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Prototype Repository

Finite element analyses of mechanical consequences due to the rock excavation and thermal load

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June 1999

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Keywords: Nuclear fuel wastes, deep repository, rock, excavation, failure, 3D finite element, plasticity, Mohr-Coulomb, heat transfer, transient, thermal-mechanical.

Foreword

This report describes the finite element analyses and simulations, that are performed in order to study mechanical consequences (rock deformation, stress and failure) around the deposition holes in the *Prototype Repository at Äspö Hard Rock Laboratory (ÄHRL).* The simulation, consider stress redistribution due to the rock excavation process and the heat transfer induced by electrical heaters that will simulate the nuclear fuel waste. This is a part of research work that is planed for the *Prototype Repository Project at ÄHRL.* The commercial finite element code ABAQUS is used for the analyses and simulations reported here.

The initial state condition is based on in-situ measured rock stress results that are obtained in the area of the Prototype Repository. Input data of rock mass properties are based on laboratory testing of cores taken from the laboratory.

Load conditions considered are the initial state of stress, stress redistribution due to boring of the full-scale deposition holes, and thermal loading during operation. A Mohr-Coulomb failure criterion has been used in the analyses to identify critical areas.

This work should be considered as a kind of scooping-up computation. The intention has been to gradually update the finite element model as more data from the investigation of the rock mass condition at the Prototype Repository test site are given.

This report shall be considered as a summary report in which the most fundamental assumptions used in the simulation and the most characteristic results are presented. More data are available on CD-rom, to which all relevant numerical results have been written. The CD-rom is available at NCC Teknik and ÄHRL.

Abstract

This report describes the finite element analyses and simulations, which are performed in order to study mechanical consequences (rock deformation, stress and possible failure) around the deposition holes in the Prototype Repository at Äspö Hard Rock Laboratory. The numerical simulation, consider stress redistribution due to the rock excavation process and the heat transfer induced by electrical heaters that will simulate the nuclear fuel waste. Two finite element models in 3-dimensions are used: (a) linear elastic model and (b) Mohr-Coulomb elastic-plastic model. For both models the following analyses and simulations are consecutively made: (i) Simulation of the successive rock excavation of the access tunnel and the deposition hole, (ii) Simulation of transient heat transfer induced by simulated nuclear fuel waste, and (iii) Transient thermal-stress analysis. Numerical results (stress, displacement and possible failure zone) at several important excavation-stages and time stations are summarised and discussed.

Sammanfattning

I denna rapport beskrivas de finita elementanalyserna och -simuleringarna, vilka är utförda för att studera mekaniska konsekvenser (bergdeformation, spänning och eventuella brott) kring de deponeringshålorna i *Projekt Prototype Repository*, vid *Äspö Hard Rock Laboratory*, p.g.a. bergdrivning och termiskta spänningar inducerad av de elektriska värmare som skall simulera det använda kärnbränslet. Två finita elementmodeller i 3-dimensioner är använda: (a) linjärt elastisk modell och (a) Mohr-Coulomb elastisk-plastisk modell. För både modeller har följande analyser och simuleringar utförts i tur och ordning: (i) Simulering av den *successiva* bergdrivningen för deponeringstunneln och deponeringshålen, (ii) Simulering av transient värmeledning inducerad av simulerat använt kärnbränsle, och (iii) Transient termospänning analys. Numeriska resultat (bergdeformation, spänning och eventuellt brottsområde) vid flera viktiga drivningsskede och tidpunkter är sammanfattade och diskuterade.

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1 Introduction

1.1 General

SKB will construct a full-scale replica of the deep repository (KBS-3) planned for disposal of spent nuclear fuel from the Swedish nuclear program. The Prototype Repository will be constructed at Äspö Hard Rock Laboratory and located at 450 m depth below the ground surface, see Figure 1-1. The Prototype Repository will include six deposition holes in which full size canisters with electrical heaters will be placed and surrounded by bentonite. The deposition tunnel will be backfilled with a mixture of bentonite and crushed rock.

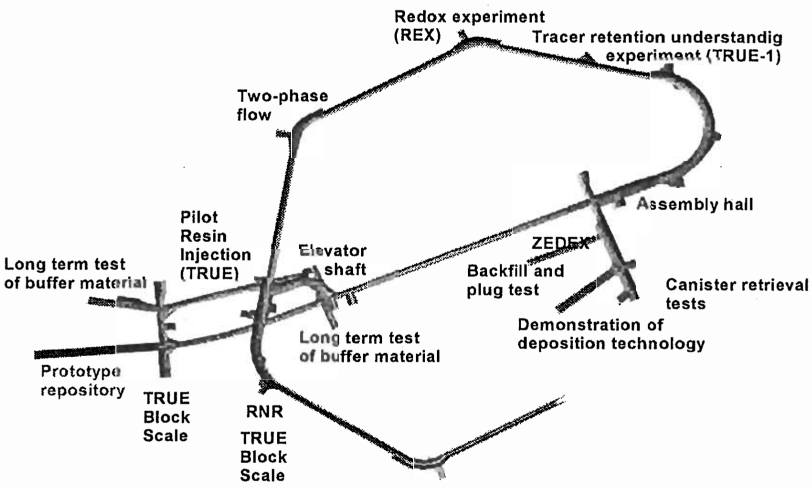


Figure 1-1. Location of the Prototype Repository and other experiments at ÄHRL

The execution of the Äspö Prototype Repository is an exercise of necessary actions to construct a deep repository from detailed characterisation to resaturation of deposition holes and backfilled tunnels. Thereby we can demonstrate the integrated function of the repository and provide a full-scale reference for validation of prediction models (T-H-M) concerning individual components as well as the complete repository system. In such a manner, we can demonstrate that it is possible to understand and quantify the processes, which take place in the engineered barriers and the host rock.

The major objectives for the Prototype Repository are:

- To test and demonstrate the integrated function of the deep repository components under realistic conditions in full-scale and to compare results with models and assumptions.
- To develop, test and demonstrate appropriate engineering standards and quality assurance methods.

- To simulate appropriate parts of the repository design and construction processes.

The Prototype Repository will consist of two sections (I and II), with four and two deposition holes respectively. A conceptual overview of the Prototype is given in Figure 1-2. Section I will be left for testing and monitoring for a long time, possible up to 20 years. Section II, will be excavated and retrieved after about 5 years. The duration is based on the time schedule for the construction of the deep repository. Evaluation of the Prototype Repository will contribute to the understanding of the processes that take place in the rock mass, backfill and buffer in the first period of time (up to 20 years) of a repository, before actual disposal in the deep repository.

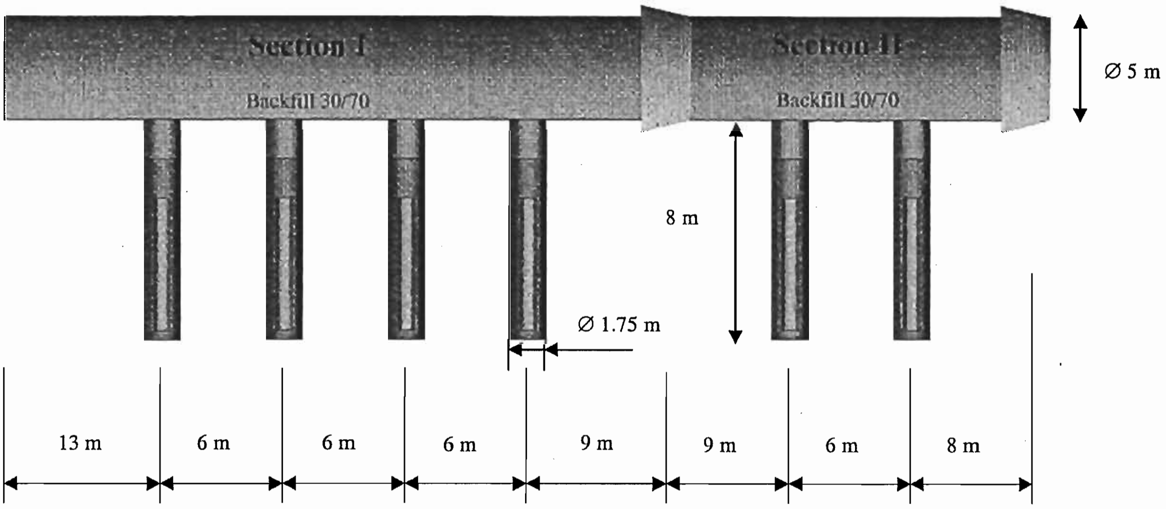


Figure 1-2. Conceptual overview of the Prototype Repository (not to scale)

The Prototype Repository Test may be divided in two phases; the construction phase and the operating phase. The construction phase includes characterisation, preparatory works and construction and the operating phase include monitoring of processes during operation.

The characterisation of rock mass at the Prototype Repository site will be executed in three stages. Each stage is intended to contribute to more detailed information about the characteristics of deposition holes and boundary conditions. Methods for deterministic characterisation will contribute to the assessment of methods for characterisation of deposition tunnels and near-field rock mass in a real repository.

The deposition holes will be mechanically excavated in full-scale (diameter 1.75 m and depth 8 m) by a TBM machine converted for down hole drilling. The boring technique, the geometric result, the surface roughness and the disturbed zone (EDZ), i.e. induced fracturing will be analysed.

Instrumentation and sampling will be used to monitor important processes and properties in the buffer material, backfill and the near field rock. The intention to minimise disturbance will however add restriction to the possible monitoring. The functions of the engineered barriers are controlled by a number of measurable properties. The intention is to measure these properties in order to study the processes. Modelling is carried out as integral parts of the test. Further details about the Prototype Repository is given in (Dahlström, 1998)

1.2 Mechanical and thermal-mechanical analyses

A number of processes will be developed during construction and operation of the repository. The intention is to study these processes in the Prototype Repository, by modelling as well as by measurements. The processes to be studied include thermal, hydraulic, mechanical and chemical processes. The modelling is divided in two stages: scooping calculations and predictive modelling.

The scooping calculations are primary made for design and condition purpose. Prediction of the behaviour of the complete Prototype Repository system i.e. the integrated function of the repository will be made by a coupled T-H-M numerical analyse. The analyses will continuously be compared and upgraded to results monitored in the Prototype Repository during operation

This report consider scooping calculations of redistribution of rock stresses due to excavation of the Prototype deposition tunnel, boring of deposition holes and thermal loading during operation. The models are used to predict the rock stress field around the deposition holes and critical areas of possible failure, i.e. microcracking and displacement in existing discontinuities around the deposition holes. The mechanical analyses will be compared to the measurements of rock mechanical consequences that will be performed during boring of the deposition holes and during operation of the Prototype Repository.

In reality, the deposition tunnel is first excavated and, then, the deposition holes are stepwise excavated. Thereafter, the canister containing the spent nuclear fuel is installed, which starts the heat generation and conduction process. The finite element simulation and analyses that are carried out in this work follow this procedure, see below.

1.3 Organisation of the report

With this Chapter as a prelude, this report is organised as follows: In Chapter 2 rock material properties are given. In Chapter 3 geostatic states are described. In Chapter 4 the finite element analyses and simulations of the rock excavation and heat transfer, as well as the thermal-stress analysis, are described. In Chapter 5 finite element results are presented. Finally, in Chapter 6 concluding remarks are given.

2 Rock material properties

The rock material properties are divided into two groups that cover: (*i*) mechanical and (*ii*) thermal and thermal-mechanical behaviour of the rock under consideration. Rock properties are based on a laboratory test of cores taken from the laboratory and engineering judgement.

2.1 Mechanical properties

The mechanical properties of the rock are assumed to be homogeneous and isotropic. No discontinuities are considered at the moment. The material parameters are assumed to be:

Young's modulus: $E=45.0$ GPa
Poisson's coefficient: $\nu=0.2$

In connection with the Mohr-Coulomb elastic-plastic model, the material parameters are assumed to be

Cohesion: $c=5.0$ Mpa
Friction angle: $\phi=40^\circ$
Dilation angle: $\psi=40^\circ$

It can be noted that a small amount of material parametric studies have also been made, which covers: (*i*) an increase of the Young's modulus to 75.0 GPa; (*ii*) a change of the cohesion to 0.5 MPa, and (*iii*) a change of the dilation angle to 0°. We note that although the fiction and dilation angles are equal only plastic flow is only associative on the meridional stress plane in ABAQUS.

2.2 Thermal and thermal-mechanical properties

The thermal and thermal-mechanical properties of the rock are also assumed to be uniformly isotropic with the material parameters:

Thermal conductivity: $\lambda_r=2.5$ W/mK;
Specific heat: $C_p=750$ J/kgK;
Density: $\rho=2700$ kg/m^3;
Thermal expansion coefficient: $\alpha=8x10^{-6}/^\circ K$.

3 Geostatic state of the rock

The geo-static state includes the initial stress and temperature states. For the rock model considered, these are assumed to be constant. Other initial states, for instance, discontinuities, pore pressure and so on, are not considered at the moment.

The initial state condition is based on in-situ measured rock stress results obtained in the area of the Prototype Repository.

3.1 Initial stress state

The initial state of stress is defined by taking mean values of the in-situ measured principal stresses reported by (Ljunggren et al., 1998).

(σ_1, σ_2, σ_3) geo-static = (34.2 MPa, 17.7MPa, 13.1MPa)

The orientation of principal axes is defined in accordance with the strike/dip orientation defined by (Ljunggren et al., 1998), which is illustrated in Fig. 3-1. Notice that due to the orientation of the geo-static stresses, no symmetric conditions can be used in the finite element modelling and, therefore, a full 3D modelling should be performed. (We note that in more traditional cases the initial stresses are giving in terms of stress components in the horizontal plane, σ_H and σ_h, and in the vertical direction, σ_V.

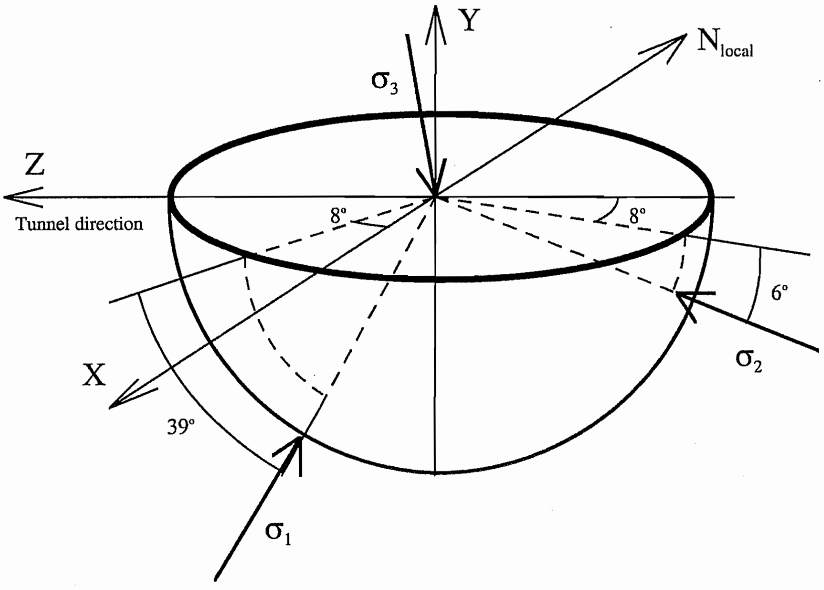


Figure 3-1 Global co-ordinate system and principal in-situ (geostatic) stress direction. Notice that the Y-axis is vertically towards the ground surface.

3.2 Initial temperature state

The initial temperature has also been assumed to be constant over the whole model. The temperature before installing the copper-canister is taken as the initial temperature, which is 14 °C.

4 Finite Element Analysis and Simulation

The finite element analyses/simulation follows the same construction procedure as for the deep repository. It can be described as follows: First the deposition tunnel is excavated. Then, the deposition holes are stepwise excavated. Thereafter, the canister containing the spent nuclear fuel is installed, which starts the heat generation and conduction process. In the finite element simulation, the following procedures are consecutively made:

(i) Excavation of the horizontal deposition tunnel;

(ii) Boring of the deposition hole. (in this case the boring is performed in 3 steps, 2.0 , 4.0 and 8 meters)

(iii) Adding the heat source to the model (See below) and perform the transient heat transfer.

(iv) Use the time-dependent temperature output from (iii) as a time-dependent thermal loading to perform a sequential thermal-mechanical transient analysis.

The main interest in the finite element simulation is to study the principal stresses, deformation and possible failure (plastic flow) at those stages that are of importance.

4.1 Two 3D finite element models

In considering the size of the tunnel (D=5 m) and deposition hole (D=1.75 m) as well as the computational capacity (SUN Ultra 1 workstation), a three-dimensional rock block of 24x35x35 m^3 is used in the finite element simulations. For the moment only one deposition hole (8 m in depth) is considered. The 3D finite element model is created in a way that the elements within the tunnel and the deposition hole can be grouped and be removed successively. Figs. 4-1 shows the 3D-rock block and the finite element mesh.

The boundary conditions are specified in such a way that the displacements in the normal direction of the rock block surfaces are restrained.

The above boundary conditions might in practice be considered to be too stiff in comparison with the rock block size. (Notice also that the simulation is to be made in a SUN Ultra 1 workstation with 128 MB RAM. Indeed an expansion to 256 MB have been made during this project in order to make the computation practically possible.) For this sake an alternative specification is also made. This is to restrain, on the bottom surface of the rock block, the rigid movements on the horizontal plane (Plane 1-3) and the rigid rotation about the vertical axis (Axis 2) and, in addition, to restrain the vertical displacements at all nodes on the bottom surface.

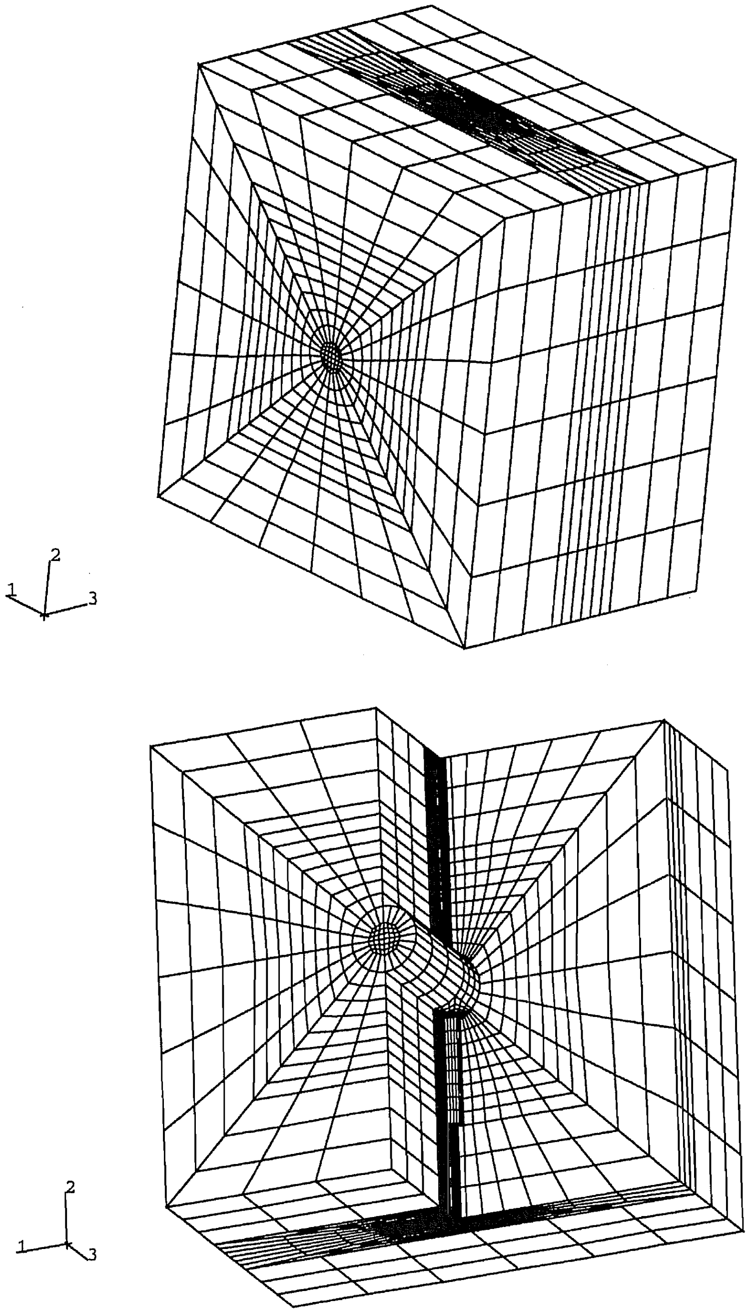


Figure 4-1. Three-dimensional rock block and the finite element mesh (upper - surface view; lower - inner view) before the excavation. Notice that axis 2 is vertically upward directed and axis 3 is the tunnel direction. The displacements in the normal direction of the block surfaces are restrained.

The finite element model described above is then applied with two material assumptions. In the first, the rock is assumed to be linear elastic, denoted as the linear elastic model. In the second, the rock is assumed to be elastic-plastic with the Mohr-Coulomb criterion as the plastic failure condition, denoted below the Mohr-Coulomb model.

4.2 Simulation of rock excavation

In general a simulation of an excavation process consists of two parts of computations: Part 1 - The establishment of the geo-static state, and Part 2 - The excavation. In what follows these are explained in somewhat more detail.

Part 1: The establishment of the geo-static state

Principally this can be done in many ways. The goal is to establish an equilibrium state in the 3D rock block such that the in-situ stresses are activated and no deformation occurs in the whole rock block. Here, the geo-static state is established through the following steps:

Step 1. Restraining all nodes in the model and activate the in-situ stresses. Compute all reaction forces.

Step 2. Removal of all the restraints except those that are to be specified for necessary boundary conditions. The geo-static state is obtained through applying the reaction forces back to the whole model while the in-situ stresses remain activating.

Part 2: The excavation (To remove elements in the model in a pre-designed, successive manner)

The numerical excavation process consists of the following five steps:

Step 1: Removal of the whole tunnel;

Step 2: Further removal of 2 meter of the deposition hole (Start from the bottom surface of the deposition tunnel)

Step 3: Further removal of 2 meter of the deposition hole (The excavation reaches 4 meter depth).

Step 4: Further removal of 4 meters of the deposition hole (The excavation of the whole deposition hole completed).

4.3 Transient heat transfer analysis

The transient heat transfer in the rock media after having installed the copper-canister containing the spent nuclear fuel is analysed in the same 3D model. The purpose is to obtain the time-dependent temperature output in the 3D model (time-dependent nodal temperatures) so that they can subsequently be used as a thermal loading in a transient thermal-stress analysis, see below.

In the analysis the temperature output on the surface of the deposition hole is used as a time-varying prescribed temperature boundary, see Tab. 4-1, after (Ageskog et al., 1998). The other boundaries are for simplicity assumed to be isolated surfaces.

Table 4-1. The temperature on the rock surface of the deposition hole.

Year	0.0	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	15
°C	14.0	52.0	59.0	64.0	67.0	68.0	69.0	70.0	70.5	71.0	71.5	71.5

4.4 Transient thermal-stress analysis

The initial state for the transient thermal-stress analysis is the state that were computed at the end of the rock excavation, i.e. Step 4 of Part 2 in Section 4.2. Hence, one can expect a loading process (and possibly unloading in some region), leading to a further development of plastic failure and stress redistribution. Here the time-dependent nodal temperature output is the time-varying load.

5 Numerical results

We shall in this section briefly report the mechanical consequences through examining the finite element results. For clarity we shall proceed our discussion in association with the two finite element models, i.e. the linear elastic model and the Mohr-Coulomb model.

5.1 Linear elastic model

Results obtained when using the linear elastic model are summarised in Figs. 5-1 and 5-2. After completing the excavation of the tunnel, the deformation is about 2.0 mm and the maximum compressive principal stress appears to be about 73 MPa and no tensile stress observed, see Fig. 5-1.

After completely excavating both tunnel and deposition-hole, the maximum compressive principal stress reaches about 107 MPa, see Fig. 5-2. Moreover, it is also shown that the maximum compressive principal stress increases, from 73 MPa to 107 MPa, as the excavation of the deposition hole progresses. After having deposited the heated canister, the thermal effects will further increase the stresses in the rock. The maximum compressive principal stress increases to 163MPa after having deposited the nuclear wastes for 1 year, and after 10 years of the deposition it tends to stabilised at a level of about 200 MPa, see Figs. 5-2 and 5-5.

The deformation reaches about 2.5 mm after all the excavation completed and after 10 years of heating the deformation reaches about 5 mm, see Figure 5-6

It should be noted that there are two small areas where the rock is observed to be subjected to tension and the maximum tensile principal stress is about 5.3 MPa. For more details we refer to the more detailed report, written to a CD-Rom, which is available at NCC-Teknik and ÄHRL.

5.2 Mohr-Coulomb model (Cohesion=5MPa)

The results obtained when using the Mohr-Coulomb model, are be summarised in Figures. 5-3, 5-4, 5-5 and 5.7.

After completing the excavation of the tunnel, the deformation is still about 2.5 mm and the maximum compressive principal stress appears to be about 74 MPa and no tensile stress observed. Moreover, two areas along the tunnel surface are found to be plastic The maximum depth of the plastic zone is estimated to be about 0.5 - 1.0 m. However, the plastic strain are small (The maximum equivalent plastic strain is about 0.12 ‰,see Fig. 5-4

After completely finishing the excavation of both tunnel and deposition-hole, the maximum compressive principal stress SP1 reaches about 104 MPa, see Figs. 5-3 and Fig. 5-

5. The plastic zone is heavily expanded nearby the intersection of the tunnel and the deposition hole. The maximum equivalent plastic strain reaches 3.2 ‰.

The thermal effects due to the deposition of nuclear fuel wastes can be summarised as follows: The maximum compressive principal stress SP1 increases to 174MPa after having deposited the nuclear wastes for 1 year, and after 10 years of the deposition it tends to stabilised at a level of about 220MPa, see Figs. 5-3. One can clearly observe the enlargement of the failure (plastic) zone, see Fig. 5-4. After 1 year of the deposition, the maximum equivalent plastic strain increases from 3.2 ‰, to 4.39 ‰, and after 10 years it reaches 6.94 ‰, see Figs 5-4 and 5-5. After 10 years of the deposition, the enlargement of the plastic zone is particularly significant in the region, nearby the deposition hole, within a depth of 1.0 m measuring from the deposition tunnel surface.

In Fig. 5-7 show the deformation before and after the heat generating. The deformation is still about 2.5 mm after the excavation of the deposition tunnel and hole. The maximum deformation reaches about 8 mm after 10 years of heating.

We note that there are still areas where the rock is subjected to tension and, in addition, the tension area has been moved in comparison to what has been observed in an elastic analysis. For more details we refer to the more detailed report, written to a CD-Rom, which is available at NCC-Teknik and ÄHRL.

5.3 Other remarks

In addition to the above observations, it should also be of interest to remark the following:

1. It has been observed that the alternative specification of the boundary conditions, see Section 3, does not alter the results so much (Say less than 5%), particularly not at those regions near the surfaces of the tunnel and deposition hole.
2. However, it has been observed that if the cohesion is assumed to be 0.5MPa in the Mohr-Coulomb model the maximum deformation can reach more than 1 cm already at the stage when the excavation of the tunnel completed and, more importantly, the rock of about 1.0 m around the whole tunnel surface is plastified.

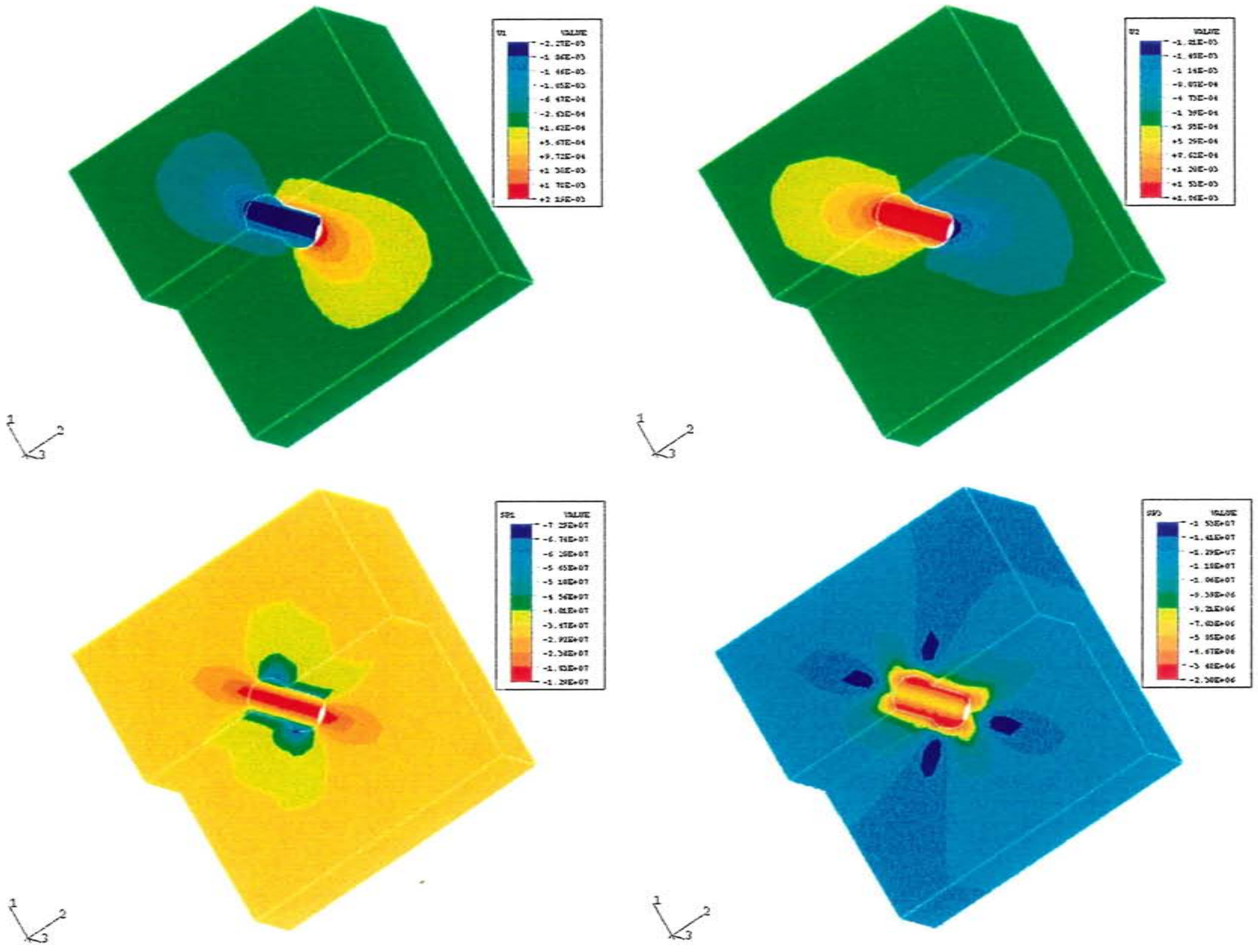


Figure 5-1. Displacements (upper) and the principal stresses (lower, SP1-minimum , SP2-maximum) after completing the tunnel excavation. Elastic model (Units: m and MPa).

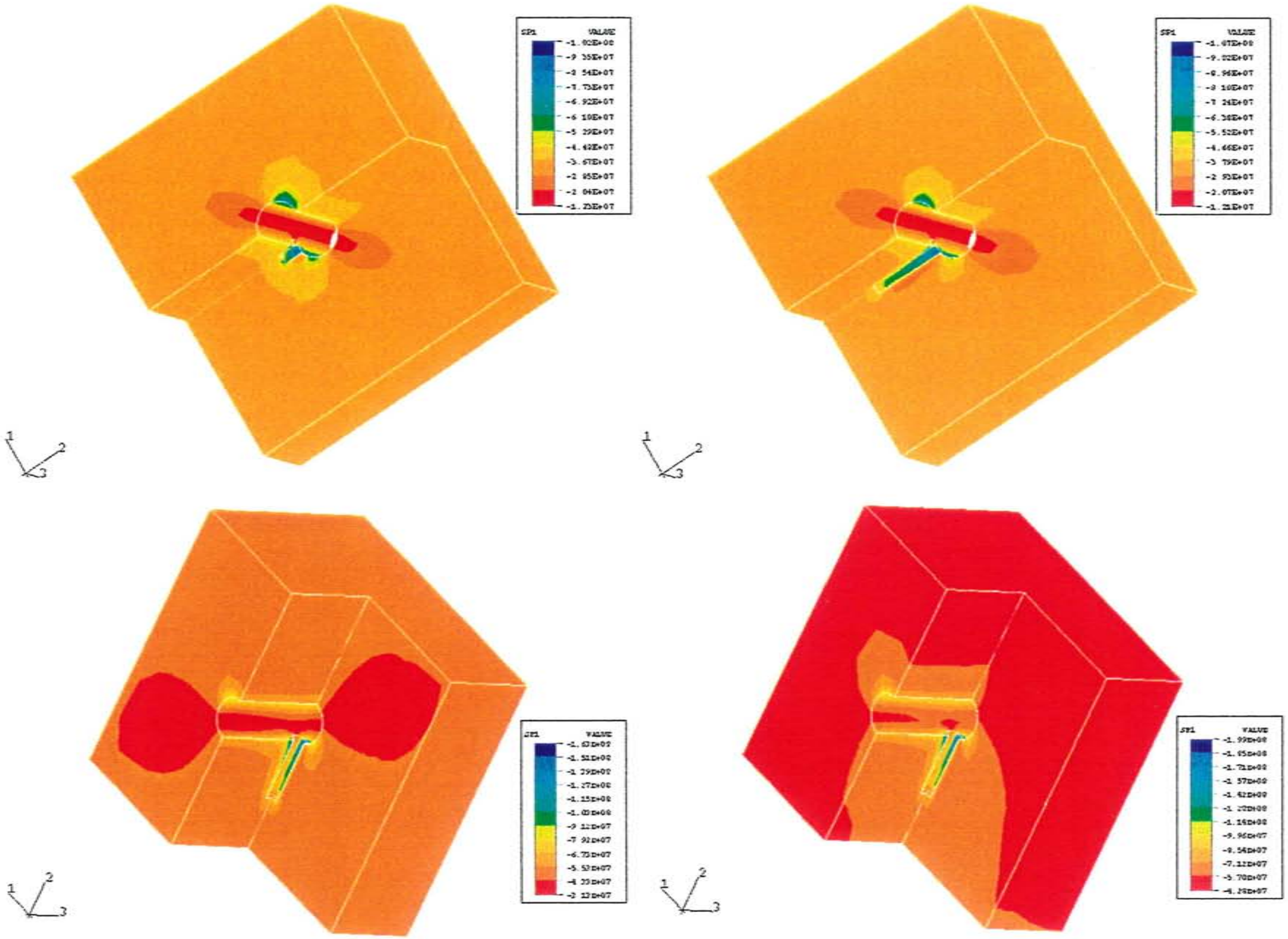


Figure 5-2. Principal stress after excavating the tunnel and deposition hole in 2 m depth (upper left) and in 8 m depth (upper right) and after 1 and 10 year of heating (lower left) and (lower right) respectively. Elastic model, units: Pa.

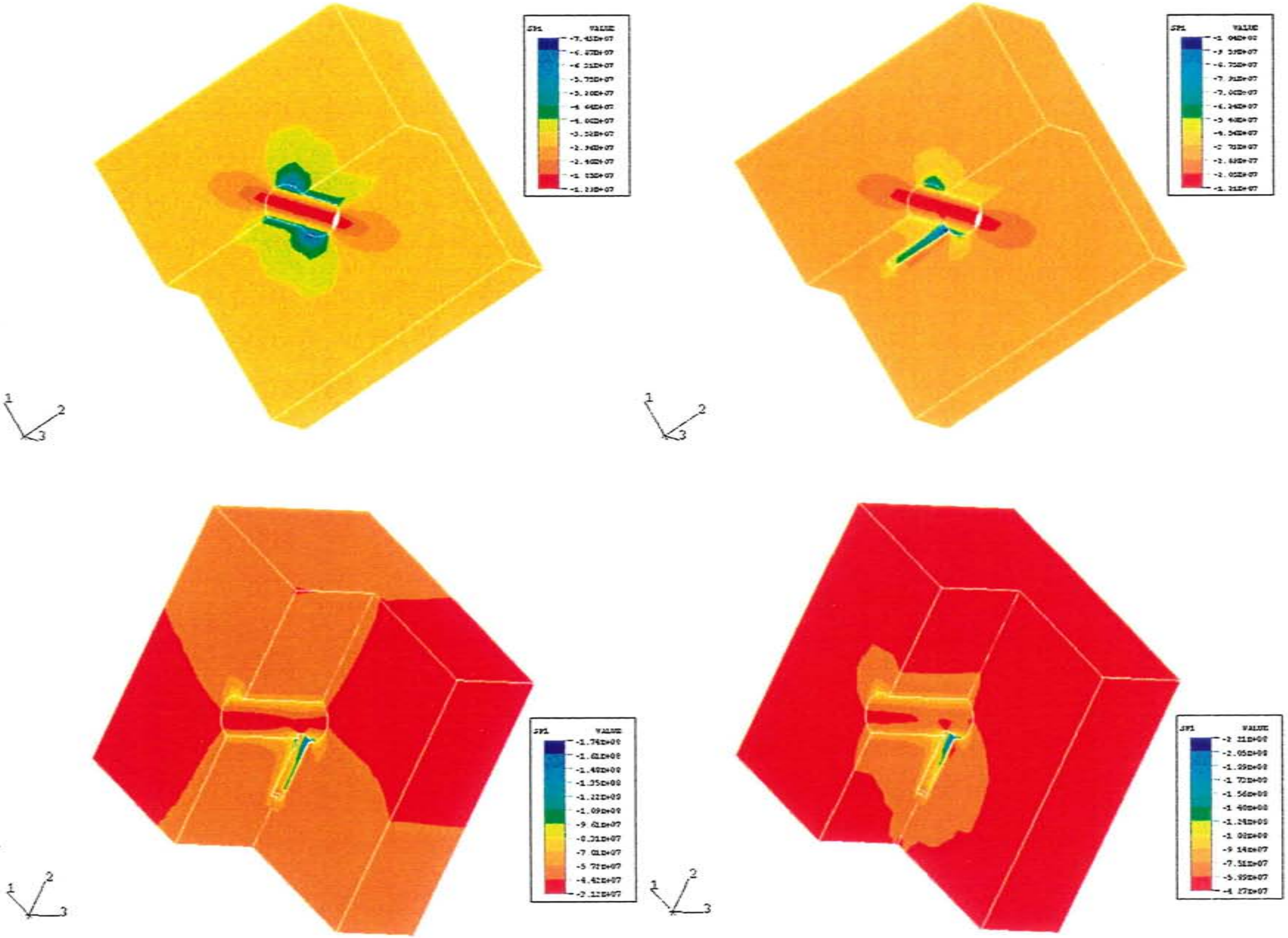


Figure 5-3. Principal stress after excavating the tunnel (upper left) and deposition hole in 8 m depth (upper right) and after 1 and 10 year of heating (lower left) and (lower right), respectively. Mohr-Coulomb model, units: Pa.

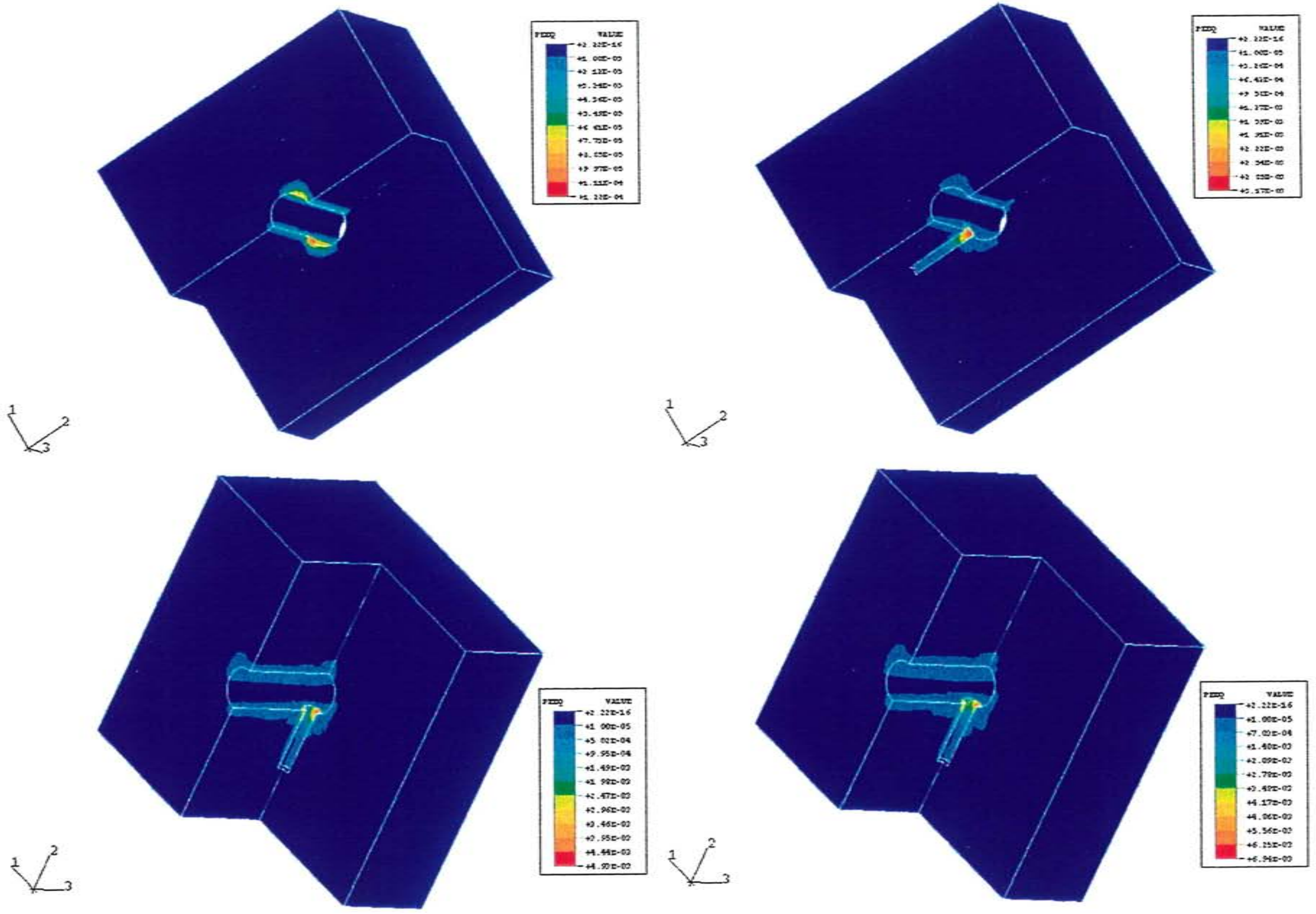
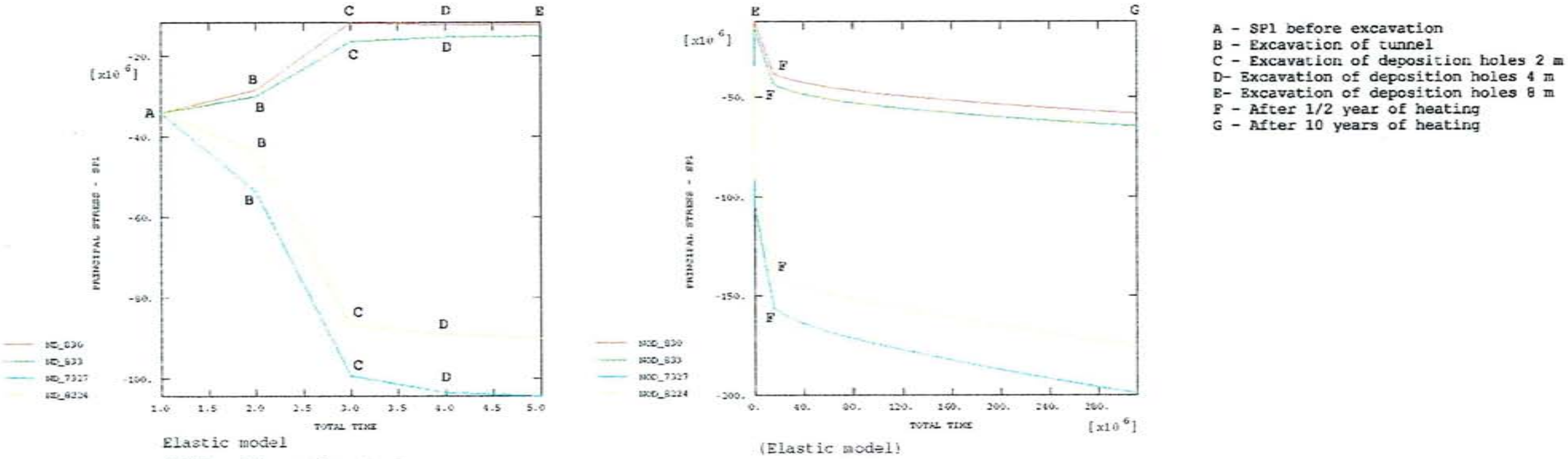
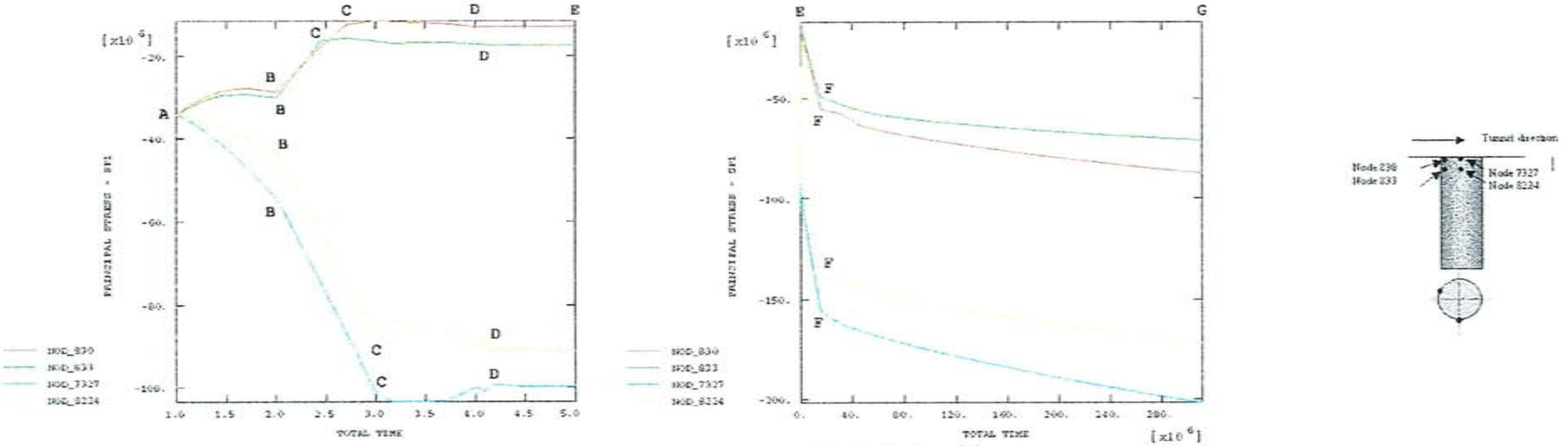


Figure 5-4. Failure (plastic) zone after excavating the tunnel (upper left) and the deposition hole (upper right) and after 1and 10 years of heating (lower left) and (lower right), respectively. Mohr-Coulomb model.



Elastic model
(TIME -> Excavation step)

(Elastic model)



Mohr-Coulumb model

Figure 5-5. Historic development of principal stresses at four particular points near the intersection of the tunnel and deposition hole during various excavation stages (left) and after having deposited the canister (right). Units: seconds and Pa.

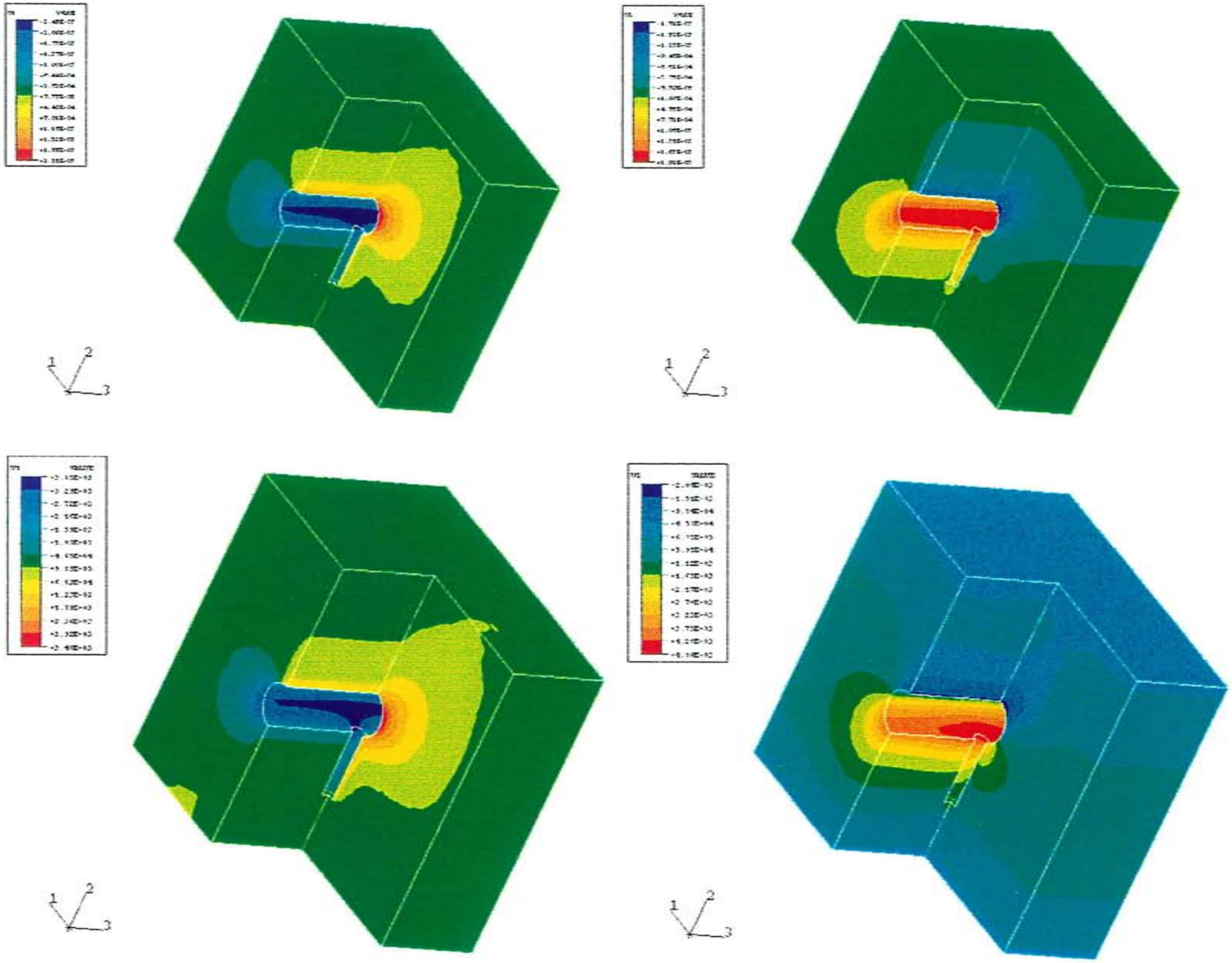


Figure 5-6 Deformation after the excavation of the tunnel and hole completed (upper) and after 10 years of the deposition of the canister (lower). Elastic model, unit m

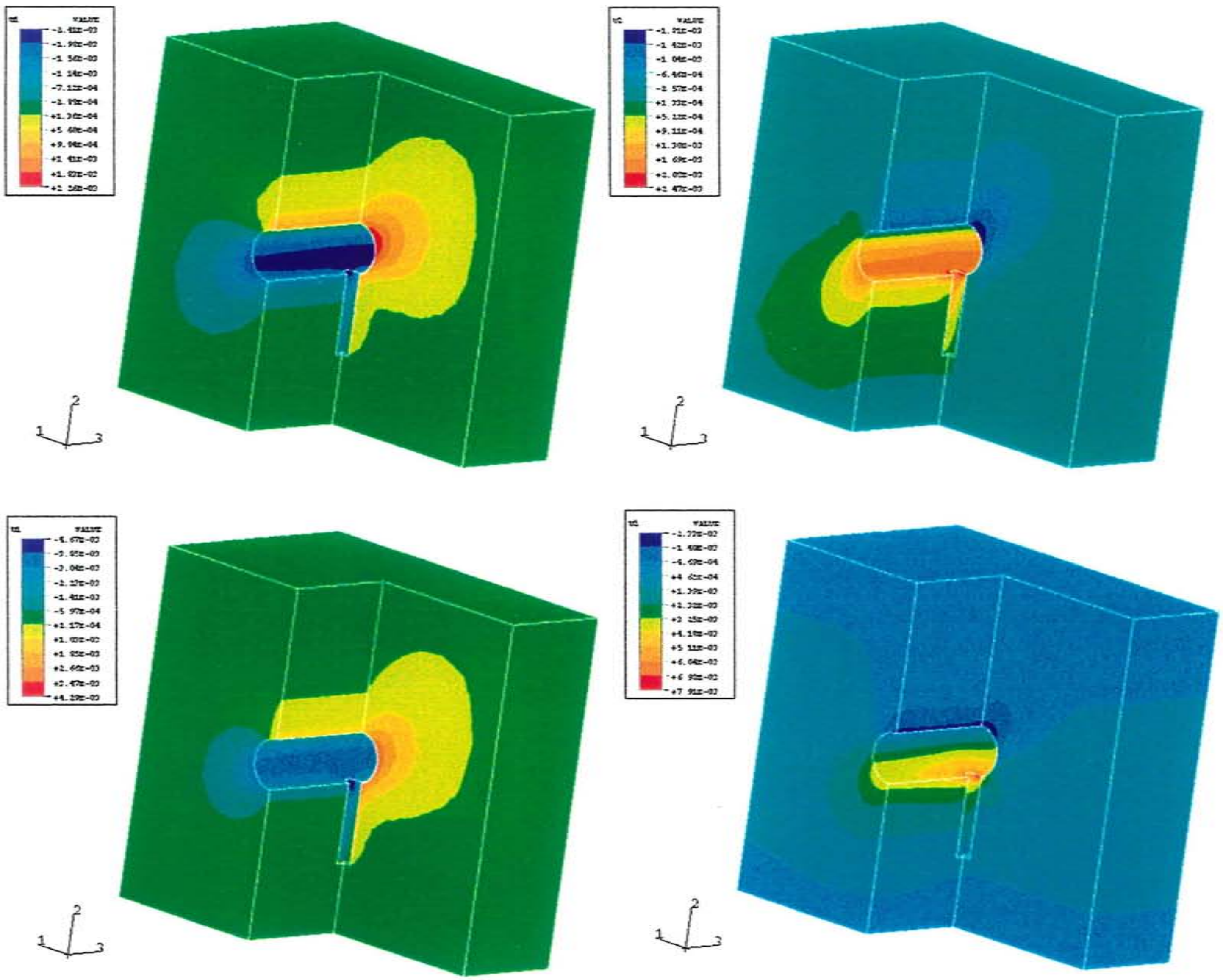


Figure 5-7. Deformation after the excavation of the tunnel and hole completed (upper) and after 10 years of the deposition of the canister (lower). Mohr-Coulomb model. Units: m

6 Closure

Due to the space limit of the report large amount results have been documented for more detailed information, data is available on CD-rom, which is available at NCC Teknik and ÄHRL. Nevertheless, the computations that have been made so far are still a kind of scooping-up investigation. To be able fully understand the rock behaviour due to the excavation and the deposition of nuclear fuel waste, more work need to be done. The studies of coupling effects of three phase (thermal-, mechanical- and hydraulic effects) of explicit and or implicit rock joints, more reliable and refined rock material models and so forth, are some of these.

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