Deep Excavation in Berlin Sand

For LUSAS version:	21.0
For software product(s):	LUSAS Bridge plus or LUSAS Civil&Structural plus
With product option(s):	Geotechnical, Nonlinear

Problem Description

Data measured during the construction of a deep excavation in Berlin with a tie-back wall has been used to establish a benchmark problem which is presented in detail by Schweiger [S1]. In this example comparison is made with the particular solution MC1 [S2] in which the water level in the excavation is lowered in a single step.

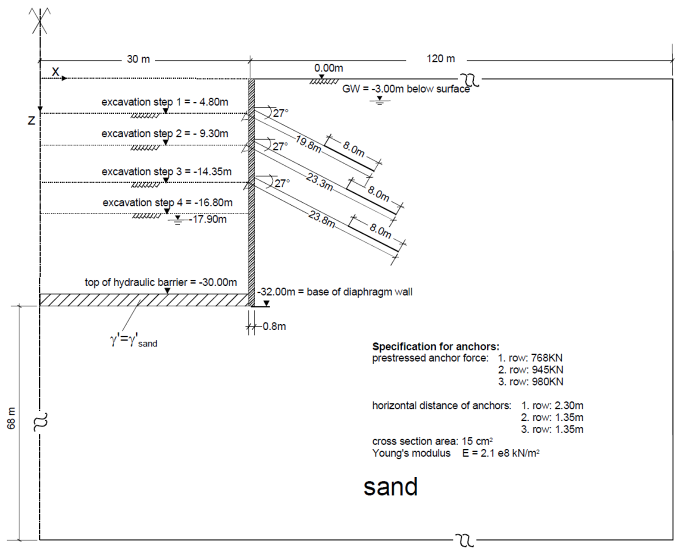


Figure 1: Deep excavation in Berlin sand

Figure 1 illustrates the layout of the tie-back wall, which was constructed in an area composed of Berlin sand with the water table found 3 metres below the ground surface.

The excavation process was carried out in four phases and reached a depth of 16.8 metres. The diaphragm wall was supported by three rows of prestressed anchors, which were spaced in the out-of-plane direction, as detailed in Figure 1.

Keywords

Two phase elements, activation, deactivation, interface elements, excavation, anchor, prestressed force, water table.

Associated Files

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

- ❑ **berlin_sand.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

This example demonstrates how different functions of LUSAS can be employed to replicate the process of dewatering during an excavation along with the installation of a retaining wall and supporting anchors.

Preparing the Model Features

A new model is created, set the analysis category as 2D, and specify the model units as kN,m,t,s,C.

Feature Geometry

The model is created by entering point coordinates using the command **Geometry > Point > By Coords**. These points define the excavation pit shape, as shown in figures 2 and 3. Then by drawing lines between these points using **Geometry > Line > By Points…** surfaces are formed from the lines using the command **Geometry > Surface > By Lines** (Figure 4). The user has a variety of options and facilities to use, which enables them to construct the model with ease. We recommend the use of the **Copy** command to reduce the time needed to develop the model.

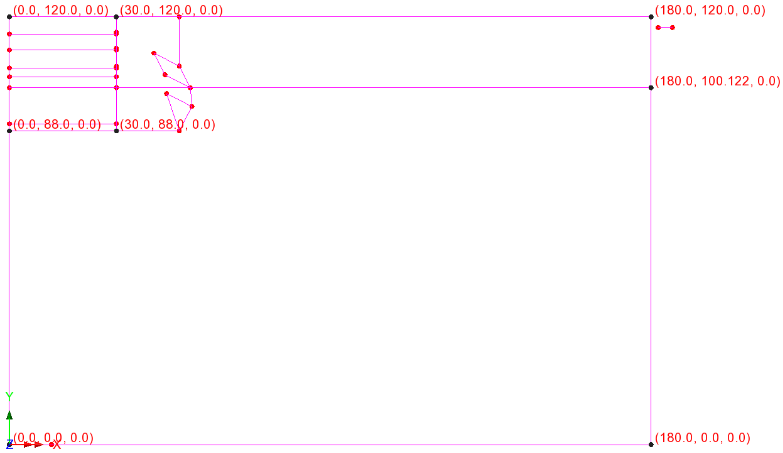


Figure 2: Geometry of deep excavation in Berlin sand, full model.

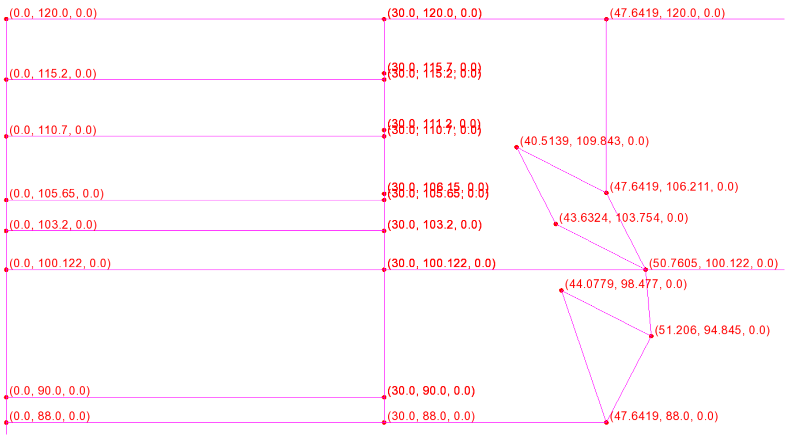


Figure 3: Geometry of the excavation and anchors

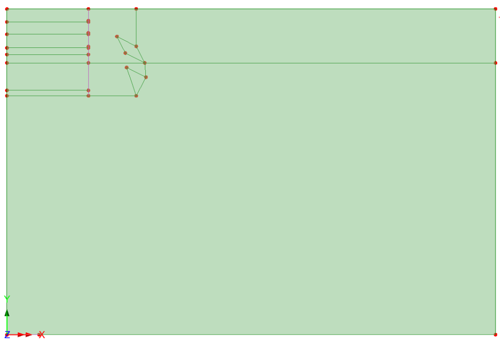


Figure 4: Forming surfaces from lines

It is important to make anchors independent of the soil mass, so they are connected directly to the diaphragm wall (Figure 5). Moreover, the points and lines of the wall are made unmergeable, with the exception of the last point, also shown in Figure 5.

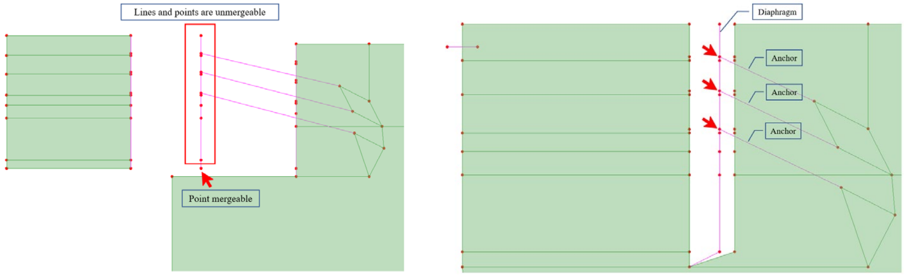


Figure 5: Lines and points status (mergeable, unmergeable), anchor connections

Preparing the Model Attributes

Defining the Mesh

- The default number of line mesh divisions is 4. This gives a somewhat coarse mesh, so the default number of line mesh divisions is increased to those shown in figure 6.

- The surface features are meshed using two phase plane strain, quadrilateral elements (QPN8P).

- The impermeable layer is meshed using plane strain, quadrilateral, quadratic elements (QPN8).

- The diaphragm wall is meshed using plain strain beams (BMI3N) with an element length of 1m.

- The anchor rods are meshed with linear bar elements (BAR2) with the number of divisions of 1. Whilst the grout uses quadratic bar elements (BAR3) of length 1m.

- Two phase plane strain interfaces elements (IPN6P) are used between the soil and wall.

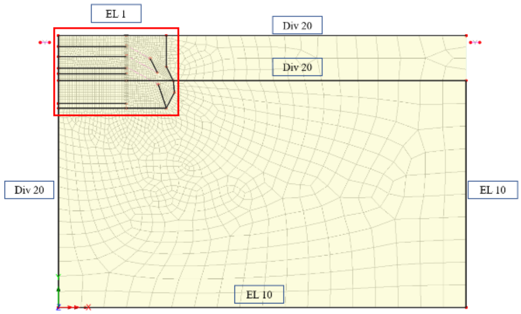


Figure 6: Model meshing

Defining the Geometric Properties

Geometric attributes for the diaphragm and anchors are created using the command **Attributes > Geometric > Line** as shown in figure 7. The wall is 80cm thick whilst the cross-sectional area of the 1st row anchor rods is 13.7cm^2 and the 2nd row anchor rods 15.3cm^2.

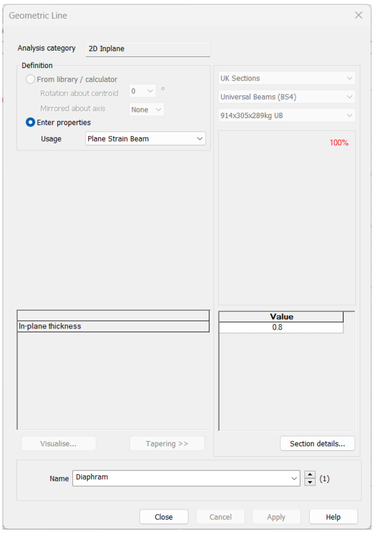


Figure 7: Geometric properties

The grouted part of the anchors is assigned a circular section (Figure 8).

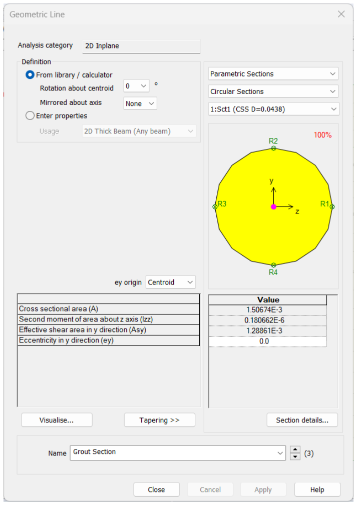


Figure 8: Geometric properties of grouted part of the anchor

Defining the Materials

Berlin sand is modelled by the Modified Mohr-Coulomb (MMC) with Rankine cut-off material and the diaphragm wall and anchors by linear elastic (LE) materials. Properties are given in table 1.

Table 1: material properties

Parameter				Anchor	Diaphragm	Hydraulic barrier
	0-20m	20-40m	>40m			
Model	MMC	MMC	MMC	LE	LE	MMC
Density	1.9 t/m^3	1.9 t/m^3	1.9t/m^3	7 t/m^3	2.4t/m^3**	1.9 t/m^3
Young's Modulus	47000 kPa	244000 kPa	373000 kPa	210E6 kPa*	30 GPa	244000 kPa
Poisson's ratio	0.3	0.3	0.3	0.15	0.15	0.3
Friction angle	35º	38º	38º	-	-	38º
Dilatancy angle	5º	6º	6º	-	-	6º
Cohesion	1.0 kPa	1.0 kPa	1.0 kPa	-	-	1.0 kPa
K_0	0.43	0.43	0.43	-		0.43

* The Young's moduli of the anchors are adjusted by dividing them by the spacing between anchors. Plane strain elements are used to model a 1m length of the excavation, so the loads applied to the anchor by the wall are only *1/space between anchors* of the actual loads.

** In the first phase of analysis 1, the diaphragm's density is assumed to be 0 T/m3 so that the wall's weight is not taken into account during this initial stage.

The anchor properties are given in table 2 and the grout properties in table 3.

Table 2: Anchor properties

	EA	A	E_{anchor}
Upper anchors	2.87E5 kN	1.37E-3 m^2	2.1E8/2.3 $kN/m^2/m$
Lower anchors	3.22E5 kN	1.53E-3 m^2	2.1E8/1.35 $kN/m^2/m$

Table 3: Anchor properties

	EA/m	A	E_{grout}
Upper anchors	$4.92x10^5$ kN/m	1.50674E-3 m^2	326.5E6 $kN/m^2/m$
Lower anchors	$8.38x10^5$ kN/m	1.50674E-3 m^2	556.2E6 $kN/m^2/m$

Additional two-phase properties are listed in table 4. Note: the hydraulic conductivity is arbitrary because there is no water flow in this problem,

Table 4: Additional hydraulic properties

Partially saturated parameters	Bulk modulus water	Hydraulic conductivity	Density fluid	Saturation at residual water content	Saturation at full water content
Sand	2.1E6 kPa	1.0 m/s	1 t/m^3	0.0	1.0

In addition, we need the properties at interface between the soil and wall. Two-phase interface elements are used because we want to use the effective rather than total stress in calculating the normal stress across the interface. However, normal interface properties are used for the section of wall facing the impermeable membrane as it is assumed that no water is present in the membrane and that the effective and total stresses are the same. Properties are given in table 5.

Table 5: Tangential slip interface properties

Interface	Angle of friction	Cohesion	Hydraulic conductivity
Wall/sand <20m	28.0º	0.8 kPa	0.0 m/s
Wall/sand > 20m	30.4º	0.8 kPa	0.0 m/s

Defining the Supports

The base of the model is constrained in both X and Y directions, while the lateral sides are limited in the X direction (Figure 9).

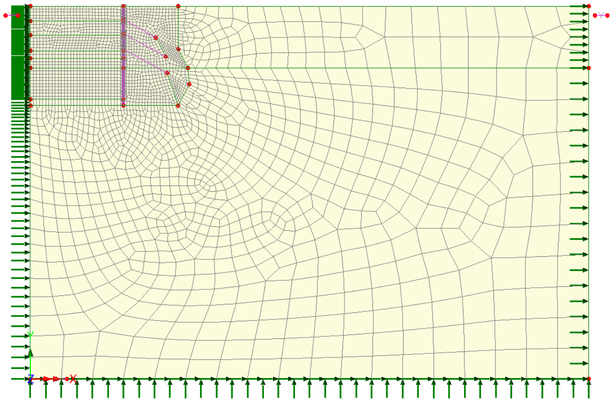


Figure 9: Boundary conditions

Defining the Loads

The anchor forces are defined through the command **Attributes > Loading > Stress and Strain** (Figure 10) with the force being divided by the space between the anchors. For the first row the applied force is 768/2.3 = 333.913 kN/m, whilst the applied forces in the second and third rows are 700 kN/m and 725.926 kN/m respectively.

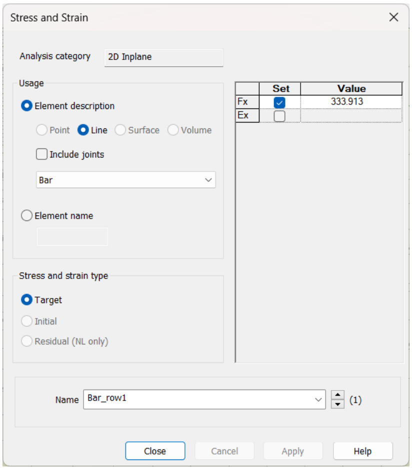
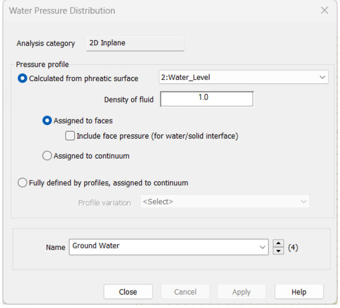
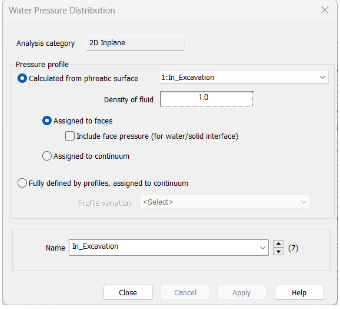


Figure 10: Prestressed force in anchor

The water pressure distribution associated with a phreatic surface is defined by the command **Attributes > Loading > Water Pressure Distribution** (Figure 11). We define two water pressure distributions as we have two phreatic levels, one inside and the other outside of the excavation area (figure 11). These are assigned to specific boundaries as illustrated in figure 12.



Out of excavation area



Inside the excavation area

Figure 11: Water Pressure Distribution attribute

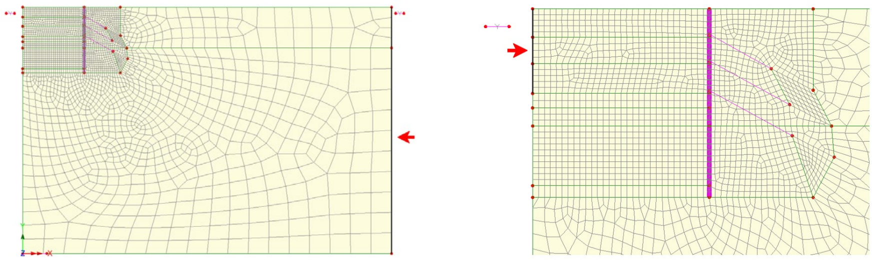


Figure 12: Assigning Water Pressure Distribution in and out of excavation area.

Lowering of the water level in the excavation is achieved using the command **Attributes > Loading > Prescribed Displacement** (figure 13). A vertical translation of -14.9m in the Y direction is applied to the phreatic surface.

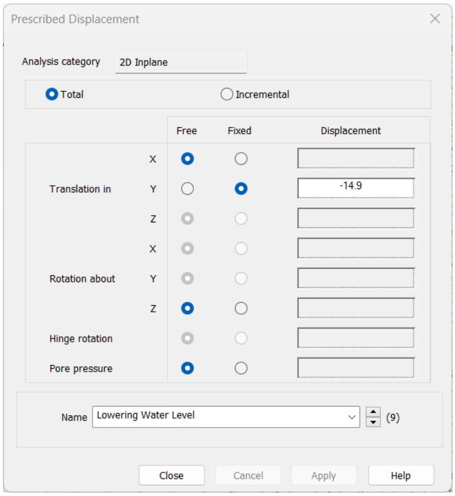


Figure 13: Lowering water level

Defining Other Attributes

To accurately simulate the excavation and supporting process, the deactivation and activation functions are used to remove soil and install the diaphragm wall and anchors.

- ❑ Activate attributes are used for activating specific anchors during specific stages. The command to be used is **Attributes > Activate and Deactivate…**
- ❑ Deactivation attributes are assigned to the sand layers to simulate the excavation process and also to the anchors before their installation. The attributes are generated using the command **Attributes > Activate and Deactivate**… The deactivation of the sand layers also requires the deactivation of the corresponding interface elements. The deactivation option **Distribute over the stage** (figure 14)

allows the residual forces to be reduced gradually over the load stage and improves convergence when the residual forces to be redistributed are large.

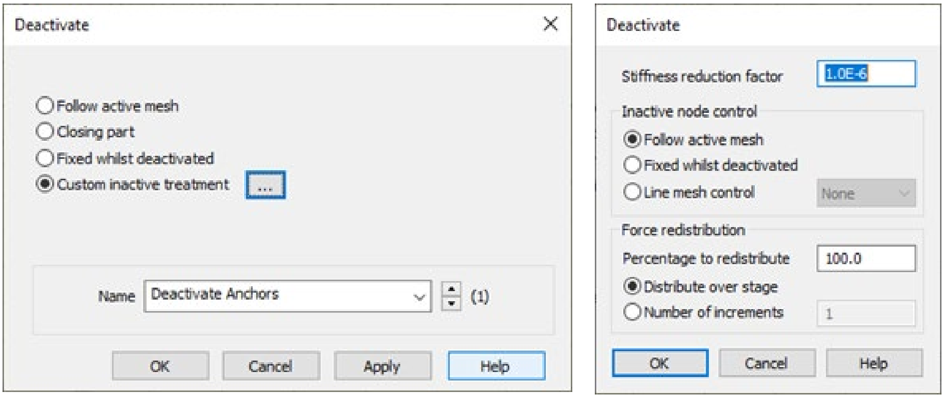


Figure 14: Deactivate attribute customization

- ❑ We define two **Phreatic Surface Attributes** which are assigned to lines shown in Figure 15.

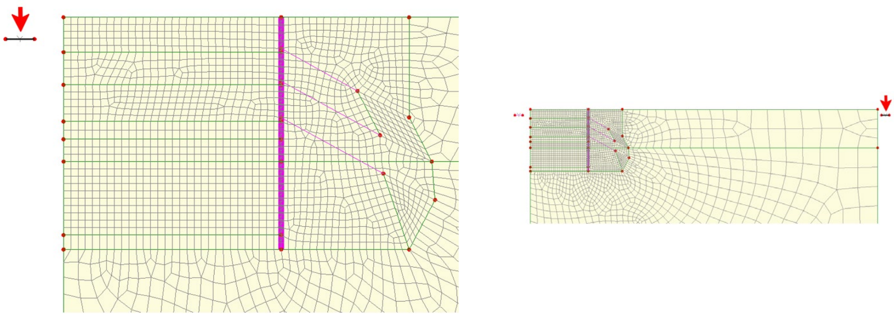


Figure 15: Phreatic Attribute

Running the Analysis

We consider the following analysis and construction stages.

Analysis 1 > Initial Phase

The first analysis (figure 16) establishes the initial stress and water pressure distributions. The wall is present but with zero density. In this particular case, this does not affect the initial stress calculation. The anchors are deactivated.

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

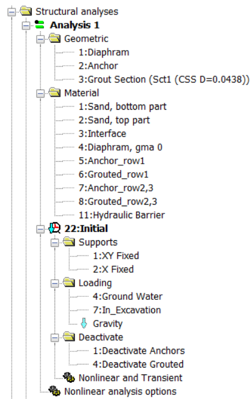


Figure 16: Initial Phase

Analysis 2 > Install Wall

In Analysis 2, we include the wall density by assigning the diaphragm material properties as shown in figure 17.

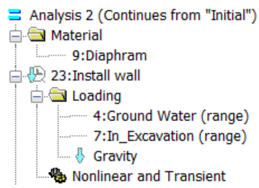


Figure 17: Install Wall phase

Analysis 2 > Lowering Water Table

In this phase we lower the water table before starting the excavation process (Figure 18). Automatic loading is used.

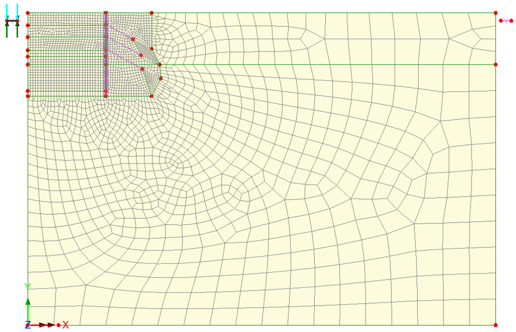


Figure 18: Lowering water table phase

Analysis 2 > Lock-in Lower Water

In the previous stage, the phreatic surface defining the water level in the excavation was lowered using automatic loading. Gravity and water pressures need to be restored prior to the use of automatic loading in the excavation stage that follows.

Analysis 2 > Excavation Layer 1

To excavate the first layer, we use deactivation by assigning **Deactivate** attribute to the soil surface. It is important to note that the interface related to this layer must also be deactivated (Figure 19). Automatic loading is used during this phase.

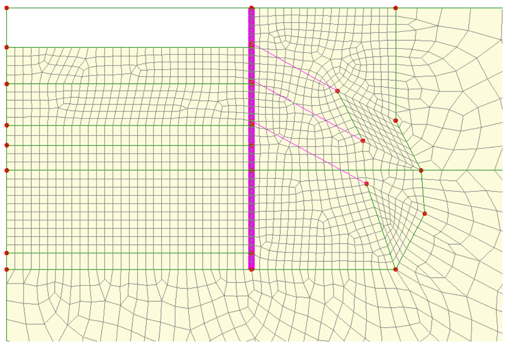


Figure 19: Excavation of first layer

Analysis 2 > Install 1st Row Anchors

The first row of anchors is activated. The user has to select the anchors, then assign them the attribute **Activate**. The prestressed load of 333.913 kN/m is included in this stage (Figure 20). Automatic loading is used to gradually apply the prestress load.

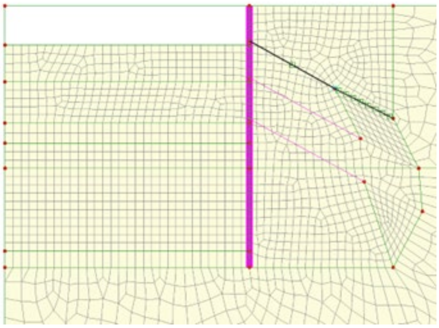


Figure 20: Installing first row anchors

Analysis 2 > Lock-in 1st Row Anchors

The anchor load was applied using automatic loading. Gravity and water pressures need to be restored prior to the use of automatic loading in the excavation stage that follows.

Analysis 2 > Excavation Layer 2

To excavate the second layer, we use deactivation by assigning **Deactivate** attribute to the soil surface. It is important to note that the interface related to this layer must also be deactivated (Figure 21).

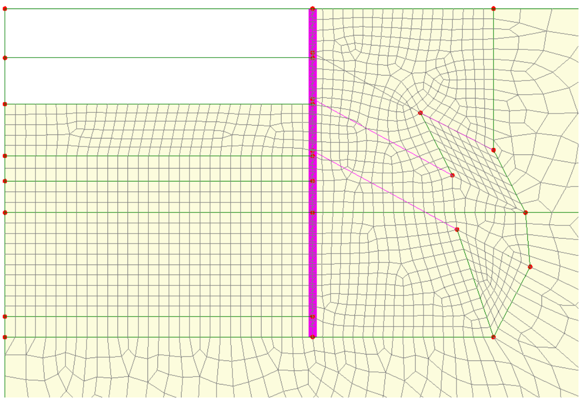


Figure 21: Excavation of second layer

Analysis 2 > Install 2nd Row Anchors

The second row of anchors is activated. The user has to select the anchors, then assign them the attribute **Activate**. The prestressed load of 700 kN/m is included in this phase (Figure 22). Automatic loading is used to gradually apply the prestress load.

Figure 22: Installing second row anchors

Analysis 2 > Lock-in 2nd Row Anchors

The anchor load was applied using automatic loading. Gravity and water pressures need to be restored prior to the use of automatic loading in the excavation stage that follows.

Analysis 2 > Excavation Layer 3

We deactivate the third layer with the interface associated (Figure 23). Automatic loading is used.

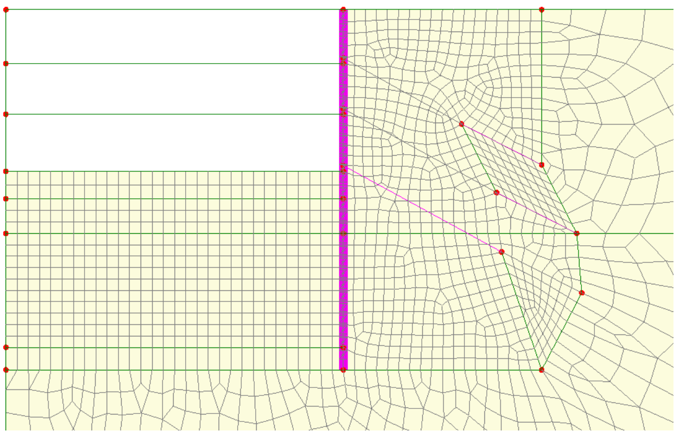


Figure 23: Excavation of third layer

Analysis 2 > Install 3rd Row Anchors

The third row of anchors is activated. The user has to select the anchors, then assign them the attribute **Activate**. The prestressed load of 725.926 kN/m is included in this phase (Figure 24). Automatic loading is used to gradually apply the prestress load.

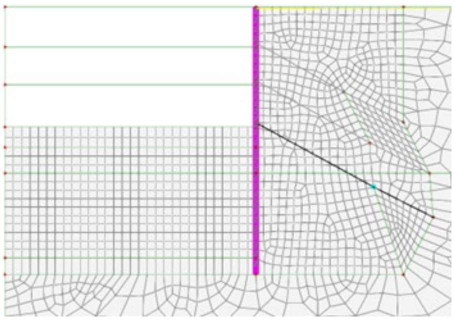


Figure 24: Installing third row anchors

Analysis 2 > Lock-in 3rd Row Anchors

The anchor load was applied using automatic loading. Gravity and water pressures need to be restored prior to the use of automatic loading in the excavation stage that follows.

Analysis 2 > Excavation Layer 4

We deactivate the fourth layer along with the associated interface (Figure 25). Automatic loading is used.

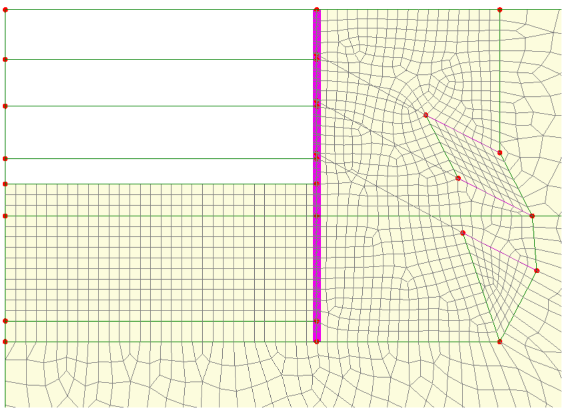


Figure 25: Excavation of fourth layer

Nonlinear solution parameters

This analysis is one of those that requires an adjustment to the solution parameters. Using the default parameters, the problem failed to solve but it was noted that for many of the iterations the maximum line search size was being used. The maximum number of iterations were increased to 30 and the **Advanced…** parameters selected (figure 26). The line search size parameters were changed to give a minimum scale size of 0.01 and a maximum scale size of 10 (figure 27). With these changes the problem solved without further issue.

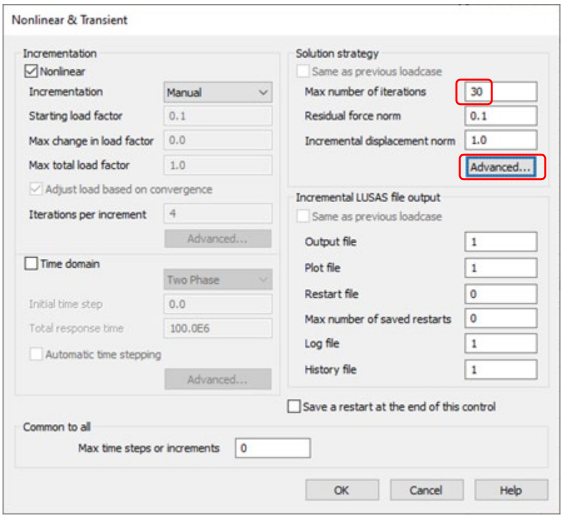


Figure 26: Increase in number of maximum allowed iterations

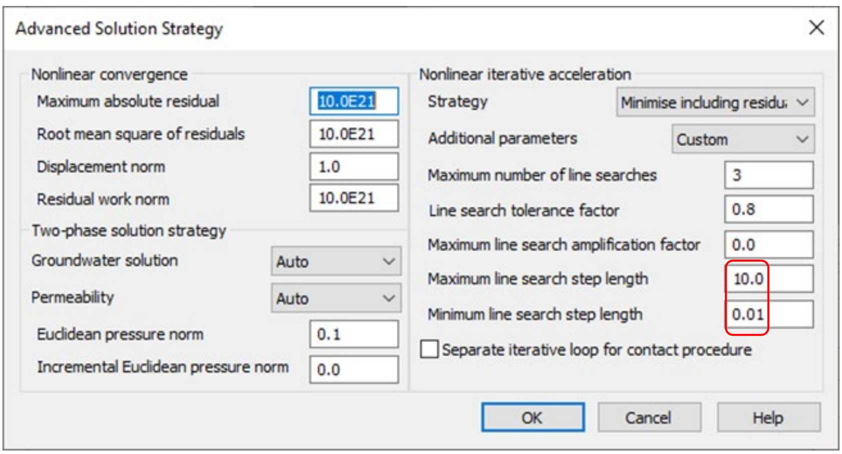


Figure 27: Change to default line search parameters

Viewing the Analysis

Figure 28 shows the porewater pressure distribution at the end of the excavation whilst figure 29 shows the resultant displacement contours plotted on the final displaced shape.

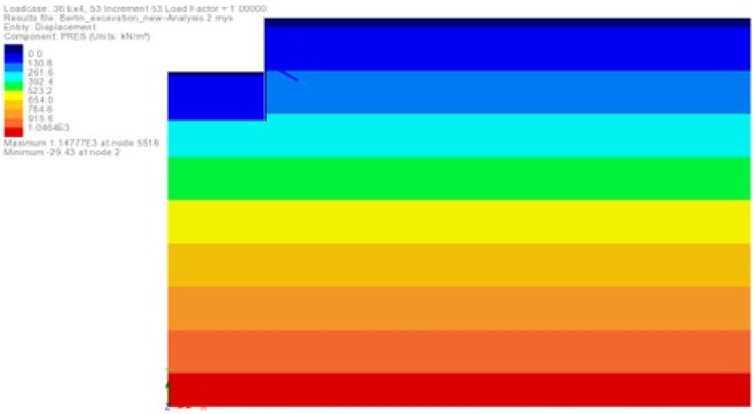


Figure 28: Pore water pressure at end of analysis

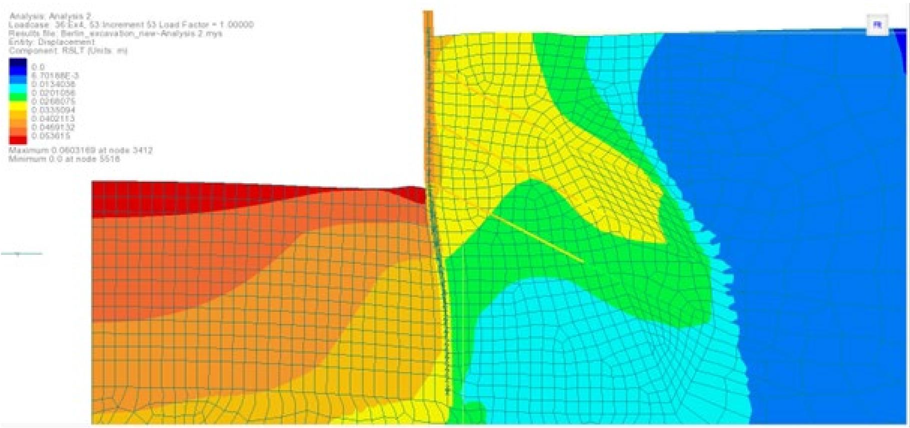


Figure 29: Resultant displacements at end of analysis

The material parameters used in the model are the same as those chosen for the model MC1 in Schwieger's report [S2]. Results for the horizontal displacement along the wall and at the surface as well as the ultimate bending moments in the wall are detailed. The displacements are extracted from LUSAS using **Utilities > Graph through 2D…** facility which allows the plotting of data along a line cutting across the model. The bending moments are extracted using **Utilities > Print Results Wizard…** From the dialog **Force/Moment – Plane Strain Beam** is selected from the **Entity** dropdown list. **Mz** is checked in the **Reported components** and **Coordinates** is also checked (figure 30).

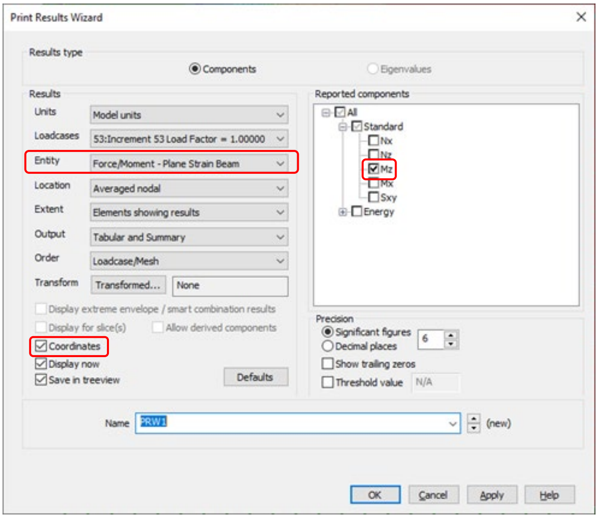


Figure 30: Extracting wall bending moments

The results are shown in figure 31. The bending moment and the Y coordinate can be selected and copied to a program such as Excel to process and plot.

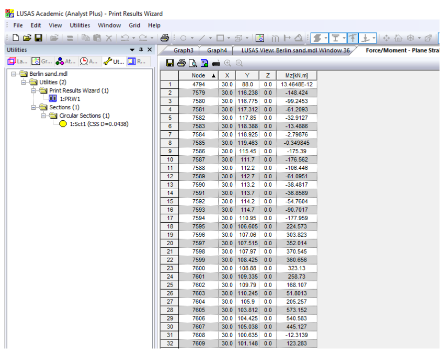


Figure 31: Print results wizard output

The displacement of the wall is in good agreement, down to a depth of 27m (figure 32). The last two metres correspond to the impermeable membrane for which the dry soil properties are used – it is assumed that there are no hydrostatic forces within the membrane. The LUSAS solution predicts a large displacement of 15mm inwards which is more or less constant over the membrane. This is to be expected as the difference in pressure across the diaphragm wall for the final two metres results with a force of 610 kN/m applied towards the excavation.

The bending moments are show in figure 32 and in good agreement to a depth of 22m. After this point, the different displaced shape of the diaphragm wall leads to a different moment distribution.

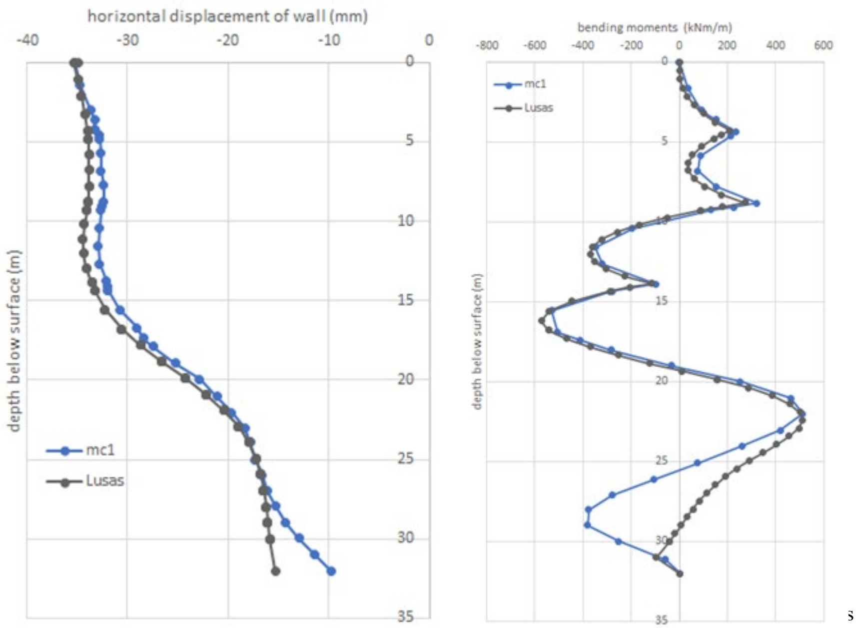


Figure 32: Comparison with PLAXIS solution MC1

Figure 33 compares the ground displacement behind the wall. The PLAXIS solution predicts both less settlement and heave than LUSAS but there is agreement in the overall trend.

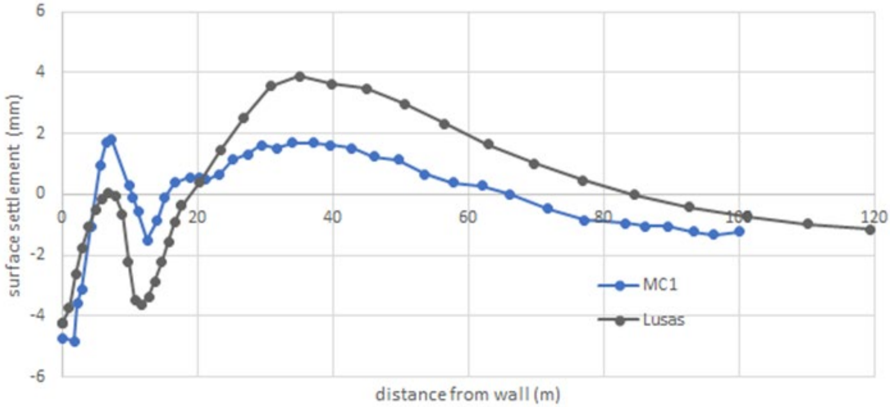


Figure 33: Comparison with PLAXIS ground settlement solution MC1

REFERENCES

S1 Schweiger, H.F., Benchmarking in geotechnics_1, Part I results of Benchmarking, Inst.for Soil Mechs and Foundation Eng., Graz Univ.Tech. Austria, CGG_IR006,2002, 2002.

S2 Schweiger, H.F., Benchmarking in geotechnics_1, Part II results of Benchmarking, Inst.for Soil Mechs and Foundation Eng., Graz Univ.Tech. Austria, CGG_IR006,2002, 2002.