PLAXIS

Assessment of Long-Term Deformation and Stability of Room-and-Pillar Structures in Salt Mines Using 3D Modelling

PLAXIS 3D 2024.3

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1. Introduction

The room-and-pillar excavation method is extensively used in the salt rock mining industry due to the inherent stability of salt rock. As the name implies, rooms are the excavated spaces, while pillars are the remaining material that serves as support structures. To ensure mine stability and maximize the extraction ratio, it is crucial to carefully design the dimensions of the rooms and pillars. For square or rectangular pillars and rooms, 3D numerical simulation of the stability and deformation of the planned room-and-pillar layout has become widely applied. This approach offers more detailed representation of the actual geometry and stress-strain conditions, and predicts behaviors more accurately.

This example illustrates the practical use of PLAXIS 3D for the preliminary assessment of stability and time-dependent deformation in salt rock under square room-and-pillar mining conditions. Figure 1 below shows the top view of the planned room-and-pillar layout for part of a salt mine, featuring square pillars and rooms with crosscuts of equal width. In this example, a 3D model representing half the width of a vertical layer of the mine is constructed to simulate the entire mine (as illustrated in Figure 1), utilizing symmetry to save computing time.

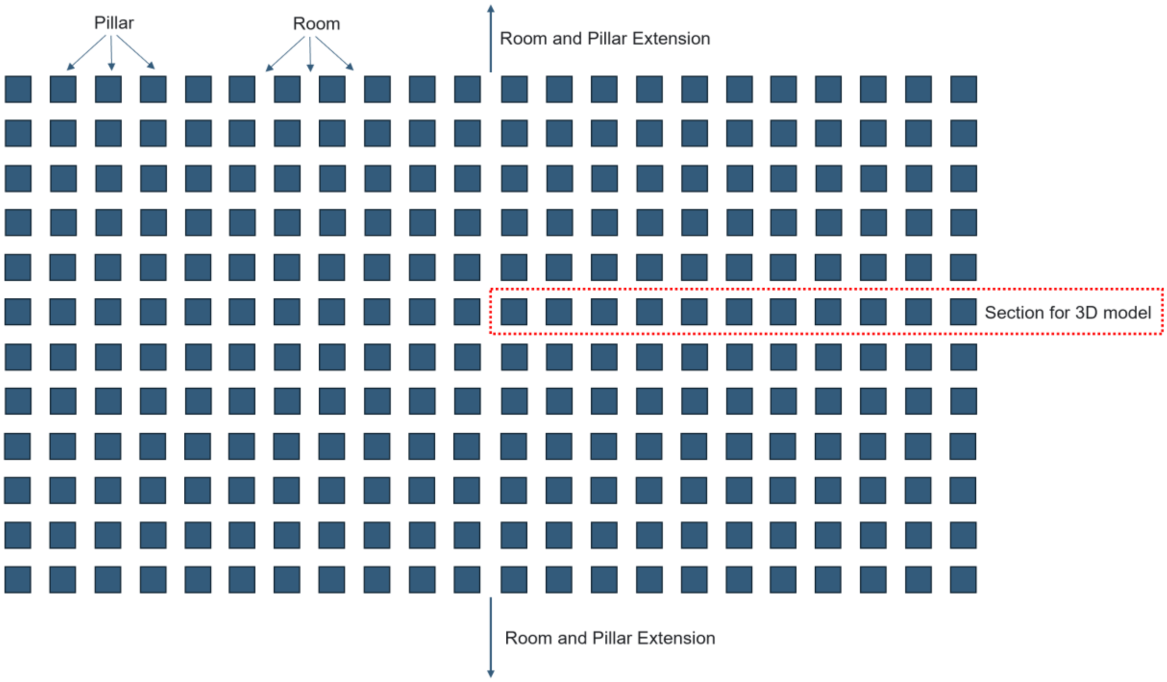


Figure 1: Arrangement of the room and square pillar mining layout (top view)

Figure 2 depicts the front view of the stratigraphy and the designed room-and-pillar layout. The stratigraphy consists of three salt rock layers interbedded with dolomite, topped by sandstone and limestone units, and overlain by overburden soil. Each salt rock layer will have square rooms excavated with dimensions of 14 meters in width and 5 meters in height. There are 25 pillars on each salt rock horizon, each measuring 23 meters in width. Excavation will proceed from the top to the bottom salt rock levels, with a 10-year time interval between each level. To utilize symmetry and optimize computing time, the model represents half the mine's width, including half of the room at the left vertical boundary.

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).

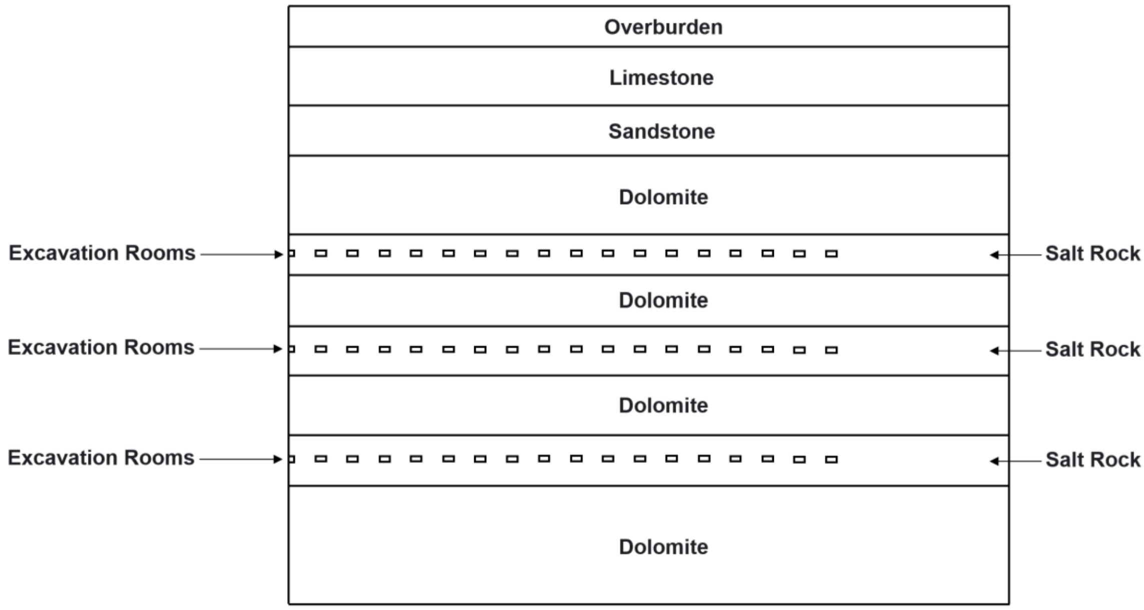


Figure 2: Stratigraphy and room-and-pillar excavation layout (front view)

Keywords: PLAXIS 3D, 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, specify the project properties (refer to Figure 3). The PLAXIS 3D model dimensions are set to 1400 m in length (from x_{min} = 0 m to x_{max} = 1400 m) and 37 m in width (from y_{min} = 0 m to y_{max} = 37 m), using 10-noded quadratic elements.

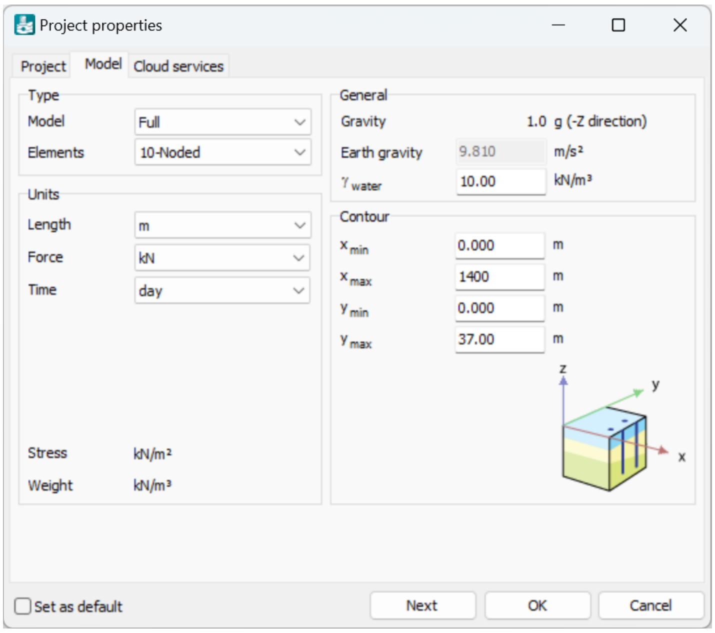


Figure 3: Definition of project properties.

Stratigraphy and material properties

The stratigraphy of the model is defined based on a borehole located at coordinates (0, 0, 0). It consists of ten horizontal soil and rock units extending from the ground surface to a depth of -600 m, as illustrated in Figure 4. Water is not considered in this model; hence, the water table is set at *Head* = -600 m, the bottom of the model, ensuring that the entire stratigraphy involved in this project is above the water level.

Table 1 summarizes the material properties for each soil and rock unit used in this model. Since the primary goal is to simulate the stability and long-term deformation of the salt materials, the non-salt materials are modeled using the Mohr-Coulomb model for simplicity. The salt units are modeled as N2PC-MCT material (Norton-based Double Power Creep with the Mohr-Coulomb Tension cut-off failure criteria) to study the time-dependent deformation of the salt rock and predict its failure and damage behavior.

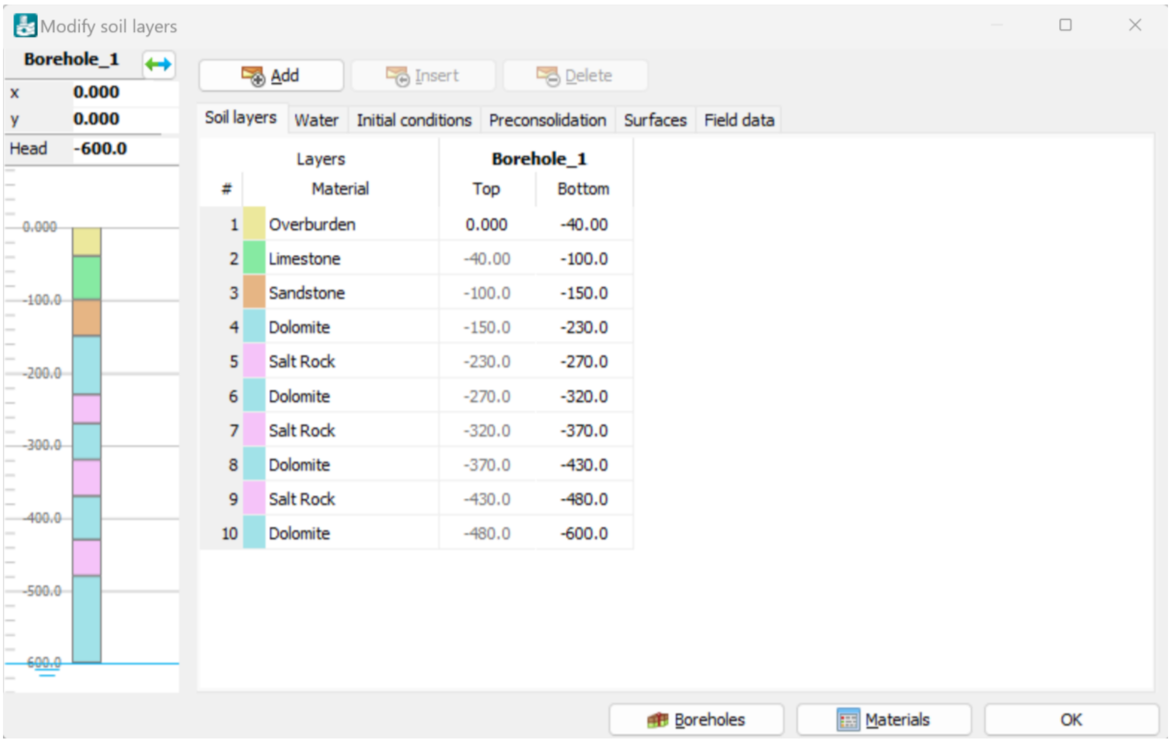


Figure 4: Definition of stratigraphy in borehole

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 γ_{unsat}	18 kN.m^{-3}	25 kN.m^{-3}	23 kN.m^{-3}	28 kN.m^{-3}	22 kN.m^{-3}
Unit weight saturated γ_{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	5000 kPa
φ'	28^{o}	48^{o}	48^{o}	38^{o}	35
ψ	0^{o}	19^{o}	20^{o}	9^{o}	8
N1	-	-	-	-	3.5
A1	-	-	-	-	2E-12 day^{-1}
N2	-	-	-	-	2.5
A2	-	-	-	-	0.8E-9 day^{-1}
q0	-	-	-	-	1000 kPa
qth	-	-	-	-	0 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 mining layout

Three strata of rooms will be excavated from the salt rock formations. Each room is designed with a height of 5 meters and a width of 14 meters. The supporting pillars exhibit a square configuration, with each side measuring 23 meters. To define the room and pillar mining layout, switch to the *Structures* mode. We will utilize the *Create surface*, *Create array* and *Extrude object* functions.

- Define the room-and-pillar layout for the top salt rock level. We will start by creating a series of surfaces, which will then be extruded to form the volume of the rooms to be excavated.
  - First, click on the *Create surface* icon, then enter the following point coordinates to create a surface: (0, 0, -245), (7, 0, -245), (7, 37, -245), (0, 37, -245). This surface will be extruded later to generate half of the room at the left boundary, representing the symmetry applied in the model.
  - Next, create the second surface using the following point coordinates (30, 0, -245) (44, 0, -245) (44, 37, -245) (30, 37, -245). Select this surface and click on the *Create array* icon. In the *Create array* window that opens, choose the “1D, in x direction” option for *Shape*, and enter 25 for the *Number of columns*. Set the *Distance between columns* in the x direction to 37 m, resulting in 24 additional copies of the surfaces being added at the same elevation in the geometry.
  - Create another surface by entering the following point coordinates: (0, 0, -245), (0, 7, -245), (918, 7, -245), (918, 0, -245). Select the newly created surface and replicate it using the *Create array* function again. Choose the “1D, in y direction” option for *Shape*, and enter 2 for the *Number of columns*. Set the *Distance between columns* in the y direction to 30 m, resulting in 1 additional copy of the surface being added to the geometry.
  - Next, multi-select all the created surfaces, then click on the *Extrude object* icon. In the *Extrude* window that opens, enter -5 for the z extrusion vector and press *Apply* to create the volume of the rooms to be mined out on the top salt rock layer. Figure 5 illustrates the geometry of the rooms to be mined out on the top salt rock level.
  - Finally, multi-select the volumes of the rooms just created, right-click on the selected volumes and choose *Group* to group the room volumes on the top salt rock layer. Rename the created Group_1 as Room_Top from the *Model explorer*, then delete all the created surfaces.

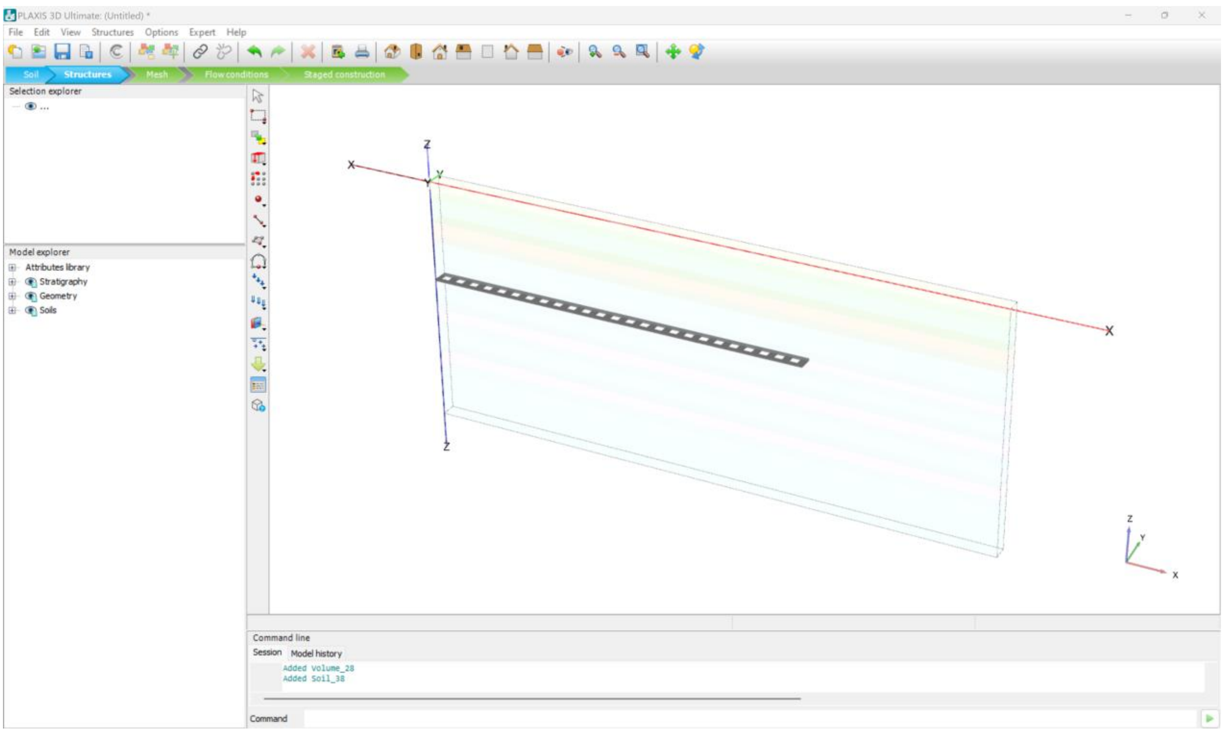


Figure 5: Geometry of the volume of the rooms to be mined out on the top salt rock layer

- Develop the room-and-pillar layout for the middle salt rock level:
  - Multi-select all the room volumes on the top salt rock layer, then click on the *Create array* icon. Choose the “1D, in z direction” option for *Shape*, and enter 2 for the *Number of columns*. Set the *Distance between columns* in the z direction to -95 m, adding a copy of the excavation room volumes to the middle layer of the salt rock unit. Group these excavation room volumes on the middle salt rock layer as Room_Middle.

- Develop the room-and-pillar layout for the bottom salt rock layer:
  - Repeat the same procedure to create a copy of the excavation room volumes on the bottom layer of the salt rock unit. This time, enter -205 for the *Distance between columns* in the z direction in the *Create array* window. Group these excavation room volumes on the bottom salt rock layer as Room_Bottom. The final geometry of the room volumes to be excavated in all three salt rock layers is illustrated in Figure 6.

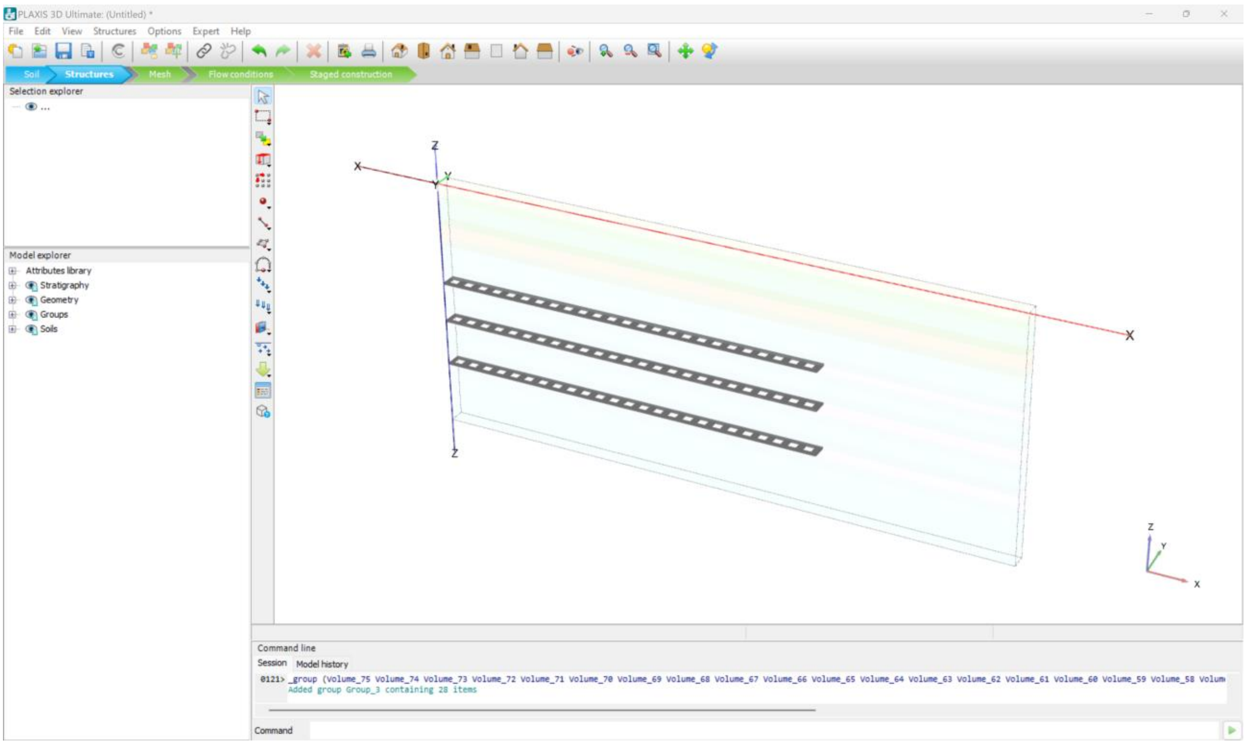
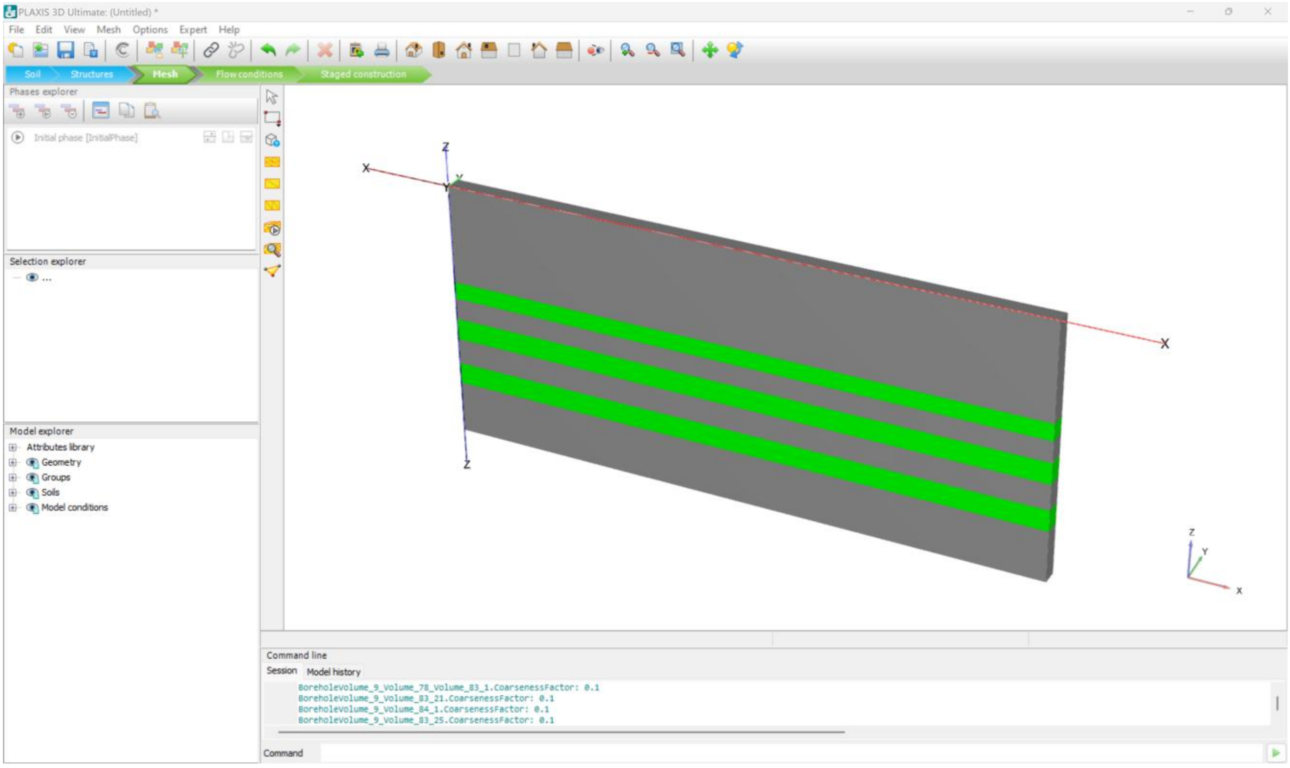


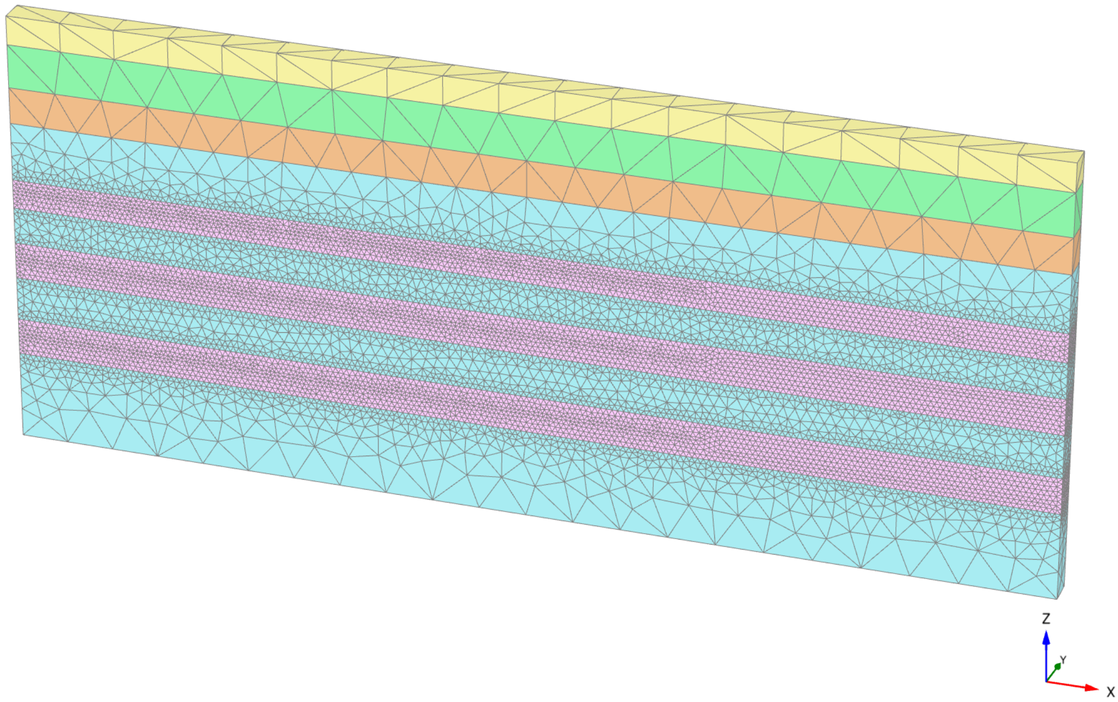
Figure 6: Spatial configuration of the rooms to be mined out across all three salt rock layers

Mesh generation

Switch to *Mesh* mode and refine the mesh by adjusting the coarseness factor of all three salt rock units to 0.1, as illustrated in Figure 7a. Next, generate a mesh using a *Medium* element distribution. The resulting mesh from the PLAXIS Output program is shown in Figure 7b.



(a) coarseness definition



(b) mesh presentation

Figure 7: Mesh generation

Definition of the construction stage

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

Initial conditions

Start by defining the initial conditions. Since that the stratigraphy of this model is horizontal, one could stick to the default initial phase behaviour and use the K0-procedure as the *Calculation type* to generate the initial stresses.

Phase 1: Excavate rooms on the top salt rock layer

Create a new phase named 'Excavate rooms on the top salt rock layer' and deselect 'Room_Top' in the *Model Explorer* to deactivate all rooms on the top salt rock level simultaneously (see Figure 8).

In the *Phases* window, navigate to the *Deformation control parameters* subtree and select the *Reset displacements to zero* option to remove the displacements calculated during the Initial conditions.

> Note: In this exercise, the mining of the rooms is simulated by deactivating all rooms at each layer simultaneously, which significantly 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.

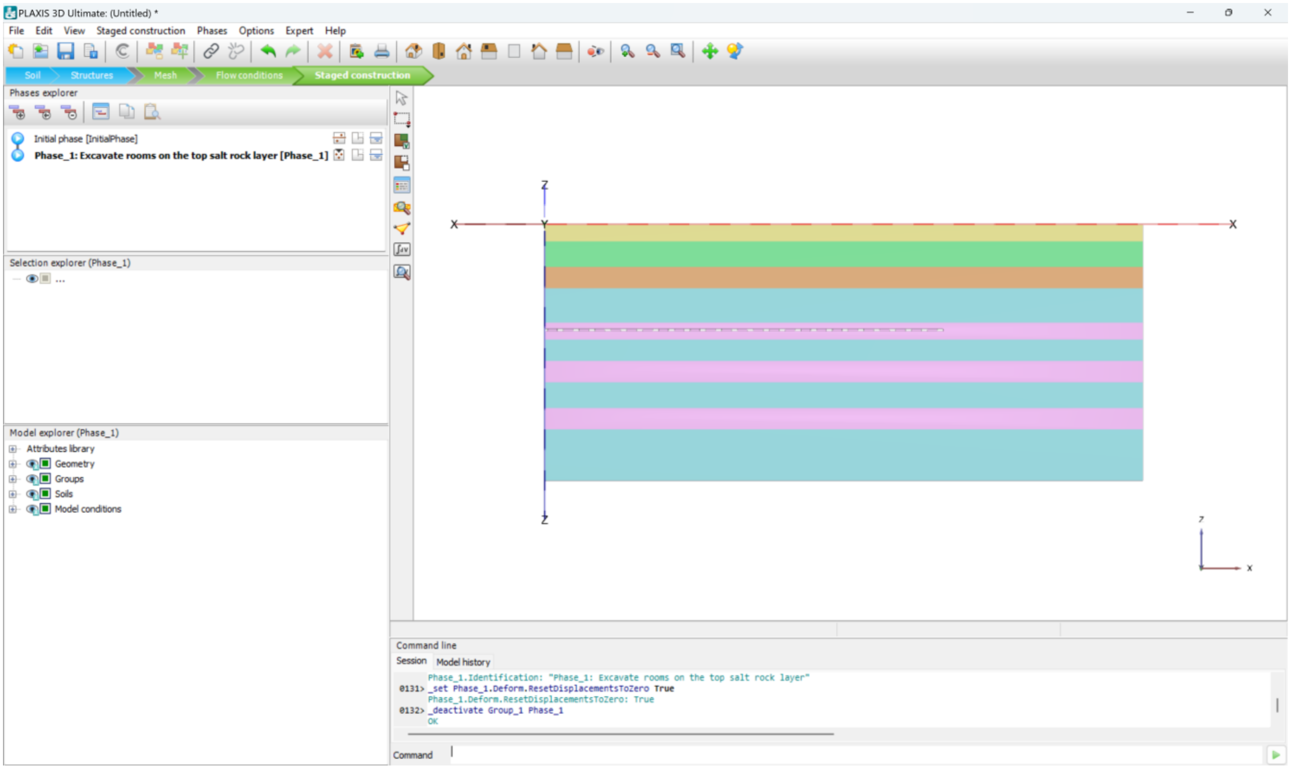


Figure 8: Excavation of rooms on the top salt rock layer

Phase 2: Creep for 10 years

Create a new phase titled 'Creep for 10 years' starting from phase 1, and set the *Time interval* to 3650 days in the *General* tab of the *Phases window* (see Figure 9).

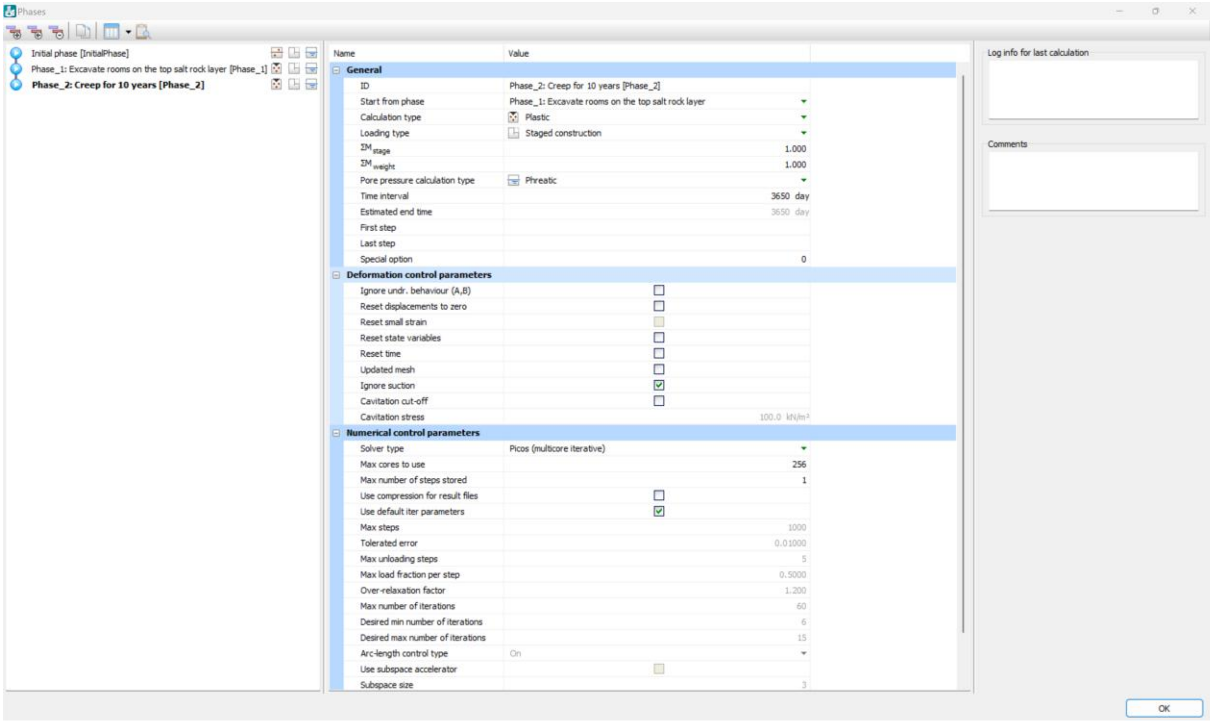


Figure 9: Time interval setup in the *General* tab of *Phases window*

Phase 3: Excavate room on the middle salt rock layer

Create a new phase titled ‘Excavate room on the middle salt rock layer’ starting from phase 2, and retain all the default settings in the *Phases window*. In the *Model Explorer*, deselect ‘Room_Middle’ to deactivate all rooms on the middle salt rock layer simultaneously (see Figure 10)

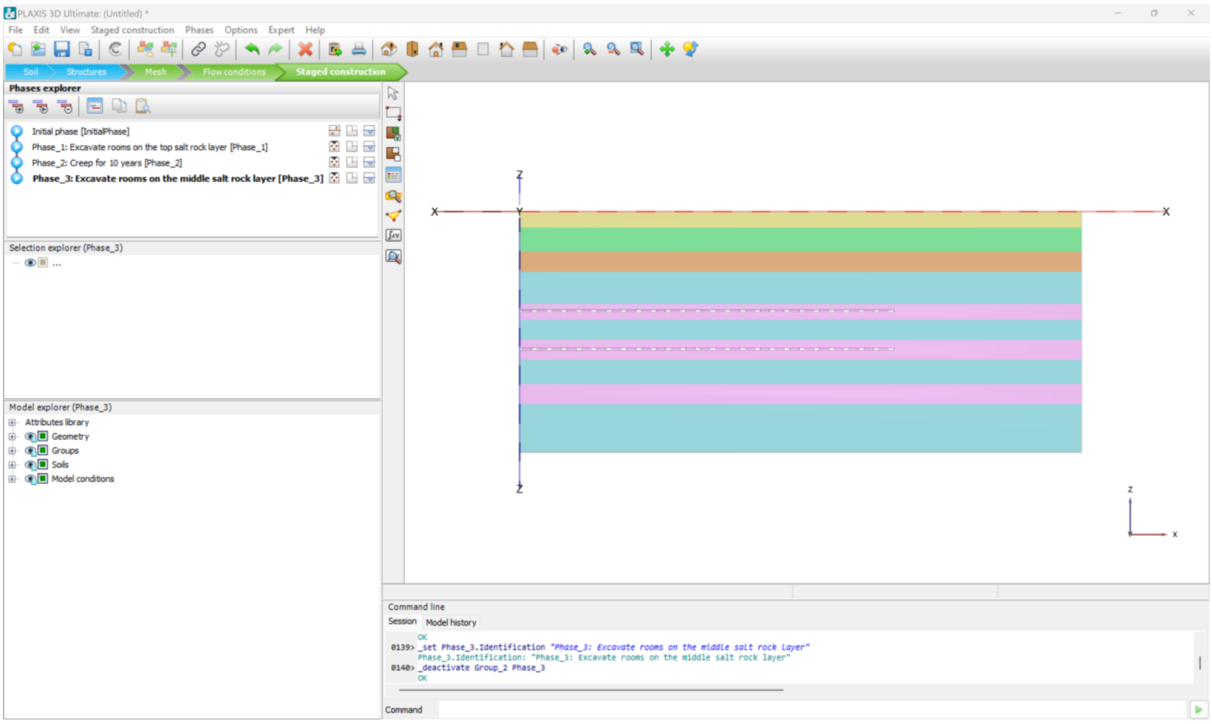


Figure 10: Excavation of rooms on the middle salt rock layer

Phase 4: Creep for 10 years

Create a new phase titled ‘Creep for 10 years’ starting from phase 3, and set the *Time interval* to 3650 days in the *General* tab of the *Phases window*.

Phase 5: Excavate rooms on the bottom salt rock layer

Create a new phase named ‘Excavate rooms on the bottom salt rock layer’ starting from phase 4, and retain all the default settings in the *Phases window*. In the *Model Explorer*, deselect ‘Room_Bottom’ to mine out all the rooms on the bottom salt rock layer simultaneously (see Figure 11).

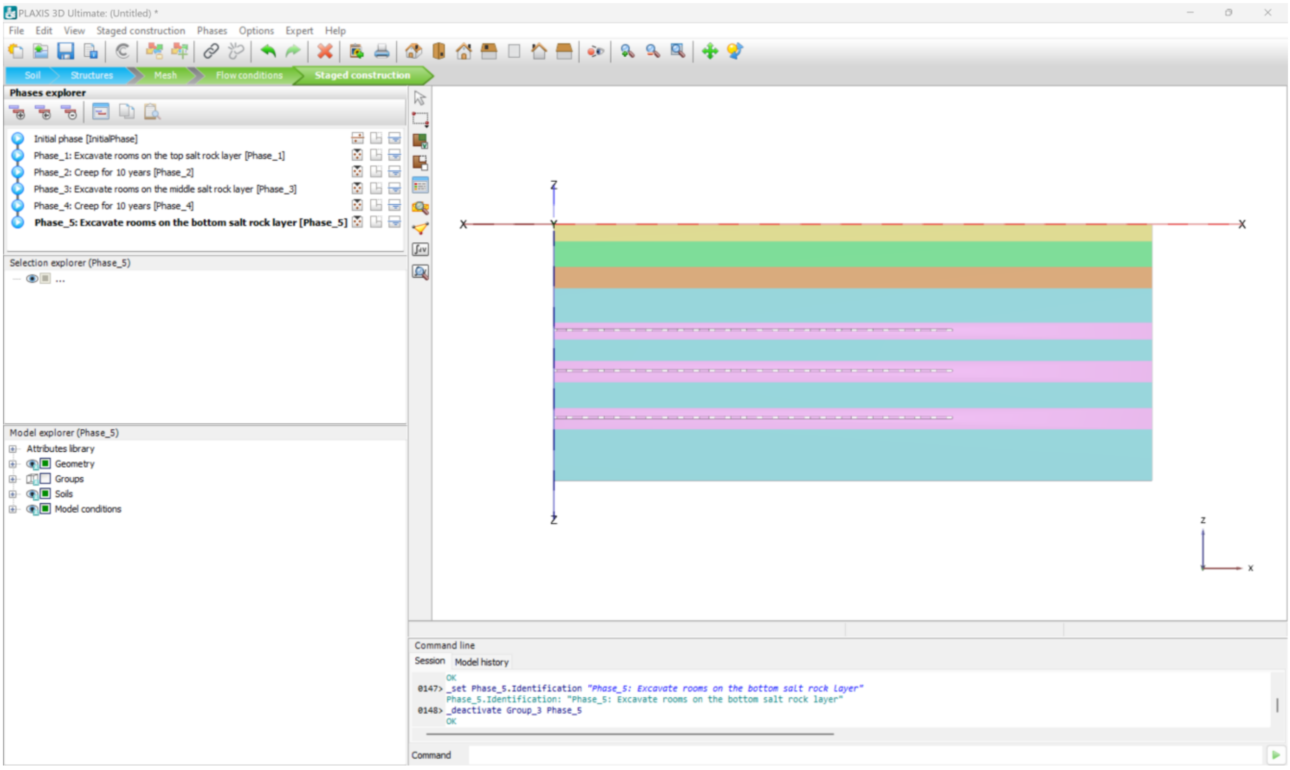


Figure 11: Excavation of rooms on the bottom salt rock layer

Phase 6: Creep for 10 years

Create a new phase titled ‘Creep for 10 years’ starting from phase 5, and set the *Time interval* to 3650 days in the *General* tab of the *Phases window*.

Phase 7: Creep for 20 years

Create a new phase titled ‘Creep for 20 years’ starting from phase 6, and set the *Time interval* to 3650 days in the *General* tab of the *Phases window*.

Phase 8: Creep for 30 years

Create a new phase titled ‘Creep for 30 years’ starting from phase 7, and set the *Time interval* to 3650 days in the *General* tab of the *Phases window*.

Before running the calculations, select nodal or stress points to monitor the evolution of local results over all intermediate steps within all phases. For this project, we are interested in ground subsidence due to excavation and room convergence. Therefore, select a few nodal points for this purpose:

- (0, 18.5, 0) to investigate the maximum ground subsidence.
- (0, 18.5, -450), (0, 18.5, -455), (7, 18.5, -452.5), and (30, 18.5, -452.5) to monitor the deformation of the roof, floor, and walls of the excavation room on the bottom salt rock layer, respectively.
- Once the monitoring points are selected, start the calculation by clicking on *Calculate*.

3.

Main Results

The main objective of this exercise is to evaluate the long-term stress and deformation effects resulting from the extraction of salt materials from salt rock units. This involves estimating room convergence and ground subsidence due to creep, as well as predicting potential tensile and shear failures in the room and pillar structure. To achieve this, contour plots of vertical displacement and time-dependent deformation graphs will be used to analyse room convergence and ground subsidence. Additionally, the distribution of major and minor principal stresses, deviatoric stress, and strength factors will be examined to assess the development of tensile and shear stresses around the room and pillar structure.

Room convergence and ground subsidence

Figure 12 depicts the vertical displacements observed 30 years post-excavation across all three salt rock levels at the vertical cross-section of the model's mid-thickness (y = 18.5 m). The maximum vertical displacement, approximately 21 cm, is observed at the roof of the room on the left boundary of the top salt rock level. This displacement extends to the ground surface, resulting in a subsidence of about 20 cm. As depth increases, vertical deformation decreases to 18 cm and 12 cm at the roofs of rooms on the left boundary of the middle and bottom salt rock layers, respectively. At the bottom salt rock level, the floor heave at the room on the left boundary is about 2 cm.

Figure 13 illustrates the time-dependent ground subsidence at the top left boundary, where the maximum subsidence is anticipated due to the mining of all three salt rock layers. The plot reveals a notable increase in the subsidence rate with each level's excavation, escalating from 1.1 mm/year to 2.3 mm/year, and then to 5.1 mm/year. 30 years after the completion of mining all three layers, the total subsidence is approximately 20 cm.

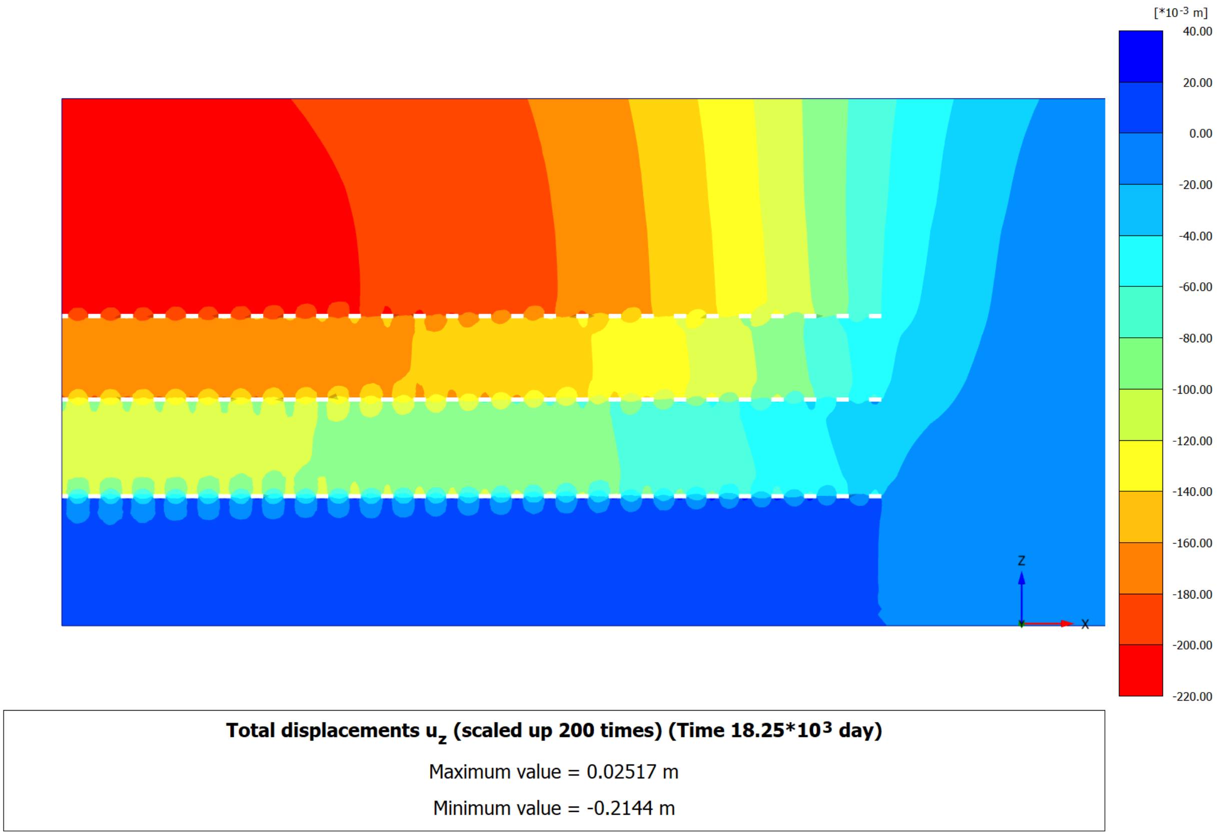


Figure 12. Contour plot of vertical displacement after 30 years creep of all excavations

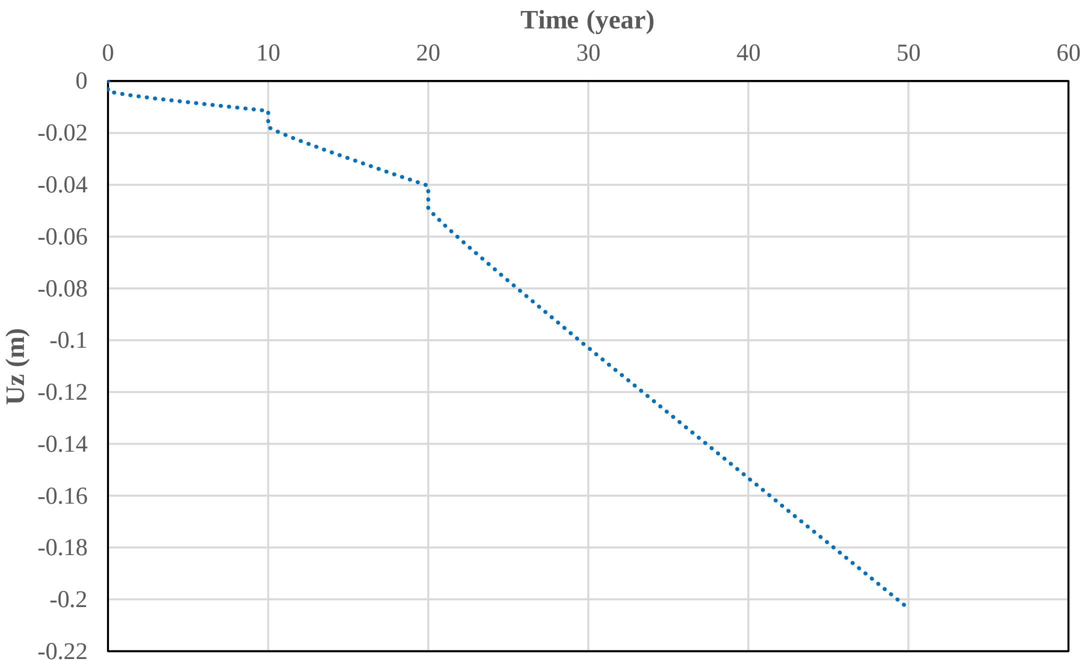
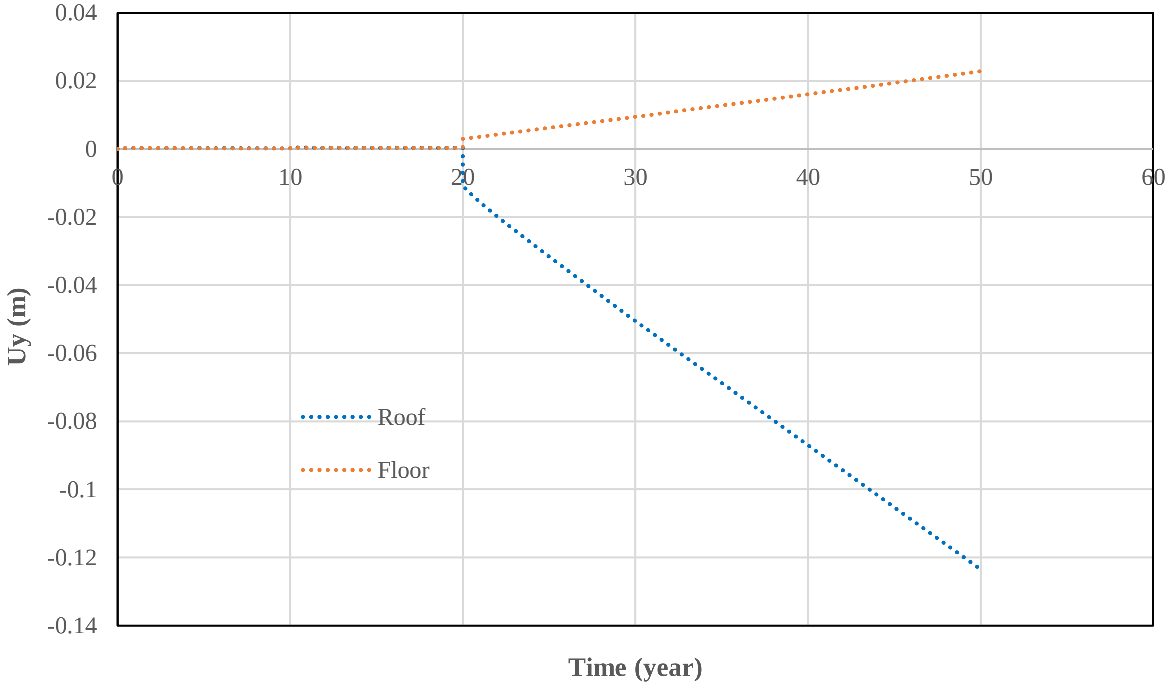
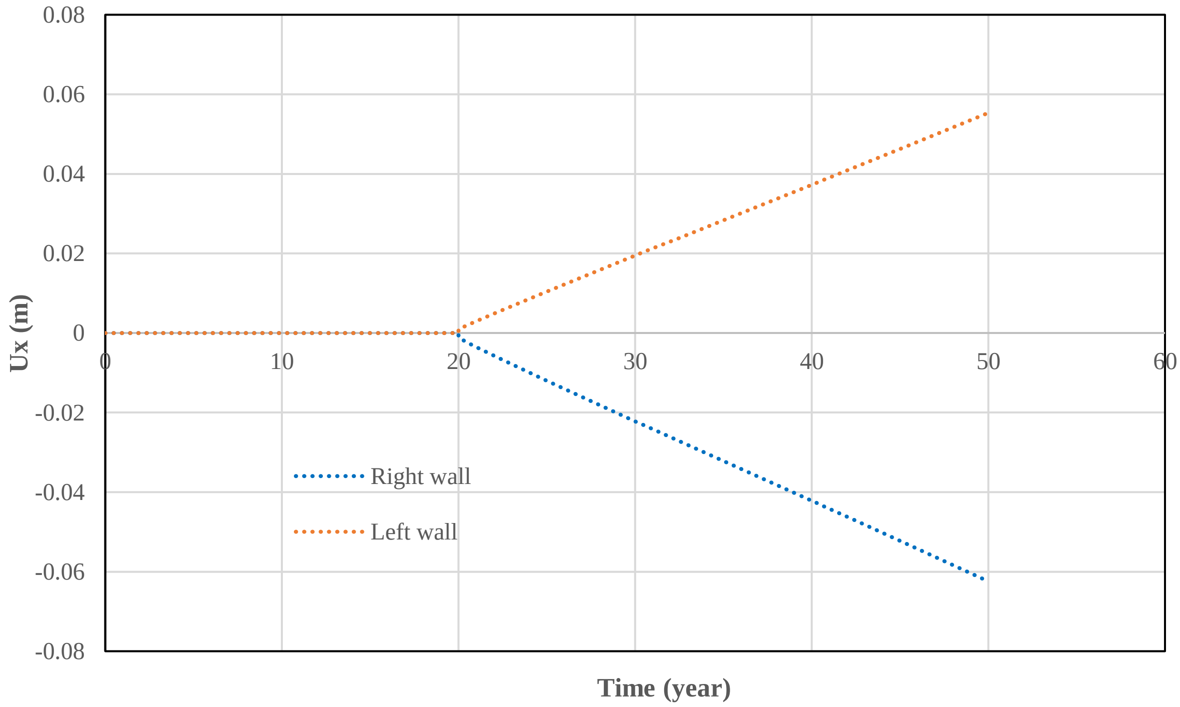


Figure 13. Time-dependent ground subsidence at the top left boundary

The assessment of room convergence was performed at the mid-points of the roof, floor, and right walls of the room located at the left boundary of the bottom salt rock level, where the most significant long-term deformation is expected. As only half of the room at the left boundary was modeled, the mid-point of the left wall of the first complete room was utilized to monitor the horizontal displacement. Inspection of the time-dependent deformation at these four locations (refer to Figure 14) reveals that creep initiated immediately upon excavation of the salt material at the bottom level. The vertical convergence rate is 3.7 mm/year at the roof and 0.7 mm/year heave at the floor, while the left and right walls exhibit convergence rates of approximately 1.8 mm/year and 2.1 mm/year, respectively.



(a) Vertical displacement of room and floor



(b) Horizontal displacement of left and right walls

Figure 14: Room convergence

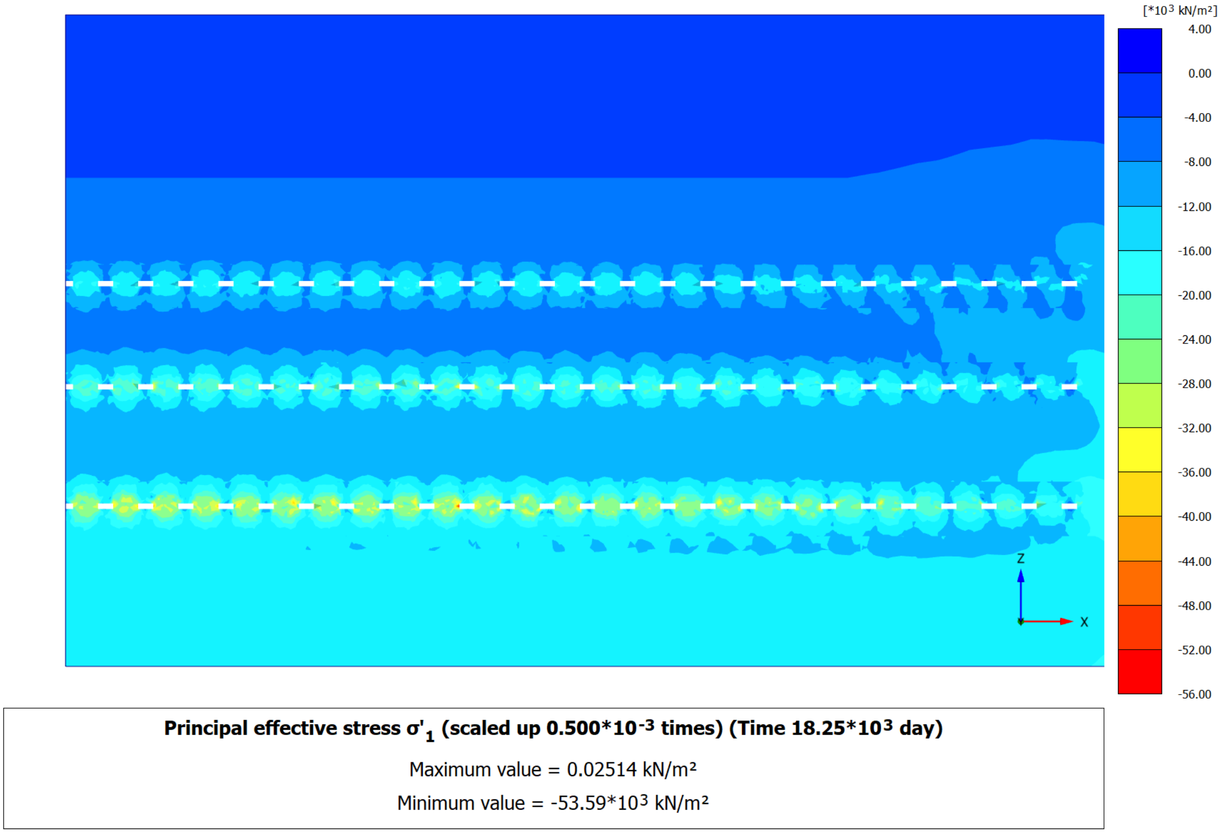
Tensile and shear stresses

Assessing tensile and shear stresses is essential for evaluating the stability of rooms and pillars in salt rock excavation, given their limited strength and the associated risk of failure and stability concerns.

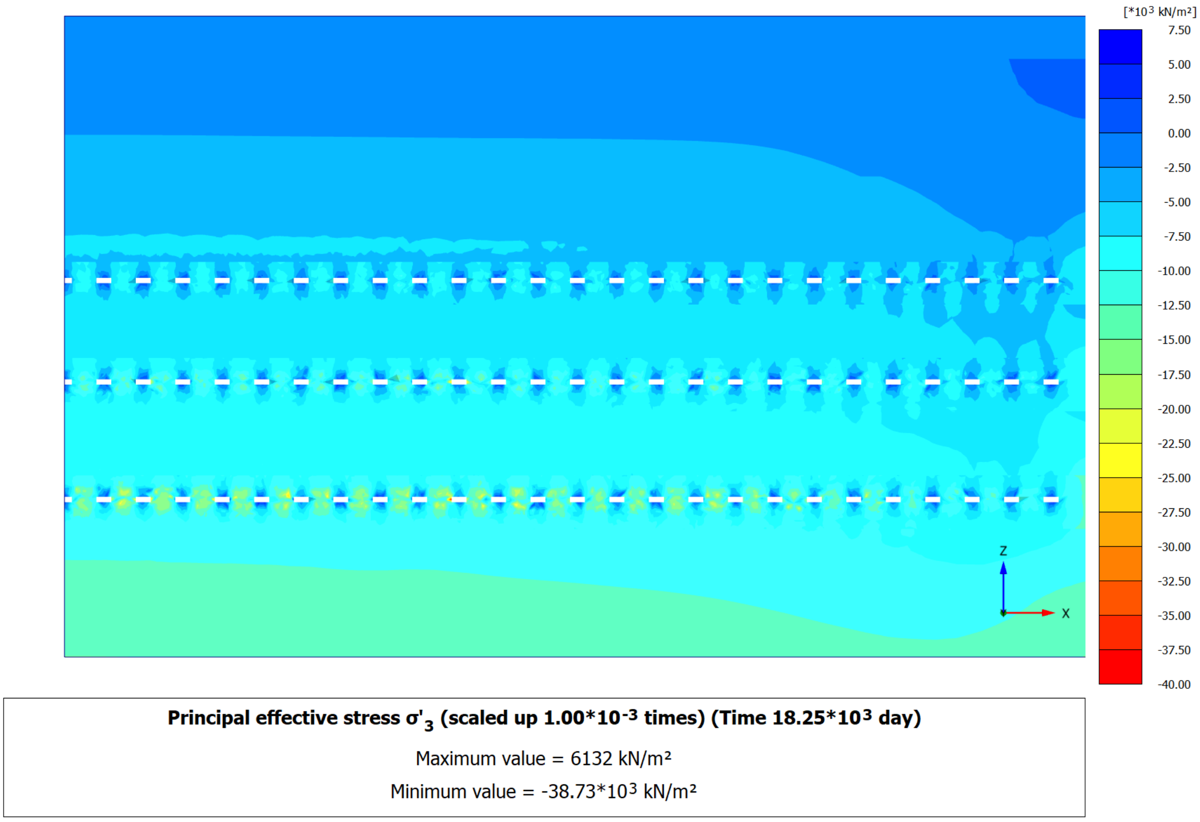
The assessment of tensile stress within the room and pillar structure can be derived from the contour plot of the principal stresses. Figure 15 presents the major and minor principal stresses 30 years post-mining of the three salt rock levels at the vertical cross-section of the model's mid-thickness (y = 18.5 m). As illustrated in Figure 15(a), the major principal stresses are predominantly compressive, concentrated at the pillars, and significantly increase with deeper levels. The minor principal stresses shown in Figure 15(b) are also primarily compressive; however, substantial tensile stresses are observed at the roof and floor of most rooms (see Figure 15(c)), suggesting the formation of fractures or tensile failure.

The evaluation of shear stress within the room and pillar structure can be performed based on the contour plot of deviatoric stress and strength factor at the vertical cross-section of the model's mid-thickness (y = 18.5 m) (see Figure 16). Figure 16(a) illustrates that, 30 years post-mining of all three salt rock levels, shear stress is predominantly concentrated at the room corners due to the square corners geometry, extending a few meters into the pillars from the walls, and intensifies with deeper levels. A close examination of the strength factor plot in Figure 16(b) reveals that strength factors below 1 are present around most rooms on the bottom salt rock layer, indicating a risk of fractures and failure collapse in the room and pillar structures.

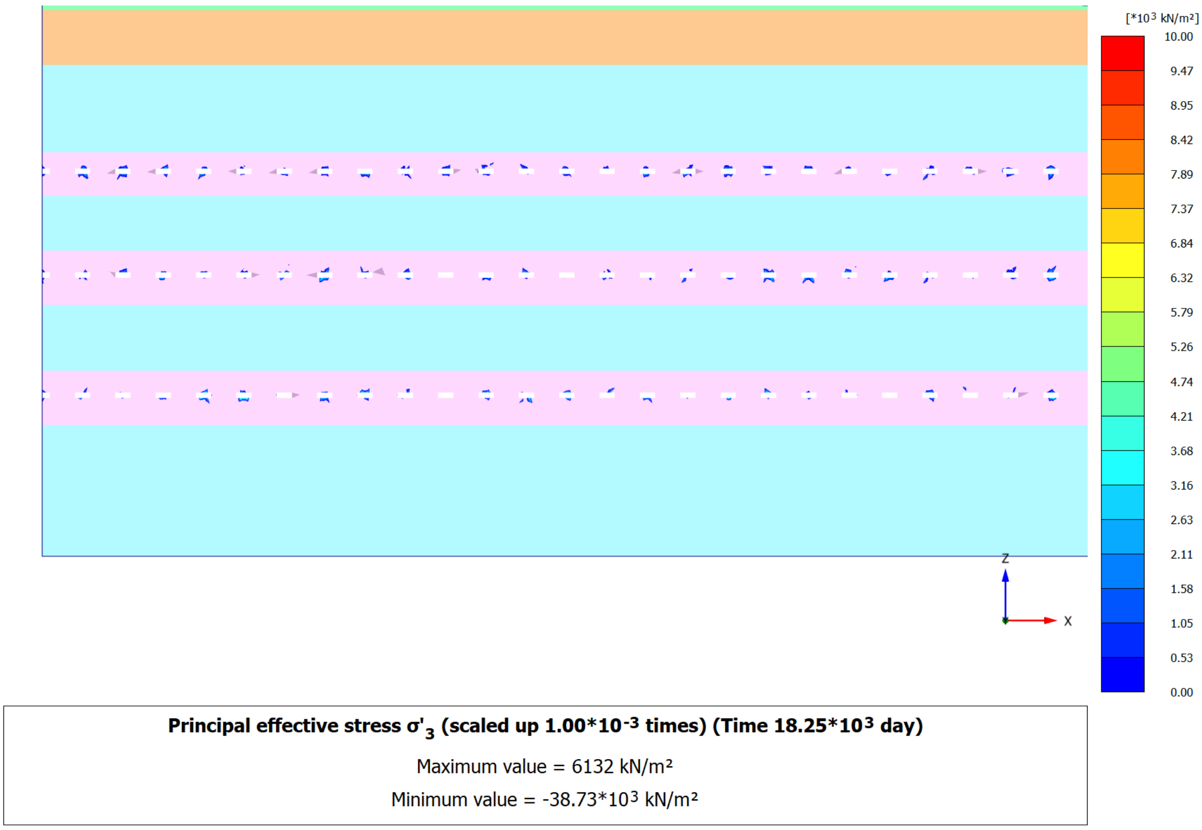
Consequently, although large-scale ground subsidence and room convergence are not concerns for this excavation, the combined failure associated with large tensile and shear stresses suggests that resizing the room and pillar structures, particularly on the third floor, and/or reinforcing the excavation openings is recommended.



(a) Major principal stress after 30 years creep of all excavations

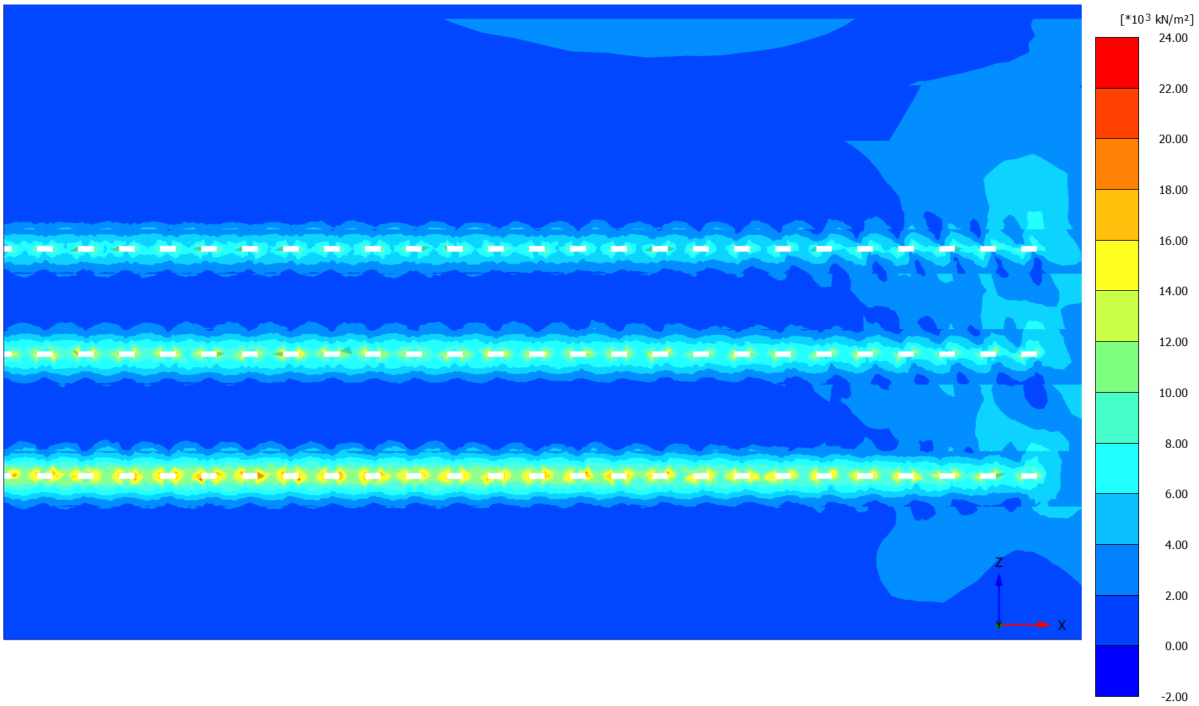


(b) Minor principal stress after 30 years creep of all excavations



(c) Minor principal stress after 30 years creep of all excavations (with scale 0-10 MPa)

Figure 15: Major and minor principal stresses after 30 years creep of all excavations

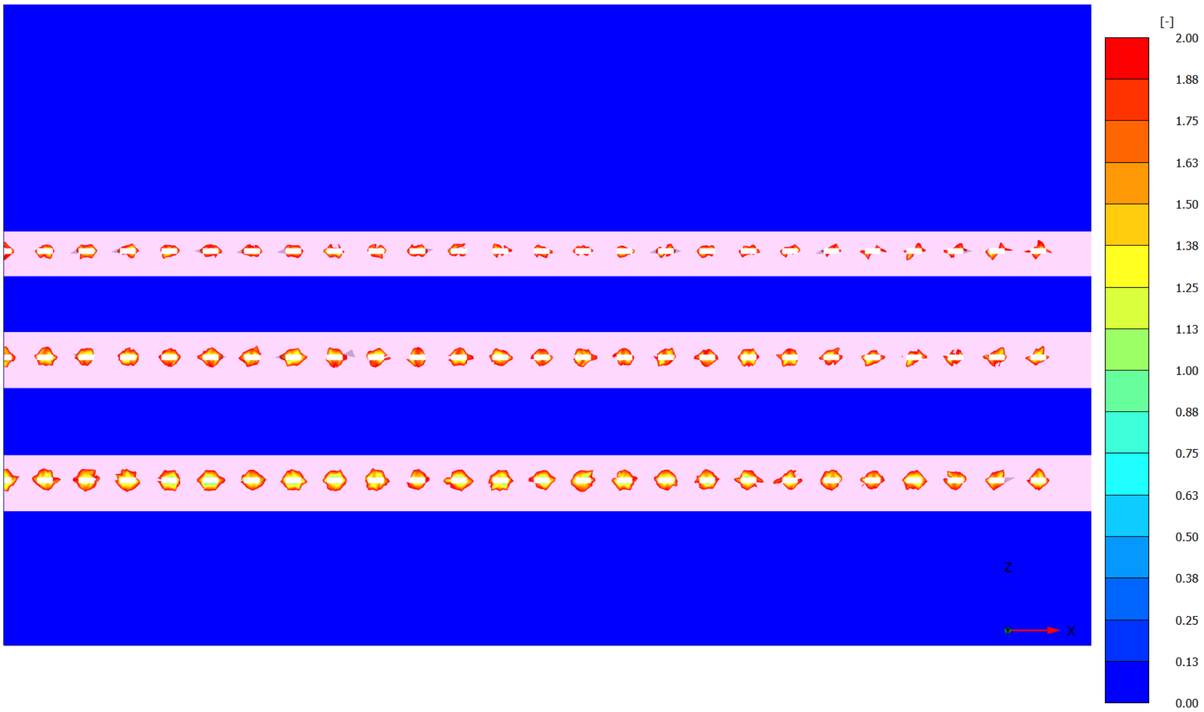


Deviatoric stress q (scaled up 2.00*10⁻³ times) (Time 18.25*10³ day)

Maximum value = 22.38*10³ kN/m²

Minimum value = 0.3249 kN/m²

(a) Deviatoric stress after 30 years creep of all excavations



[CreepRock-N2PC-MCT] Strength Factor (scaled up 5.00 times) (Time 18.25*10³ day)

Maximum value = 5.670 -

Minimum value = 0.000 -

(b) Strength factor after 30 years creep of all excavations (with scale 0 - 2)

Figure 16: Deviatoric stresses and strength factor after 30 years creep of all excavations

4.

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