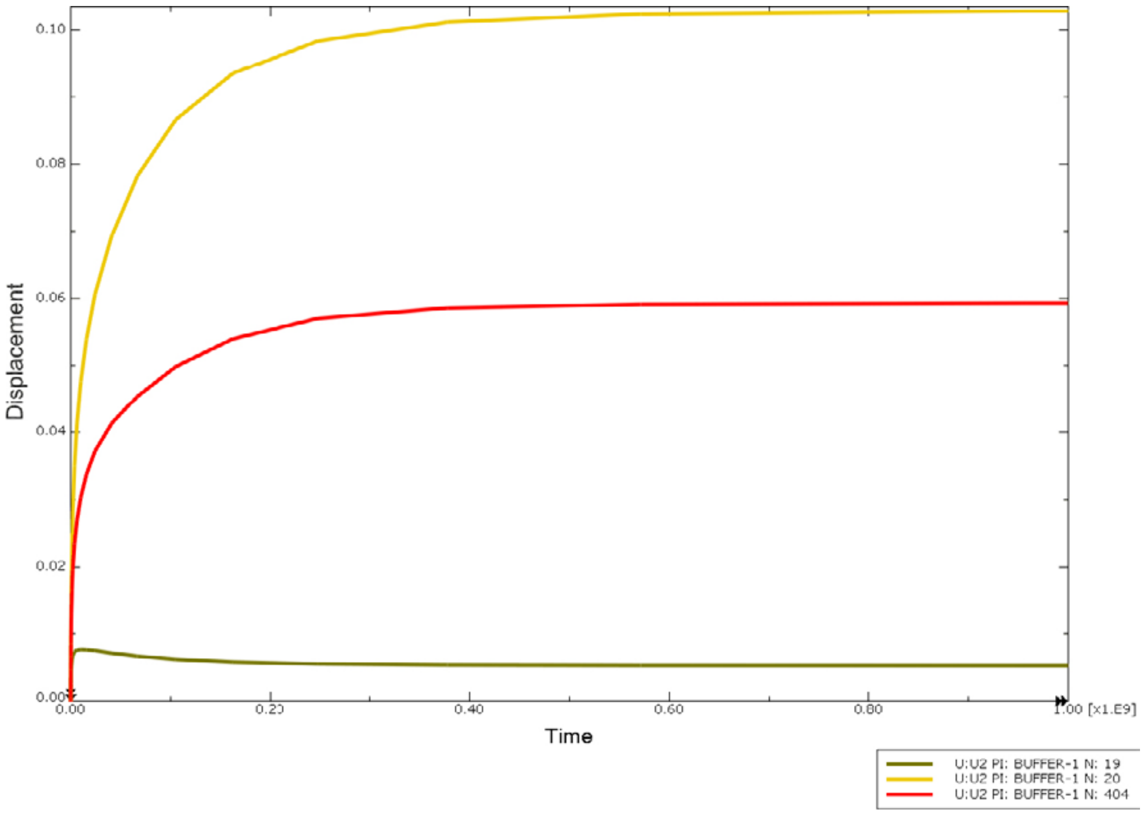

Figure 4-2. *Displacements in the upper part of the buffer (m) as function of time (s)*
— *interface buffer/backfill*
— *halfway between backfill bottom and canister top*
— *top of canister.*

Figure 4-3 shows the distribution of the vertical displacements and the average stress after completed swelling.

Figure 4-3 shows e.g. that

- the influence of the loose pellets filling on top is not very strong since it is only compressed with about 1 cm the main reason being that the vertical stress is laterally spread and thus much smaller in the roof than in the floor above the deposition hole. However, the compression of the pellets filling is judged to be proportional to the thickness, which means that the upwards expansion may increase two cm if the thickness is trebled,
- the expansion reaches down to the top of the canister where the displacement is about 1 cm,
- the difference in displacement pattern between the buffer and the backfill reveals that there is a rather strong friction effect between the upper buffer part and the rock surface but not in corresponding parts of the backfill. The reason is that there is a swelling pressure in the buffer that influences the friction but not in the backfill,
- there is a jump in average stress in the interface between the buffer and the backfill from about 3.5 MPa in the buffer to about 1.5 MPa in the backfill. The reason for this discrepancy is that the buffer swells and the backfill is compressed, which leads to a difference in direction of the principal stress that is vertical in the compressed backfill and horizontal in the swelling buffer. The vertical stresses are the same (see Figure 4-4) but the horizontal stresses are different which leads to a difference in average stress.

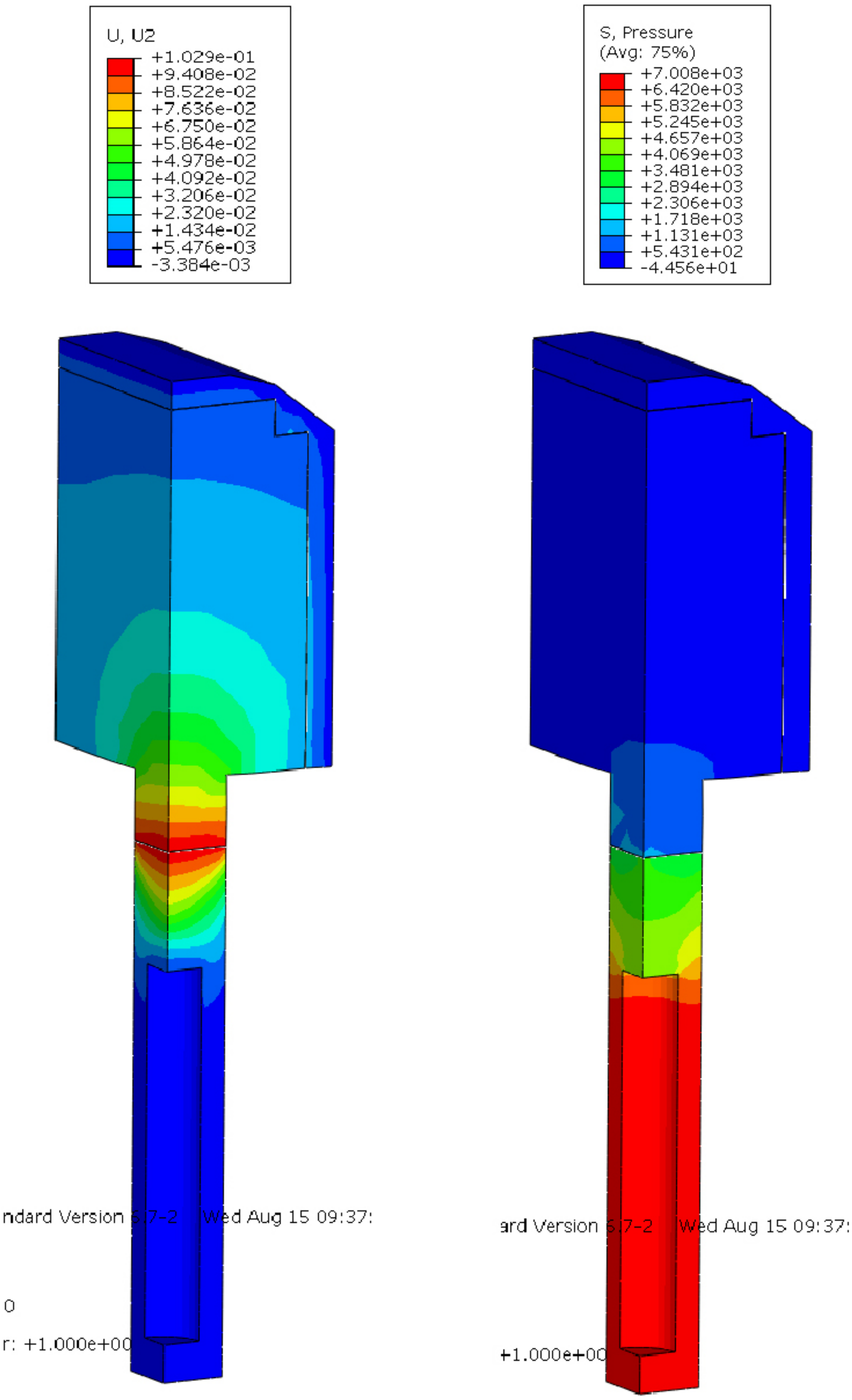

Figure 4-3. *Vertical displacements (U, m) and average stress (S, MPa) in the buffer and backfill after completed swelling (base case).*

Figure 4-4 shows the final distribution of the void ratio in the buffer and the final vertical stresses in the upper part of the buffer and lower part of the backfill. The strong increase in void ratio above the canister is obvious. In the dark green zone on the top of the canister the void ratio is between 0.85 and 0.875. Since the critical density 1,950 kg/m^3 corresponds to a void ratio of 0.87 the density criterion for the buffer seems to be met also after such strong swelling.

The vertical stress plot shows that the vertical stress in the contact zone between the buffer and the backfill is about 2.5 MPa.

The calculations were done with some conservative assumptions as

- no swelling pressure from the backfill,
- no friction between the backfill and the rock,
- very loose pellets filling (no homogenisation).

In spite of these assumptions the buffer seems to stay within the density criterion 1,950 kg/m^3. In Chapter 6 the sensitivity of changes in some of the important parameters will be analysed.

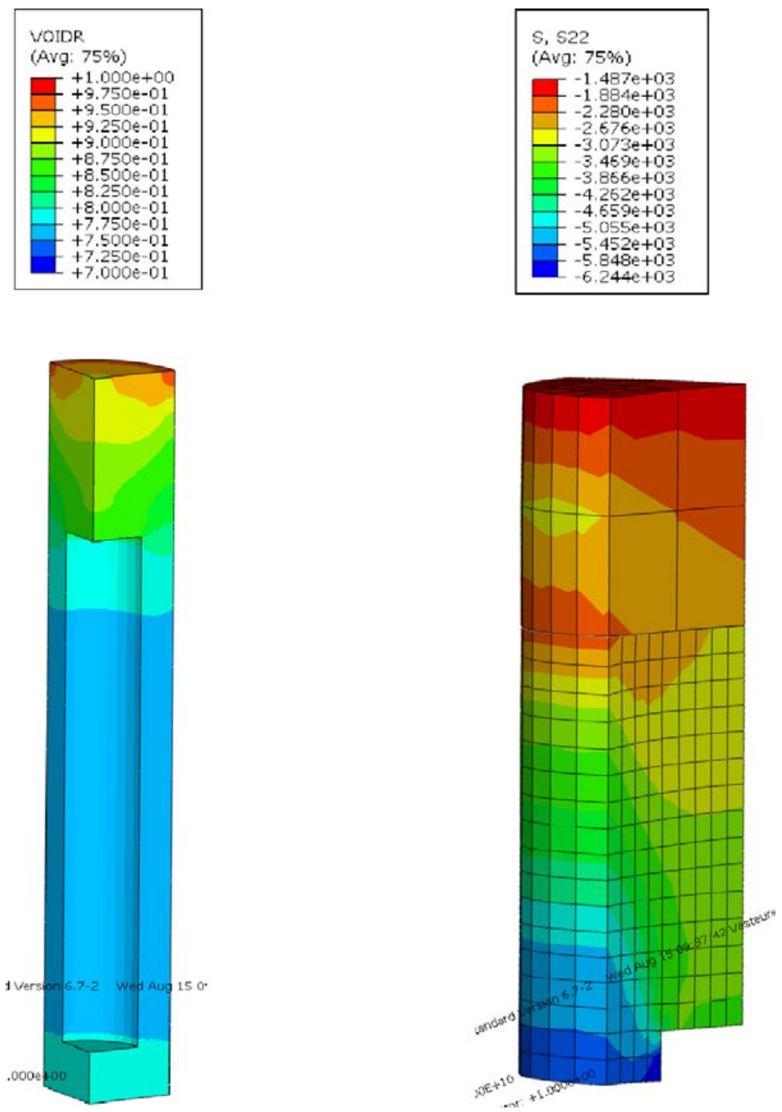

Figure 4-4. *Void ratio in the buffer (left) and vertical stress in the upper part of the buffer and the lower part of the backfill (MPa) after completed swelling (base case).*

5 Swelling against dry tunnel

5.1 General

An extreme situation that is not expected to occur but must be analysed is when there is enough water available to saturate the buffer material and no water at all for wetting the backfill. For this case all materials except the backfill are modelled in an identical way as for the wet case. The backfill model is complicated since the major part of the backfill consists of separate blocks piled in a way that is not known today. Most deformations will take place in the horizontal joints between the blocks and in the pellets filling and the properties of especially the joints are not known.

The blocks have been modelled as separate units with contact elements that have a thickness of 4 mm separating the different blocks.

Only one case has been analysed so far since the influence of changed properties can easily be analysed as will be shown below. The reported calculation is considered sufficient for design purpose but additional calculations will be done with updated geometry and sensitivity analyses. E.g. the pellets filling on the floor has not been included in the presented model. In the calculations of the dry case identical geometry, element mesh and material models as in the wet case have been used with exception of the backfill material.

5.2 Material models

5.2.1 General

The following materials have identical properties and initial conditions as in the calculations of the dry case described in Chapter 4:

- The buffer material
- The rock
- The canister
- The contact surfaces between the buffer/backfill and the rock and between the buffer and the canister.

These models will not be further described in this chapter.

5.2.2 Backfill

There are three different parts included in the dry backfill, namely the blocks, the joints between the slots and the dry pellets filling.

Block section

The backfill blocks are modelled as a linear elastic material with the following properties:

E = 500 MPa
v = 0.2
Initial average stress p_0 = 0 MPa

The value of the E-modulus and Poisson's ratio v have not been measured for the reference backfill and the choice of those parameters was based on tests on bentonite blocks intended for buffer blocks /5-1/ with higher density. Later tests on backfill blocks indicate that the E-modulus is only about 200–300 MPa. However, the blocks are very stiff compared to the pellets filling and the joints so the results are rather insensitive to the elastic properties of the blocks.

Pellet section

Also the pellets are modelled as linear elastic but with the following properties

E = 3.24 MPa
v = 0.3
Initial average stress p_0 = 0 MPa

The compressibility of different pellets fillings have been tested and reported by Johannesson /1-6/. The E-modulus used is evaluated from those measurements for an increase in stress from 0 to 1 MPa. At higher stresses the E-modulus increases.

Joints between blocks

Since the bottom bed on which the blocks rest cannot be made as a completely plane or horizontal surface the backfill blocks will be placed slightly uneven in relation to each other. This means that there will be joints that are not even due to slightly inclined blocks that also have slightly different heights. The properties of these joints between the blocks are not known but they will have compression and friction properties that deviate significantly from the properties of the blocks.

As a first assumption that can be used for the calculations the joints have been assumed to have the following properties (both horizontal and vertical):

- Average joint thickness: 4 mm.
- Compression properties: the joints are closed at an external pressure of 10 MPa.
- Friction angle ϕ = 20°.

Figure 5-1 shows the stress-compression relation that has been used for the joints.

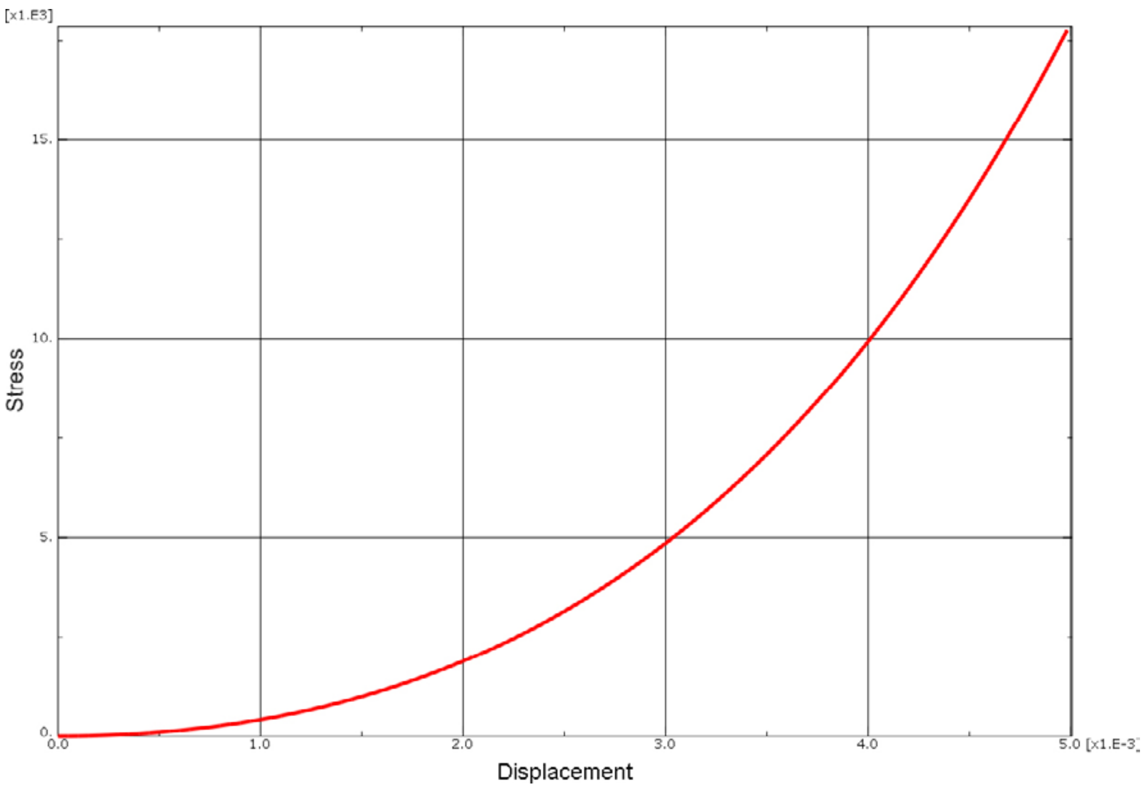

Figure 5-1. *Mechanical model of the joints between blocks. The displacement or compression (m) of the joint is plotted as a function of the total stress (kPa) perpendicular to the joint. After 4 mm compression the joint is closed.*

5.3 Element model

The geometry used for the model was shown in Figure 2-1. The element mesh for the calculation with dry backfill is shown in Figure 5-2.

The geometry and the mesh of the buffer, canister, rock, pellets filling and the contact element are identical to the corresponding mesh for the wet case.

The backfill blocks in the tunnel have the following geometry:

- Backfill blocks: 0.82×0.82×0.51 m^3

The backfill in the upper meter of the deposition hole is modelled as one solid block with the same elastic properties as the other backfill blocks.

It is a full 3D model of a quarter of a deposition hole and tunnel section with symmetry planes in three of the four vertical boundaries yielding a model of a long tunnel with deposition holes with 6 m distances. There are contact surfaces in all contacts between the rock and the buffer and backfill as well as between the buffer and the canister.

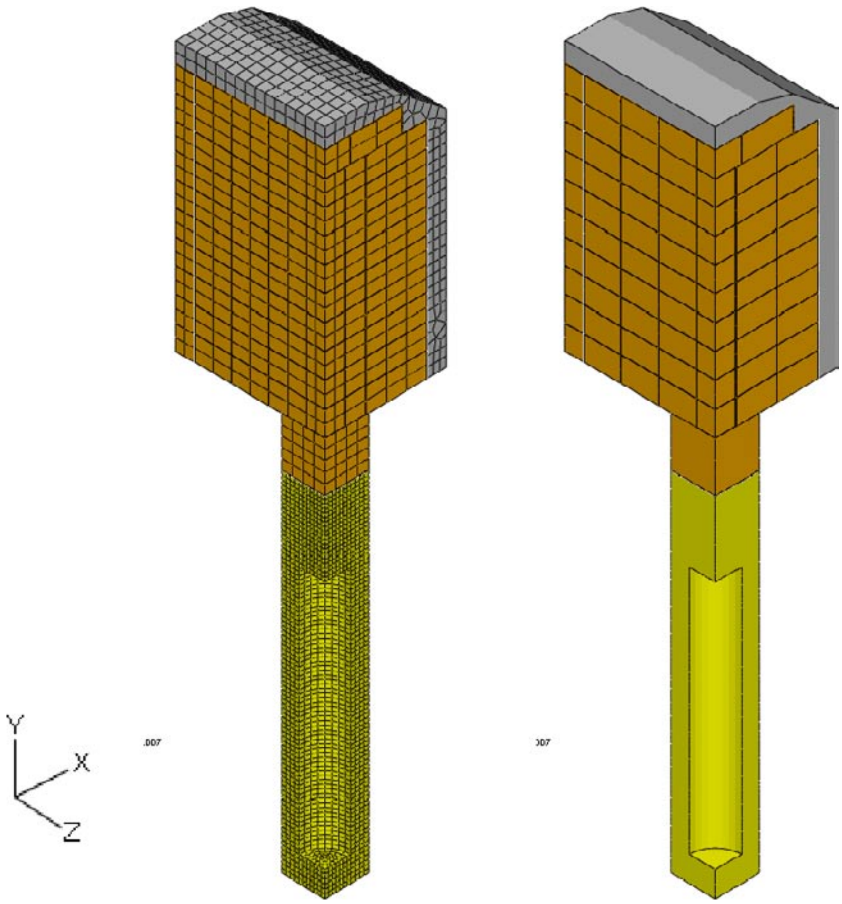

Figure 5-2. *Element mesh for the calculation with dry backfill (left) and the backfill block configuration (the canister and rock are not included).*

5.4 Boundary conditions

The mechanical and hydraulic boundary conditions are identical to the boundary conditions used in the calculation of the wet case (Section 4.4).

5.5 Calculation sequence

See Section 4.5.

5.6 Results

Some initial calculations with slightly different block geometries have been performed but only the last one with the geometry according to Figure 5-2 will be shown.

Figure 5-3 shows the displacement of three points in the buffer between the canister and the backfill bottom as function of time. Both the magnitude and the time agree surprisingly well with the base case of the wet backfill. The displacement of the interface between the buffer and backfill is slightly less than 9 cm.

Figure 5-4 shows the distribution of the vertical displacements and the average stress after completed swelling.

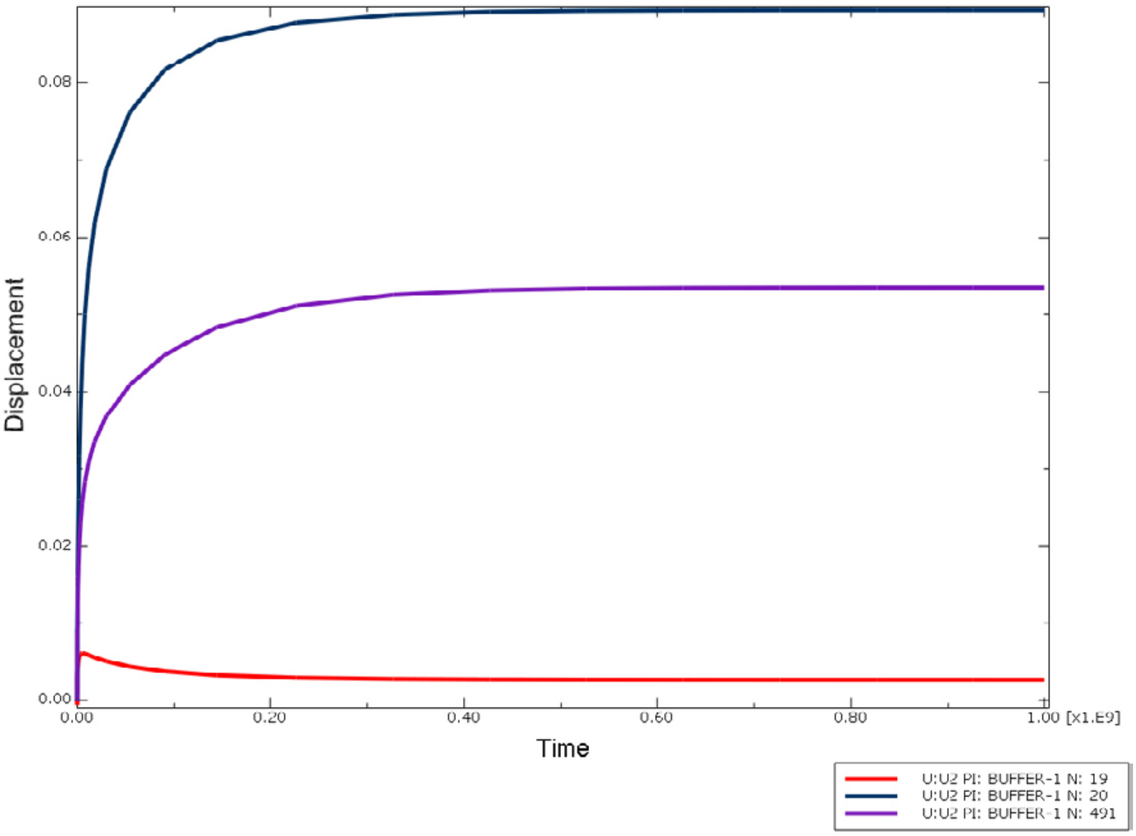

Figure 5-3. *Displacements in the upper part of the buffer (m) as function of time (s) in the case of dry backfill*
— *interface buffer/backfill*
— *halfway between backfill bottom and canister top*
— *top of canister.*

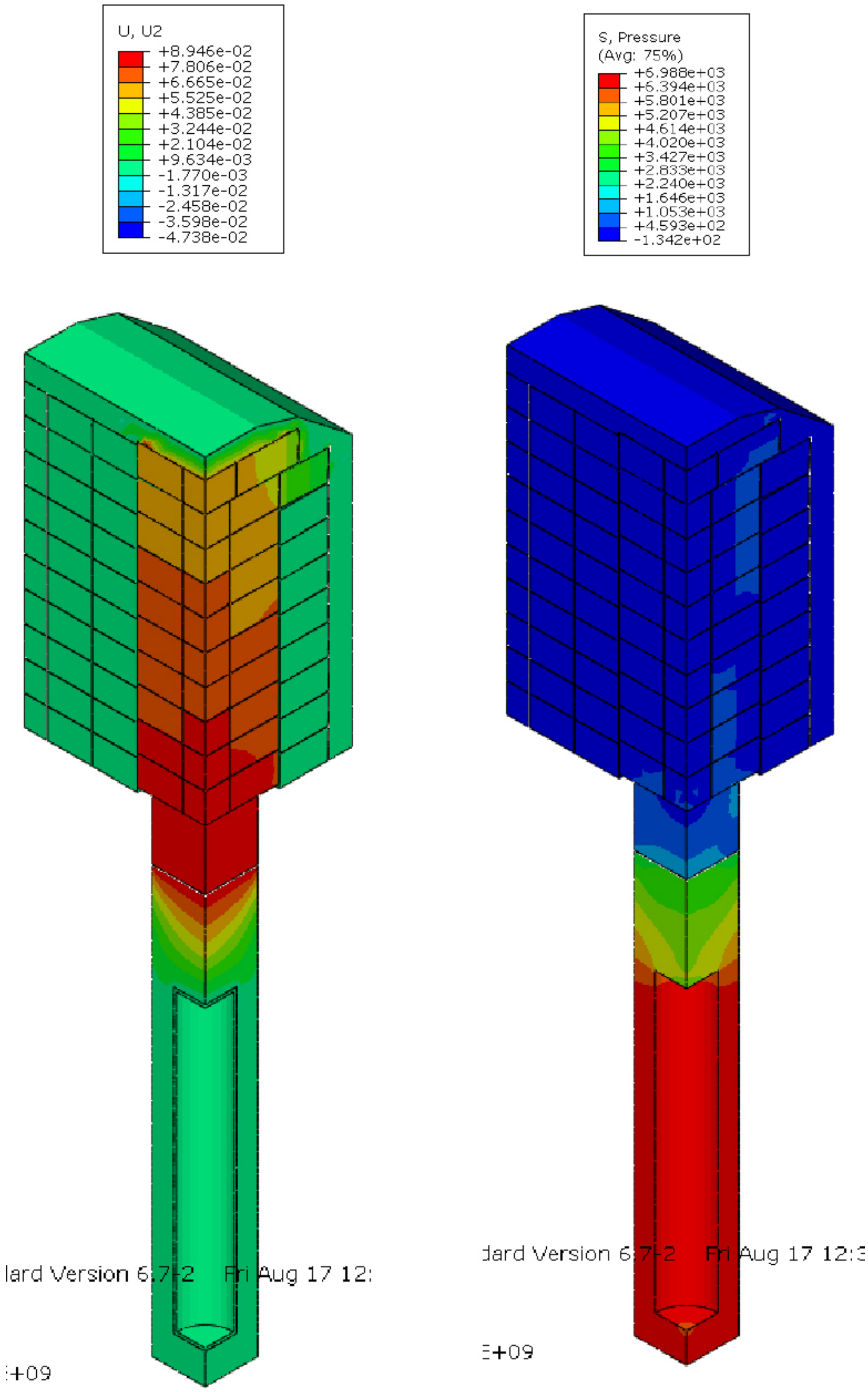

Figure 5-4. *Vertical displacements (U, m) and average stress (S, MPa) in the buffer and backfill after completed swelling (dry case).*

Figure 5-4 shows e.g. that

- the compression and thus also stress distribution in the backfill is limited to the block pile above the deposition hole since there is an insignificant spreading of the stress due to the vertical joints between the blocks,
- the influence of the loose pellets filling at the roof is strong since it stands for more than half of the total compression, which thus means that the compressibility of the pellets filling is important and the effect of an unfilled section very strong,

- the expansion reaches down to the top of the canister where the displacement is about 1 cm,
- the backfill block in the top of the deposition hole is compressed very little. The block only moves upwards and opens the joint between the bottom backfill block and the floor of the tunnel,
- a similar jump in average stress as for the wet base case takes place in the interface between the buffer and the backfill from about 3.5 MPa in the buffer to about 2.0 MPa in the backfill.

There is of course an influence of backfill block size and piling geometry. In the model example the blocks have been piled without individual shifting (masonry bond). If there is a masonry bond the stress distribution will increase and the swelling decrease. On the other hand if the backfill blocks are smaller and without masonry bond the stresses will be more concentrated and the swelling larger.

Figure 5-5 shows the final distribution of the void ratio in the buffer and the final Mises stresses in the backfill. The void ratio distribution resembles very much the distribution in the wet base case, which is natural considering that the upwards total swelling of the buffer/backfill interface is similar.

Figure 5-5 also shows that the Mises stresses can be rather high (10 MPa) at the upper rim of the backfill block in the deposition hole. These stresses indicate that the rim may be partly crushed.

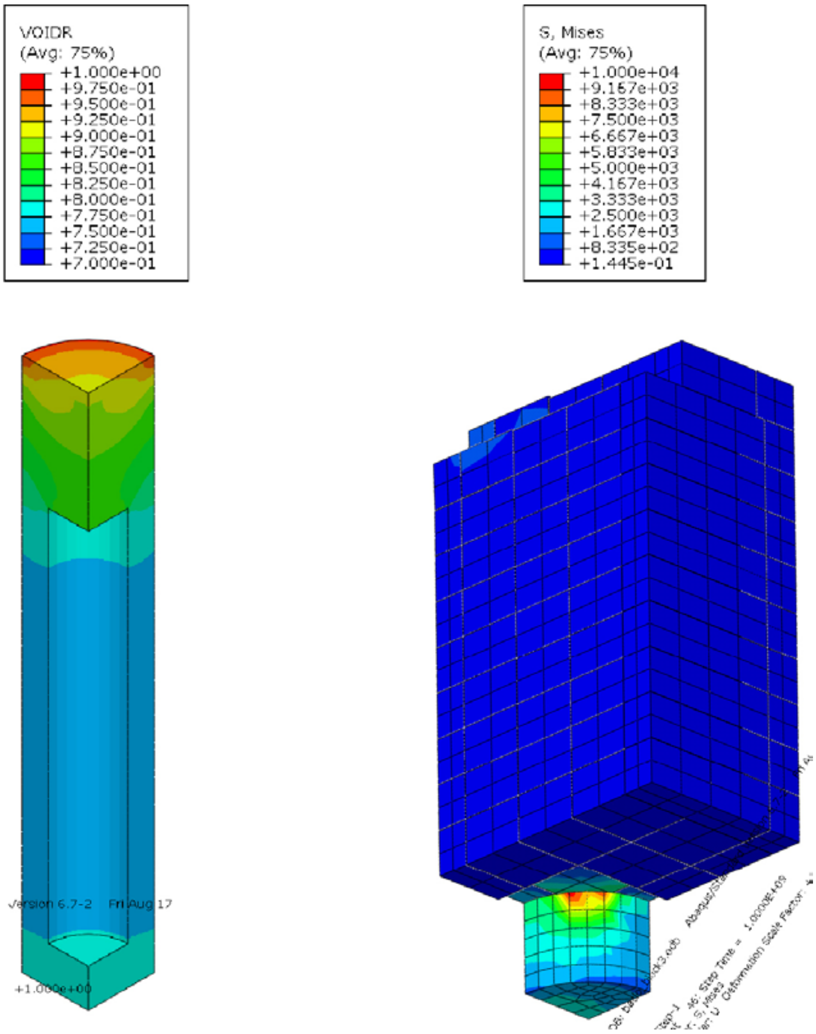

Figure 5-5. *Void ratio in the buffer (left) and Mises stress in the backfill (MPa) after completed swelling (dry case).*

6 Evaluation and conclusions

6.1 Compilation of results

Besides the dry case and the wet base case, nine different calculations with varying material properties have been performed. Table 6-1 summarises the results. The table shows the parameters that have been changed compared to the base case, the resulting upwards displacement of the buffer/backfill interface and the heave of the canister after completed swelling.

Reference model

E(backfill) = 50 MPa,

E(pellets) = 3.24 MPa

ϕ_c = 8.7°

p_0 = 0 MPa (swelling pressure)

The influence of the friction angle in the contact elements at the buffer and backfill boundaries is illustrated in Figure 6-1. The void ratio distribution in the buffer after completed equilibrium is plotted.

6.2 Influence of different conditions

The calculated upwards swelling of the buffer varied between 2 and 15 cm for the different wet cases while it was about 10 cm for the dry case. For the wet case the following influence of different factors was found:

Influence of friction angle between the buffer and its surroundings

There is a strong influence of the friction angle on both the upwards swelling and the canister heave. The friction is important for preventing especially canister displacements. The unrealistic case of no friction yields strong unacceptable influence on the buffer with an upwards swelling of 15 cm and a strong heave of 5 cm of the canister. The buffer density gets much lower than 1,950 kg/m^3 (e = 0.87) both beneath and above the canister. The friction angle needs to be higher than about 8° in order not to have a density at saturation lower than 1,950 kg/m^3 close to the canister at the conditions used for the modelling. It is also interesting to see that a very high friction angle yields very high void ratio at the contact between the buffer and the backfill (higher than 1.0 at the upper rim of the buffer) since the friction prevents swelling and causes a higher density gradient in the upper part of the buffer.

Table 6-1. Compilation of modelling results.

Model	Characteristic Deviation from reference model	Displacement of the buffer/ backfill interface (mm)	Canister heave (mm)
Baclo_block3	Block model	89.5	2.6
Baclo3b	Reference model	102.9	5.5
Baclo3b1	ϕ_c = 4.4°	116.1	8.0
Baclo3b2	ϕ_c = 17.0°	94.3	3.5
Baclo3b3	ϕ_c = 0°	153.9	50.0
Baclo3b4	$E_{pellets}$ = 50 MPa	94.4	5.0
Baclo3b5	$E_{backfill}$ = 25 MPa	145.7	7.0
Baclo3b6	$E_{backfill}$ = 100 MPa	74.1	3.7
Baclo3b7d	p_0 = 3 MPa, $E_{pellets}$ = 50 MPa	23.9	0.8
Baclo3b7e	p_0 = 1 MPa, $E_{pellets}$ = 50 MPa	44.4	1.7
Baclo3b8	p_0 = 3 MPa, $E_{pellets}$ = 50 MPa, ϕ_c = 0°	58.4	17.0

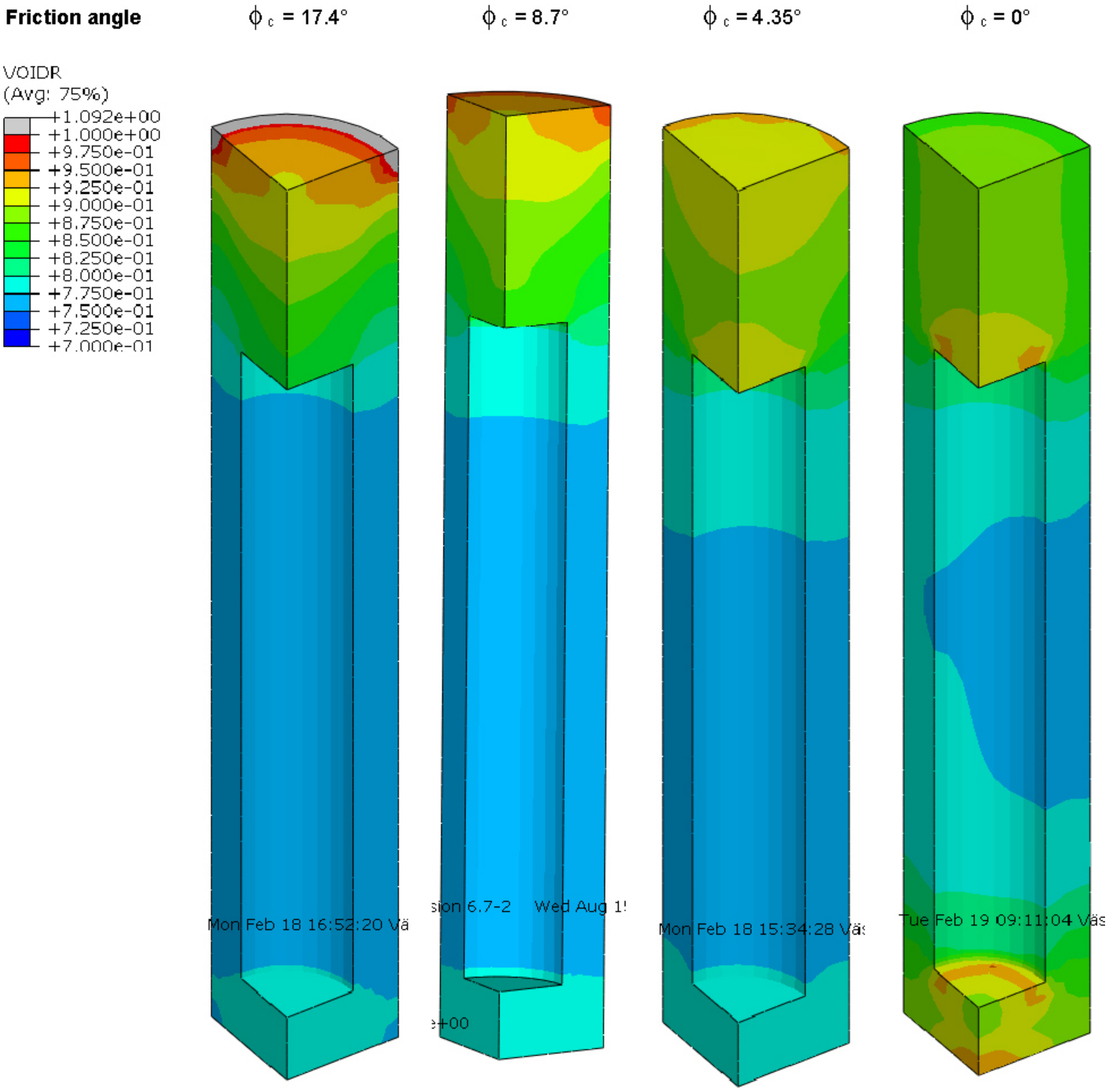

Figure 6-1. Void ratio distribution in the buffer after completed swelling for different values of the friction angle between the buffer and the rock and canister.

Influence of backfill stiffness

The influence of the backfill stiffness is as expected strong. Both buffer swelling and canister heave are twice as large at the E-modulus E = 25 MPa than at the E-modulus E = 100 MPa. The influence of the stiffness of the pellets filling is not strong since there are no pellets on the floor in the model used.

Influence of the swelling pressure in the backfill

The swelling pressure from the backfill is not included in the reference case, which of course is very conservative if the extreme situation of completely water saturated backfill is studied. The influence is strong with both buffer swelling and canister heave reduced to less than 50% at the swelling pressure 1 MPa and to less than 25% at the swelling pressure 3 MPa.

Influence of a dry backfill

Only one calculation has been done with dry backfill as reported in Chapter 5. The difference between this case and the reference case is small (9 and 10 cm heave respectively), which manly depends on that the average stiffness of the backfill seems to be similar for those cases and that no swelling pressure of the backfill was assumed for the reference case. The influence of the friction angle between the buffer and its surroundings is judged to be as strong as for the wet case.

6.3 Conclusions and further work

The calculations show that there are three parameters that are critical for the swelling, namely the friction angle between the buffer and its surroundings, the stiffness of the backfill and the swelling pressure of the backfill. For the case of wet backfill material only the combination of a low friction angle and a low swelling pressure (which is not a realistic case) can violate the density criterion. The wet case does thus not seem to be critical. Regarding the dry case there are some shortcomings of the calculations:

- In the new reference design there is pellet filling on the floor that has not been included in the models. This will increase the swelling somewhat but not very much since the thickness is only about 8 cm.
- The properties of the joints between the blocks and the influence of block stacking geometry (“masonry”) are not well known and the data used in the model is estimated. This is a critical part for the dry case but the compression relation used in the model is probably conservative.
- The influence of the saturation and homogenisation phase of the buffer is not included (concerns also the wet case) but is estimated not to increase the swelling.

Additional calculations of the dry case that consider these items are desired.

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