Technical Report

# TR-06-13

# Consequences of loss or missing bentonite in a deposition hole

## A theoretical study

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August 2006

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*Keywords:* Bentonite, Erosion, Self-sealing, Modelling, Swelling.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

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# Abstract

The swelling properties of bentonite make the buffer material swell and close open gaps or channels to form a more homogeneous buffer. These properties are important not only for homogenising the buffer after installation of the bentonite blocks but also after long time if openings in the buffer would appear.

However, the swelling and sealing of bentonite cannot take place unhindered since there is a resistance to swelling caused by friction both internally in the bentonite and between the bentonite and the surrounding fixed walls represented by the rock surface and the canister.

In order to investigate how well the buffer material seals openings resulting from different processes, a number of finite element calculations have been performed.

The finite element code ABAQUS was used for the calculations. The bentonite has been modelled as completely water saturated. The mechanical properties of the buffer controlling the swelling and consolidation phase are based on the models and properties derived for MX-80.

1) One of the investigated scenarios concerns either huge loss of bentonite after extremely long time of erosion or the improbable case of one to three missing bentonite rings at the upper end of the canister. The rings are 50 cm thick and 1–3 of them are assumed to be forgotten during the installation of the buffer. This case can thus also represent an extreme loss of bentonite by erosion or bentonite dispersion and subsequent colloid transportation after fresh water intrusion (corresponds to 1,200–3,600 kg dry mass).

The results show that when large amounts of bentonite are lost or missing from start the bentonite swells and fills the empty space but the density and resulting swelling pressure are rather low due to the friction in the buffer and the friction against the rock surface. For 50 cm opening the swelling pressure is in average 0.5–1.0 MPa in almost the entire former hole. However, if the rock surface is smooth and the resulting friction against the rock is halved the swelling pressure will be above 1 MPa in a majority of the former space.

For 100 cm opening the average swelling pressure between the canister and the rock will be about 300 kPa in the weakest section. If the opening is 150 cm, corresponding to three missing bentonite rings, the base case yields that a large volume will be unfilled or have a swelling pressure below 100 kPa.

2) Erosion during and after installation of the buffer may under unsatisfactory conditions cause significant loss of bentonite. The erosion will stop when an endplug in the deposition tunnel is built and sealed. The plug is intended to function about 12 weeks after installation start.

The base case (worst case) of the erosion is a flow of 0.1 l/min into a deposition hole that erodes 10 g dry weight of bentonite per litre water. This yields over 12 weeks a total amount of flowing water of 12,100 l and a total dry mass of eroded bentonite of 121 kg.

Calculations of the swelling and homogenisation of the buffer after local loss of that amount of bentonite have been done assuming two different geometries of the empty space. In one of the geometries half a donut located at the rock surface reaching all around the periphery of the deposition hole was simulated. The results show that the swelling results in a remaining strong decreased density and swelling pressure due to the friction in the bentonite. However, the swelling pressure after completed homogenisation is not below 1 MPa in any of the cases with a donut thickness varying from 3.4 cm to 13.4 cm.

3) The consequences of piping and erosion are a small channel that leads the water and bentonite solution out through the buffer into the backfill. Such a pipe will ultimately swell up and seal when the water flow has stopped. FEM modelling of the process of self-sealing of long

open tubes in compacted bentonite has yielded some interesting results. A long open tube does not seal completely but a reduced density with an infinitely small hole will remain.

The following remarks regarding these calculations are important:

1. The influence of the friction angle between the bentonite and the rock and canister is large.
2. The material model of Na-bentonite is valid at void ratio interval 0.7–1.5, which means that the strong swelling and gel-formation that will take place at the swelling bentonite surface in non-saline water is not modelled.
3. The material parameters used represent average values and non-linearity is not taken into account.

The uncertainties about the material model at strongly swelling bentonite make the results somewhat uncertain especially at high void ratios. The results should therefore be checked by performing laboratory swelling tests that model some of the cases.

# Sammanfattning

Bentonits svällningsegenskaper får buffertmaterialet att svälla varigenom öppningar och kanaler stängs och bufferten blir mer homogen. Dessa egenskaper är viktiga inte enbart för att homogenisera bufferten efter installation av bentonitblocken, men också ifall tomrum eller kanaler skulle uppstå i bufferten efter lång tid.

Bentonitens svällning och tätning kan dock inte äga rum obehindrat eftersom både den inre friktionen i bentoniten och friktionen mellan bentoniten och de omgivande stela väggarna, som utgörs av bergytan och kapseln, orsakar ett motstånd mot svällning.

Ett antal finita-element beräkningar har gjorts för att undersöka hur väl buffertmaterialet tätar öppningarna som orsakats av olika processer. Finita-element koden ABAQUS användes för beräkningarna. Bentoniten har modellerats som helt vattenmättad. Buffertens mekaniska egenskaper som kontrollerar svällnings- och konsolideringsfasen är baserade på modeller och egenskaper som härletts för MX-80.

1) Ett av de undersökta scenarierna avser antingen en mycket stor förlust av bentonit efter extremt långvarig erosion eller det osannolika fallet att en till tre bentonitringar saknas vid den övre änden av kapseln. Ringarna är 50 cm tjocka och 1–3 av dem förmodas ha glömts vid installationen av bufferten eller försvunnit vid av erosion. Detta fall kan alltså även avse en extrem förlust av bentonit genom erosion eller upplösning av bentoniten med efterföljande kolloidtransport efter inträngning av färskvatten (motsvarar 1 200–3 600 kg torr massa).

Resultaten visar att när stora mängder bentonit försvinner eller saknas från start sväller bentoniten och fyller tomrummen, men den resulterande densiteten och svälltrycket är ganska låga beroende på friktionen i bufferten och mot bergytan. För en öppning på 50 cm blir svälltrycket i medeltal 0,5–1,0 MPa i nästan hela det tidigare hålet. Men om bergytan är slät och friktionen mot berget halveras, kommer svälltrycket att vara över 1 MPa i huvudparten av det tidigare utrymmet.

För en öppning på 100 cm kommer svälltrycket mellan kapseln och berget att i medeltal vara 300 kPa i den svagaste sektionen. Om öppningen är 150 cm, vilket motsvarar tre saknade bentonitringar, ger basfallet att en stor volym kommer att bli ofylld, eller ha ett svälltryck som är mindre än 100 kPa.

2) Erosion under och efter installationen av bufferten kan orsaka en betydande förlust av bentonit under ogynnsamma förhållanden. Erosionen kommer att upphöra när en ändplugg i deponeringstunneln är byggd och förseglad. Pluggen avses vara i funktion ca 12 veckor efter påbörjad installation.

Basfallet (värsta fall) av erosion är ett flöde på 0,1 l/min in i ett deponeringshål som eroderar 10 g torr-vikt bentonit per liter vatten. Under en period på 12 veckor ger detta ett totalt vattenflöde på 12 100 liter och en total massa av eroderad bentonit på 121 kg.

Beräkningarna av svällningen och homogeniseringen av bufferten efter en lokal bentonitförlust av denna storleksordning har gjorts med antagande av två olika hålgeometrier. I en av geometrierna simulerades en halv badring, som är belägen vid bergytan och sträcker sig runt deponeringshålets periferi. Resultaten visar en bestående reduktion av densitet och svälltryck beroende på friktionen i bentoniten. Svälltrycket efter avslutad homogenisering blir dock inte under 1 MPa i något av fallen med en ringtjocklek på mellan 3,4 och 13,4 cm.

3) Piping och erosion i bufferten leder till att en kanal uppstår som leder vattnet och bentonitlösningen ut genom bufferten in i återfyllnaden. En sådan kanal kommer till slut att svälla igen och tätas när vattenflödet har upphört. FEM-modellering av processen med självförsegling av långa öppna kanaler i kompakterad bentonit har givit några intressanta resultat. En lång öppen kanal förseglas inte helt och hållet, utan en lägre densitet med ett oändligt litet hål kommer att bestå.

Följande påpekanden avseende dessa beräkningar är viktiga:

1. Friktionsvinkeln mellan bentoniten och berget respektive kapseln är av stor betydelse för resultaten.
2. Materialmodellen för Na-bentonit gäller vid ett portal på 0,7–1,5, vilket betyder att den kraftiga svällningen och gelformationen som kommer att äga rum vid den svällande bentonitytan i icke salthaltigt vatten inte har modellerats.
3. De använda materialparametrarna är medelvärden och eventuella olinjäriteter har försummats..

Osäkerheterna avseende materialmodellen vid kraftigt svällande bentonit gör resultaten något osäkra, särskilt vid höga portal. Vissa resultat bör därför kontrolleras med svällningsförsök i laboratorium.

# Innehåll

# 1 Introduction

The swelling properties of bentonite make the buffer material swell and close open gaps or channels to form a more homogeneous buffer. These properties are important not only for homogenising the buffer after installation of the bentonite blocks but also after long time if openings in the buffer would appear.

Except for the natural slots that exist after installation such spaces may appear due to several processes:

1. The unexpected event of missing bentonite rings caused by severe mistakes during installation.
2. Erosion before closure of the repository caused by strong water inflow into deposition holes if the water inflow is so strong that it is not prevented by the buffer until the water flow and high water pressure gradients are stopped by temporary plugs. If the erosion is strong, large openings of missing bentonite may locally be formed.
3. Long term erosion of bentonite in fractures intersecting the deposition hole mainly caused by bentonite dispersion and subsequent colloid transportation after fresh water intrusion.
4. Small channels caused by piping and rather limited short term erosion.

However, the swelling and sealing of bentonite cannot take place unhindered since there is a resistance to swelling caused by friction both internally in the bentonite and between the bentonite and the surrounding fixed walls represented by the rock surface and the canister.

In order to investigate how well the buffer material seals the openings resulting from the mentioned processes a number of finite element calculations have been performed.

# 2 FEM-program, material model and modelling strategy

## 2.1 General

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

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 /1/. An overview of how ABAQUS handles the THM-processes for buffer and backfill materials is given in other SKB reports (see e.g. /2, 3 and 4/).

For the swelling and consolidation processes used in the presented calculations ABAQUS Standard has been used.

## 2.2 Bentonite properties

The bentonite has been modelled as completely water saturated. This is for some scenarios a simplification since e.g. erosion before closure of the repository takes place before full saturation of the buffer. 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 very strong swelling that takes place after such large loss of bentonite.
- The models for water saturated bentonite are much simpler 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 properties** of the buffer controlling the swelling and consolidation phase are based on the models and properties derived for MX-80 by Börgesson et al. /2/. *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 2-1.

$$\Delta e = \kappa/(1+e_0)\Delta \ln p \qquad (2\text{-}1)$$

where $\kappa$ = porous bulk modulus, $e_0$ = initial void ratio

Poisson's ratio $v$ is also required.

*Drucker Prager Plasticity* model contains the following parameters:

$\beta$ = friction angle in the *p*-*q* plane

$d$ = cohesion in the *p*-*q* plane

$\psi$ = dilation angle

$q = f(\varepsilon^d_{pl})$ = yield function

The yield function is the relation between Mises' stress $q$ and the plastic deviatoric strain $\varepsilon^d_p$ 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 2-2.

Some calculations were also done with a constant hydraulic conductivity $K$=1.0·10$^{-13}$ m/s.

**Table 2-1. Yield function.**

| *q* (kPa) | $\varepsilon_{pl}$ |
|---|---|
| 112 | 0 |
| 138 | 0.005 |
| 163 | 0.02 |
| 188 | 0.04 |
| 213 | 0.1 |

**Table 2-2. 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 | $7.0.10^{-11}$ |
| 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 $\rho_W$ and bulk modulus $B_W$ of the pore water as well as the density $\rho_S$ and the bulk modulus of the solid particles $B_S$ are required parameters. The following parameters are used for Na-bentonite:

**Pore water**

$\rho_W$= 1,000 kg/m$^3$ (density of water)

$B_W$= 2.1 ·10$^6$ kPa (bulk modulus of water)

**Particles**

$\rho_S$ = 2,780 kg/m$^3$ (density of solids)

$B_S$ = 2.1 ·10$^8$ kPa (bulk modulus of solids)

## 2.3 Contact elements

The contact between *the buffer 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 $\varphi$ and without cohesion $c$. The following basic value has been used:

$\varphi$ = 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.

The *surfaces of the open space* are also furnished with contact surfaces so that when the gap is closed the expansion is stopped and the surfaces cannot pass each other. Also the empty part of the rock surface is supplied with contact surfaces.

## 2.4 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 $\rho_m$=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:

$u$ = –7 MPa

$p$ = 7 MPa

$e$ = 0.77

# 3 Large part of the bentonite buffer missing

## 3.1 General

This chapter deals with a scenario that concerns either huge loss of bentonite after extremely long time of erosion or the improbable case of one to three missing bentonite rings at the upper end of the canister. The rings are 50 cm thick and are assumed to be forgotten during the installation of the buffer, i.e. the first full block is put in place on top of the canister when only 6–8 out of 9 rings have been installed, which yield a gap of 50–150 cm at the top of the canister. This case can also represent an extreme loss of bentonite by erosion or bentonite dispersion and subsequent colloid transportation after fresh water intrusion. The lost volume when one ring is missing is

$\Delta V = 0.77\ m^3$

and the loss of dry mass of bentonite is

$\Delta m = 1{,}200$ kg

This is about 10 times more mass lost than expected for the worst case of bentonite erosion before closure of the deposition drift (see Chapter 4). It corresponds to an erosion of 10 g/l at a flow rate of 1 l/min during 3 months. The scenario of 1–3 missing rings is thus more representative for long time erosion or long time colloid transportation.

## 3.2 Element mesh

The element meshes of two cases are shown in Figure 3-1. The meshes are axial symmetric and have contact surfaces with friction property defined between the buffer and the rock and between the buffer and the canister. The empty space at the 0.5–1.5 m gap is furnished with contact surfaces at the bentonite surfaces. Only the bentonite is modelled.

## 3.3 Calculations

The basic calculations comprise the basic cases at the empty space 0.5 m, 1.0 m and 1.5 m. One to two more calculations were also done for each case in order to investigate the influence of the friction against the rock. Table 3-1 shows the calculations. The hydraulic boundary consists of a constant water pressure at the rock surface. The empty space where bentonite is missing is supposed to be filled with water, which is modelled by applying a constant water pressure at the bentonite surface.

The last three calculations were done with a different geometry with the missing bentonite located in the centre of the buffer instead of close to the upper lid.

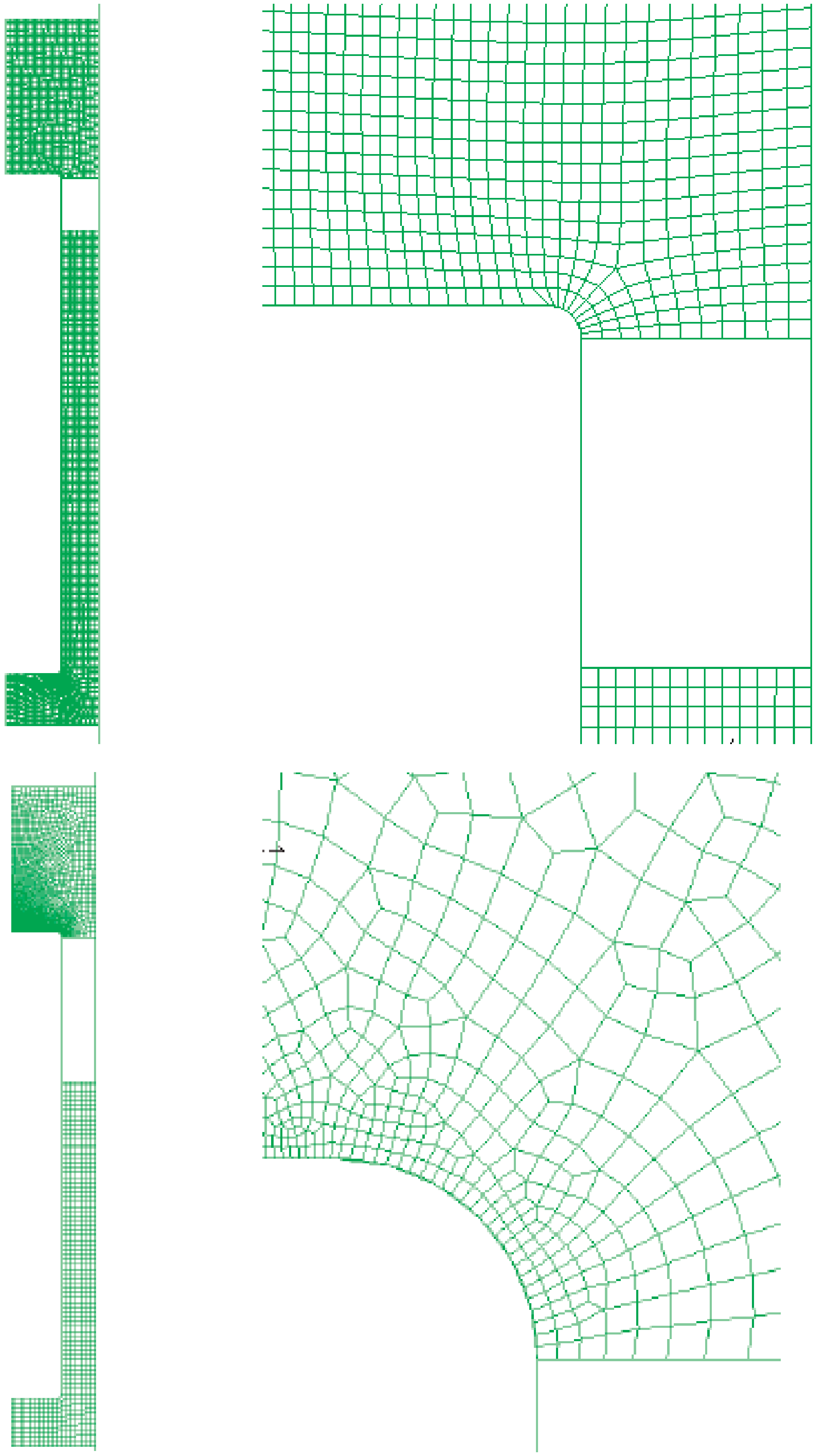


***Figure 3-1.** Element meshes used for the calculations regarding missing bentonite rings by erosion or emplacement mistakes. Upper: 1 ring missing. Lower: 3 rings missing. The entire meshes and enlargements of the critical parts are shown. Axial symmetry around the left boundary*

**Table 3-1. Definition of calculations.**

| Calculation | Definition | Space | Remark |
|---|---|---|---|
| Case1_2c | Base case. M-C $\phi$=8.7° | 1 ring – 0.5 m | |
| Case1_2d | Low friction M-C $\phi$=4.36° | 1 ring – 0.5 m | |
| Case1_2e | High friction M-C $\phi$=17.0° | 1 ring – 0.5 m | Did not converge |
| Case1b_2c | Base case. M-C $\phi$ 8.7° | 2 rings – 1.0 m | |
| Case1b_2c2 | Low friction M-C $\phi$=4.36° | 2 rings – 1.0 m | |
| Case1c_2c | Base case. M-C $\phi$=8.7° | 3 rings – 1.5 m | |
| Case1c_2c2 | Low friction M-C $\phi$=4.36° | 3 rings – 1.5 m | |
| Case1_3c | Base case. M-C $\phi$=8.7 | 1 ring – 0.5 m | Additional calculation with different geometry |
| Case1b_3c | Base case. M-C $\phi$=8.7° | 2 rings – 1.0 m | Additional calculation with different geometry |
| Case1c_3c | Base case. M-C $\phi$=8.7° | 3 rings – 1.5 m | Additional calculation with different geometry |

## 3.4 Results

### 3.4.1 Case 1 (one missing ring)

The results of the base case calculation of Case1 are shown in Figures 3-2 and 3-3.

The void ratio (Figure 3-2) increases from the initial value 0.77 up to 1.7 as a maximum during the swelling. When the open space has been closed and the two parts have come in contact after 1–2 years the swollen bentonite starts to consolidate and is compressed by the inner swelling bentonite. It then takes a very long time until complete equilibrium is reached (about 54 years). The consolidation of the bentonite is hindered by the friction in the bentonite and on the rock surface and a rather strong inhomogeneity still prevails after equilibrium. The maximum void ratio is 1.3–1.4 close to the canister and the average void ratio in the former open space is about 1.2.

The swelling pressure (average effective stress) shown in Figure 3-3 also remains very inhomogeneous. The remaining stress is below 1,000 kPa in a large part of the former open space.

The influence of the friction between the bentonite and the rock is investigated by the other two cases. The case with high friction did not converge, since the bentonite got struck to the rock wall and the elements were too much distorted. The results from the calculation with low friction are shown in Figures 3-4 and 3-5. The plots show that the gap is closed faster and that the final stage differs somewhat from the base case.

A direct comparison of the average swelling pressure in the two cases is shown in Figure 3-6. The difference is not very strong but important. In the base case the pressure is below 1,000 kPa in a large part of the former open space all the way between the rock and the canister, while for the low friction case the pressure is below 1 MPa only at a small ring around the canister.

### 3.4.2 Case 1b (two missing rings)

The results of the calculations with two missing rings (1 m gap) are shown in Figures 3-7 to 3-10.

Figure 3-7 shows the course of swelling for the base case. After a rather long time the space is almost completely filled with bentonite but there is a small remaining final opening and the void ratio is rather high close to that opening (1.7). The existence of the open space may be caused by model simplifications, but the results anyway show that the density is so low that the expected swelling pressure might very well be below 100 kPa as illustrated in Figure 3-8.

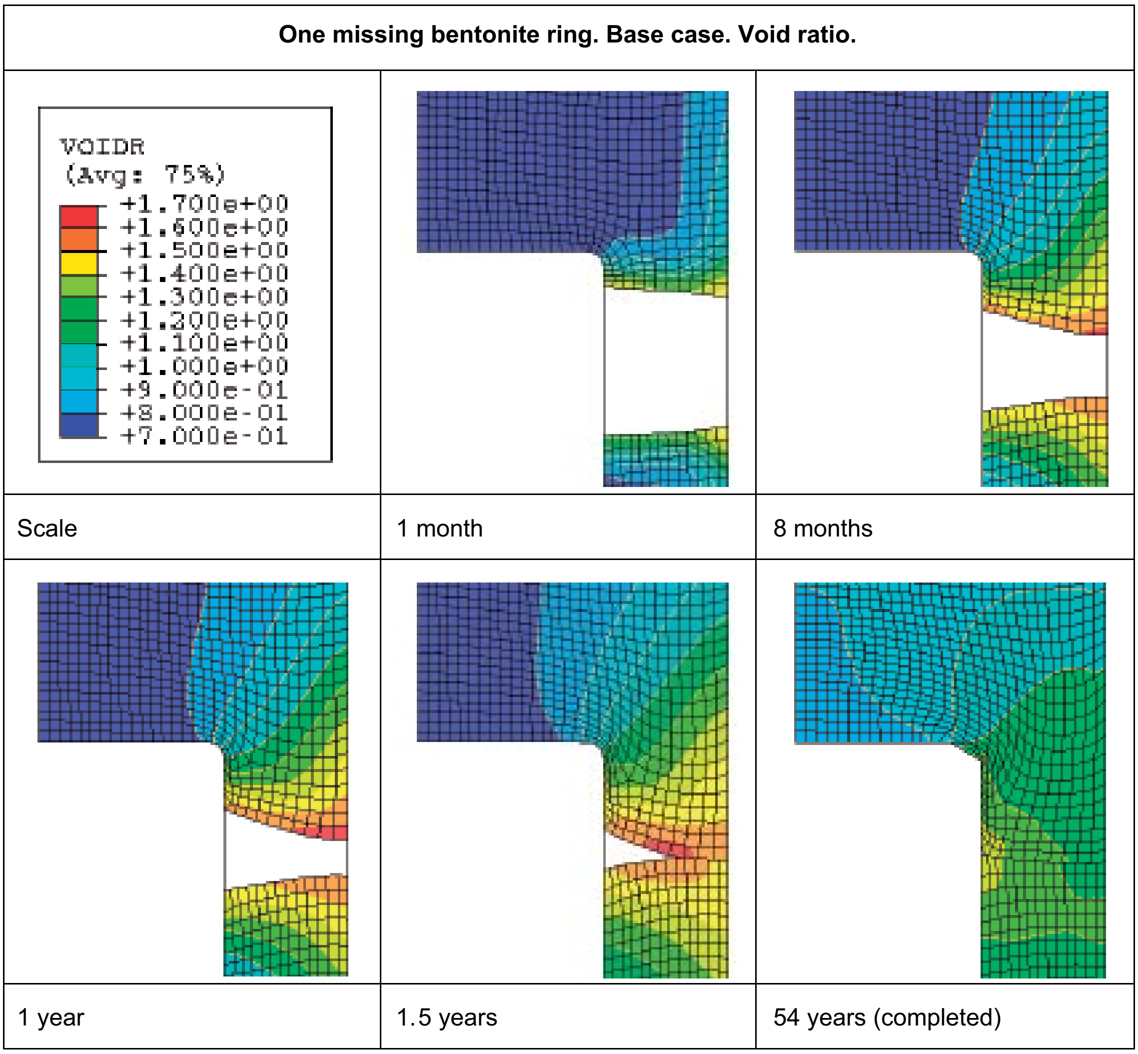



***Figure 3-2.*** *Void ratio plotted at different times for the base case with one missing ring.*

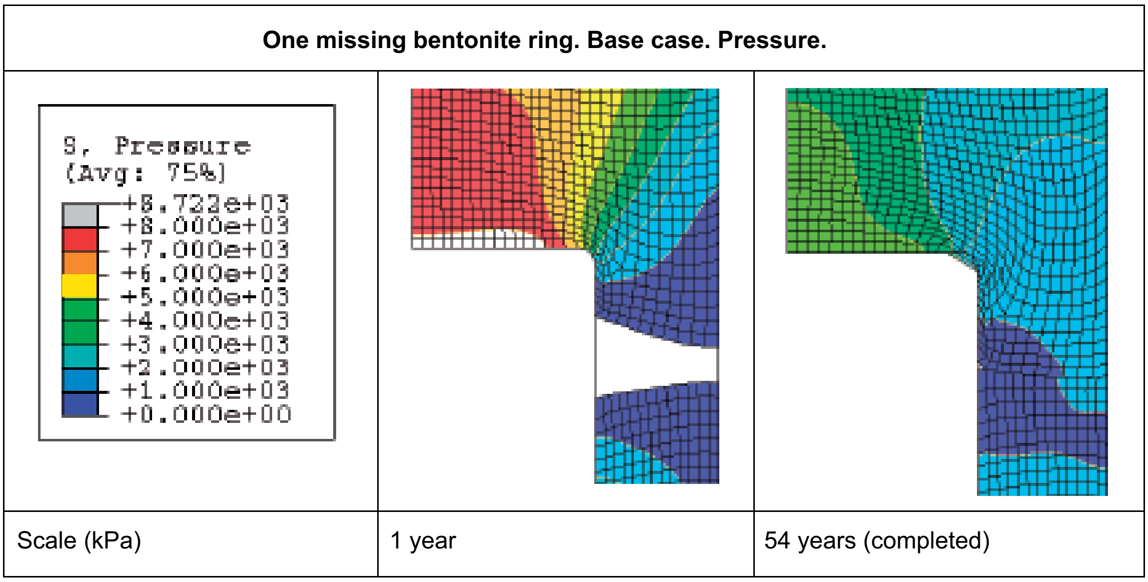



***Figure 3-3.*** *Average stress plotted at different times for the base case of one missing ring.*

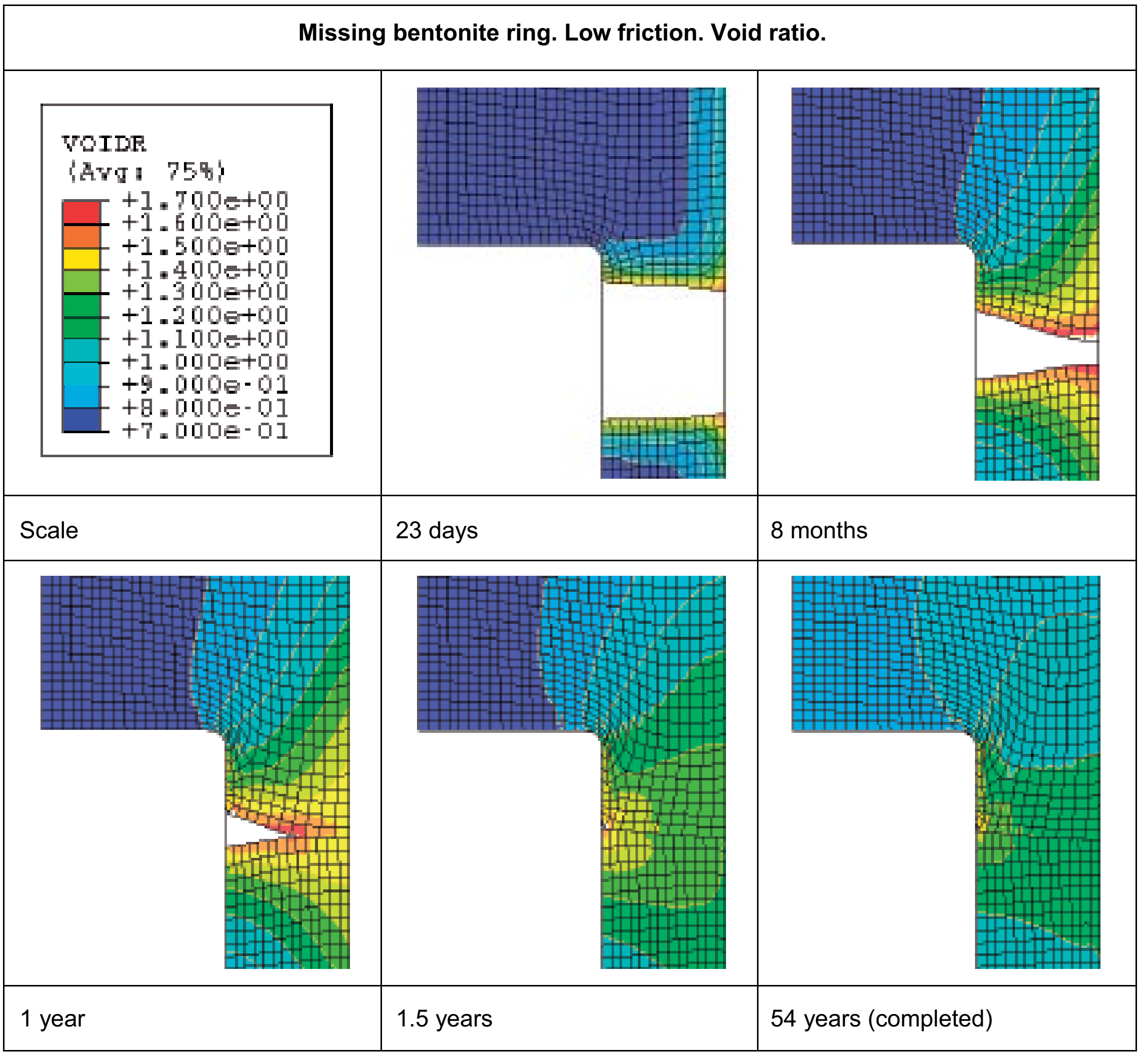



***Figure 3-4.*** *Void ratio plotted at different times for the case with low friction.*

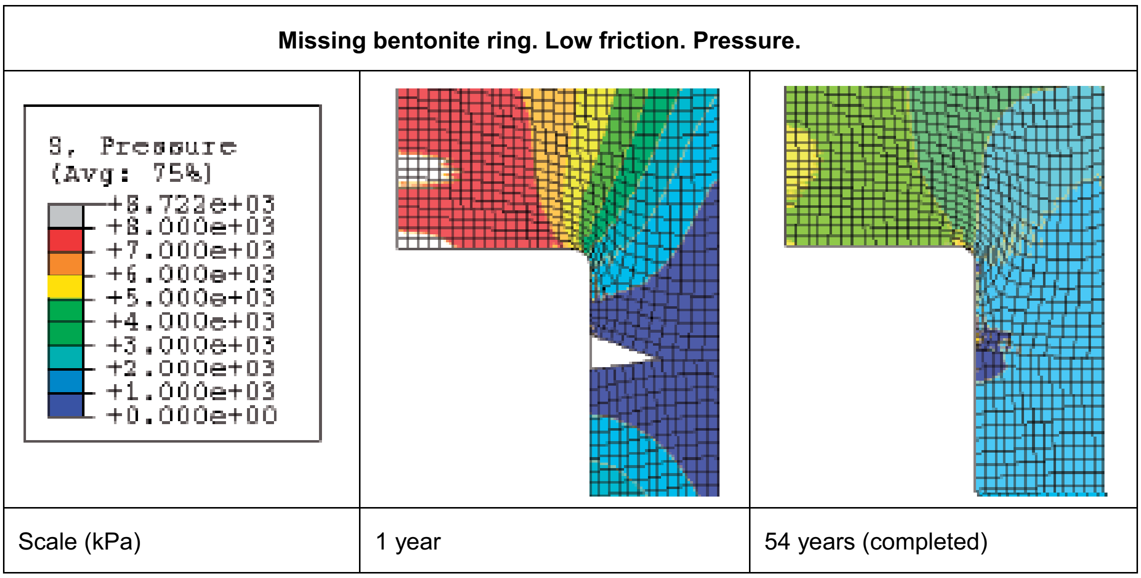
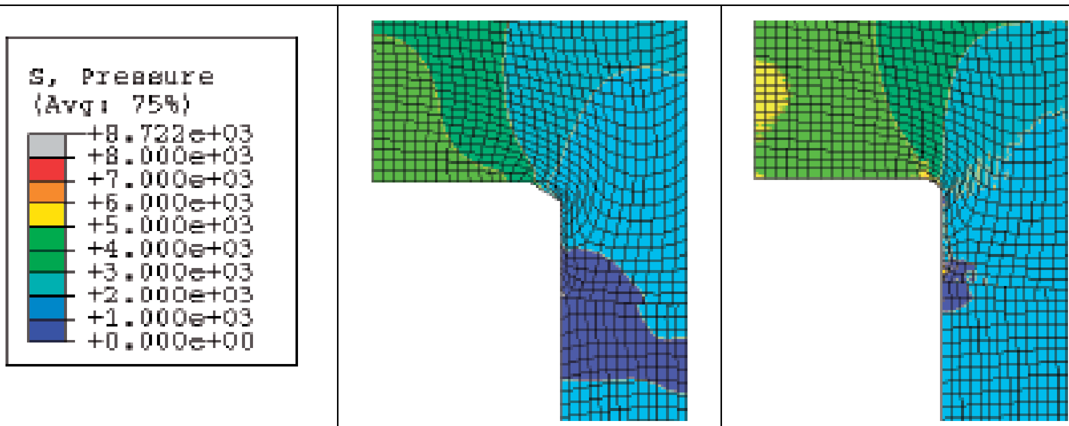



***Figure 3-5.*** *Average stress plotted at different times for the low friction case.*

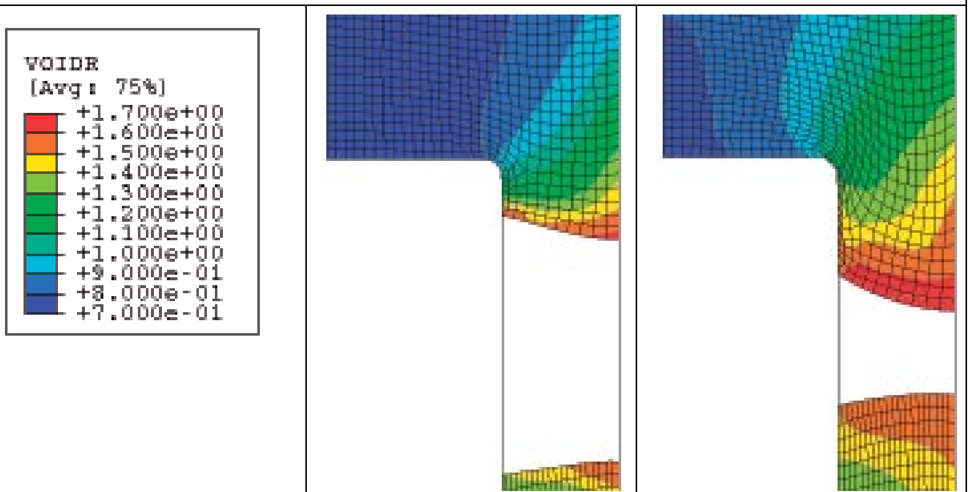
| Missing bentonite ring. Final state. Pressure. | | |
|---|---|---|



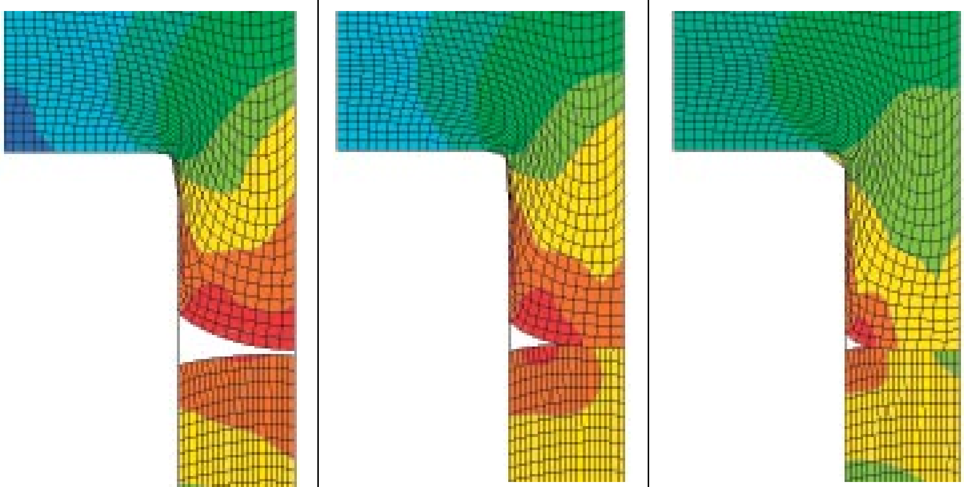

| Scale (kPa) | Base case | Low friction |
|---|---|---|

*__Figure 3-6.__ Comparison between the final average stress of the base case (left) and the case with low friction.*

| Two missing bentonite rings. Base case. Void ratio. | | |
|---|---|---|




| Scale | 230 days | 3.2 years |
|---|---|---|



| 5.7 years | 7.3 years | Completed |
|---|---|---|

*__Figure 3-7.__ Void ratio plotted at different times for the base case with two missing ring.*

**Two missing bentonite rings. Base case. Pressure at final stage.**

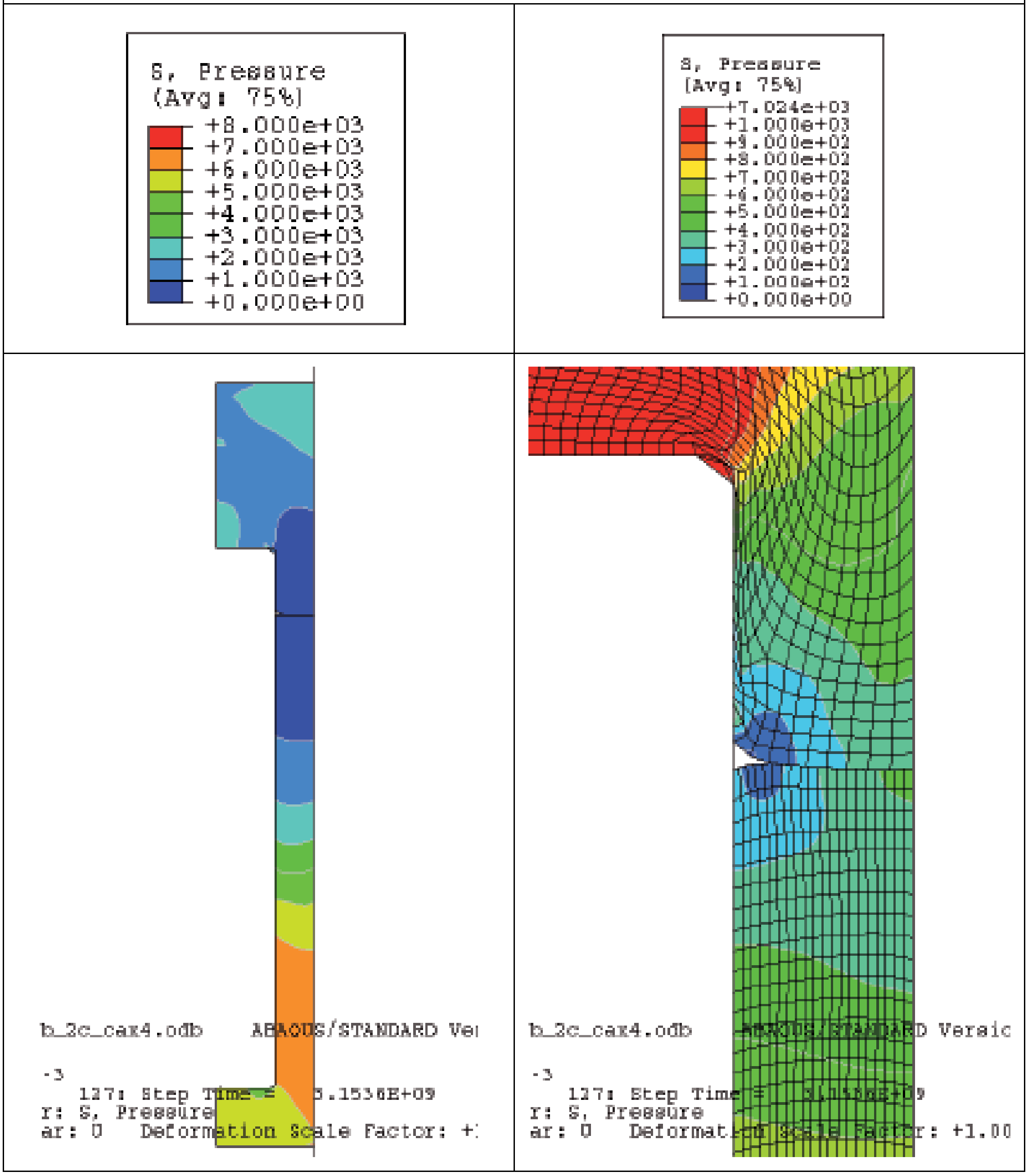



***Figure 3-8.*** *Average stress (kPa) at final stage for the base case of two missing rings. Observe the difference in scale. 1 MPa steps in the left figure and 100 kPa in the right.*

The influence of the friction between the rock and the buffer is shown in Figures 3-9 and 3-10. Figure 3-9 shows the void ratio for the low friction case. The slot is completely closed and the void ratio varies between 1.2 and 1.5 instead of between 1.4 and more than 1.7, which was the case for the full friction case. Figure 3-10 show a direct comparison of the swelling pressure at the two cases. Instead of an open space with no swelling pressure, the lowest swelling pressure for the low friction case is 300 kPa at the canister.

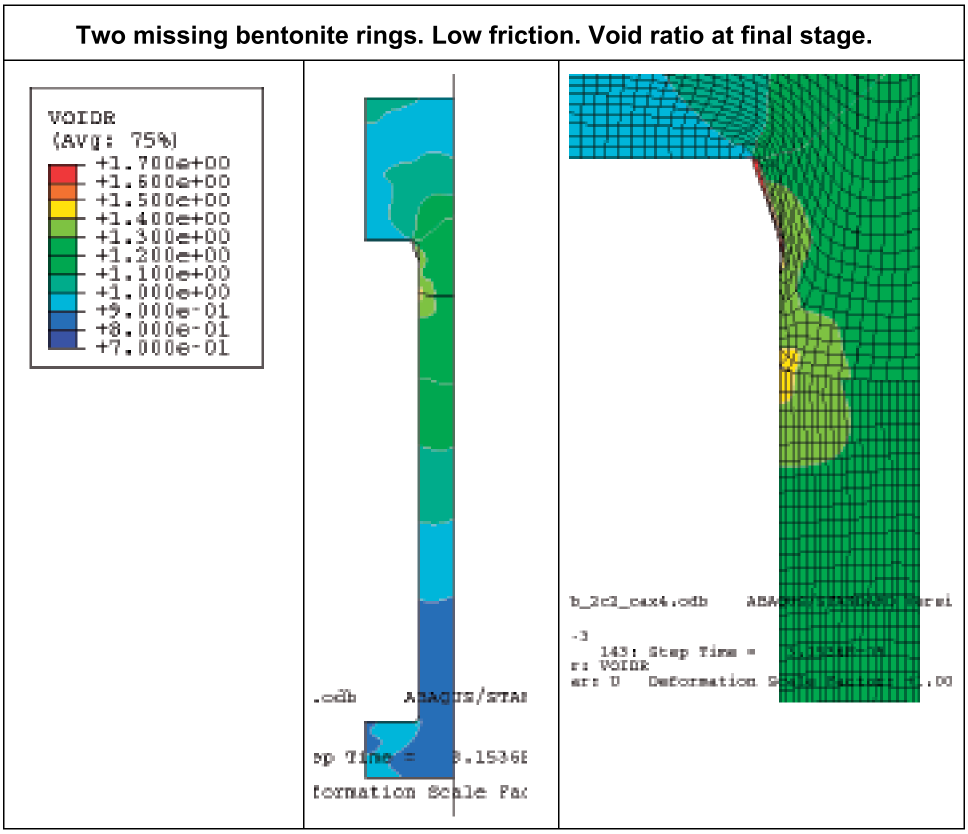



***Figure 3-9.*** *Void ratio at final stage for the case of low friction and two missing rings.*

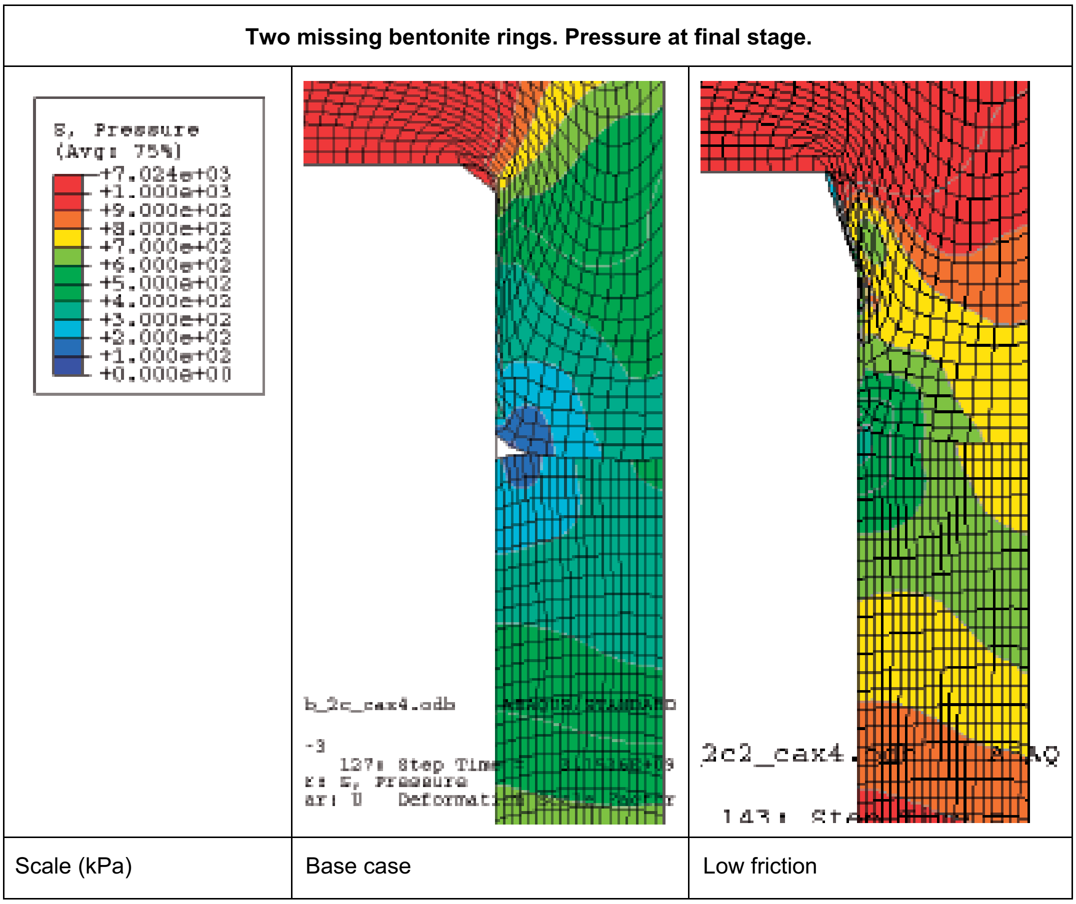



***Figure 3-10.*** *Swelling pressure (kPa) at final stage for the case of two missing rings. Base case (left) and the case of low friction.*

### 3.4.3 Case 1c (three missing rings)

The results of the calculations with three missing rings (1.5 m gap) are shown in Figures 3-11 and 3-12. The final stages for the base case and the low friction case are compared concerning the void ratio (Figure 3-11) and the swelling pressure (Figure 3-12). The results show that a gap of about 20 cm is left between the upper and lower parts in the normal case, while a halved friction between the bentonite and the surroundings imply that the gap will be closed and the void ratio will vary between 1.3 and 1.7 and the swelling pressure between 100 and 400 kPa in the border between the upper and lower buffer parts.

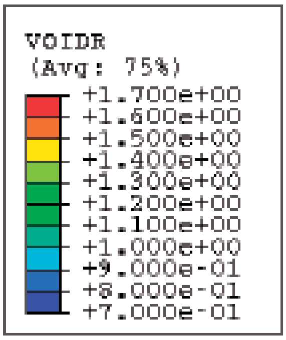
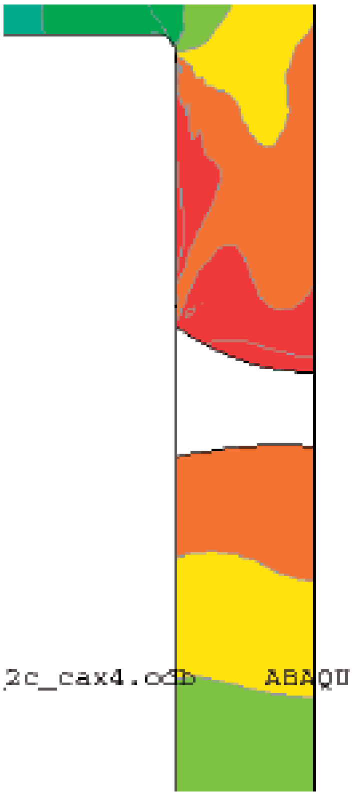
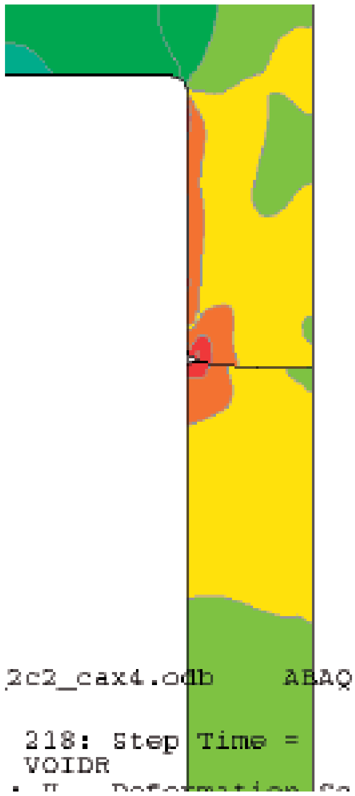
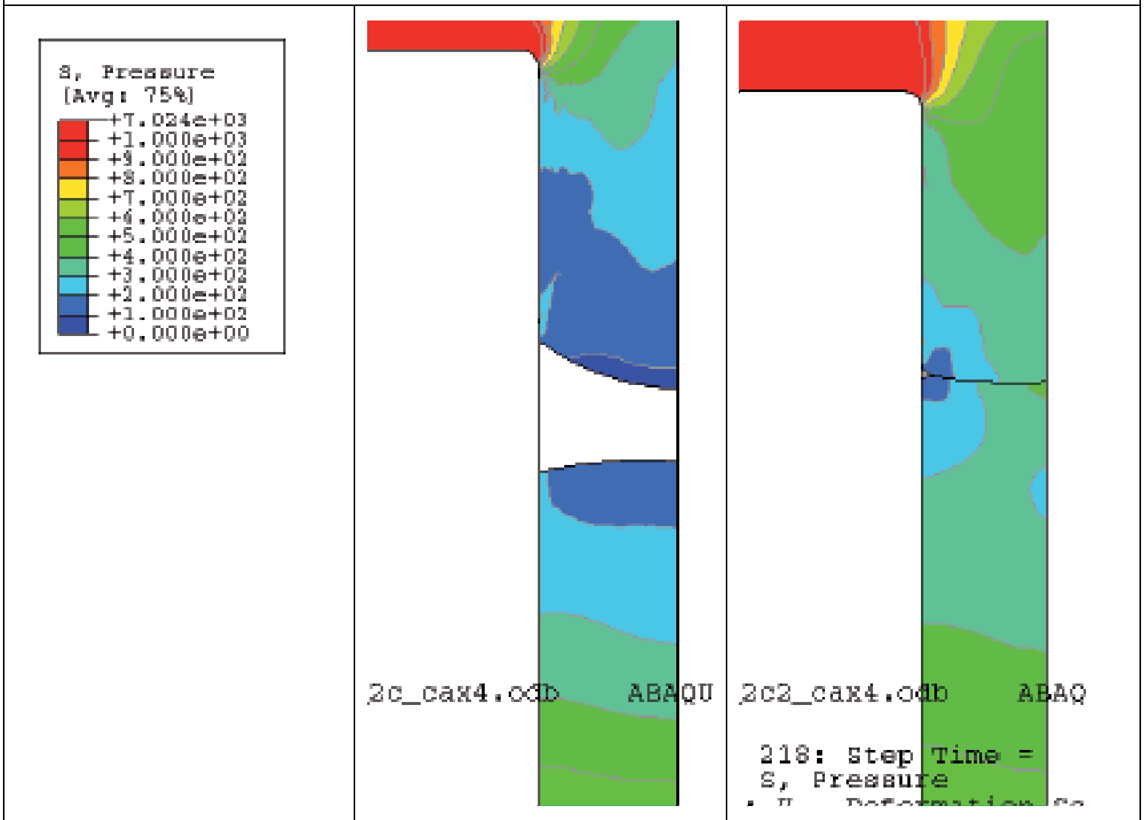
<table>
<tr><th colspan="3">Three missing bentonite rings. Void ratio at final stage.</th></tr>
<tr>
<td>
</td>
<td>
</td>
<td>
</td>
</tr>
<tr><td>Scale (kPa)</td><td>Base case</td><td>Low friction</td></tr>
</table>

***Figure 3-11.*** *Void ratio at final stage for the case of three missing rings. Base case (left) and the case of low friction.*

**Three missing bentonite rings. Pressure at final stage.**




| Scale (kPa) | Base case | Low friction |
|---|---|---|

***Figure 3-12.*** *Swelling pressure (kPa) at final stage for the case of three missing rings. Base case (left) and the case of low friction.*

### 3.4.4 Bentonite cavity located close to the centre of the canister

Three additional calculations were performed with a different simplified element mesh. The reason for doing these calculations was mainly to see if the location of the cavity had a large influence on the results. The same cavities corresponding to one, two or three missing bentonite blocks were analysed but the element meshes were simplified in such a way that the canister was prolonged so that no bentonite was modelled above or below the canister. This way no swelling and support from the bentonite below or above the canister was gained so that this case can be considered a little conservative. In addition the problems and possible errors with bentonite swelling round the canister corners were avoided.

Figure 3-13 shows the resulting void ratio after equilibrium at all three calculations. The figure shows the influence of the size of the cavity. The results also show that the final void ratio at this geometry is higher than at the original geometry, which is logical since in the original geometry the expansion is be helped by the swelling of the bentonite above the canister. These results thus show that the possible errors caused by elements getting stuck on the corner of the canister are of minor importance.

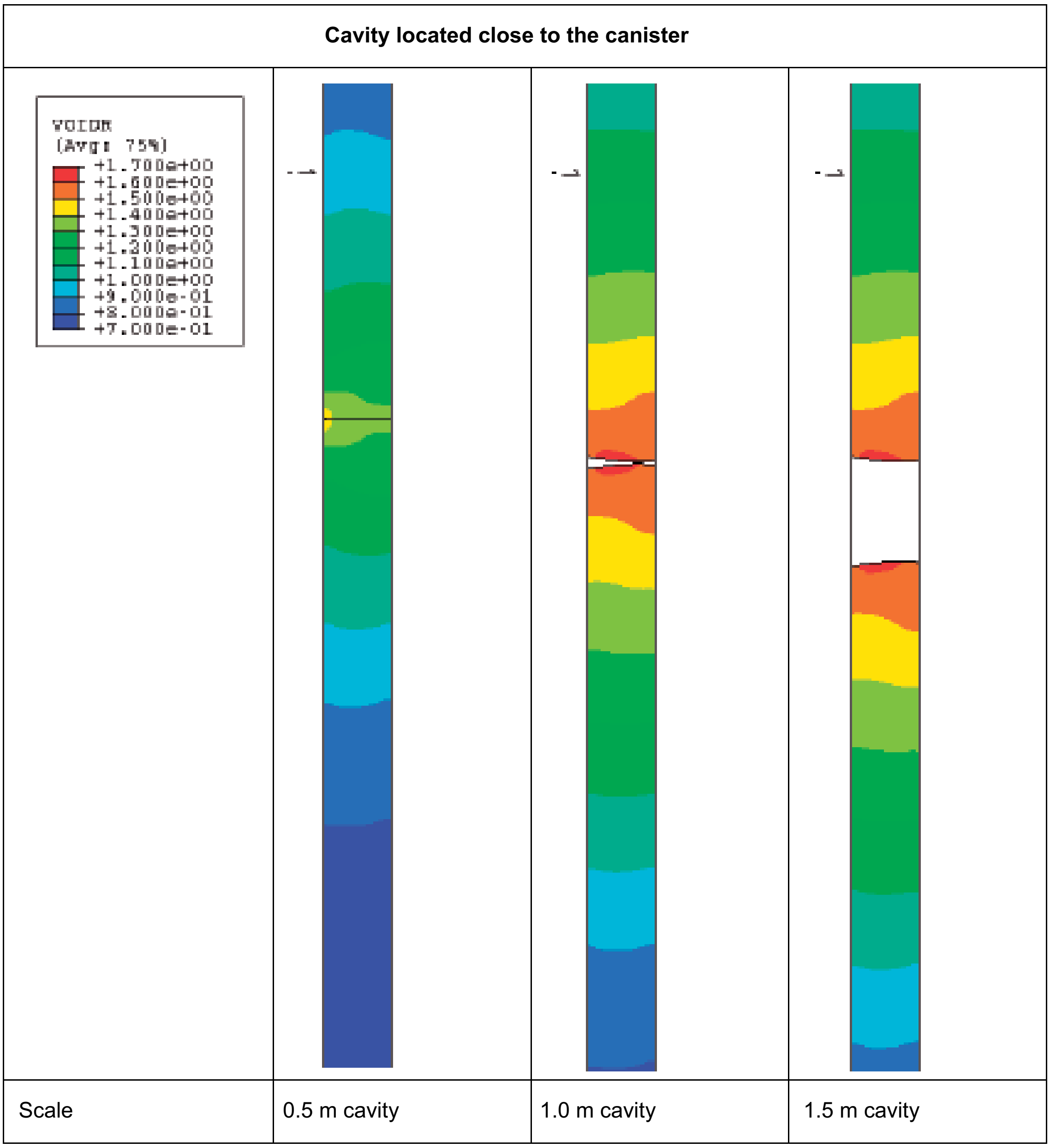



***Figure 3-13.*** *Void ratio at final stage for the three cases of a simplified geometry with a central cavity. Base case properties.*

## 3.5 Conclusions and remarks

When large amounts of bentonite are lost or missing from start the bentonite swells and fills the empty space but the density and resulting swelling pressure is rather low due to the friction in the buffer and the friction against the rock surface. For 50 cm opening the swelling pressure will be in average 0.5–1 MPa in almost the entire former hole in the base case. However, if the rock surface is smooth and the resulting friction against the rock is halved the swelling pressure will be above 1 MPa in a majority of the former space.

For 100 cm opening the swelling pressure will be rather low close to the canister in the base case with pressure below 100 kPa or even an unfilled part left, while the low friction case yields a minimum swelling pressure more than 300 kPa.

If the opening is 150 cm corresponding to three missing bentonite rings the base case yields that a large volume will have a swelling pressure below 100 kPa and even be unfilled. However, the influence of the friction between the bentonite and the rock and canister is large and with halved friction almost the entire opening will be filled.

The swelling is gained by the swelling of the bentonite above or below the canister, which is shown by the calculations that do not include that part of the buffer.

The influence of the friction between the buffer and the surrounding rock and canister is strong as shown by the calculations done with halved friction. In the base case calculations the friction is assumed to be the same as in the bentonite but tests done on contact properties show that the friction is only about 60% if the surface is fairly smooth /2/. However, there are several reasons to stick to the base case:

1. There is no evidence that the deposition hole drilling can be made so that the rock surface will be without irregularities and it cannot be excluded that the interaction between the copper and the bentonite will force the slip to take place in the bentonite.
2. The friction angle of the bentonite is a function of the swelling pressure and increases with decreasing swelling pressure while the base case friction angle is valid at the initial swelling pressure 7 MPa.
3. The average friction angle in the interval 0–7 MPa is about 10 degrees which yields a friction angle of about 6 degrees if the rock and canister surfaces are smooth. The base case value 8.69 degrees thus represent some kind of average.

The following remarks regarding these calculations are important:

4. The material model of Na-bentonite is valid at void ratio interval 0.7–1.5 (see /2/), which means that the strong swelling and gel-formation that will take place at the swelling bentonite surface in non-saline water is not modelled.
5. The material parameters used represent average values and the non-linearity of friction is not taken into account.

The uncertainties about the material model at strongly swelling bentonite make the results somewhat uncertain especially at high void ratios. The results should therefore be checked by performing laboratory swelling tests that model some of the cases.

# 4 Loss of bentonite from erosion

## 4.1 General

Erosion during and after installation of the buffer may cause significant loss of bentonite under unsatisfactory conditions. The erosion will stop when the plug is built and sealed. The plug is intended to function about 12 weeks after start of the installation.

The base case (worst case) of the erosion is a flow of 0.1 l/min into a deposition hole that erodes 10 g dry weight of bentonite per litre water. This yields over 12 weeks a total amount of flowing water of 12,100 l and a total mass of eroded bentonite of 121 kg.

At the dry density of the buffer $\rho_d$=1,570 kg/m$^3$ (corresponding to the void ratio 0.77 and the density at saturation $\rho_m$=2,000 kg/m$^3$) the volume of bentonite that will be lost is 0.077 m$^3$.

- Dry mass lost: 121 kg
- Volume lost: 0.077 m$^3$

Two different cases will be considered; half a donut at the rock surface and half a sphere at the rock surface.

## 4.2 Case A: Half donut

### 4.2.1 General

The first case simulates erosion that comes from an intersecting horizontal fracture that digs a hole in form of half a donut around the buffer at the rock surface. It can also be interpreted as a 5 meter long half pipe running along an inclined or vertical fracture. This is a more realistic erosion scenario during the installation phase, while the half donut may come from long term erosion through a horizontal fracture.

The geometry of the half donut or half pipe should thus yield a total empty volume of 0.077 m$^3$ at the inside of or along a deposition hole. If the inner pipe radius is 0.067 m this condition is approximately fulfilled.

### 4.2.2 Calculations

The influence of the thickness or inner radius of the donut has also been investigated by varying the radius. In addition the influence of how the water is supplied to the bentonite has been investigated. In the base case water is supplied from the entire rock surface and from inside the eroded open space. In the other cases water is available from only the open space and the backfill or from only the backfill. Table 4-1 shows the different cases that have been modelled.

For these calculations the base case is defined as the case with the pipe radius 0.067 m. The element mesh of the base case is shown in Figure 4-1. The other two cases have similar meshes but other radiuses of the half donut.

The calculations were done in a similar way as the calculation of the missing bentonite ring described in Chapter 3. The bentonite properties and initial conditions of the base cases described in Chapter 2 were used.

**Table 4-1. Definition of calculations of case A (half donut).**

| Calculation | Radius of eroded half donut (m) | Water supply from | Remark |
|---|---|---|---|
| CaseA2_2c | 0.067 | Inside space + rock surface + backfill | Base case |
| CaseA2_2c2 | 0.067 | Inside space + backfill | |
| CaseA2_2c3 | 0.067 | Only backfill | |
| CaseA3_2c | 0.134 | Inside space + rock surface + backfill | Larger hole |
| CaseA3_2c2 | 0.134 | Inside space + backfill | |
| CaseA3_2c3 | 0.134 | Only backfill | |
| CaseA5_2c | 0.034 | Inside space + rock surface + backfill | Smaller hole |

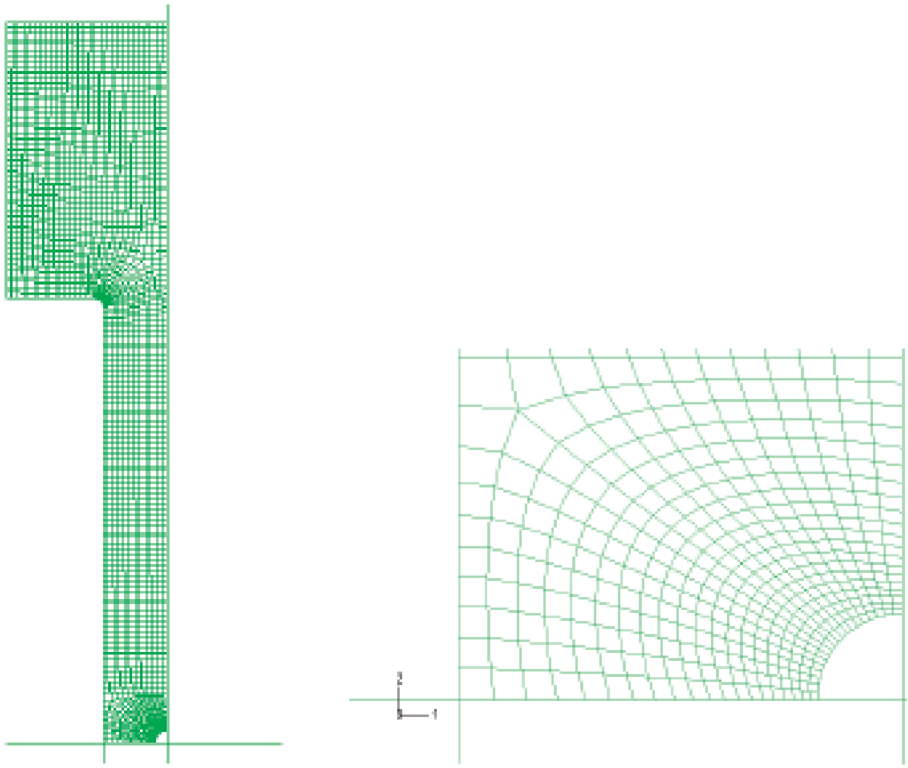


*Figure 4-1. Element mesh of the calculation of Case A with half donut and radius 0.067 (base case). The mesh is axially symmetric around the left side and the bottom plane is a symmetry plane. The whole mesh and an enlargement of the part with the empty donut are shown.*

### 4.2.3 Results

#### *Base case (A2)*

The results of the base case calculations with water supplied from the open hole, the rock and the backfill are shown in Figures 4-2 and 4-3. The swelling is strongest at the rock surface due to the supply of water there, which yields a rather peculiar swelling pattern. The rock surface is at first covered and the hole is enclosed by bentonite in a couple of weeks. Then the rest of the empty space is filled and followed by decreased void ratio due to the swelling of the inner bentonite and subsequent compression of the gel. The maximum void ratio is above 1.7 during the swelling and then returns to a value between 1.0 and 1.5 with an average of about 1.2 in the former hole.

The minimum swelling pressure after equilibrium is higher than 1 MPa as shown in Figure 4-3.

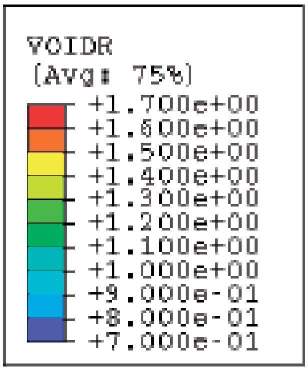
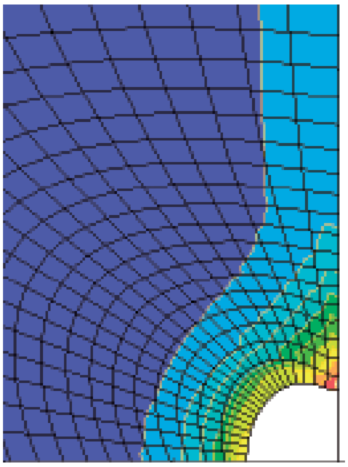
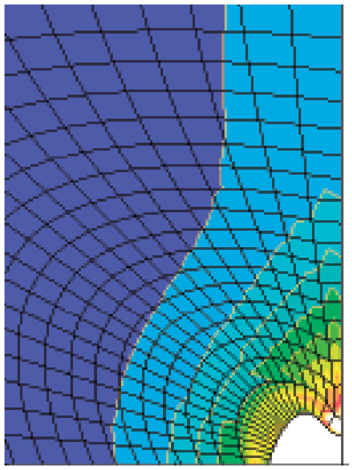
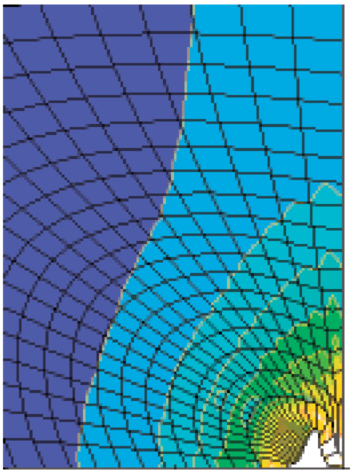
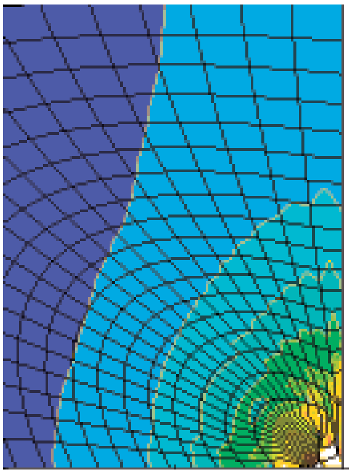
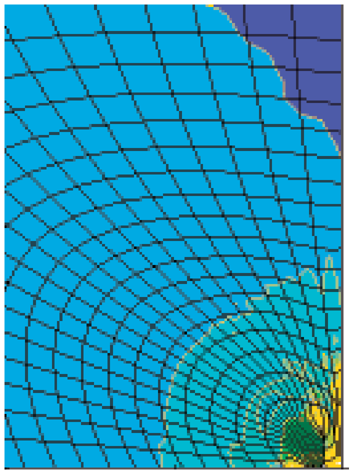
| Eroded half donut. Base case. Case2_2c. Void ratio. | | |
|---|---|---|
|   |  |  |
| Scale | 4 days | 12 days |
|  |  |  |
| 21 days | 1 month | 2.2 years (completed) |

***Figure 4-2.*** *Void ratio plotted at different times for the base case. Water supply from hole, rock and backfill*

The end state is rather "shaky" in the sense that both swelling pressure and void ratio in the former hole varies a lot in a not quite logical way. The reason for this scatter is probably the strong deformation of the elements.

The influence of the water supply is illustrated in Figures 4-4 and 4-5. If water is not supplied by the rock the wetting rate is much slower and the swelling process rather different. There is very little swelling along the rock surface. The swelling is instead folded along the rock surface. The time to equilibrium is also very long. If no water is supplied from the open hole itself but only from the backfill the swelling process is also quite different. No loose bentonite, which is later compressed, is formed. Instead the void ratio continues to increase during the entire swelling until the end.

In spite of the different wetting and swelling paths the end states do not differ very much. The average void ratio in the hole is about 1.1 and the minimum swelling pressure above 1 MPa.

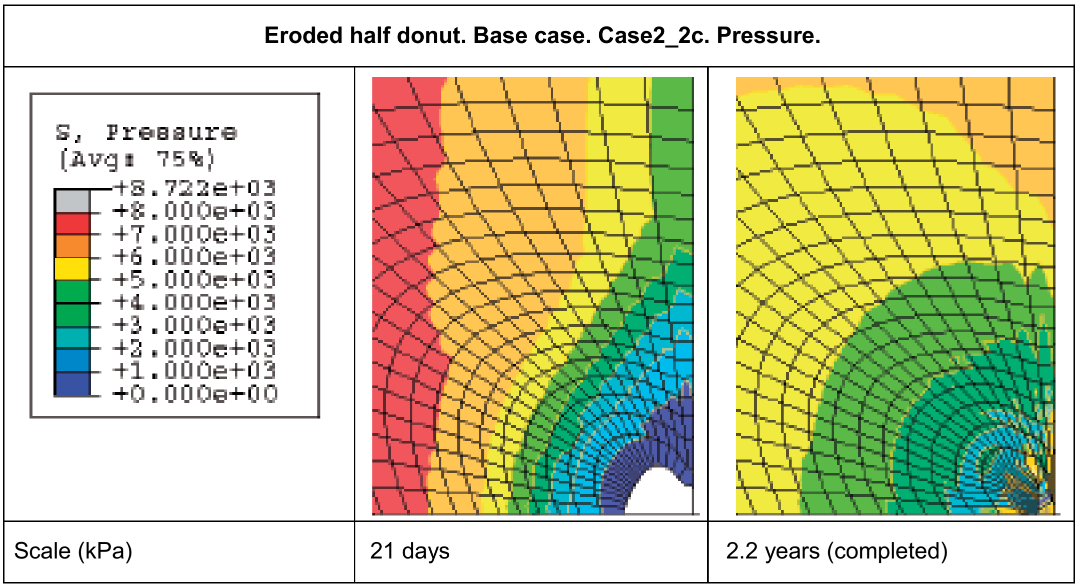



***Figure 4-3.*** *Average stress plotted at different times for the base case. Water supply from hole, rock and backfill*

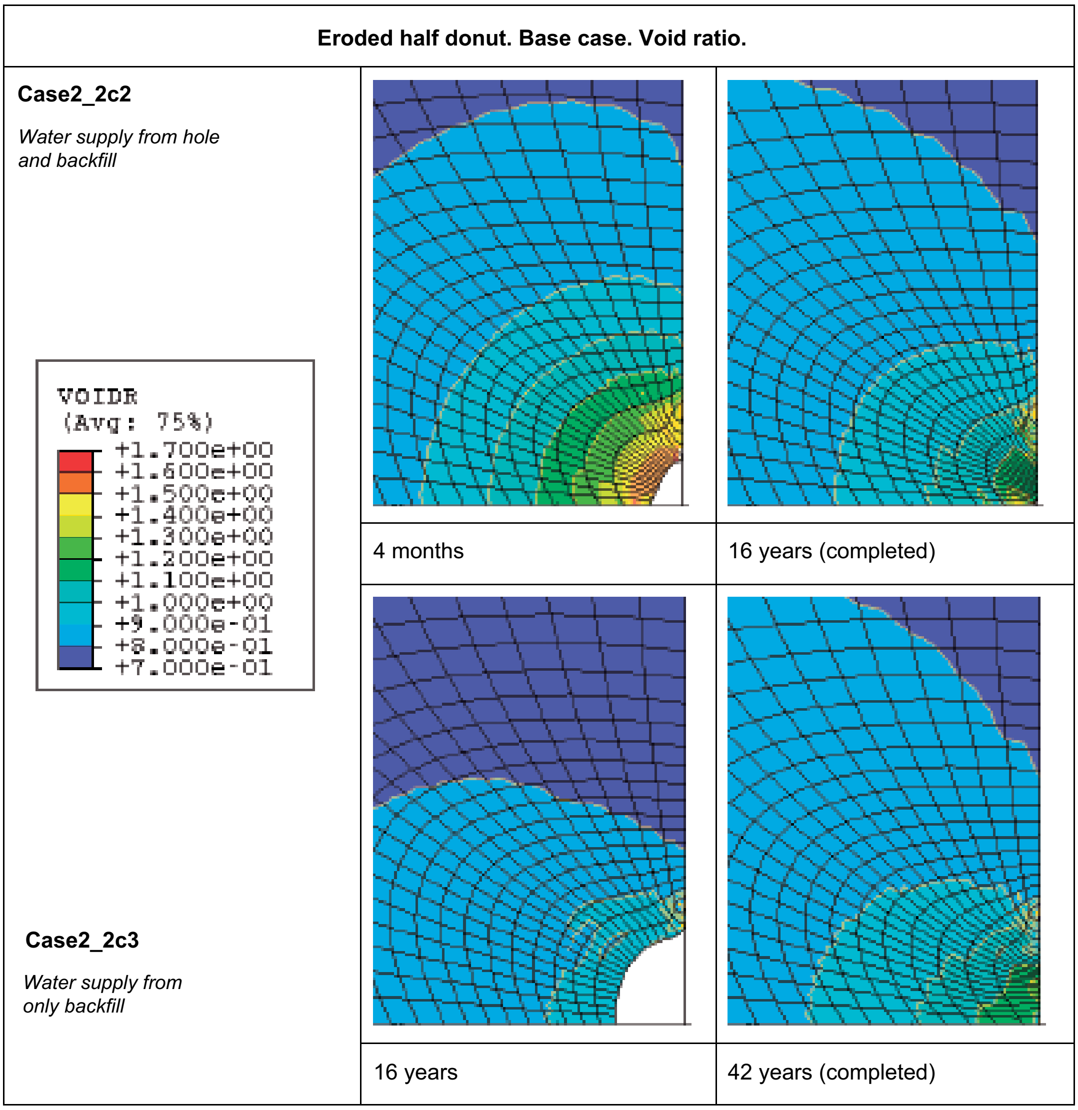



***Figure 4-4.*** *Void ratio during and after swelling for the base case. Differing water supply*

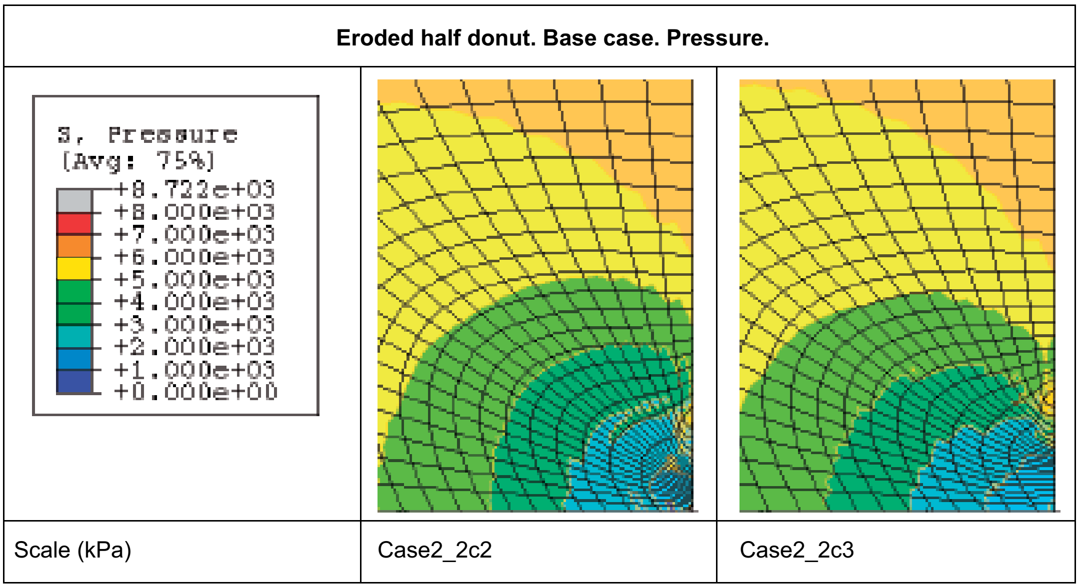



***Figure 4-5.*** *Final average stress of the base case with deviating water supply. Water supply from the hole and the backfill (left) and from only the backfill (right)*

### *Larger hole*

The same calculations were done with half donut with double radius, i.e.13.4 cm instead of 6.7 cm, which is caused by 3–4 times more eroded bentonite mass. The element mesh is very similar to the mesh shown in Figure 4-1 but has a larger hole. Figures 4-6 and 4-7 show the final state in these calculations.

The results are very similar to the results of the base case. The swelling pressure is above 1 MPa everywhere in the former hole and the maximum void ratio is below 1.3. The solutions are in fact “better” than the solutions of the base case since there is less scatter.

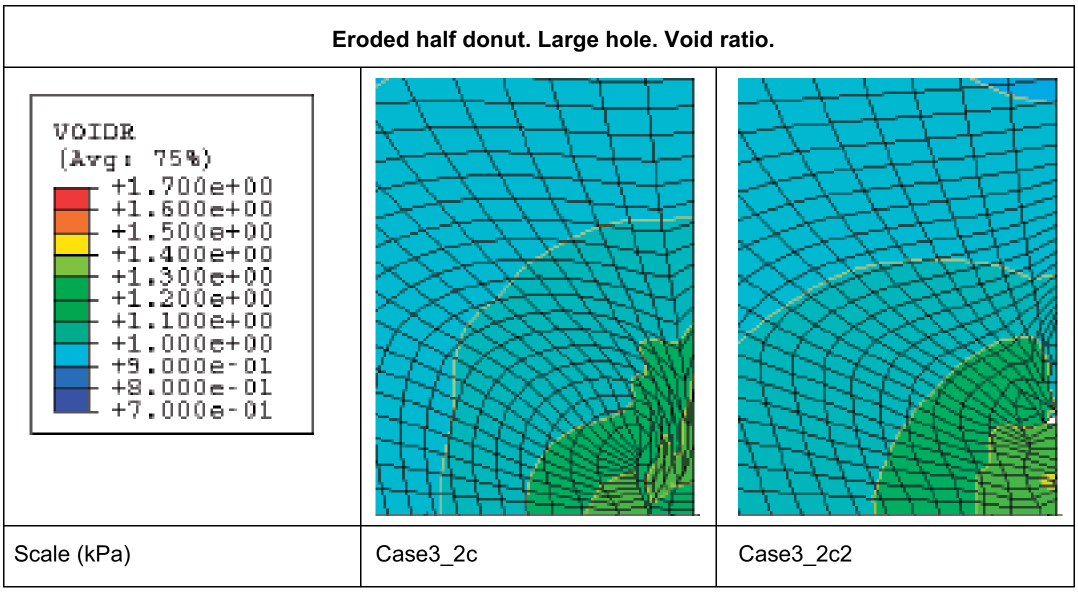



***Figure 4-6.*** *Final void ratio in the case with a larger hole. Water supply from the hole, the rock and the backfill (left) and from only the hole and the backfill*

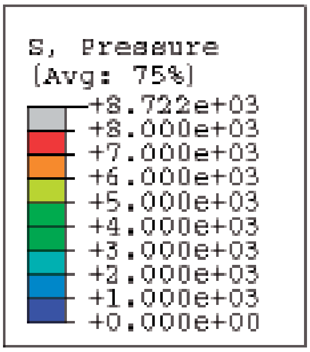
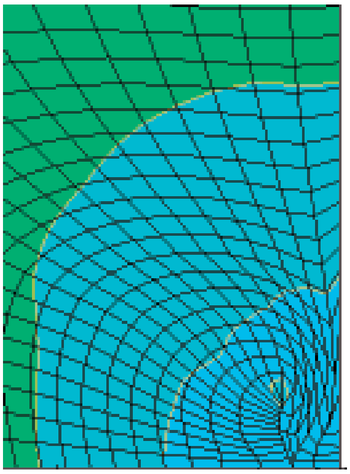
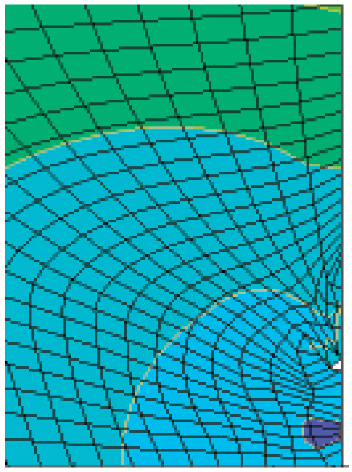
| Eroded half donut. Base case. Pressure. | | |
|---|---|---|
|  |  |  |
| Scale (kPa) | Case3_2c | Case3_2c2 |

***Figure 4-7.*** *Final swelling pressure in the case with a larger hole. Water supply from the hole, the rock and the backfill (left) and from only the hole and the backfill*

### *Smaller hole*

The calculation with a smaller hole (half radius) yielded very similar results. Only one calculation was performed.

## 4.3 Case B: Half sphere derived from point erosion

If water enters the deposition hole in one point, at e.g. a fracture intersection, the erosion may be very local around the inflow spot, which may result in a loss of bentonite in a half sphere like configuration. This is a more severe case than the donut case since the lost bentonite is local instead of distributed around the canister.

Considering the same erosion case as the base case i.e. 10 g/l, 0.1 l/min and 3 months the total volume of bentonite lost will be 0.077 $m^3$. The radius of a half sphere that yields that volume is 0.263 m.

The element mesh of this model is shown in Figure 4-8.

The model is simplified in the sense that it is axially symmetric around a line that goes through the centre of the sphere, which yields that both the canister and the rock surface are modelled as planar. This is judged to have an insignificant influence on the results.

In this calculation only one wetting case was considered, namely the case that water is available only inside the hole and not at the rock surface. The bentonite model and the contact surfaces are identical to those of the previous calculations, with the friction angle 8.7 degrees. Figures 4-9 and 4-10 show the results.

The results show that the swelling process is similar to the previous cases. Due to the friction against the rock there is very little swelling along the rock surface. Instead the bentonite between the canister and the hole swells and seals the hole. Due to the rather thin buffer left between the canister and the spherical hole, the resulting void ratio after completion is rather high (> 1.5), which yields a swelling pressure below 1 MPa in about 1/3 of the buffer.

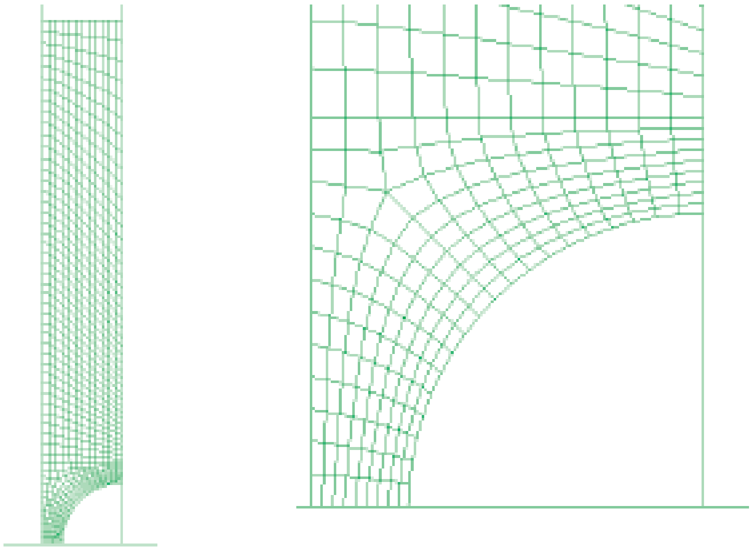


***Figure 4-8.*** *Element mesh of the calculation of Case B with half sphere with the radius 0.263 m. The mesh is axially symmetric around the bottom side. The whole mesh and an enlargement of the empty part are shown.*

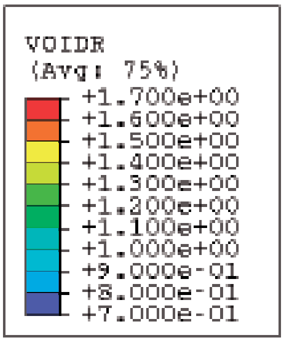
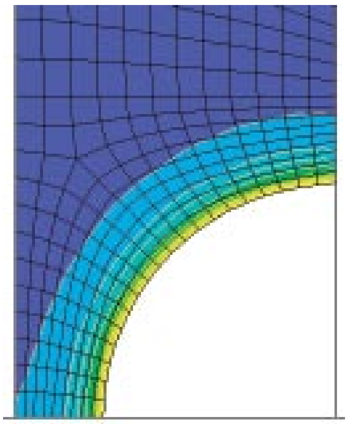
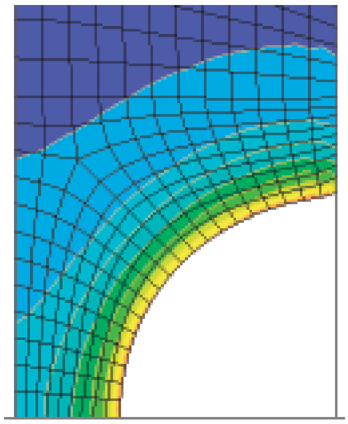
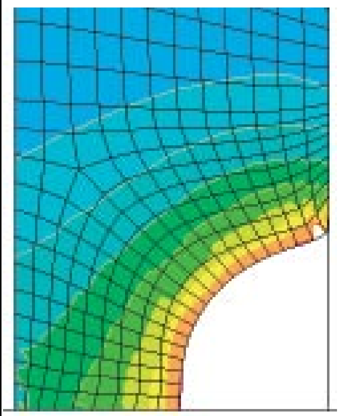
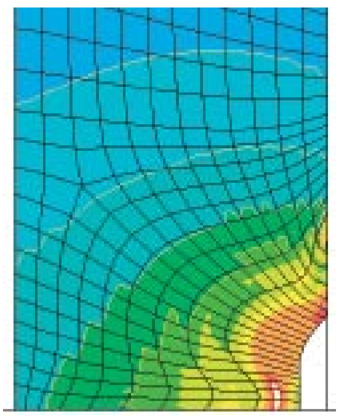
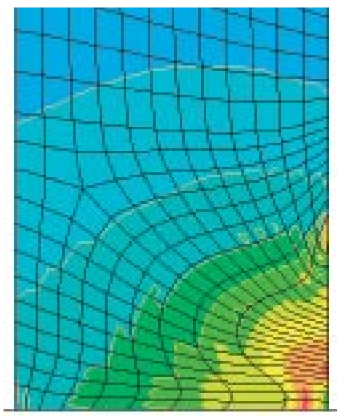
<table>
<tr><th colspan="3">Eroded half sphere. Void ratio.</th></tr>
<tr><td>
</td><td></td><td></td></tr>
<tr><td>Scale</td><td>12 days</td><td>2 months</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>1.6 years</td><td>6.3 years</td><td>32 years (completed)</td></tr>
</table>

***Figure 4-9.*** *Void ratio plotted at different times for a half sphere. Water supply from only the hole*

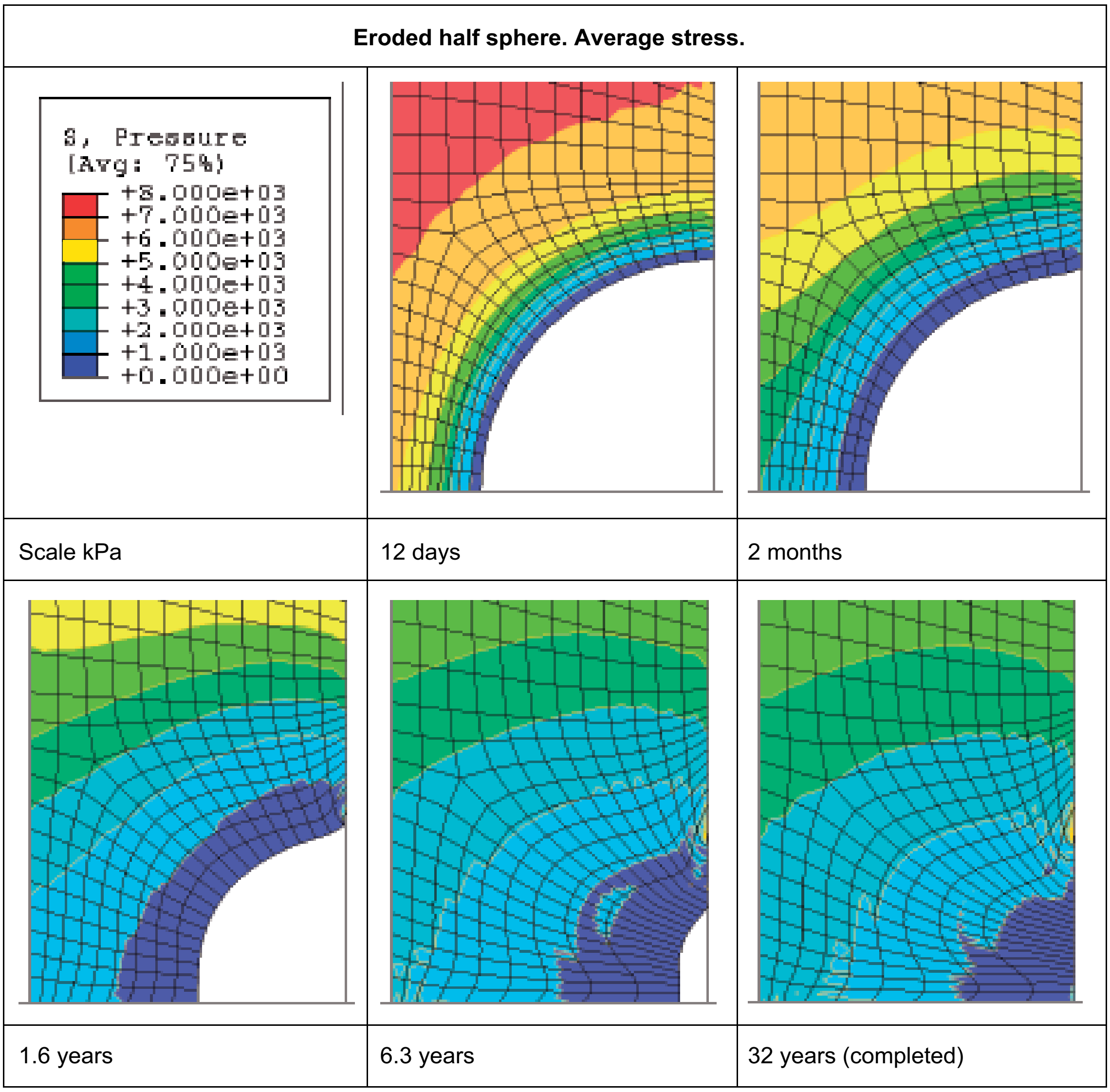



***Figure 4-10.*** *Swelling pressure plotted at different times for a half sphere. Water supply from only the hole*

## 4.4 Conclusions and comments

The calculations of the swelling and homogenisation of a half donut resulting from erosion show that the swelling yields a strong decrease in density and swelling pressure due to the friction in the bentonite. However the swelling pressure after completed homogenisation is in none of the cases with donut radius varying from 3.4 cm to 13.4 cm below 1 MPa. The influence of the radius seems to be insignificant due to the long distance to the bentonite boundaries.

If half a sphere is created instead of a donut the consequences are more severe, since the radius of the sphere is larger for the same amount of bentonite and thus the mass of bentonite left between the sphere and the canister much less. However, in 2/3 of the distance between the buffer and the rock the buffer has a swelling pressure higher than 1 MPa.

The same remarks concerning the bentonite properties and the friction between the bentonite and the rock or canister surface made in Chapter 3 are valid also for the calculations presented in Chapter 4.

# 5 Self-sealing of long small channels

## 5.1 General

The consequences of piping and erosion are a small channel that leads the water and bentonite solution out through the buffer into the backfill. Such a pipe will ultimately swell up and seal when the erosion has stopped. The efficiency of that sealing has been investigated with some calculations. Such calculations are also valuable in order to study the sealing in more general terms since the geometry can be simplified and the effect of a complex mesh and the element size can be studied.

## 5.2 FEM model

### 5.2.1 Geometry

One-dimensional axial symmetric elements have been used, which thus simulates an infinitely long and perfectly round hole. The base case corresponds to a pipe radius of 1 cm and a distance to the bentonite outer boundary of 10 m, but also the combination 5 cm hole and 50 m boundary was checked. The number of elements were initially 100 (see Figure 5-1) but were increased at first to 400 and finally to 800 in order to have small elements close to the hole. For the same reason the element size was reduced with decreasing distance from the hole.

### 5.2.2 Results

The calculations are compiled in Table 5-1.

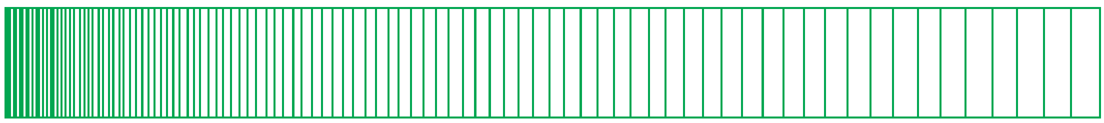


***Figure 5-1.*** *10 m element mesh with 100 elements for the modelling of long small pipes in bentonite. Axial symmetry around a vertical axis 1 cm left of the mesh.*

**Table 5-1. Compilation of the calculations modelling the self sealing of long small pipes in bentonite.**

| Case | Hole radius (m) | Outer radius (m) | Number of elements | Smallest element (m) | Largest element (m) | Remaining pipe radius after swelling (m) | Remark |
|---|---|---|---|---|---|---|---|
| A | 0.01 | 10 | 100 | | | $6.7 \cdot 10^{-3}$ | No good solution |
| B | 0.01 | 10 | 400 | | | $3.2 \cdot 10^{-3}$ | –"– |
| C | 0.05 | 50 | 100 | | | $33.5 \cdot 10^{-3}$ | –"– |
| D | 0.05 | 50 | 400 | | | $16 \cdot 10^{-3}$ | –"– |
| E | 0.01 | 10 | 800 | $23 \cdot 10^{-6}$ | $2.7 \cdot 10^{-2}$ | $162 \cdot 10^{-6}$ | |
| F1 | 0.01 | 10 | 800 | $5 \cdot 10^{-6}$ | $2.7 \cdot 10^{-2}$ | $90 \cdot 10^{-6}$ | |
| F2 | 0.01 | 10 | 800 | $5 \cdot 10^{-6}$ | $2.7 \cdot 10^{-2}$ | $85 \cdot 10^{-6}$ | $\phi_d$=0 |
| F3 | 0.01 | 10 | 800 | $5 \cdot 10^{-6}$ | $2.7 \cdot 10^{-2}$ | $40 \cdot 10^{-6}$ | $\phi_d$=0 $c$=0 |

$\varphi_d$=dilatancy angle; $c$=cohesion

For cases A–D the radius of the hole and the number of elements were varied. For cases E and F the size of the elements was strongly reduced with decreasing radius and a minimum element size of only 5 µm applied. For cases F1–F3 the influence of dilatancy and cohesion in the bentonite was studied.

All calculations yielded a remaining hole after completed swelling. Cases A–D showed that the scale is not important for the solution in the sense that the remaining hole is directly proportional to the initial hole at otherwise equal conditions. A and C yielded identical results just as B and D if the geometry is scaled. Thus, all pipe radiuses can be derived from the results of one calculation by scaling the geometry.

However, the results of calculations A–D also showed that the elements close to the pipe were too large since the final relation between the stress (or void ratio) and the radius was very irregular and strange and yielded a remaining large hole. For calculations E and F the number of elements was increased and the element sizes close to the hole strongly reduced.

The results are best illustrated with plotted relations between the void ratio or swelling pressure and the radius. Figures 5-2 and 5-3 show those relations for the last 4 calculations (E and F1–F3).

The figures show that cases E and F1 agree very well until a radius less than about 1 mm where the void ratio increases and the swelling pressure decreases more for case F1, which has smaller elements. The remaining pipe is also smaller for case F1. It thus seems as the end solution depends on the mesh resolution and that the swelling pressure goes asymptotic towards zero together with the radius.

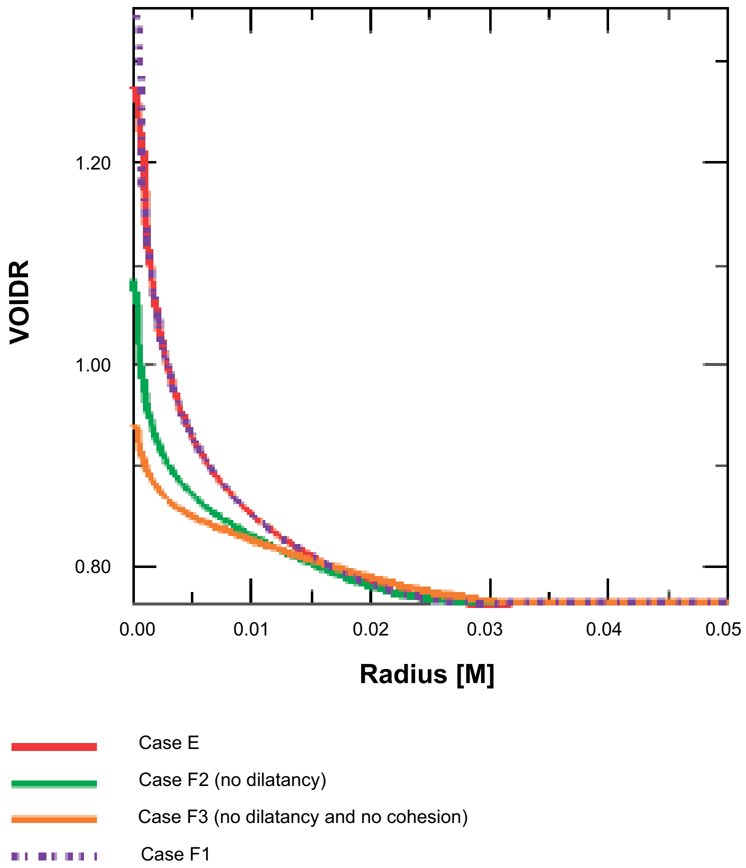



*Figure 5-2. Void ratio as function of radius after swelling and sealing of a pipe with 1 cm radius.*

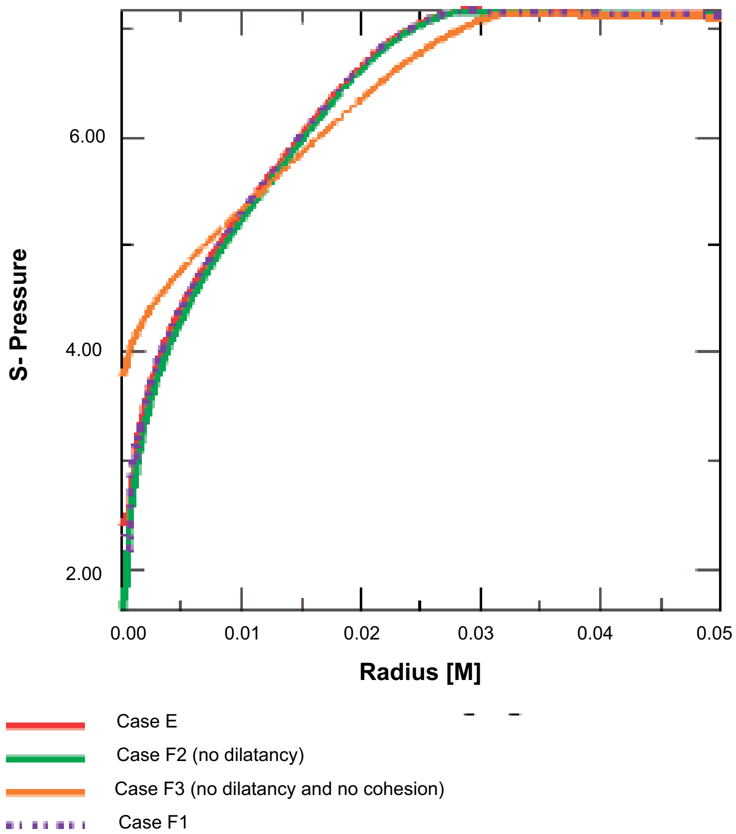



***Figure 5-3.*** *Swelling pressure (MPa) as function of radius after swelling and sealing of a pipe with 1 cm radius.*

The two final cases (F2 and F3) illustrate the sensitivity to the material model. In case F2 the dilatancy angle (2°) was removed, which yields better homogenisation with a much lower maximum void ratio but no difference in swelling pressure compared to the base case, the reason being that the bentonite does not increase in volume during pure shear. In case F3 both the dilatancy and the cohesion (*d*=100 kPa) were removed, which yields both decreased maximum void ratio and increased minimum swelling pressure.

## 5.3 Conclusions and comments

The FEM modelling of the process of self-sealing of long open tubes in compacted bentonite have yielded some interesting results. A long open tube does not seal completely but a reduced density that decreases with decreasing radius will remain just like for the larger holes. The following conclusions and observations were made:

- The final stage is independent of the initial radius of the hole if the geometry is scaled to the radius i.e. all the results for all initial hole radiuses can be derived from one calculation.
- All calculations yielded a remaining open pipe after completed homogenisation.
- There is a strong influence of element size on the remaining hole radius. It seems that at infinitely small elements the radius zero would correspond to a singularity with both swelling pressure and density approaching zero asymptotically. An analytical solution should be done to study this phenomenon.
- The remaining density gradient is caused by the shear resistance in the clay with the friction as dominating parameter.

- The results are only valid for circular tubes. Fracture like openings will behave completely different and yield much better homogenisation.

The element model is idealised symmetric since it is “one-dimensional” in the sense that there is a rotational symmetry around the centre of the hole. In a real open channel there are irregularities that probably will make the pipe collapse. This may change the resulting void ratio distribution in the micro scale but probably not in the mm scale.

# References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/4/ **Börgesson L, Hernelind J, 2006.** Canister displacement in KBS-3V – a theoretical study. SKB TR-06-04, Svensk Kärnbränslehantering AB.