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



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.



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 1^{st} row anchor rods is 13.7cm² and the 2^{nd} row anchor rods 15.3cm².

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Mirrored ab	out axis None		Universal Beams (BS4)	
C Enter proper	ties		914x305x289kg UB	
Usage	Plane Strain Beam	~		100%
In-plane thicknes	3		Value 0.8	
In-plane thicknes Visualise	• Taj	pering >>	Value 0.8	ction details

Figure 7: Geometric properties

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

Analysis category 2D Inplane		
Definition		Parametric Sections
Rotation about centroid	0 ~ °	Circular Sections
Mirrored about axis	None 🗸	1-5ct1 (CSS D=0.0438)
Enter properties		1.301 (035 0-00030)
e Cross sectional area (A)	y origin Centroid ~	R4
Second moment of area about	z axis (lzz)	0.180662E-6
Eccentricity in y direction (ey)	an (Gy)	0.0
Visualise	Tapering >>	Section details
Name Grout Section		~ (3)

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.

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	35°	38°	38°	-	-	38°
Dilatancy angle	5°	6°	60	-	-	60
Cohesion	1.0 kPa	1.0 kPa	1.0 kPa	-	-	1.0 kPa
K ₀	0.43	0.43	0.43	-		0.43

Table 1: material properties

* 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
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	EA	А	Eanchor
Upper anchors	2.87E5 kN	$1.37E-3 m^2$	2.1E8/2.3
			kN/m²/m
Lower anchors	3.22E5 kN	1.53E-3 m ²	2.1E8/1.35
			kN/m²/m

Table 3: Anchor properties

	EA/m	А	Egrout
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.

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

Table 5:	Tangential	slip	interface	properties
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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).



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.

Stress and Strain			>
Analysis category	2D Inplane		
Usage Element descrip Point Include joint Bar Element name	tion ne Osurface Ovolume is v	Ex	Value 333.913
Stress and strain ty Target Initial Residual (NL on	ре (у)		
Name Ba	r_row1		✓ ▲ (1)
	Close	ancel Apply	Help

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.

Water Pressure Distribution	× Water Pressure Dis	tribution ×
Analysis category 20 Inplane	Analysis category	2D Inplane
Pressure profile	Pressure profile	
O Calculated from phreatic surface 2:Water_Level	 Calculated from 	phreatic surface 1:In_Excavation ~
Density of fluid 1.0		Density of fluid 1.0
 Assigned to faces 	 Assigner 	d to faces
 Include face pressure (for water/solid interface) 	1	clude face pressure (for water/solid interface)
Assigned to continuum	Assigner	d to continuum
O Fully defined by profiles, assigned to continuum	Fully defined by	profiles, assigned to continuum
Profile variation <select></select>	F	Profile variation <select> <</select>
Name Ground Water	Name In	Excavation
Close Cancel Apply Help		Close Cancel Apply Help
Out of excavation area	Ins	side 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.

Analysis category	2D Inplan	B		
O Total			ital	
		Free	Fixed	Displacement
	x	0	\circ	
Translation in	Y	0	•	-14.9
	z	0		
	×	0		
Rotation about	Y	0		
	z	0	0	
Hinge rotation		0		
Pore pressure		0	0	
Name Lowe	ering Wate	r Level		(9)

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.

Deactivate	× Deactivate
Follow active mesh Closing part Fixed whilst deactivated Or Custom inactive treatment	Stiffness reduction factor ILCE=6 Inactive node control Follow active mesh Fixed whilst deactivated Line mesh control None ~
	Force redistribution Percentage to redistribute 100.0
Name Deactivate Anchors	(1) O Distribute over stage Number of increments
OK Cancel Apply	Help OK Cancel Help

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**.



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



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



Figure 16: Initial 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.



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.



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.



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.

Incrementation		Solution strategy				
Nonlinear		Same as previous loadcase				
Incrementation	Manual 🗸	Max number of iterations	30			
Starting load factor	0.1	Residual force norm	0.1			
Max change in load factor	0.0	Incremental displacement norm	1.0			
Max total load factor	1.0		Advanced			
Adjust load based on co	onvergence	Incremental I USAS file output	-			
Iterations per increment	4	Same as previous loadcase				
	Advanced	Output file	1			
Time domain		Plot file	1			
	Two Phase 🗸 🗸	Restart file				
Initial time step	0.0	May or other of environmentation				
Total response time	100.0E6	Max number of saved restarts				
Automatic time stepping	9	Log he	1			
	Advanced	History file	1			
		Save a restart at the end of this	control			
Common to all						
Max time steps of	or increments 0					

Figure 26: Increase in number of maximum allowed iterations

Nonlinear convergence			Nonlinear iterative accele	eration		
Maximum absolute residual 10.0E21		Strategy	Minimise	including resid	du; ~	
Root mean square of residuals 10.0E21		Additional parameters	Custom	~		
Displacement norm 1.0		1.0	Maximum number of line	e searches	3	
Residual work norm 10.0E21		Line search tolerance factor		0.8		
Two-phase solution strategy			Maximum line search an	plification fac	tor 0.0	
Groundwater solution	ater solution Auto ~		Maximum line search at	10.0	10.0	
Permeability	Aut	0 \	Maximum ine search su	epiengui	10.0	
Euclidean pressure norm 0.1		Minimum line search step length				
Incremental Euclidean press	ure norm	0.0	Separate iterative loo	op for contact	procedure	

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).

Dan die tune			
nesura type	Components		Egenvalues
Results			Reported components
Units	Model units	~	
Loadcases	53:Increment 53 Load Factor = 1.000	00 V	Standard
Entity	Force/Moment - Plane Strain Beam	~	
Location	Averaged nodal	~	
Extent	Elements showing results	~	⊕ □Energy
Output	Tabular and Summary	~	
Order	Loadcase/Mesh	~	
Transform	Transformed None		
Display of Display of Coordinate Of Coordina	extreme envelope / smart combination re for slice(s) Allow derived compor ates now treeview Defa	sults nents sults	Precision © Significant figures © Decimal places □ Show trailing zeros □ Threshold value N/A
	Name		√ × (new)

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.

🔀 LUSAS Academic (Analyst Plus) - Print Results Witz	erd					
File Edit View Utilities Window Grid He	lp .					
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Print Results Wizard (1)	2	7579	30.0	116.238	0.0	-148.424
- 00 1/PRW1	3	7580	30.0	116.775	0.0	-99.2453
Sectors (1)	4	7581	30.0	117,312	0.0	-61.2093
Circular Sections (1)	5	7582	30.0	117.85	0.0	-32,9127
- C 1:Sct1 (CSS D=0.0438)	6	7583	30.0	118.388	0.0	-13.4886
	7	7584	30.0	118,925	0.0	-2.79076
	8	7585	30.0	119.463	0.0	-0.349845
		7586	30.0	115.45	0.0	-175.39
	10	7587	30.0	111.7	0.0	-176.562
	11	7588	30.0	112.2	0.0	-106.446
	12	7589	30.0	112.7	0.0	-61.0951
	13	7590	30.0	113.2	0.0	-38.4817
	14	7591	30.0	113.7	0.0	-36,8569
	15	7592	30.0	114.2	0.0	-54,7604
	16	7593	30.0	114.7	0.0	-90.7017
	17	7594	30.0	110.95	0.0	-177.959
	18	7595	30.0	106.605	0.0	224,573
	12	7596	30.0	107.08	0.0	303.823
	20	7597	30.0	107,515	0.0	352.014
	21	7598	30.0	107.97	0.0	370.545
	22	7599	30.0	108.425	0.0	360.656
	23	7500	20.0	103.03	0.0	323.13
	24	7601	30.0	109.335	0.0	258.73
	25	7662	30.0	109.79	0.0	168.107
	26	7603	30.0	110.245	0.0	51,8013
	27	7604	30.0	105.9	0.0	205.257
	28	7605	30.0	103.812	0.0	573.152
	29	7606	30.0	104.425	0.0	540.583
	30	7607	30.0	105,038	0.0	445.127
	31	7608	30.0	100.635	0.0	-12,3139
	00	3140	100.0			400.000

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.