

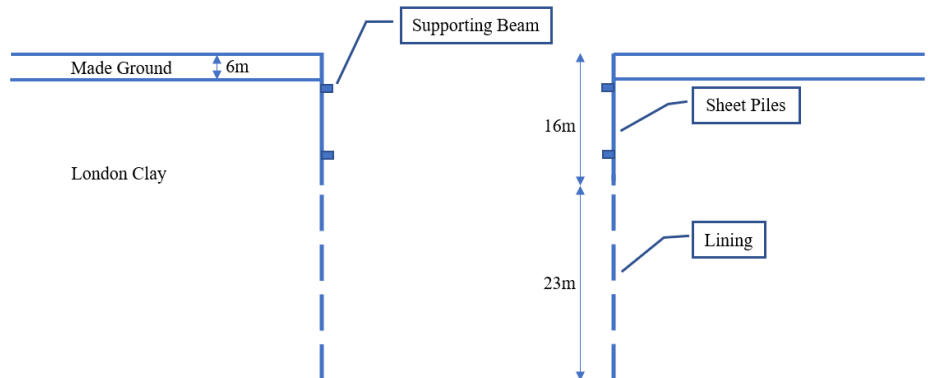
Tunnel Shaft

For LUSAS version:	23.0
For software product(s):	LUSAS Bridge plus or LUSAS Civil&Structural plus
With product option(s):	Geotechnical, Nonlinear

Problem Description

Tunnel shafts are vertical or inclined underground structures that connect the surface to tunnels, essential for construction access, ventilation, emergency egress, and operational functions like sewage, water, or rail.

This example of a vertical shaft has a diameter of 28m and a height of 39m. It is excavated through layers of made ground and London clay, with the made ground being 6m thick. To provide support, sheet piles supported by beams are used in the upper portion of the shaft, while sequential linings are utilised in the lower portion as shown in the following image. The water table is at 6m depth. Axial symmetry is assumed.



Tunnel shaft details

Keywords

Two Phase Elements, Interface Elements, Excavation, Pore Pressure, Structural Elements, Drained, Undrained.

Associated Files

Associated files can be downloaded from the user area of the LUSAS website.



tunnel_shaft.lvb carries out automated modelling of the example.

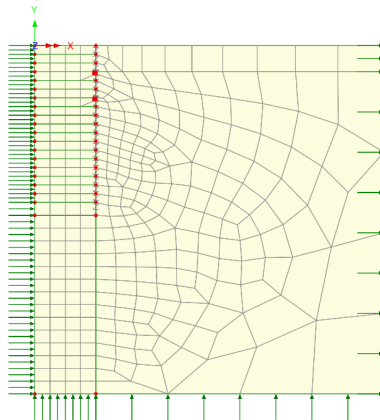
- Use **File > New** to create a new model of a suitable name in a chosen location.
- Use **File > Script > Run Script** to open the lvb file named above that was downloaded and placed in a folder of your choosing.

Objectives

Through this example, we demonstrate how different functions of LUSAS can be employed to develop the model, including construction stages of the supporting system comprising sheet piles, lining, and supporting beams.

Modelling overview

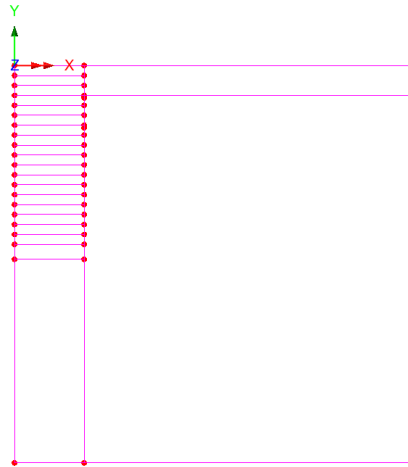
The model is created using an analysis category of **2D Axisymmetric** with model units of **kN,m,t,s,C**.



The model created from running the supplied script

Feature Geometry

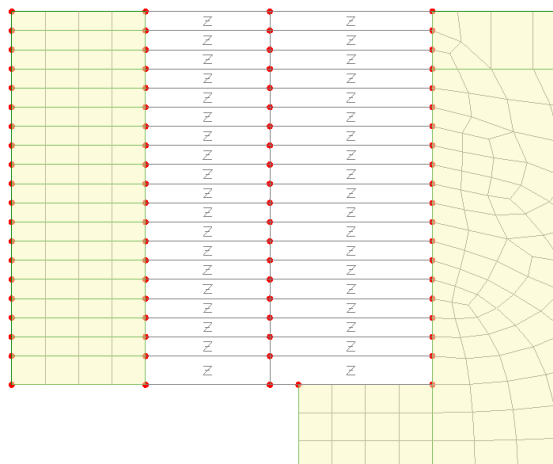
The model is created by entering point coordinates using the command **Geometry > Point > By Coords** to define the levels to be excavated as shown in the following image. Then, lines are connected between these points to form surfaces by using the menu item **Geometry > Surface > By Lines**. There are a variety of options and facilities to use, to enable easy construction of the model and the use of the **Copy** command will reduce the time needed.



Model geometry

An interface line mesh is defined and assigned to both sides of the sheet piles/linings.

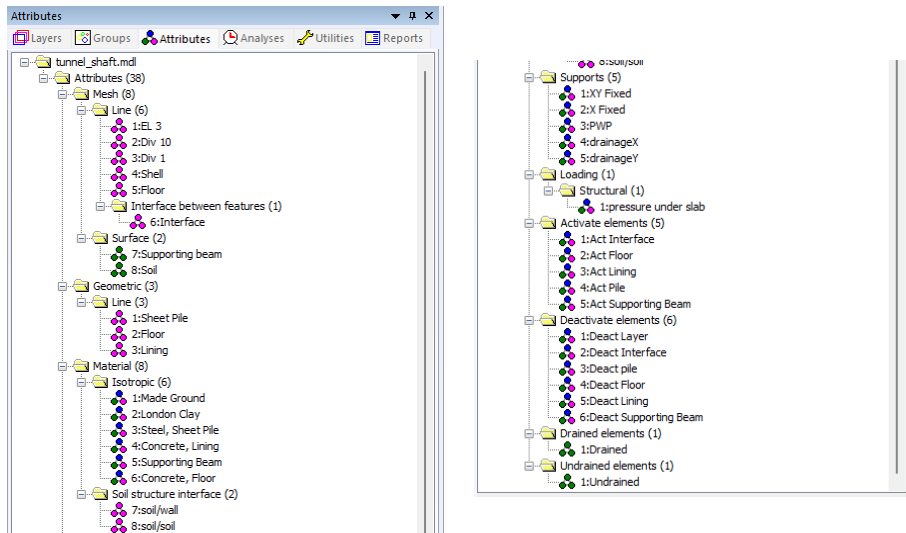
The image below (expanded view for clarity) shows the interface along the excavation.



Interface along the sheet piles and linings

Model attributes

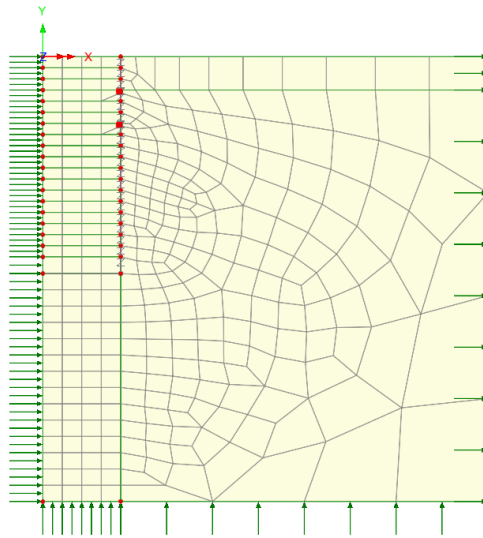
Model attributes (mesh, material, geometric properties, etc.) defined and assigned to the model are held in the Attributes treeview.



Model Attributes

Mesh

The surface features are meshed using quadrilateral axisymmetric two-phase elements (QAX8P) as shown in the following image.



Model meshing

The sheet piles and floor are meshed with quadratic axisymmetric shell elements (BXS13).

The supporting beams are meshed using quadrilateral axisymmetric elements (QAX8)

The interface is meshed with axisymmetric two-phase interface elements (IAX6P).

Geometric Properties

All geometric attributes are created using the command **Attributes > Geometric > Line**.

Table 1 lists the geometric properties for structural elements.

Table 1. Geometric properties for structural elements

Feature	Thickness (m)
Sheet Pile	0.02
Lining	0.5
Floor	0.5

Materials

The Made Ground and London clay are modelled by the Modified Mohr-Coulomb (MMC) with Rankine cut-off material. The sheet piles, linings, supporting beams and the floor by linear elastic (LE) materials. Properties are given in Table 2.

Tunnel Shaft

Table 2: Material properties

Parameter	Made Ground	London Clay	Concrete	Steel
Model	MMC	MMC	LE	LE
Density	1.8 t/m ³	1.9 t/m ³	2.4 t/m ³	7.8 t/m ³
Young's Modulus	30.0E3 kPa	80-150 kPa*	14.0E6 kPa	210.0E6 kPa
Poisson's ratio	0.3	0.2	0.2	0.3
Friction angle	35°	25°	-	-
Dilatancy angle	0°	0°	-	-
Cohesion	15 kPa	130 kPa	-	-
K ₀	0.4264	0.5774	-	-

* Young's modulus varies linearly with depth from 80 kPa to 150 kPa.

Additional two-phase properties are given in Table 3. It is important to note that the London Clay is modelled with fully saturated two-phase properties. During excavation, the pore water pressure drops temporarily and goes negative. If we use partially saturated material properties, the negative pressure is interpreted as a degree of saturation with the soil losing water as the negative pressures increase. Partially saturated properties are used in the Made Ground to automatically account for the water content of the soil above and below the phreatic surface.

Table 3: Additional hydraulic properties

Partially saturated parameters	Bulk modulus water	Hydraulic conductivity	Density fluid	Saturation at residual water content	Saturation at full water content
Made Ground	2.1E6 kPa	1.0E-5 m/s	1 t/m ³	0.0	1.0
London Clay		1.0E-11 m/s		-.*	-.*

In addition, we need the properties at the interface between the soil and sheet piles/linings. Prior to installing the sheet pile and lining, the soil to be excavated and that outside of the shaft are held together by interface elements with very high shear and normal stiffnesses, and a large cohesion to ensure that the soil blocks displace together without slip or excessive normal penetration of the surfaces. After installation of the shaft, the interface shear stiffness as well as the angle of friction and cohesion are reduced to model the slip conditions between the London clay and shaft.

Table 4: Tangential slip interface properties

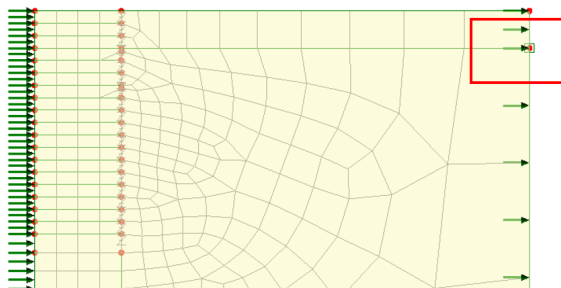
	Angle of friction	Cohesion	Kn	Ks	Hydraulic conductivity
Interface before installing support system*	45.0°	1E20 kPa*	1E9 kN/m	1E9 kN/m	1.0 m/s
Interface after installing support system	18.0°	95 kPa	10 Kn factor	0.15 Ks factor	0.0 m/s

*Cohesion is set to a high value to prevent slip.

Supports

The base of the model is constrained in both X and Y directions, while the lateral sides are limited in the X direction.

To take into account the water table situated at a depth of -6m, the menu item **Attributes > Support > Pore Pressure** is used to define the value **Open** which is then assigned to the point shown.



Pore pressure support at point 45

Loads

Gravity is the only load considered in the model.

Other Attributes

Activation and deactivation attributes are used to model the removal of soil and the installation of the supporting system. The excavation and installation of the supporting system is completed in a series of load cases or stages.

Activate attributes are used for activating specific beams, floor and linings at specific stages. Deactivate attributes are used for deactivating soil layers and adjacent interfaces to simulate the excavation process, as well as for the beams and linings that are to be

installed as the shaft construction progresses. For both, the menu item **Attributes > Activate and Deactivate** is used.

Drained and undrained conditions are defined at specific stages using the menu item **Attributes > Pore Water Pressures > Drained/Undrained**.

Construction stages considered

Two analyses are run to consider the construction stages. In the first, the excavation and installation of the lining is done in a single stage. In the second, the excavation is performed in one stage and the lining installed in the second.

Analysis 1

Initial Phase

The first stage establishes the initial stress and water pressure distributions. The supporting beams, floor, and linings are not present during this stage and so are deactivated. To deactivate any element, we first select the element and then assign the deactivate attribute to them.

Gravity is included in this phase by right-clicking on the load case name and selecting gravity.

Nonlinear analysis control properties are defined for this stage, with all the parameters left at their default values.

Installing Sheet Piles

The sheet pile is activated. The interface elements adjacent to the pile are changed to allow for slip between the soil and pile.

Excavation of soil adjacent to pile

The excavation phases from ex1 to ex8 simulate the excavation process of soil layers adjacent to the sheet piles. In these phases we deactivate the layer in question and the corresponding interface elements. The supporting beams are activated in the appropriate excavation phase.

As London clay is highly impermeable and we are not modelling time we assign the undrained attribute to it during the excavation.

Excavation of soil and installation of lining

For the final stages of the construction (excavation phases ex9 to ex19), the soil is excavated and the lining installed.

Install floor

The floor at the bottom of the excavation pit is activated.

Long Term Case

During the excavation process, as the water does not have sufficient time to flow through the almost impermeable clay, the medium is treated as undrained resulting in excess pore water pressure building up in the soil. However, over the long term, the initial hydrostatic pressure distribution is restored. This leads eventually to a pore water pressure of almost 325kPa being applied to the base of the concrete slab forming the floor. To avoid the imposition of such a large pressure the space below the slab is drained.

The long-term conditions are given by changing the soil status to ‘drained’ setting the porewater pressure below the slab to zero and restoring the porewater pressures along the boundary to their initial values by using the ‘drainage’ boundary support condition.

Analysis 2

Excavation of soil adjacent to pile

Stages 1 to 8 simulate the excavation process of soil layers adjacent to the sheet piles. In these stages we deactivate the layer in question and the corresponding interface elements. The supporting beams are activated in their own stages following the excavation of the soil.

Excavation of soil and installation of lining

During excavation below the level of the piles, the soil is excavated in one phase, followed in the next phase by the installation of the lining.

Install floor

The floor at the bottom of the excavation pit is activated.

Long Term Case


The long-term conditions are given by changing the soil status to ‘drained’, setting the porewater pressure below the slab to zero and restoring the porewater pressures along the boundary to their initial values.

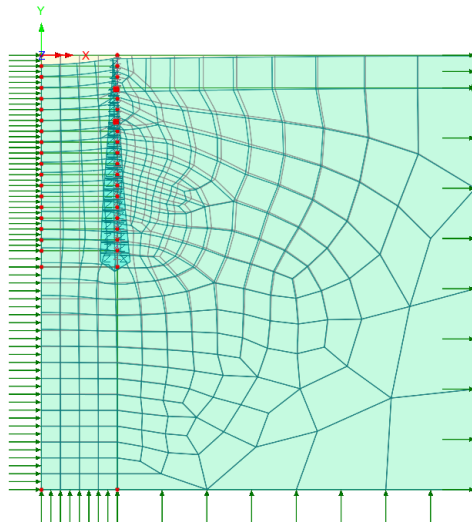
Running the Analysis



Ensure all analyses are selected and press **OK** to run the analysis.

Viewing the Results

Analysis results are present in the Analyses  Treeview.

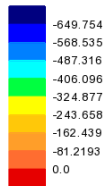


- Turn off the deformed mesh and geometry layers and supports and loading before viewing the results that follow.

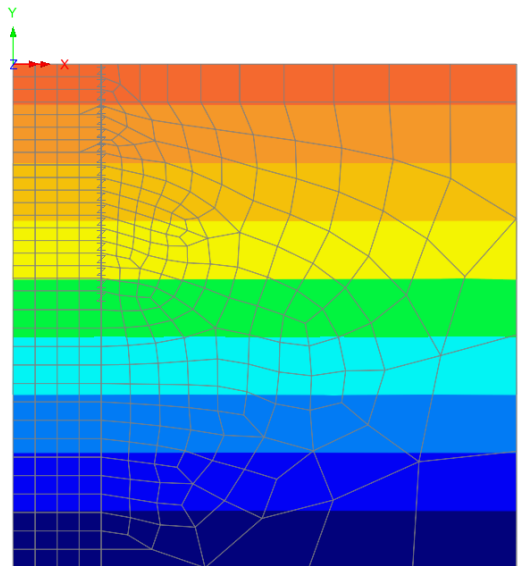
Stress

- With **Analysis 1, Initial** loadcase active, add the **Contours** layer and select the entity **Stress – Two phase axisymmetric** and component **SY_eff** to view the vertical effective stress for the initial stage.

Analysis: Analysis 1
 Loadcase: 1:Initial, 1:Increment 1
 Results file: tunnel_shaft-Analysis 1.mys
 Entity: Stress - Two phase axisymmetric
 Component (Averaged nodal): SY_eff (Units: kN/m²)



Maximum 0.635295 at node 4 of element 4
 Minimum -730.338 at node 109 of element 130



Vertical effective stress at initial stage (kN/m²)

Displacement

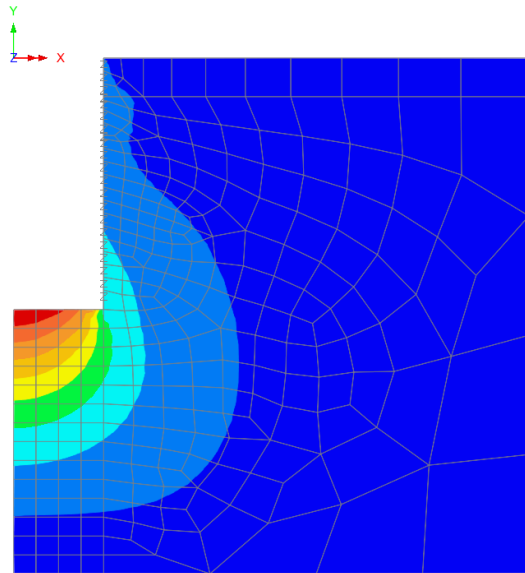
Displacement contours following construction in one step and in separate steps can be viewed.

- In **Analysis 1**, set active loadcase **Long Term pwp**.
- Change the contours layer to plot contours of entity **Displacement** and component **RSLT**
- Set the **Soil mass** group as only visible.
- Because the line in the Floor group is also in the Soil mass group, set the **Floor** group to be invisible.
- Turn off fleshing.

Analysis: Analysis 1
Loadcase: 23.Long Term pwp, 23:Increment 23
Results file: tunnel_shaft-Analysis 1.mys
Entity: Displacement
Component (Nodal): RSLT (Units: m)

0.0
8.1208E-3
0.0162416
0.0243624
0.0324832
0.040604
0.0487248
0.0568456
0.0649664

Maximum 0.0730872 at node 933
Minimum 0.0 at node 65



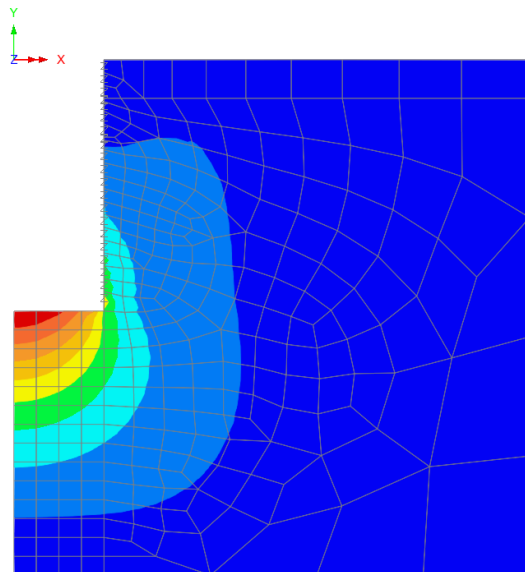
Displacement at end of construction - excavate and line in one step

- In **Analysis 2**, set active loadcase **Long Term pwp (Copy 1)**.

Analysis: Analysis 2
Loadcase: 59.Long Term pwp (Copy 1), 36:Increment 36
Results file: tunnel_shaft-Analysis 2.mys
Entity: Displacement
Component (Nodal): RSLT (Units: m)

0.0
8.19956E-3
0.0163991
0.0245987
0.0327983
0.0409979
0.0491974
0.0573969
0.0655965

Maximum 0.0737961 at node 933
Minimum 0.0 at node 65



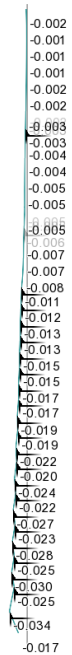
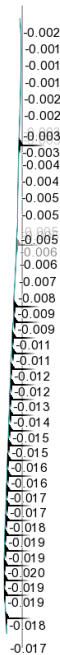
Displacement at end of construction - excavate and line in separate steps

Both analyses give similar results with a maximum resultant displacement of 73-74 mm at the bottom of the shaft.

Sheet piles and linings

To see the development of the displacement in the sheet piles and linings with depth for the final phase of each analysis:

- Turn off the contours layer
- Turn on the deformed mesh layer.
- Set the **Piling** group as only visible and set the **Lining** group also visible.
- Add a values layer to plot values of entity **Displacement** and component **DX** to 3 decimal places on the deformed mesh.
- Set active the last loadcase from each analysis.



Analysis 1 – excavate and line in one step

Analysis 2 – excavate and line in separate steps

Displacement of shaft wall at end of construction

It is observed that the greatest horizontal displacement reaches 20mm for the first analysis and is in the order of 30-34mm for the second.

Pore Pressure

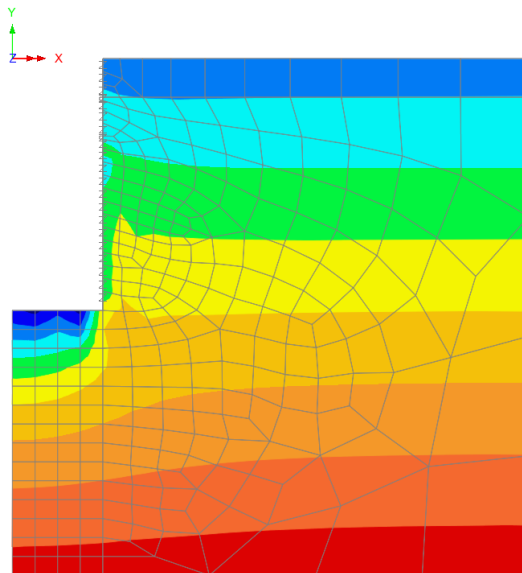
The contours of water pressure distribution can be viewed for Analysis 1. Firstly, after the installation of the shaft floor, and then for the long-term pressure.

- Turn off the deformed mesh and values layers.
- Set the group **Soil mass** as only visible.
- Turn on the contours layer and change it to show contours of entity **Stress – Two phase axisymmetric** and component **PRES**
- Resize the view.

Analysis: Analysis 1
Loadcase: 22:install floor, 22:Increment 22
Results file: tunnel_shaft-Analysis 1.mys
Entity: Stress - Two phase axisymmetric
Component (Averaged nodal): PRES (Units: kN/m²)

■	-212.37
■	-106.185
■	0.0
■	106.185
■	212.37
■	318.656
■	424.741
■	530.926
■	637.111

Maximum 711.947 at node 65 of element 44
Minimum -243.72 at node 940 of element 299

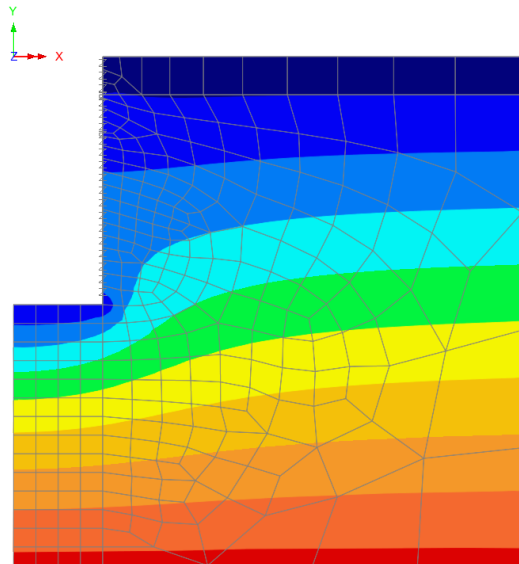


Pore pressure after installation of shaft floor

Analysis: Analysis 1
 Loadcase: 23 Long Term pwp, 23/Increment 23
 Results file: tunnel_shaft-Analysis 1.mys
 Entity: Stress - Two phase axisymmetric
 Component (Averaged nodal): PRES (Units: kN/m²)



Maximum 725.94 at node 65 of element 44
 Minimum -59.2098 at node 10 of element 6



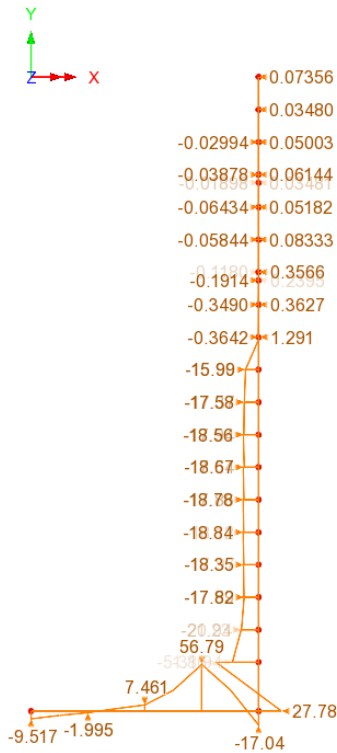
Pore pressure long term

Bending Moments and Hoop stresses

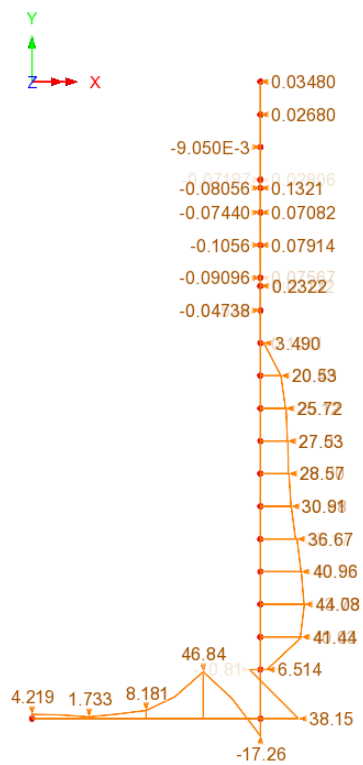
Bending moments and hoop stresses at the end of construction can be plotted for the piling, lining and floor by setting only those features visible and adding a diagrams layer.

Bending moments

- Turn on the geometry layer.
- Set the **Piling** group as only visible and set the **Lining** and **Floor** groups to be also visible.
- Add the diagrams layer to show diagrams of component **Force/Moment** – **Axisymmetric thick shell** and entity **Mz**.



Analysis 1 – excavate and line in one step

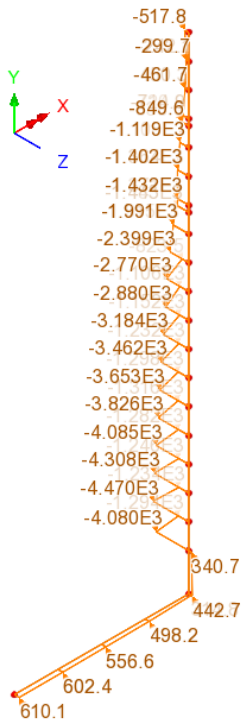
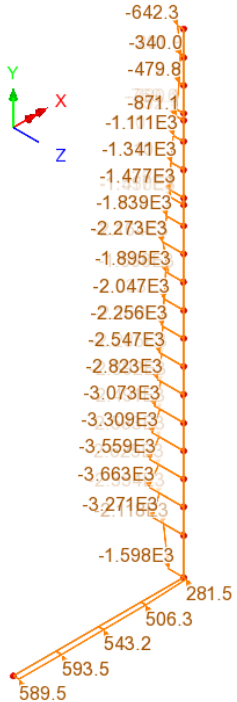


Analysis 2 – excavate and line in separate steps

Bending moments at end of each analysis (kN.m/m)

Hoop stresses

- For the diagrams layer for component **Force/Moment – Axisymmetric thick shell**, change the entity to Nz entity to plot a diagram of hoop stress.
- Set an isometric view to see the diagrams more clearly.



Analysis 1 – excavate and line in one step

Analysis 2 – excavate and line in separate steps

Hoop stresses at end of each analysis (kN/m)

