# PLAXIS

## Long-Term Deformation and Stability of Room and Pillar in Salt Mines

PLAXIS 2D 2024.3

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# 1.

# Introduction

This example presents a practical application of PLAXIS 2D for the preliminary assessment of the stability and time-dependent deformation of salt rock subject to the room and pillar mining. The planned room and pillar layout of a salt mine incorporates several panels separated by barrier pillars (see Figure 1 below). Each panel consists of multiple long rooms with rib pillars. Given the geometry of the long rooms and the room and pillar layout within each panel, a 2D plane strain model is employed to simplify the 3D problem, thereby reducing modelling effort (Obert and Duvall, 1967). In this example, a 2D plane strain model is constructed to simulate the cross-section of a single panel within the room and pillar layout.

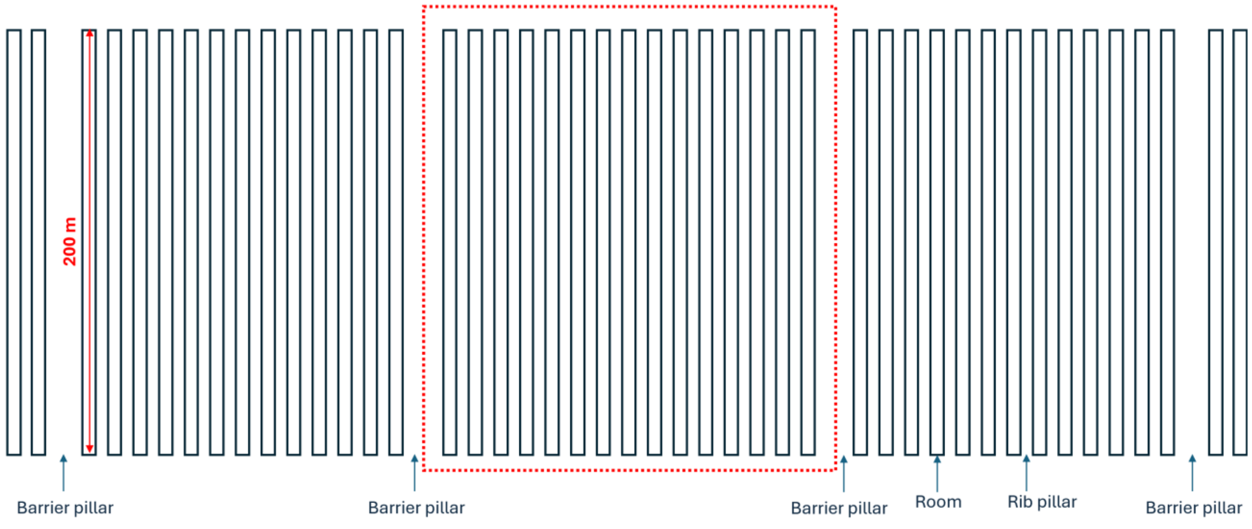



Figure 1: Configuration of the long room and pillar mining layout (top view)

The stratigraphy and the designed room and pillar layout are shown in Figure 2. Three salt rock layers are interbedded with the dolomite formation, above which are the sandstone and limestone units overlain by the overburden soil. On each of the salt rock units, rooms with the same width (15 m) and height (5 m) are to be excavated. There are 21 rooms on the top and middle salt rock layers and 20 rooms on the bottom salt rock layer. The pillar width is 15 m for the top and middle salt rock layers, and it is 16 m for the bottom salt rock layer. The excavation progressed from the top to the middle, and then to the bottom salt layer, with a 10-year time interval between each level.

Mechanical behaviour of the salt rock is complex, it exhibits time-dependent deformation (creep) behaviour, which may cause stability issues in deep underground excavations and must be considered in stability analyses (Swift et al., 2001). In this example, the Norton double power creep law with Mohr-Coulomb and Tension cut-off failure criteria (N2PC-MCT) is applied to simulate the time-dependent deformation behaviour and predict the potential failure and damage of the salt rock structures (Plaxis, 2022). Strength factor is employed to evaluate the stability conditions (McCreath and Diederichs, 1994).

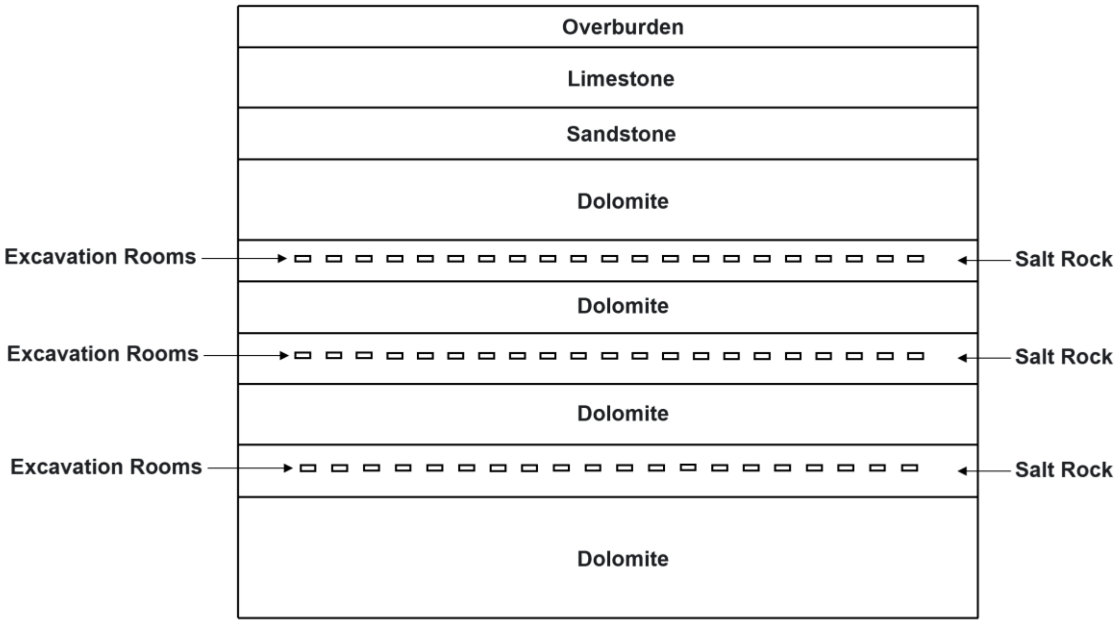



Figure 2: Stratigraphy and room and pillar excavation layout (front view).

**Keywords**: PLAXIS 2D, Salt rock, N2PC-MCT, Room and pillar, Excavation, Principal stresses, Strength factor.

# 2.

# Model Construction

*Project properties definition*

First, in the *Model* tabsheet of the *Project properties* window, define the project properties (see Figure 3). The plane strain model is set as 724 m wide (from $x_{min}$ = 0 m to $x_{max}$ = 724 m) and 600 m deep (from $y_{min}$ = -600 m to $y_{max}$ = 0 m with 15-noded triangular elements.

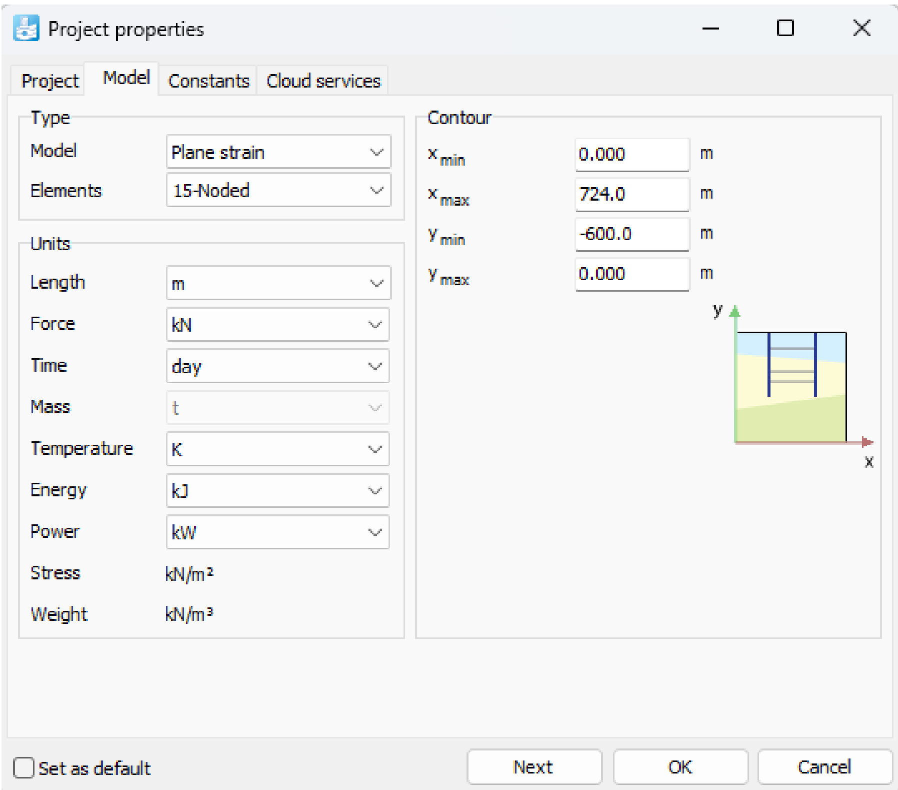



Figure 3: Definition of project properties.

*Stratigraphy and material properties*

Stratigraphy of the model is defined based on a borehole at (0, 0). It is constituted by ten horizontal soil and rock units ranging from the ground surface to a depth of -600 m as shown in Figure 4. Water is not considered in this model and the water table is therefore set at *Head* = -600 m corresponding to the bottom of the model, such that the entire stratigraphy involved in this project is above the water level.

Table 1 summarizes the material properties of each soil and rock unit applied in this model. The non-salt materials are simulated based on the Mohr-Coulomb model. The salt units are modelled as N2PC-MCT material (Norton-based Double Power Creep with the Mohr-Coulomb and Tension cut-off failure criteria), to study the time-dependent deformation of the salt rock and predict its failure and damage behaviour.

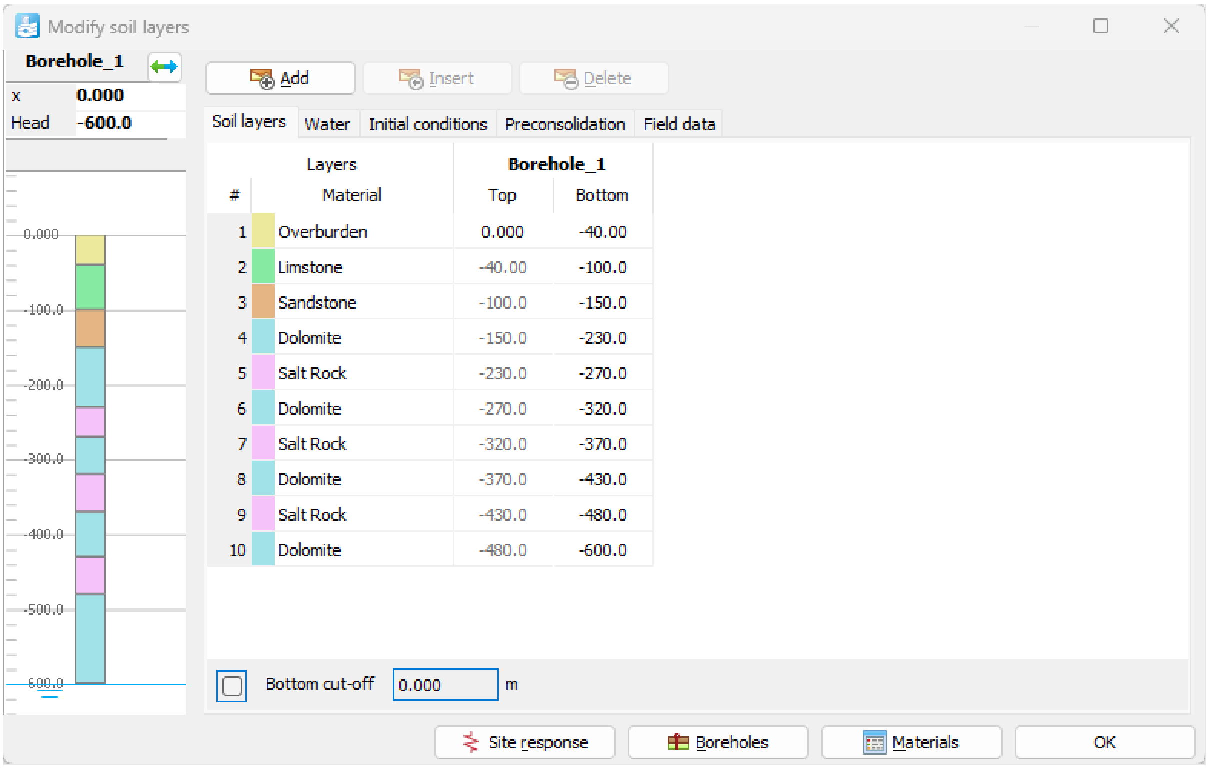



Figure 4: Definition of stratigraphy in borehole

Table 1: Material properties of the soil and rock units

| Material Name | Overburden | Limestone | Sandstone | Dolomite | Salt Rock |
|---|---|---|---|---|---|
| Soil Model | Mohr-Coulomb | Mohr-Coulomb | Mohr-Coulomb | Mohr-Coulomb | User-defined |
| Model in DLL | - | - | - | - | CreepRock-N2PC-MCT |
| Unit weight unsaturated $\gamma_{unsat}$ | 18 kN.m$^{-3}$ | 25 kN.m$^{-3}$ | 23 kN.m$^{-3}$ | 28 kN.m$^{-3}$ | 22 kN.m$^{-3}$ |
| Unit weight saturated $\gamma_{sat}$ | 18 kN.m$^{-3}$ | 25 kN.m$^{-3}$ | 23 kN.m$^{-3}$ | 28 kN.m$^{-3}$ | 22 kN.m$^{-3}$ |
| Drainage Type | Drained | Drained | Drained | Drained | Drained |
| E | 20E3 kPa | 30E6 kPa | 15E6 kPa | 38E6 kPa | - |
| G | - | - | - | - | 13E6 kPa |
| v | 0.3 | 0.3 | 0.25 | 0.2 | 0.25 |
| $c'_{ref}$ | 8 kPa | 5000 kPa | 4000 kPa | 6200 kPa | 4000 kPa |
| φ' | 28° | 48° | 48° | 38° | 43 ° |
| ψ | 0° | 19° | 20° | 9° | 15 ° |
| N1 | - | - | - | - | 2.5 |

| | | | | | |
|---|---|---|---|---|---|
| A1 | - | - | - | - | 0.05E-9 $day^{-1}$ |
| N2 | - | - | - | - | 3.5 |
| A2 | - | - | - | - | 0.8E-9 $day^{-1}$ |
| q0 | - | - | - | - | 1000 kPa |
| $q_{th}$ | - | - | - | - | 3000 kPa |
| Tension cut-off | True | True | True | True | - |
| Tensile strength | 0 kPa | 8000 kPa | 3000 kPa | 10000 kPa | 1800 kPa |
| $K_0$ determination | Automatic | $K_{0,x} = K_{0,z} = 1$ | $K_{0,x} = K_{0,z} = 1$ | $K_{0,x} = K_{0,z} = 1$ | $K_{0,x} = K_{0,z} = 1$ |

*Room and pillar layout*

Three layers of rooms are to be mined out from the salt units. All rooms are designed as 5 m height and 15 m width. Pillars on the top and middle salt rock layers are 15 m width, and it is 16 m width on the bottom salt rock layer.

To define the room and pillar layout, go to the *Structures* mode and create the first room on the top salt rock layer by creating 4 geometry lines (see Figure 5):

- from (55, -245) to (70, -245),
- from (70, -245) to (70, -250),
- from (70, -250) to (55, -250),
- from (55, -250) to (55, -245).

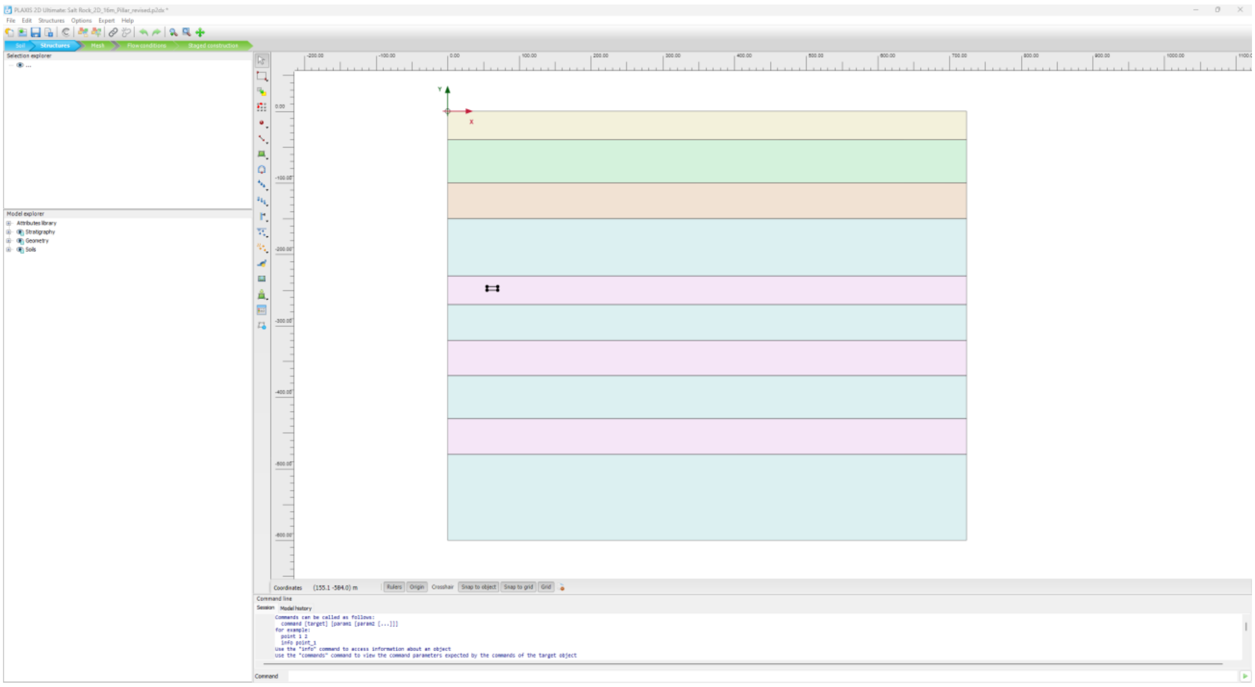


Figure 5: Geometry of the first room

Select the created four lines then click on the *Create array* icon from the vertical mode tool bar. In the opened *Create array* window, select the "1D, in x direction" option for *Shape*, and input 21 for the *Number of columns*. Set 30 m as the *Distance between columns* in x direction such that 20 copies of the room will be added to the geometry (see Figures 6 and 7 below).

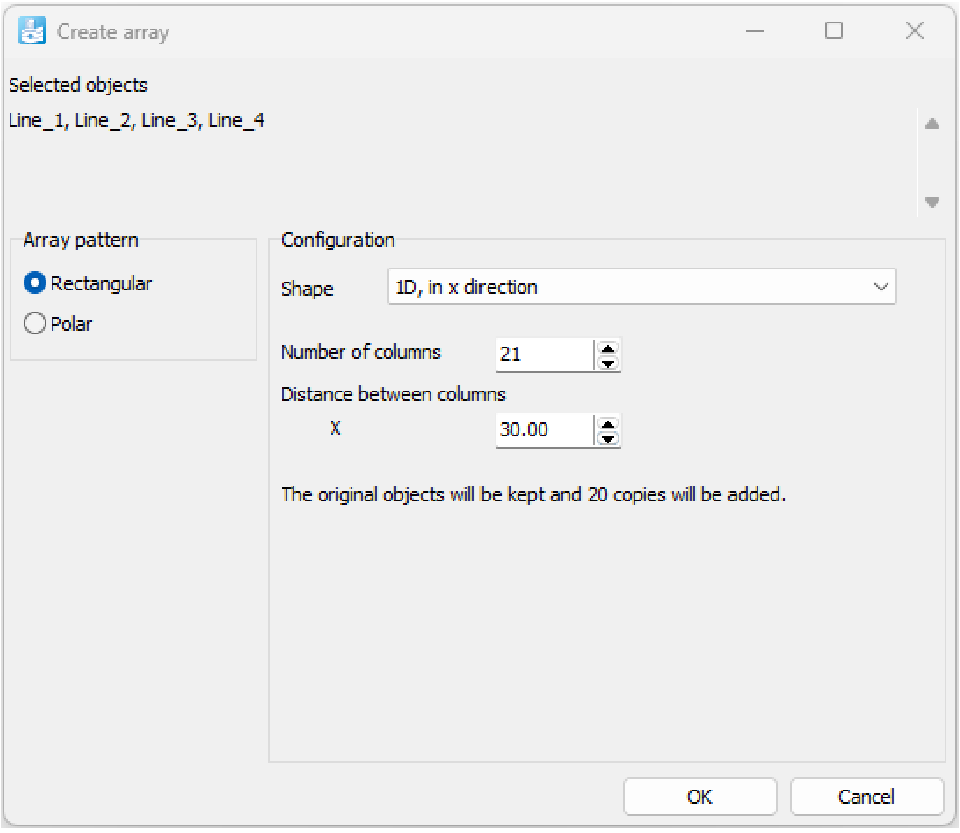



Figure 6: Generation of rooms using "Create array" option

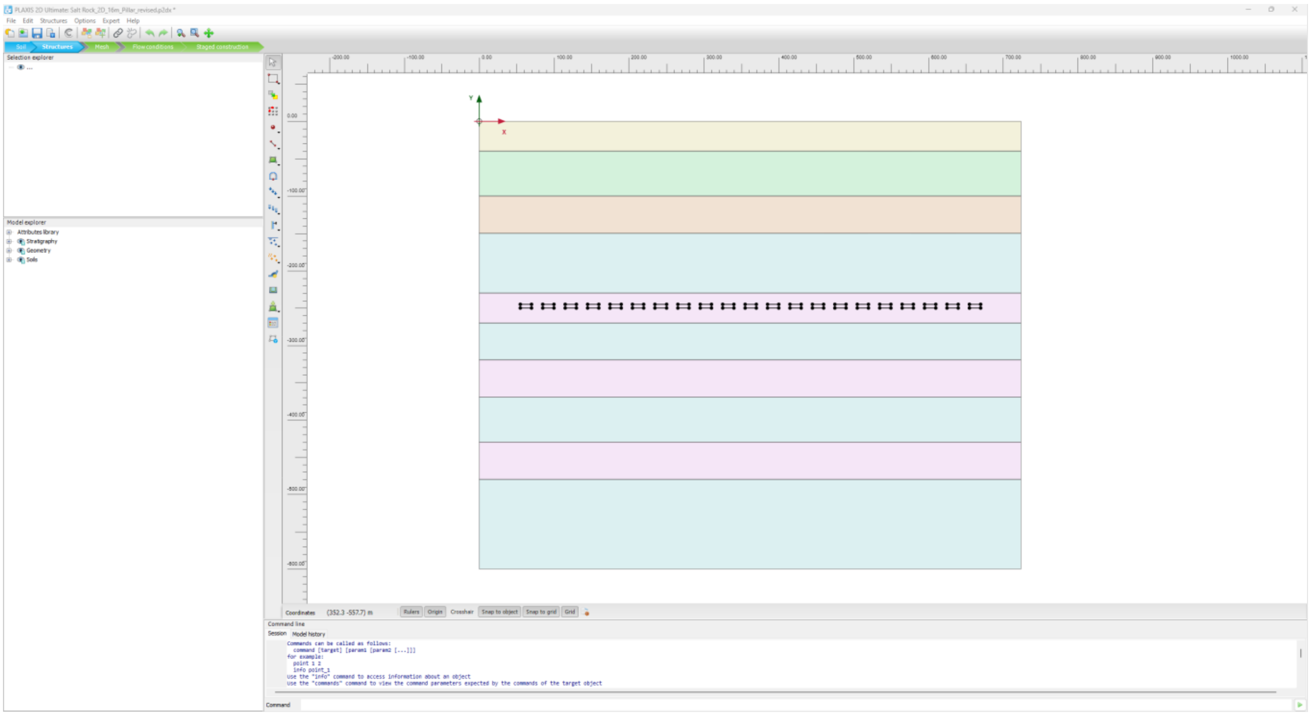


Figure 7: Generation of rooms on the top salt rock layer

Next, repeat the same procedure to create the rooms in the middle salt rock layer. Again, define the first room by creating four lines:

- from (55, -340) to (70, -340),
- from (70, -340) to (70, -345),
- from (70, -345) to (55, -345),
- from (55, -345) to (55, -340).

Then select the above four lines and create a horizontal array in the x direction. Input 21 for the *Number of columns* and 30 m for the *Distance between columns* in x direction. Again, 20 copies of rooms will be added to the middle layer of the salt unit (see Figure 8).

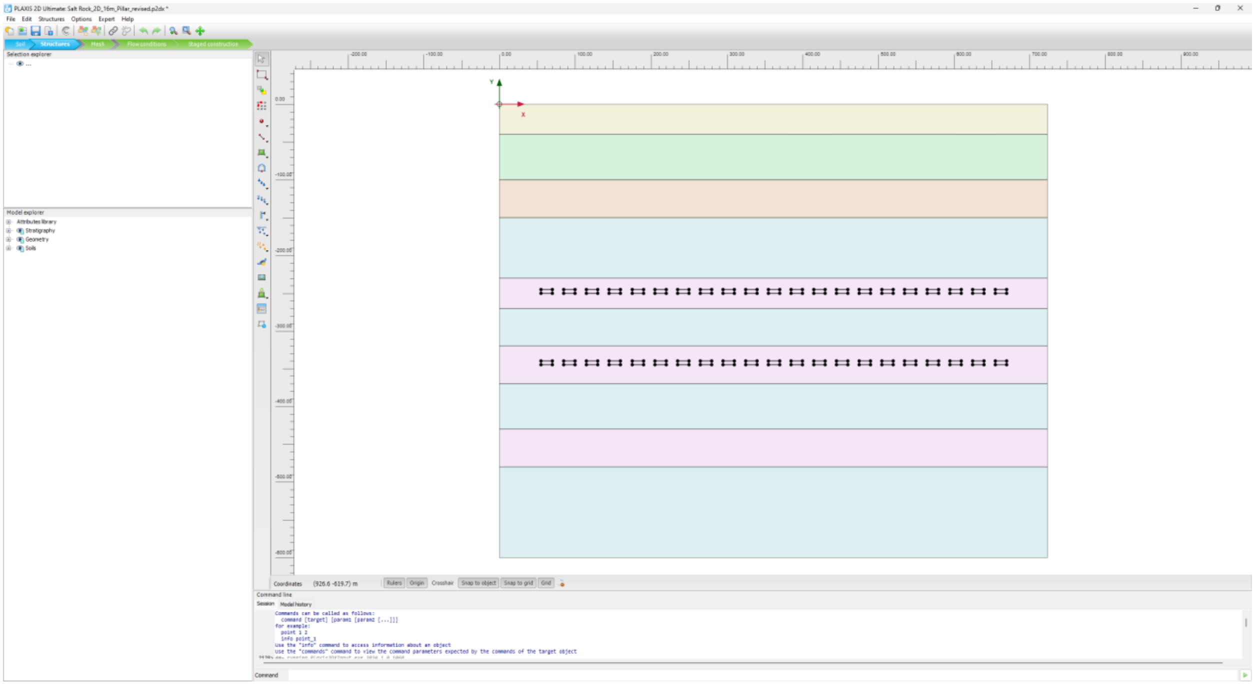


Figure 8: Generation of rooms on the middle salt rock layer

Finally, define the rooms on the bottom salt rock unit by repeating the same procedure. Define the first room by creating four lines:

- from (60, -450) to (75, -450),
- from (75, -450) to (75, -455),
- from (75, -455) to (60, -455),
- from (60, -455) to (60, -450).

Then, select the above four lines and create a horizontal array in the x direction. This time input 20 for the *Number of columns* and 31 m for the *Distance between columns* in x direction, so that 19 copies of rooms will be added to the bottom layer of salt unit. The resulting complete room and pillar layout is now presented in Figure 9.

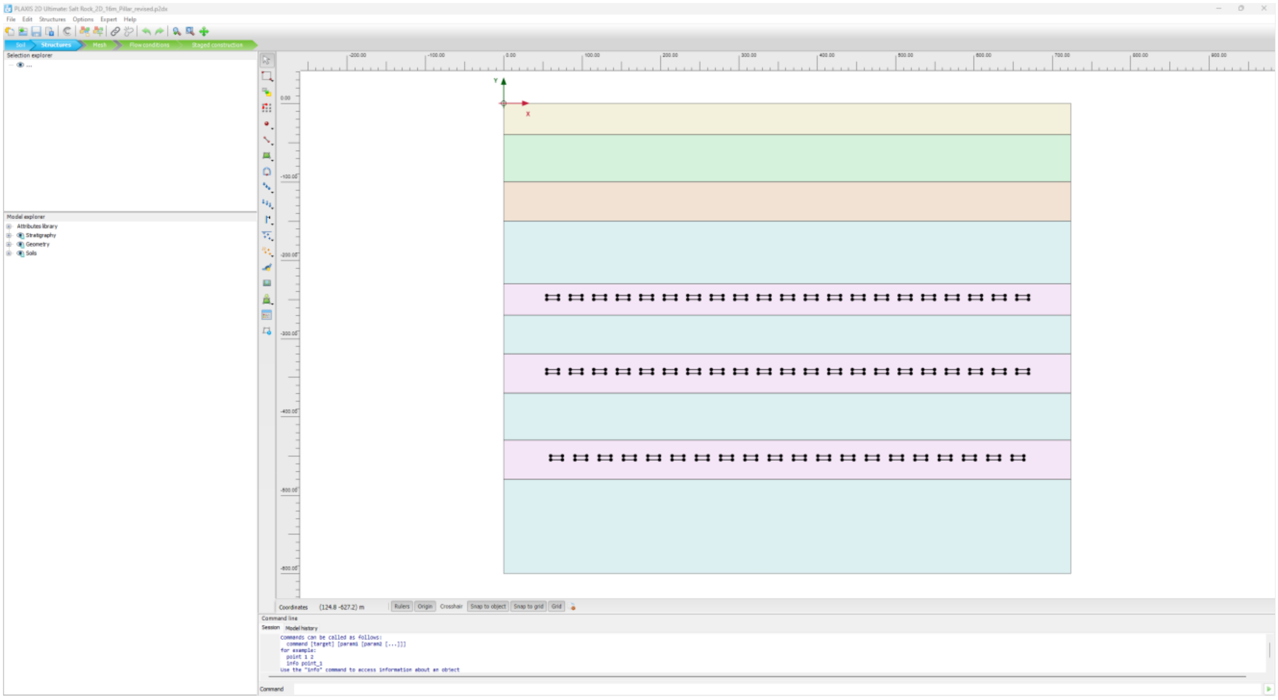
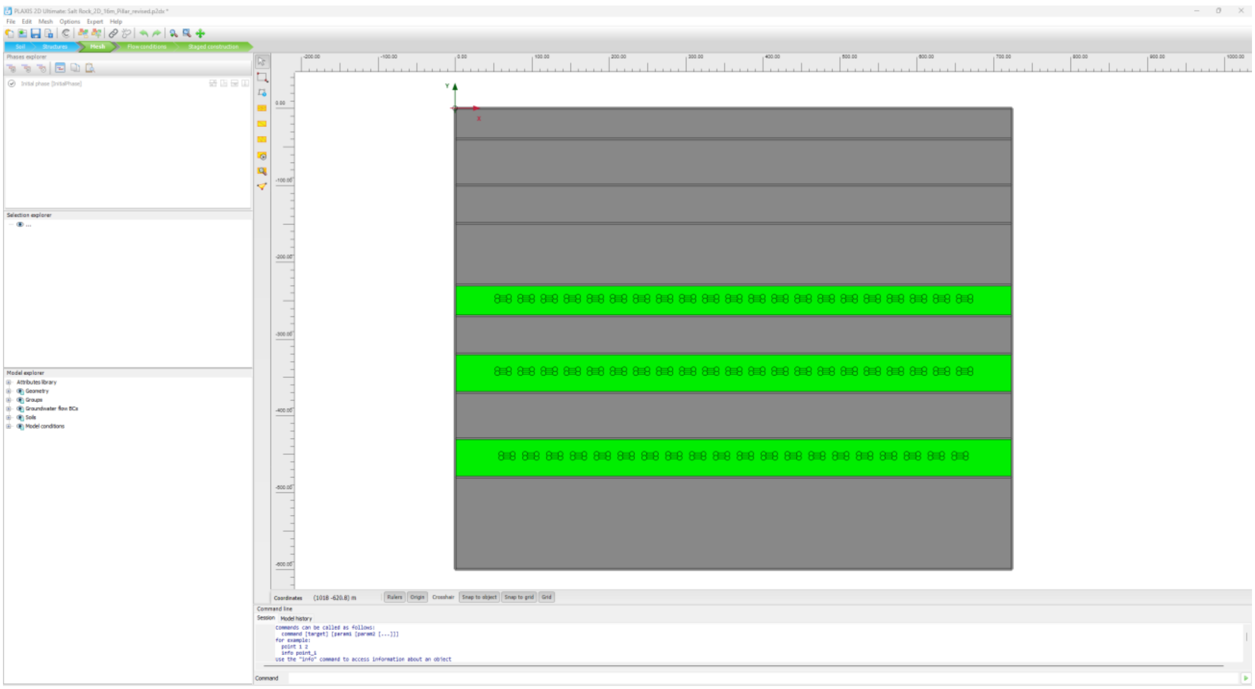


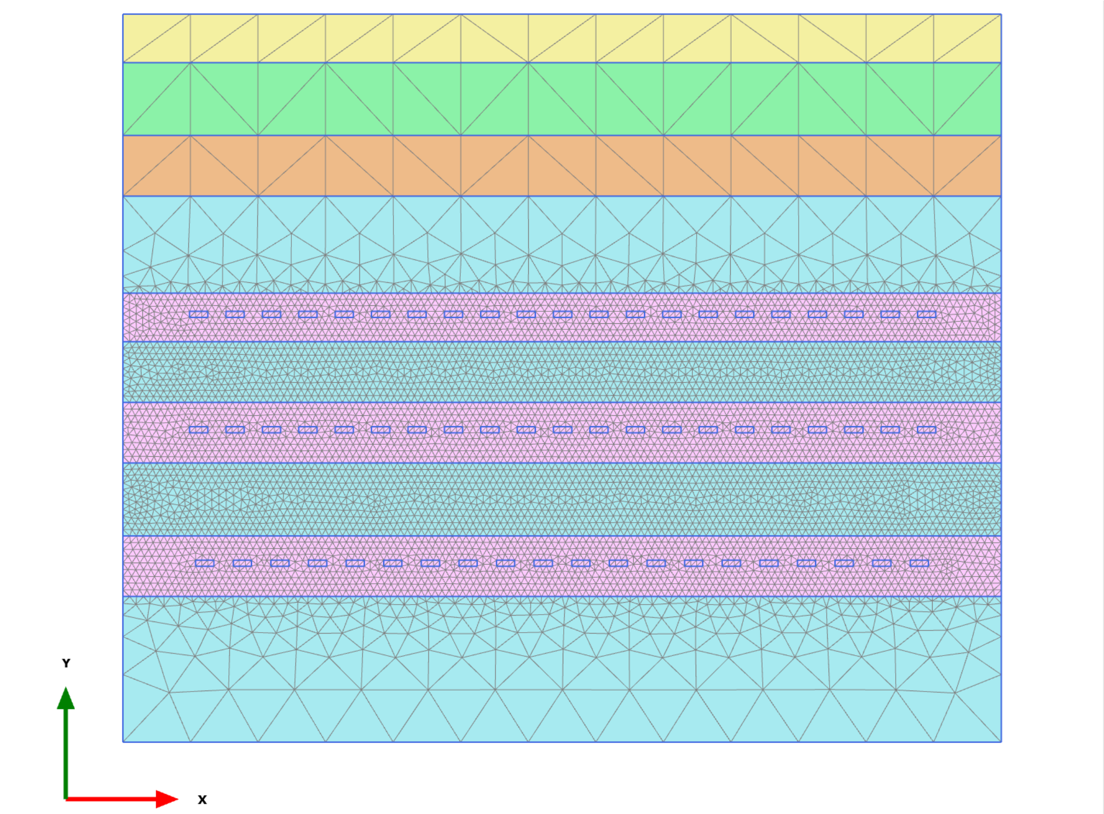
Figure 9: Generation of rooms on all three salt rock layers

## *Mesh generation*

Go to the *Mesh* mode and refine the mesh by setting the coarseness factor of all geometrical entities in the three salt rock units to 0.1 as shown in Figure 10a. Then, generate a mesh using a *Medium* element distribution. The generated mesh from PLAXIS Output program is presented in Figure 10b.



(a) coarseness definition




(b) mesh presentation

Figure 10: Mesh generation

*Construction stage definition*

Go to the *Staged construction* mode and define the phases for room and pillar excavations.

***Initial conditions***

First define the initial conditions. Since the stratigraphy of this model is horizontal, the *K0-procedure* will be used as the *Calculation type* to generate the initial stresses.

***Phase 1: Excavate rooms on the top salt rock layer***

Create a new phase entitled “Excavate rooms on the top salt rock layer” and deactivate the clusters from all the rooms on the top salt rock layer (see Figure 11).

Note: To easily deactivate the clusters from all the rooms simultaneously, the *Group* functionality can be used. First select all rooms from the top salt rock unit using the *Select multiple objects* tool from the vertical mode tool bar, then right click on any selected room and select the *Group* option to group the rooms. Afterwards, rename the *S_Group_1* to *Room_Top* from the Model explorer and then deselected it to mine out the rooms.

In this exercise, the mining of the rooms is simulated by deactivating all rooms at each layer simultaneously, which overestimates the stress state in the model. Future parametric studies would be necessary to examine the impact of the mining sequence on the stability and deformation of the excavation.

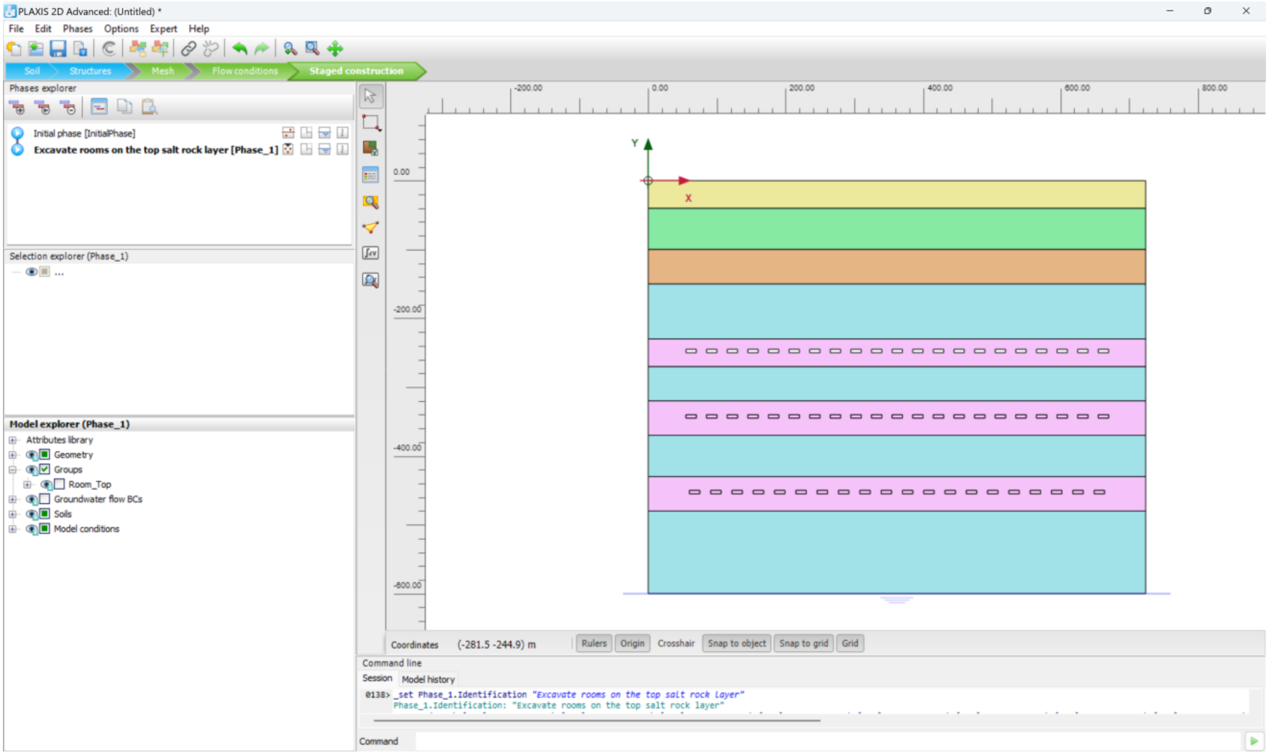



Figure 11: Excavation of rooms on the top salt rock layer

### *Phase 2: Creep for 10 years*

Create a new phase entitled “Creep for 10 years” starting from phase 1 and set 3650 days as the *Time interval* in the *General* tab of the *Phases* window (see Figure 12).

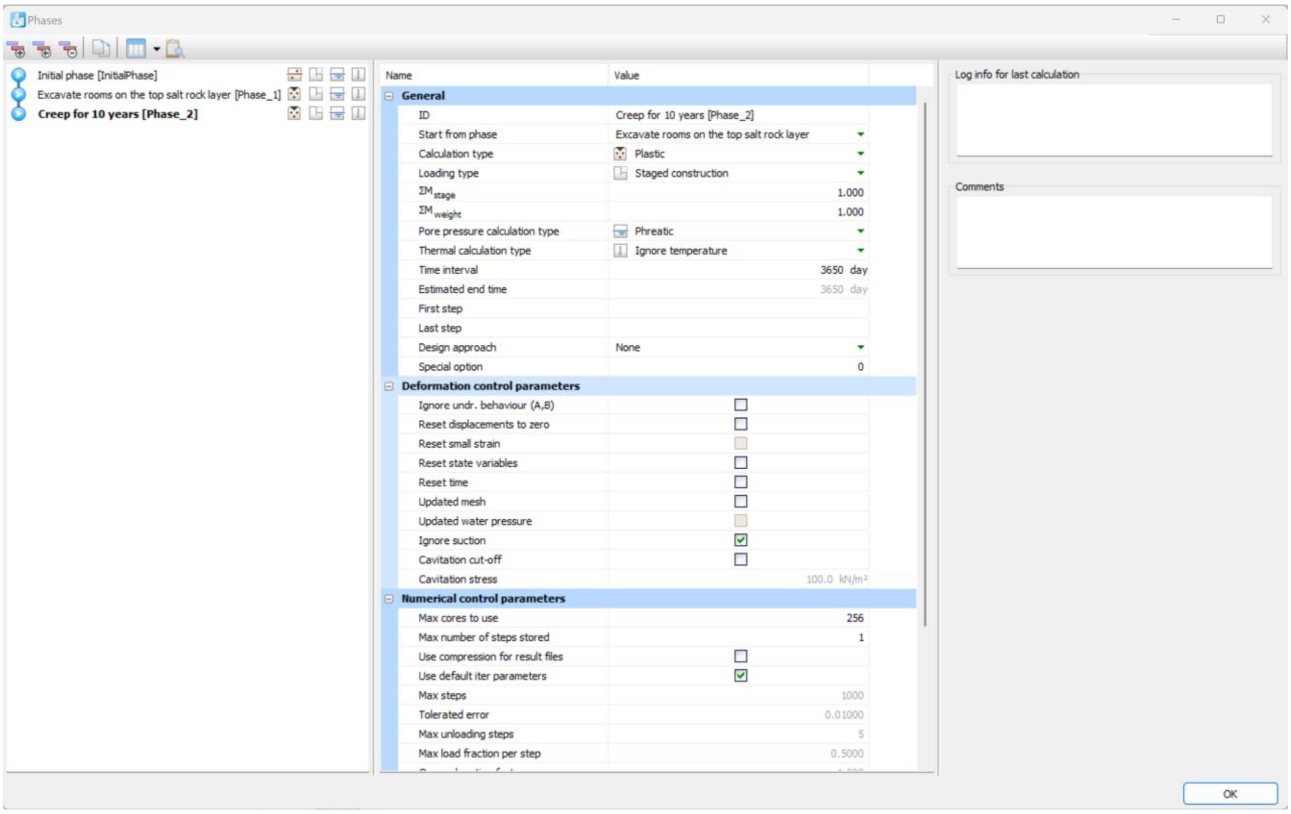



Figure 12: Time interval setup in the "General" tab of Phases window

### *Phase 3: Excavate rooms on the middle salt rock layer*

Create a new phase entitled “Excavate rooms on the middle salt rock layer” starting from phase 2 and keep all the default settings from the *Phases* window. Group all rooms on the middle layer of the salt units as “Room_Middle”, then mine out the rooms by deselecting “Room_Middle” from the Model explorer (see Figure 13).

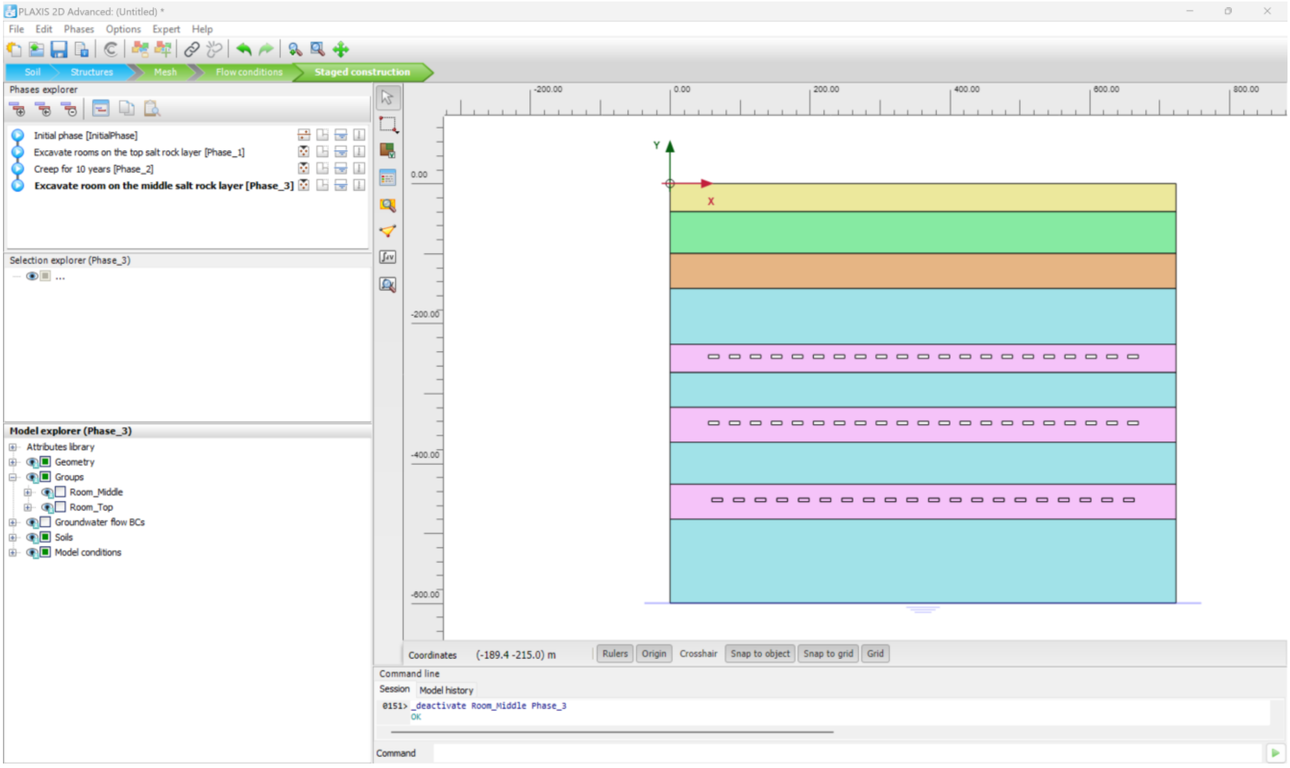


Figure 13: Excavation of rooms on the middle salt rock layer

### *Phase 4: Creep for 10 years*

Create a new phase entitled "Creep for 10 years" starting from phase 3 and set 3650 days as the *Time interval* in the *General* tab of *Phases* window.

### *Phase 5: Excavate rooms on the bottom salt rock layer*

Create a new phase entitled "Excavate rooms on the bottom salt rock layer" starting from phase 4 and keep all the default settings from the *Phases* window.

Group all rooms on the bottom layer of the salt rock units as "Room_Bottom", then mine out the rooms by deselecting "Room_Bottom" from the *Model explorer* (see Figure 14).

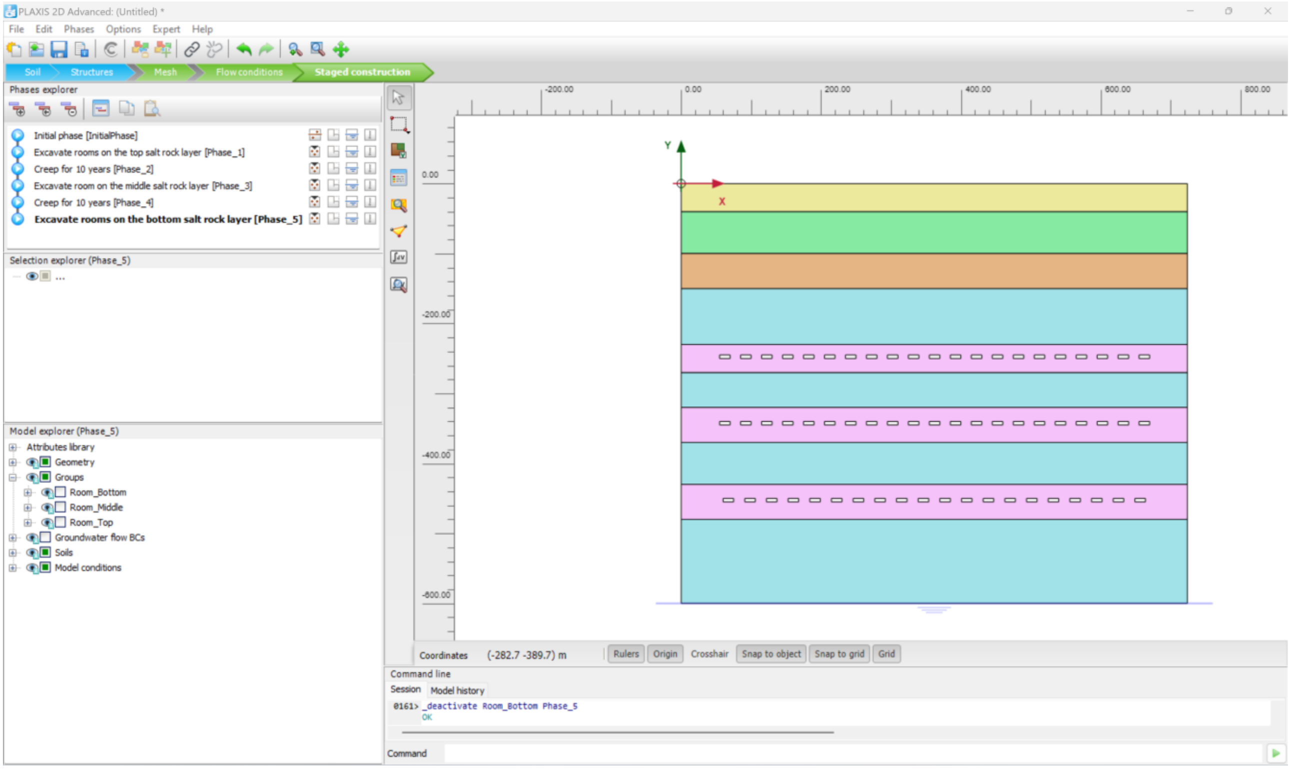


Figure 14: Excavation of rooms on the bottom salt rock layer

### *Phase 6: Creep for 10 years*

Create a new phase entitled “Creep for 10 years” starting from phase 5 and set 3650 days as the *Time interval* in the *General* tab of the *Phases* window.

### *Phase 7: Creep for 20 years*

Create a new phase entitled “Creep for 20 years” starting from phase 6 and set 3650 days as the *Time interval* in the *General* tab of the *Phases* window.

### *Phase 8: Creep for 30 years*

Create a new phase entitled “Creep for 30 years” starting from phase 7 and set 3650 days as the *Time interval* in the *General* tab of the *Phases* window.

Before running the calculations, one can select nodes or stress points to monitor the development of a specific result over intermediate steps. For this project we are interested in the ground subsidence due to the excavation process and resulting convergence of the rooms. Therefore, a few nodes can be selected for this purpose (see Figure 15) for instance:

- (362, 0) to investigate the maximum ground subsidence,
- (377.5, -450), (377.5, -455), (370, -452.5) and (385, -452.5) to monitor the deformation of the roof, floor, and the walls of the excavation room.

Once the monitoring points have been selected, start the calculation by clicking on *Calculate*.

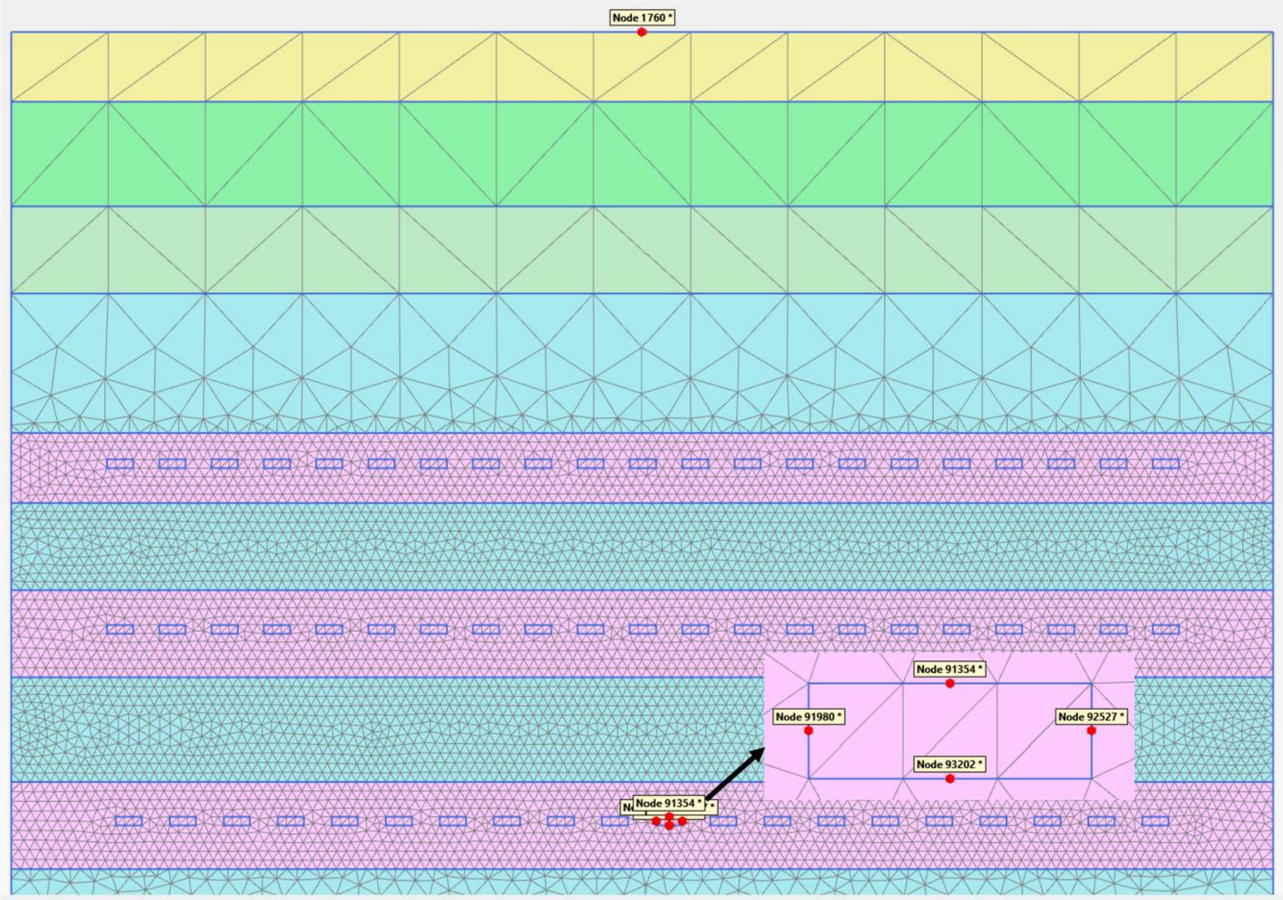



Figure 15: Monitoring points for curve selection

# 3.

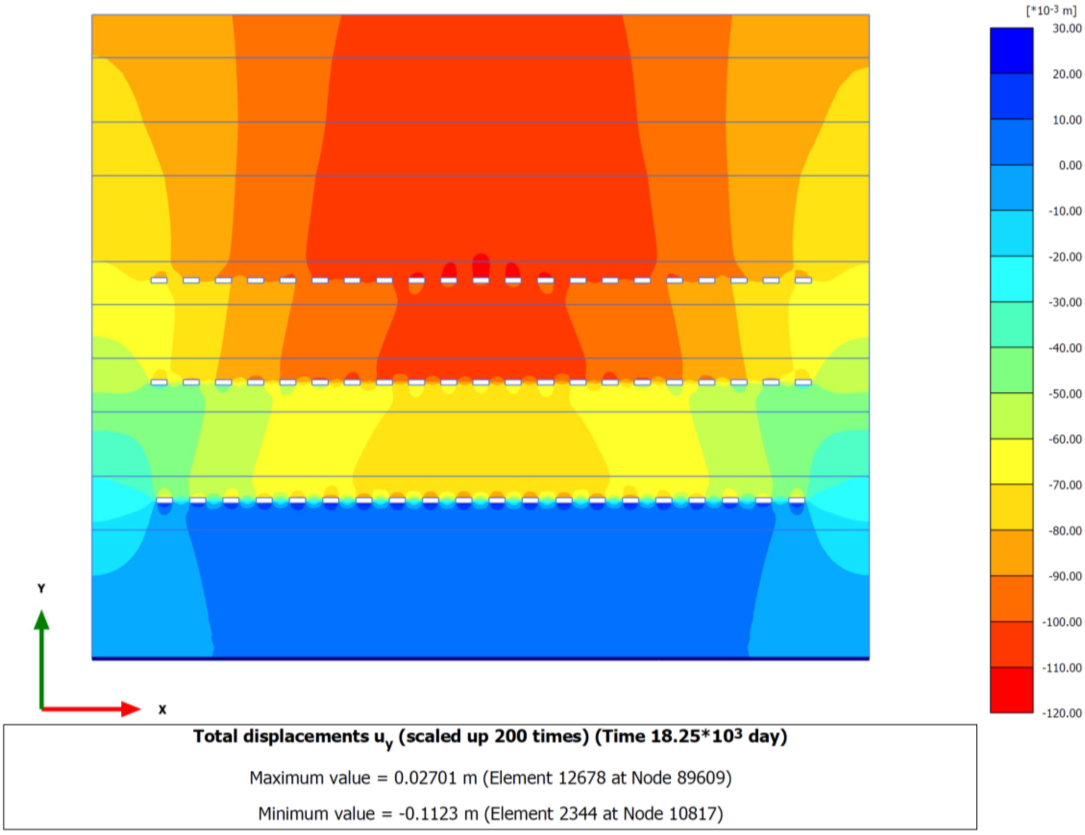
# Main Results

Interpretation of the results of this finite element analysis is accomplished by studying the time-dependent deformation behaviour and stability of the pillar structures around the rooms. In the following sections, contour plots of vertical and horizontal displacements and curve plots of room convergence are presented for the evaluation of the long-term deformations. Additionally, contour plots of major and minor principal stresses, deviatoric stress, and strength factor are employed to evaluate and predict mine stability conditions.

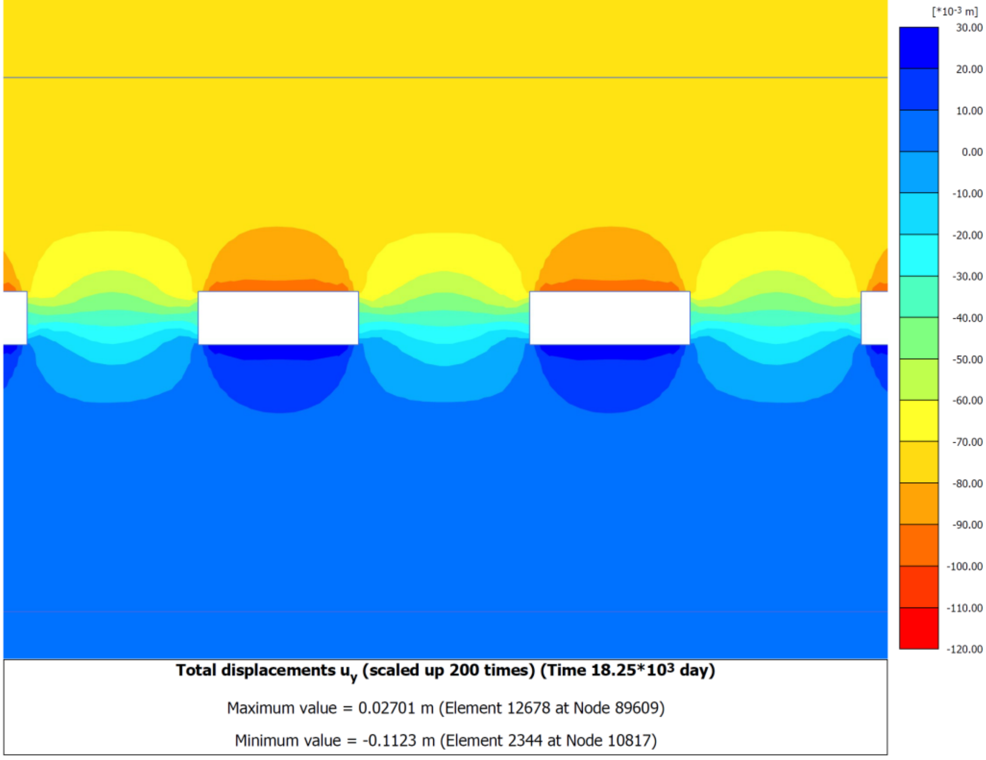
*Vertical and horizontal displacements*

Figures 16 and 17 present the vertical and horizontal displacements of 30 years creep after the completion of all three salt rock level excavations. From top to the bottom salt rock levels, vertical displacement reduces at the room roofs, and horizontal displacement increases at the room walls. The maximum vertical deformation occurs at the roof of the central room of the top salt rock level, which transmits to the ground surface vertically and generates a maximum subsidence of about 11 cm. At the central room of the bottom salt rock level, heave of the floor is about 2 cm, and the horizontal convergence of the walls is approximately 8 cm.

Inspection of the time-dependent displacement of the room at the centre of the panel (see Figure 18) on the bottom salt rock level indicates a slight heave caused by the mining of the upper and middle salt layers. Once the salt rocks on the bottom level were mined out, significant creep deformation began. The vertical convergence rate at the midpoint of the roof is approximately 2.8 mm/yr while the floor converges at a rate of approximately 0.6 mm/yr. The convergence rates of the two walls are nearly identical, with both converging at about 2.8 mm/yr.

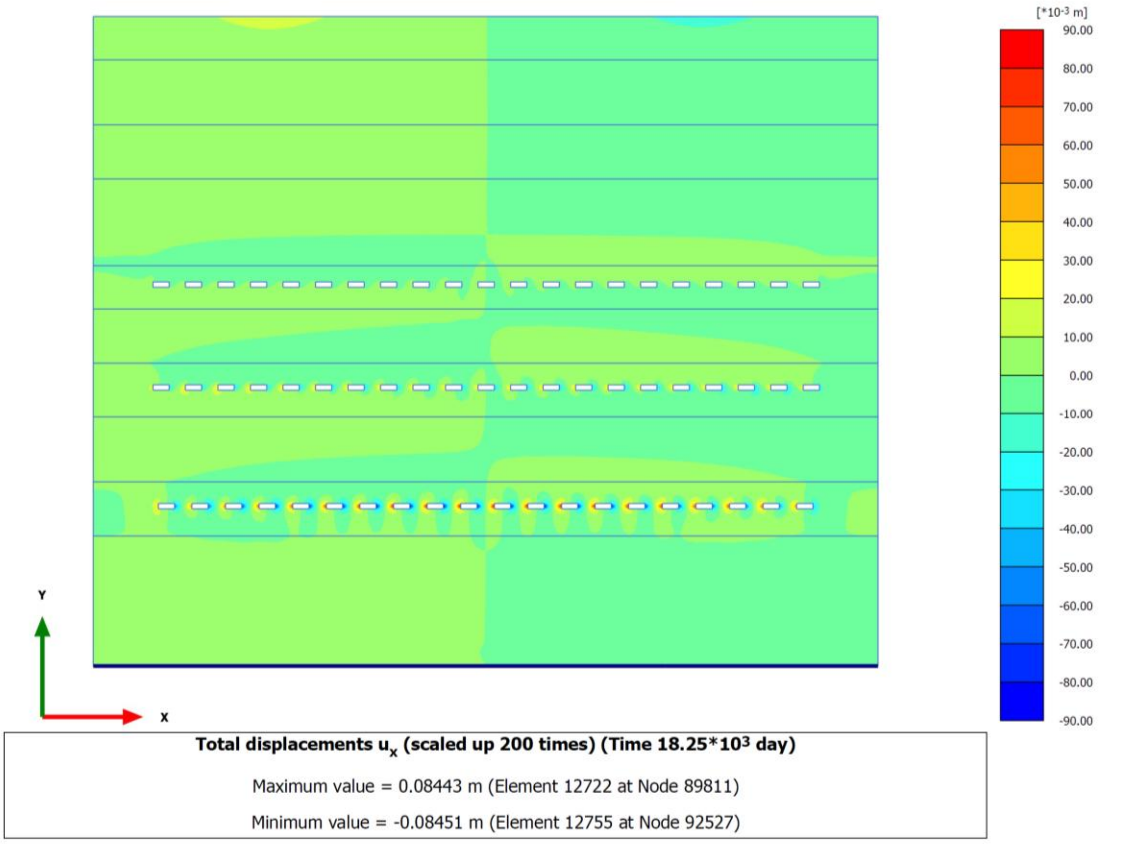



(a) Contour plot of the complete model

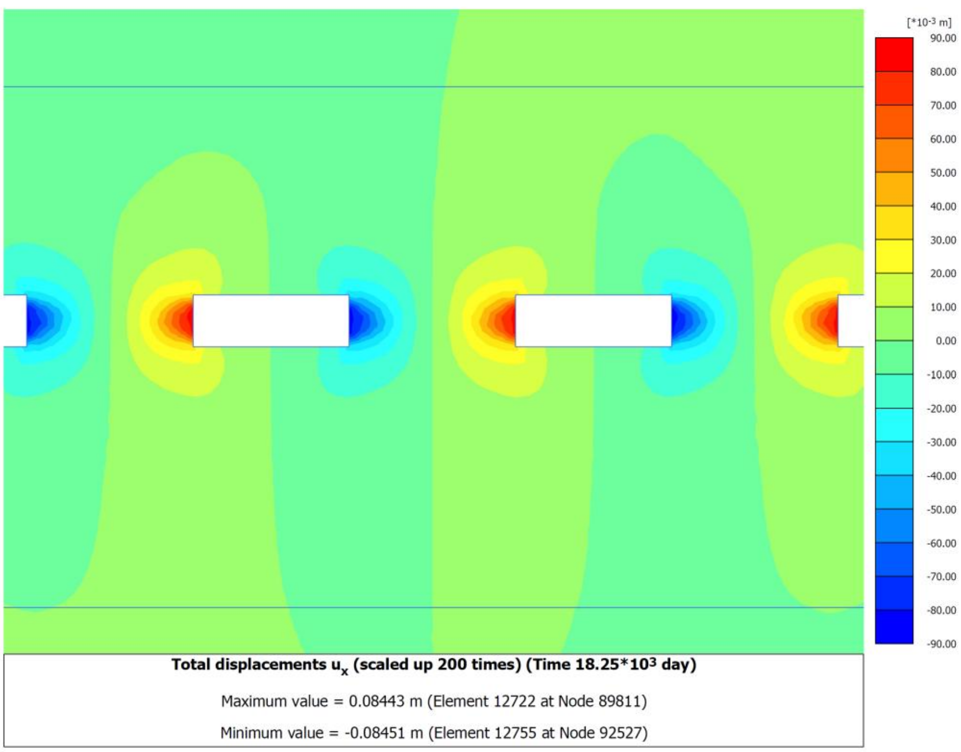



(b) Contour plot of the central rooms on the bottom salt rock layer

Figure 16: Vertical displacement after 30 years creep

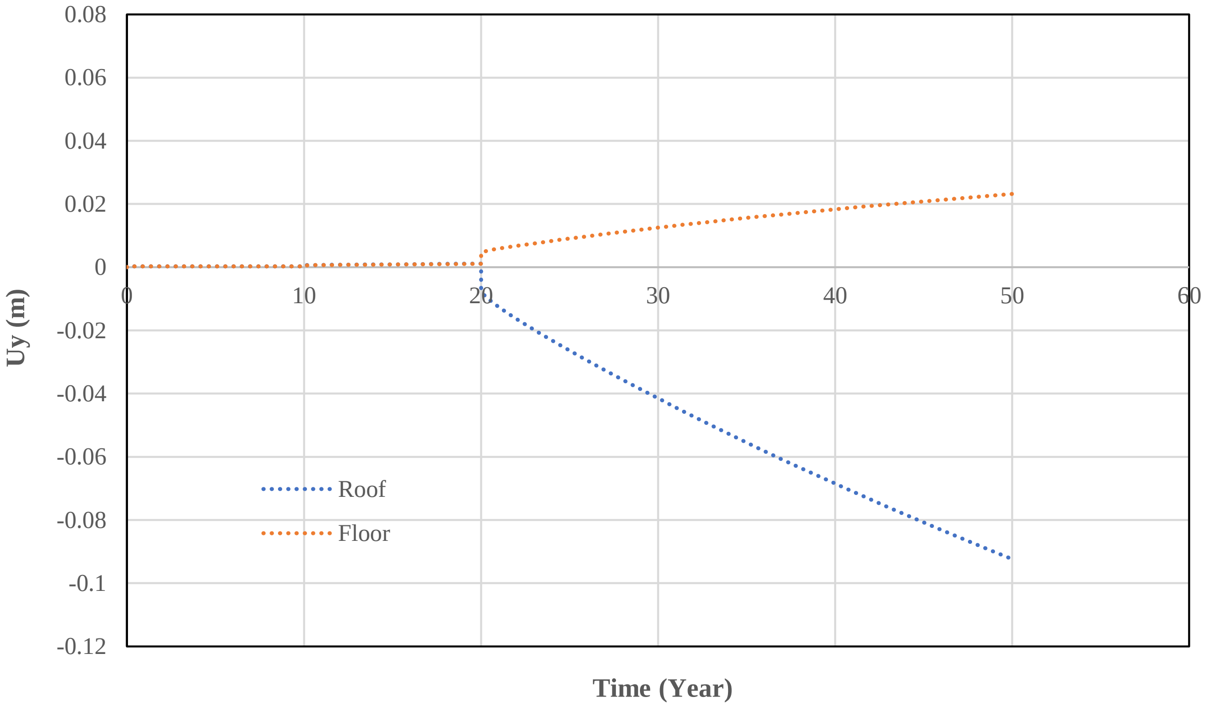



(a) Contour plot of the complete model

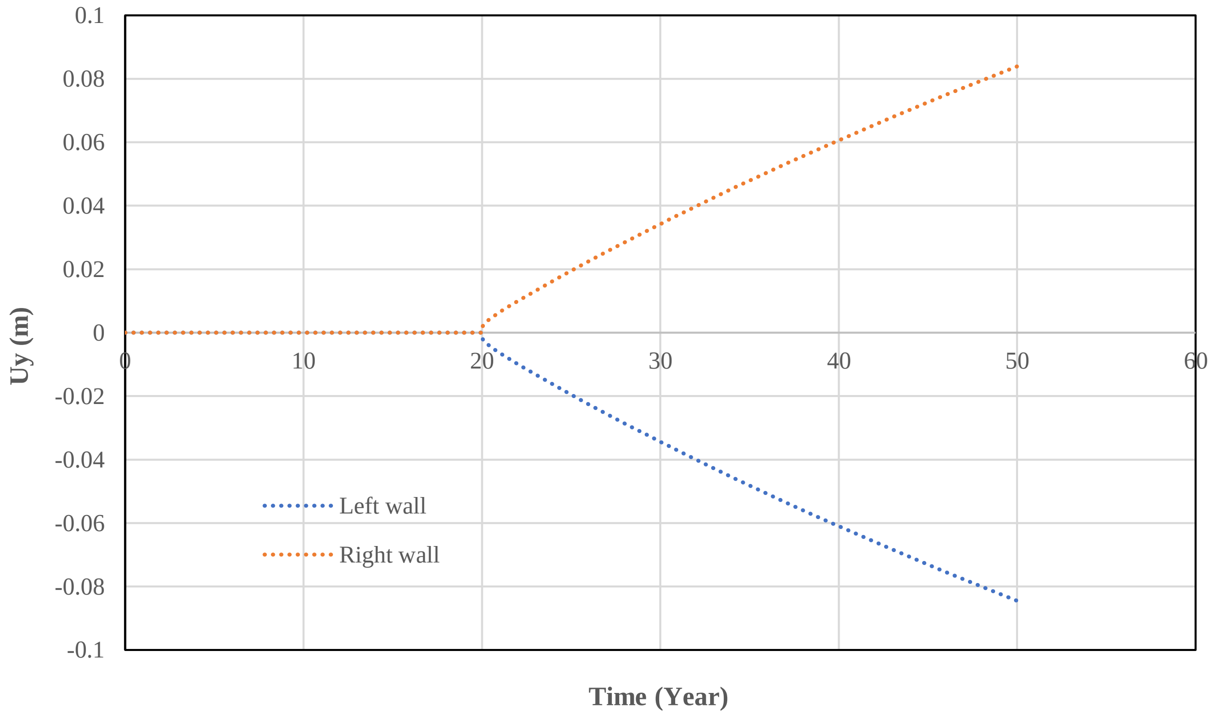



(b) Contour plot of the central rooms on the bottom salt rock layer

Figure 17: Horizontal displacement after 30 years creep




(a) Vertical displacement of the room and floor




(b) Horizontal displacement of the left and right walls

Figure 18: Convergence of the centre room on the bottom salt rock layer

Figure 19 illustrates the time-dependent ground subsidence resulting from the excavation of three layers of salt rock. The plot reveals that the subsidence rate accelerates with the excavation of the middle and bottom salt rock layers. After 30 years of mining all three layers, the total subsidence is approximately 10.6 cm at the ground surface.

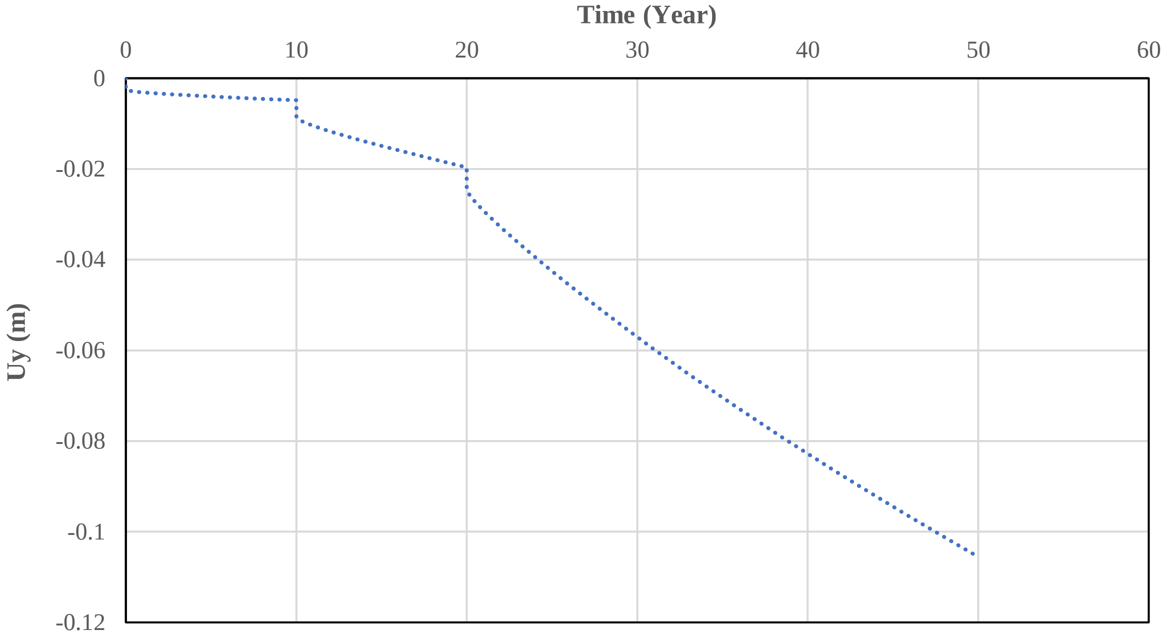


Figure 19: Time-dependent ground subsidence

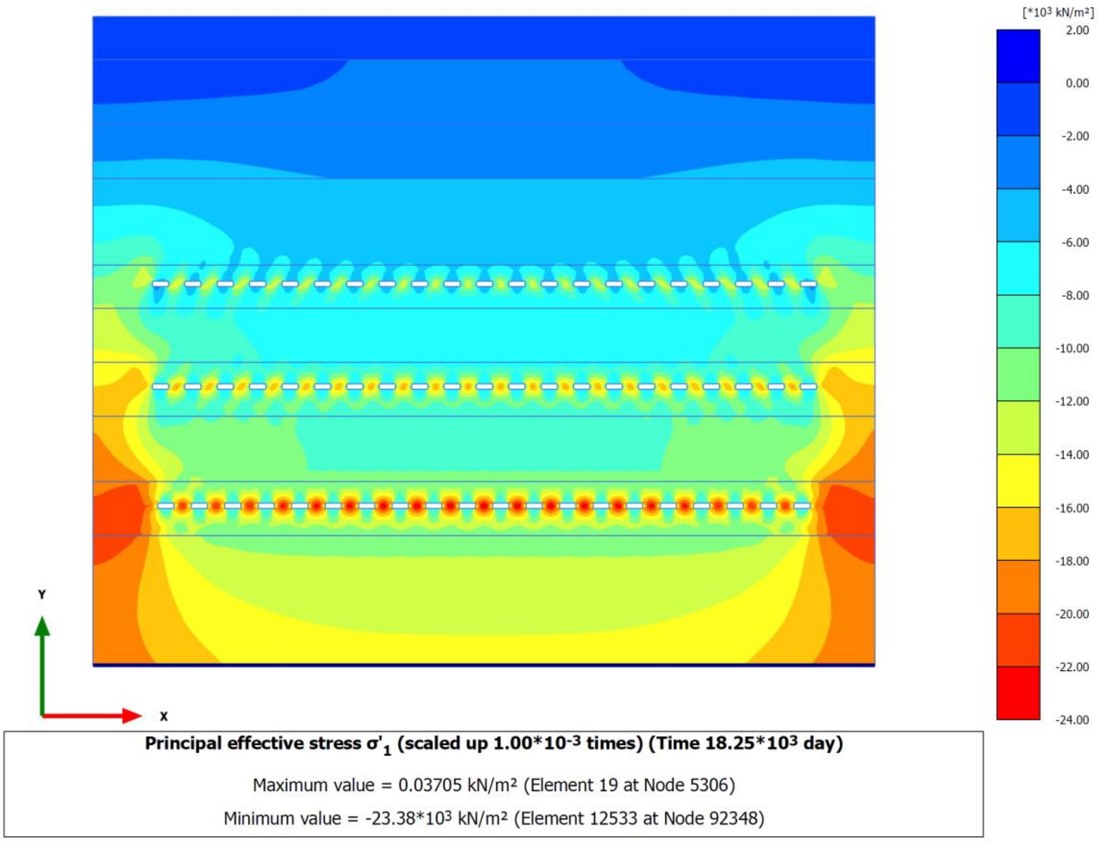
*Major and minor principal stresses*

Figures 20 and 21 display the major and minor principal stresses developed after 30 years of mining in the three layers of salt rock. As shown in Figure 20, the major principal stresses at all three levels are predominantly compressive and are primarily concentrated in the main body of the pillars. Around the rooms, much less compressive stresses are developed due to stress relaxation from the convergence. From top to the bottom levels, the compressive stress increases, especially at the main body of the pillars, where stresses rise from about 13 to 23 MPa.

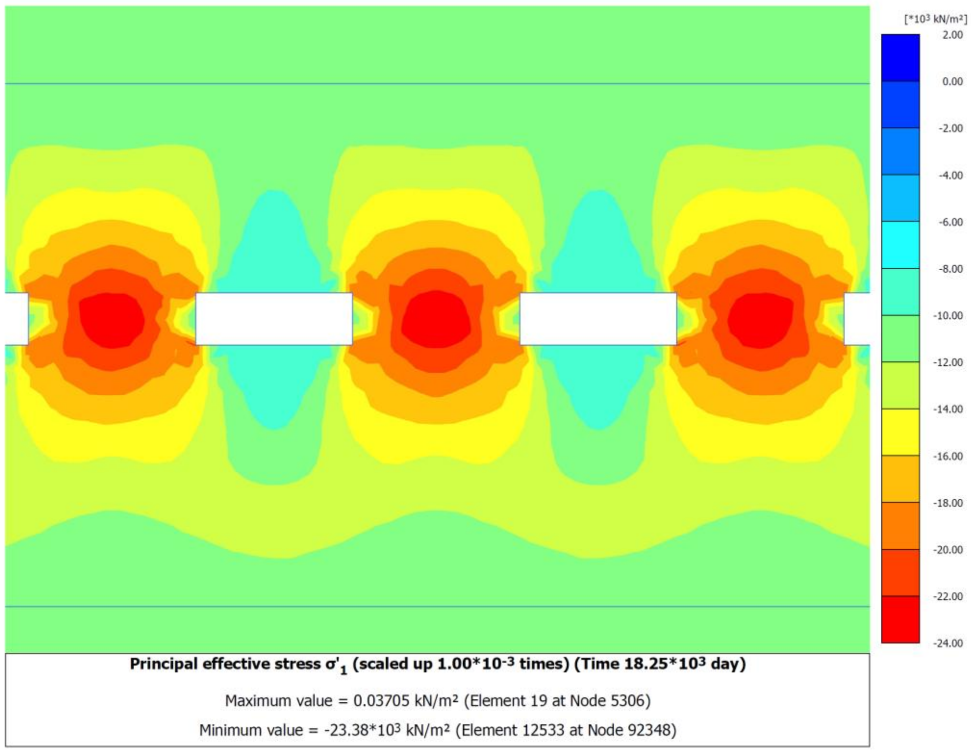
The minor principal stresses observed after 30 years creep shown in Figure 21 is also mainly compressive. However, development of tensile stresses can be seen at the roof and floor of the rooms as well as the sides of the pillars, due to the stress relaxation associated with the convergence process. From the top to the bottom levels, compressive stresses in the main body of the pillars increase and tensile stresses at the roof, floor and walls of the rooms also rise. At the bottom level of the salt rock unit, tensile stresses exceed 1 MPa in some areas around the rooms, which may initiate the formation of openings or small fractures at the roof, floor or sides of the pillars.

*Deviatoric stress and strength factor*

The distribution of the deviatoric stress after 30 years of the three layers salt rock mining shown in Figure 22 indicates that higher shear stress develops from the corner of the rooms and extends a few meters inside the pillars from the walls. The high shear stress concentrations at the room corners are attributed to the rectangular geometry of the rooms. From top to the bottom levels, shear stress in the room and pillar structure increases. The maximum shear stress is about 12 MPa at the centre of the panel on the bottom salt rock level. Based on the plot of the strength factor shown in Figure 23, strength factors are close to 1 at the sides of most pillars in the bottom layer, indicating the possible degradation of the pillars and potential occurrence of fractures or failure collapse. Therefore, it may be necessary to either adjust the room and pillar dimensions or provide additional support for the excavated openings on the bottom floor.

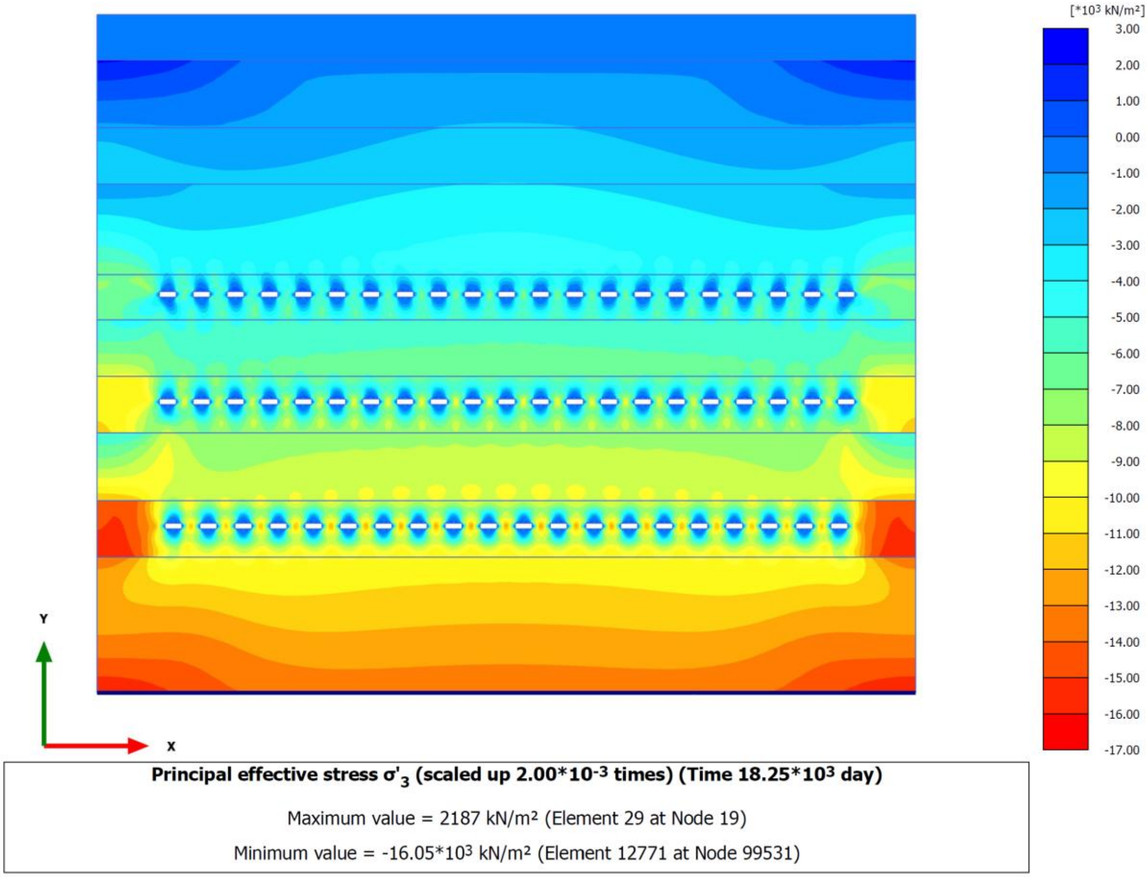



(a) Contour plot of the complete model

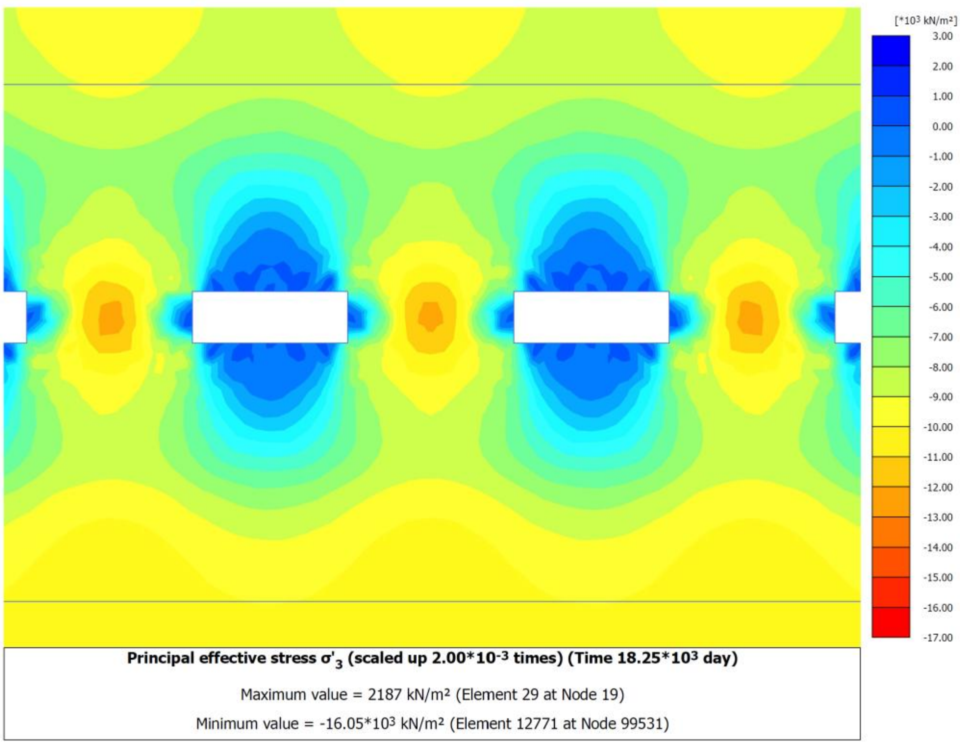



(b) Contour plot of the central rooms on the bottom salt rock layer

Figure 20: Major principal stresses after 30 years creep

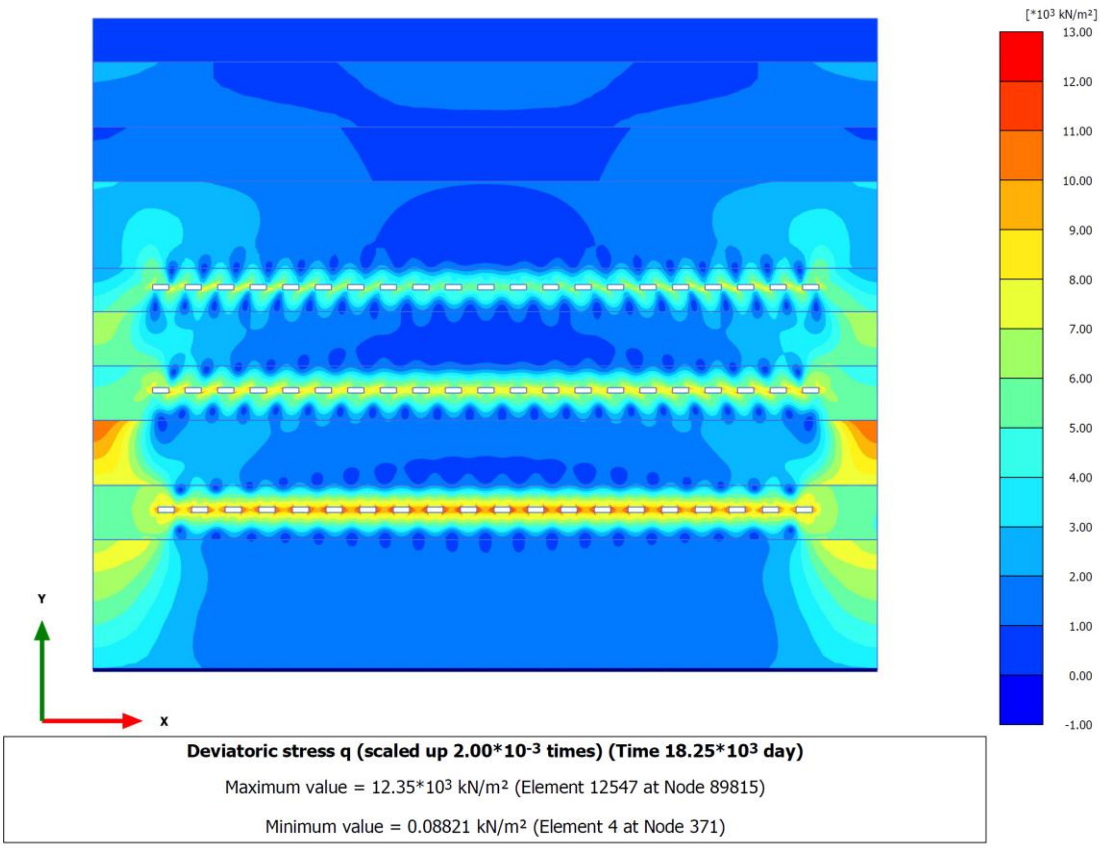



(a) Contour plot of the complete model

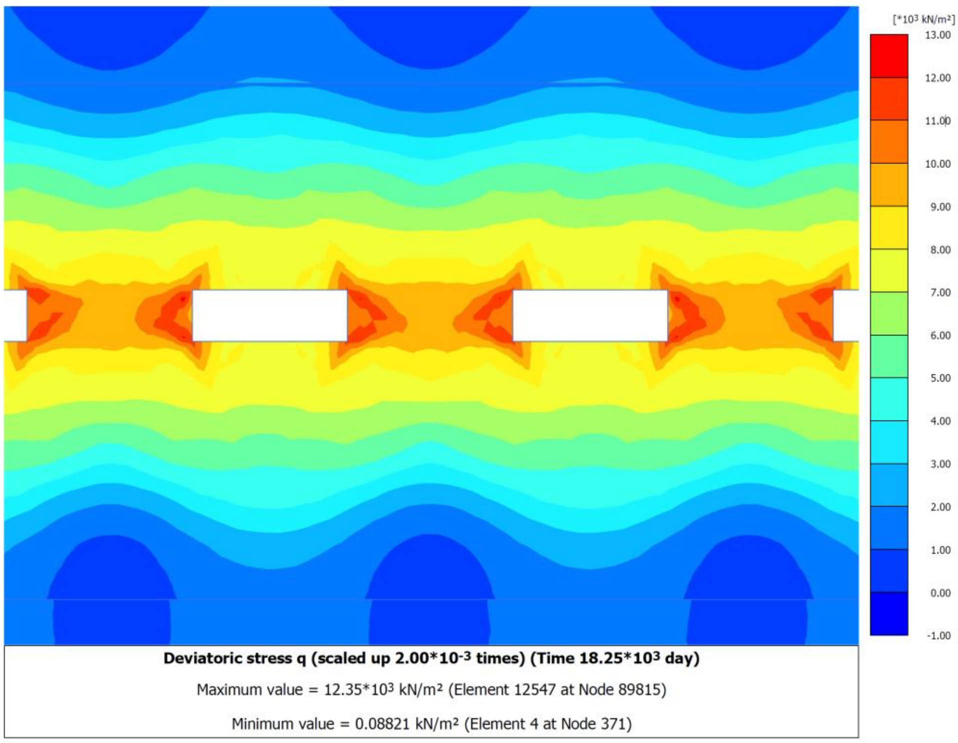



(b) Contour plot of the central rooms on the bottom salt rock layer

Figure 21: Minor principal stresses after 30 years creep

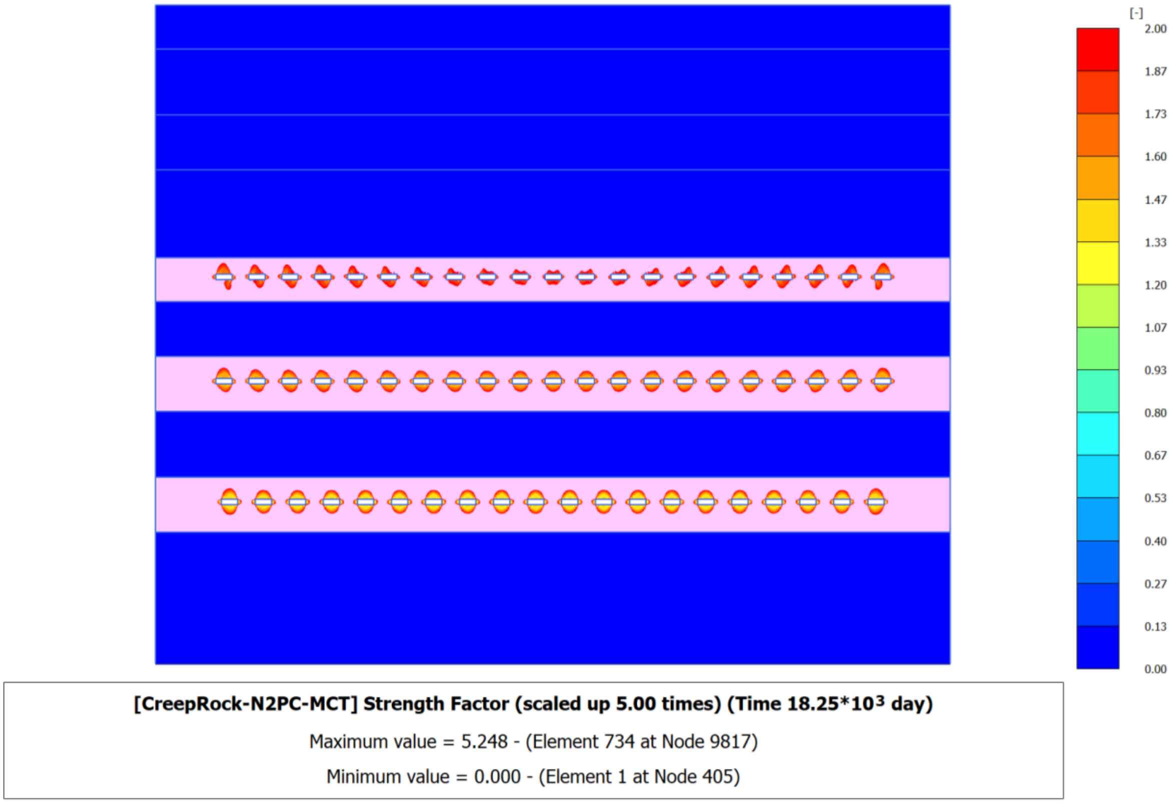



(a) Contour plot of the complete model

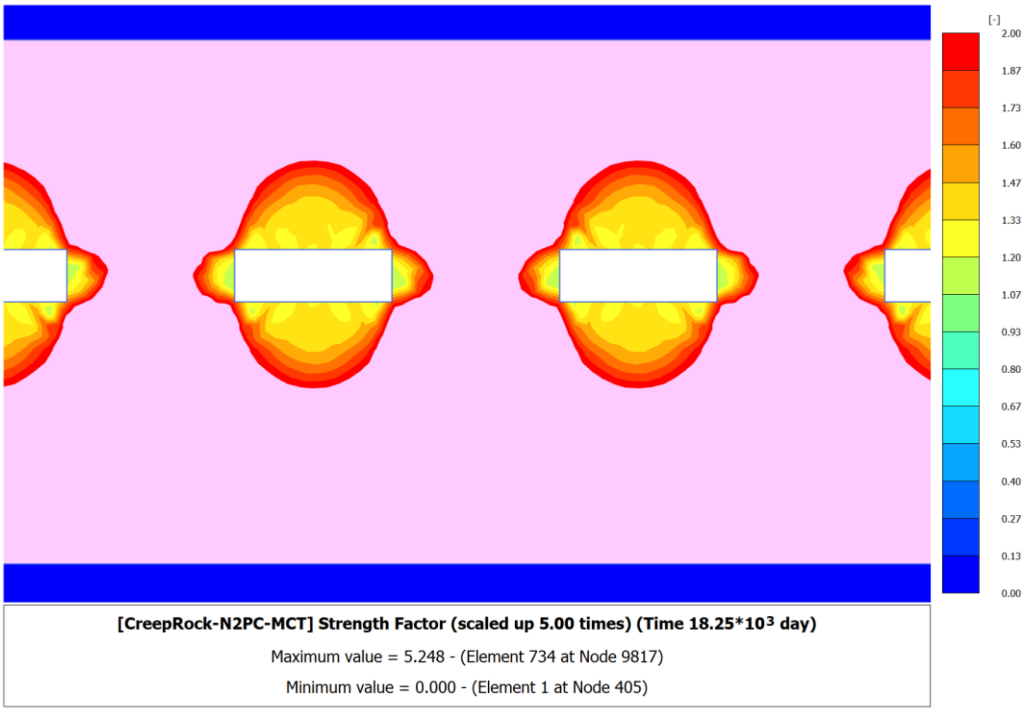



(b) Contour plot of the central rooms on the bottom salt rock layer

Figure 22: Deviatoric stresses after 30 years creep




(a) Contour plot of the complete model




(b) Contour plot of the central rooms on the bottom salt rock layer

Figure 23: strength factor after 30 years creep

# 4.

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