10 Cyclic vertical capacity and stiffness of circular underwater footing [ADV]

This tutorial illustrates how to calculate the vertical bearing capacity and vertical stiffness of a circular stiff underwater footing (e.g. one of the footings of a jacket structure) exposed to cyclic loading during a storm. The storm is idealised by a distribution of load parcels with different magnitude. The cyclic accumulation tool is used to obtain soil parameters for the UDCAM-S model . The example considers a circular concrete footing with a radius of 11 m, placed on an over-consolidated clay layer.

The procedure for establishing non-linear stress-strain relationships and calculating load-displacement curves of a foundation under a cyclic vertical load component is presented. The analysis of the circular footing is performed with a 2D axisymmetric model. The soil profile consists of clay with an overconsolidation ratio, OCR, of 4, submerged unit weight of 10 kN/m^3 and an earth pressure coefficient, K_0 of 1. The (static) undrained shear strength from anisotropically consolidated triaxial compression tests has a constant value with a depth of s_u^C = 130 kPa. The maximum shear modulus, G_{max}, of the clay is 67275 kPa. The cyclic behaviour of the soil is based on contour diagrams for Drammen clay (Andersen, Kleven & Heien, 1988 [2]) assuming that the behaviour is representative of the actual clay.

10.1 Objectives

- Obtain the UDCAM-S model input parameters by running the cyclic accumulation procedure, determining the stress-strain curves and optimising the material model parameters.
- Calculate the total cyclic vertical bearing capacity.
- Calculate the vertical stiffness accounting for cyclic loading for both the total and the cyclic component.

10.2 Geometry

The soil properties and footing geometry are shown in Figure 134 (on page 153) .

[2] Andersen, K.H., Kleven, A., Heien, .D. (1988). Cyclic soil data for design of gravity structures. Journal of Geotechnical Engineering, 517–539.

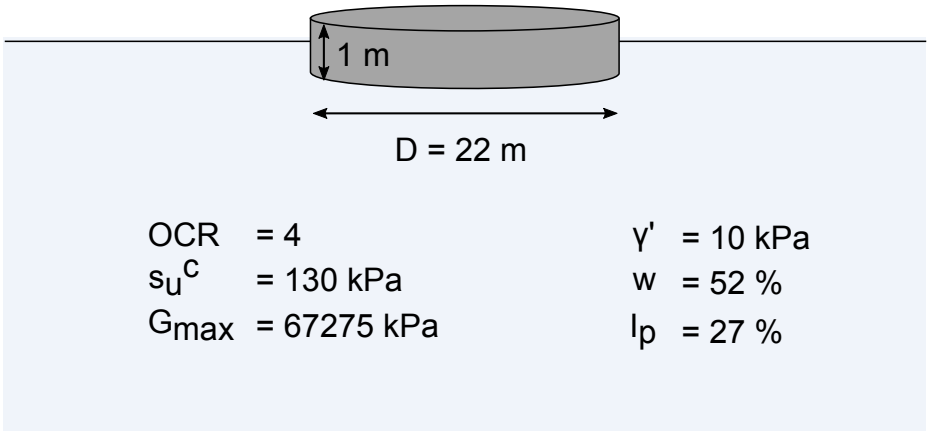

Figure 134: Geometry of the project

10.3 Create new project

To create a new project, follow these steps:

1. Start the Input program and select **Start a new project** from the **Quick select** dialog box.
2. In the **Project** tabsheet of the **Project properties** window, enter an appropriate title.
3. In the **Model** tabsheet make sure that
   a. Model is set to **Axisymmetry** and that
   b. Elements is set to **15-Noded**.
4. Define the limits for the model contour as
   a. x_{min} = 0.0 m, x_{max} = 40.0 m
   b. y_{min} = -30.0 m and y_{max} = 0.0 m

10.4 Define the soil stratigraphy

The sub-soil layers are defined using a borehole.

To define the soil stratigraphy:

1. Click the **Create borehole** button and create a borehole at x = 0.
   The **Modify soil layers** window pops up.
2. Create a single soil layer with top level at 0.0 m and bottom level at -30.0m.
3. For simplicity, water is not taken into account in this example. The groundwater table is therefore set below the bottom of the model, and the soil weight is based on the effective (underwater) weight.
4. In the borehole column specify a value of -50.00 for **Head**.

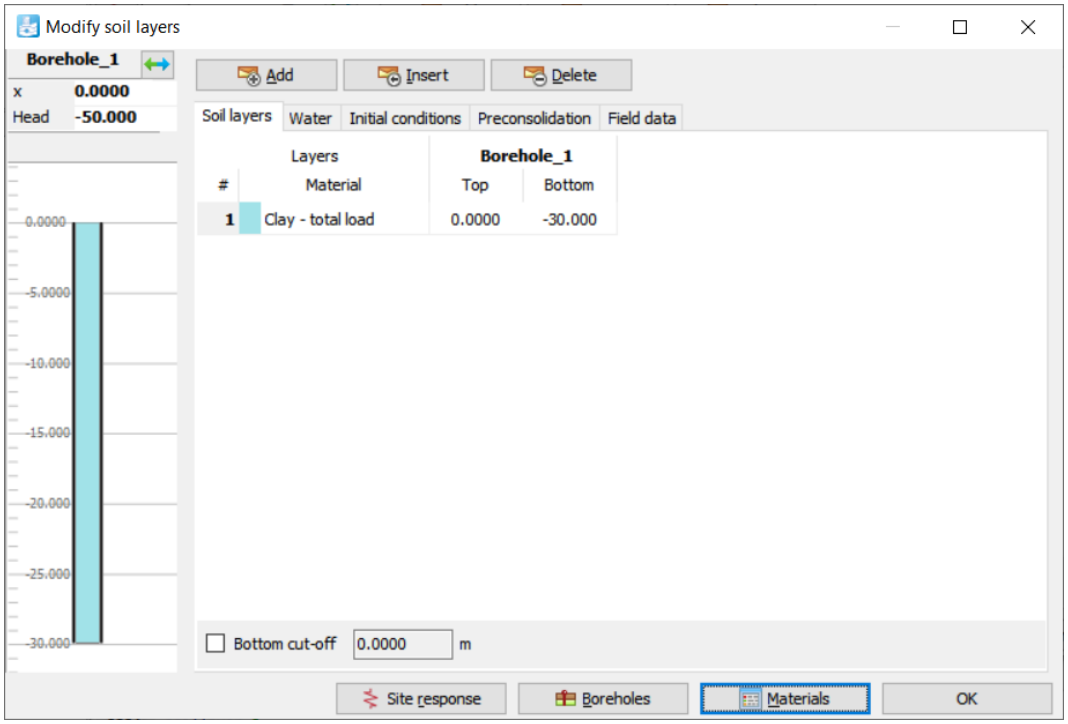

Figure 135: Soil layer

10.5 Create and assign material data sets

Three material data sets need to be created; two for the clay layer (Clay - total load and Clay - cyclic load) and one for the concrete foundation.

Open the **Material sets** window.

10.5.1 Material: Clay - total load

The model parameters for this material will be determined by the cyclic accumulation and optimisation tool.

The other properties are as shown in Table 22 (on page 154) :

Table 22: Material properties

Parameter	Name	Clay - total load	Unit
General			
Identification	-	Clay - total load	-

Parameter	Name	Clay - total load	Unit
General			
Soil model	-	UDCAM-S model	-
Drainage type	-	Undrained (C)	-
Unsaturated unit weight	γ_{unsat}	10	kN/m^3

To create the material set, follow these steps:

1. Choose **Soil and interfaces** as the **Set type** and click the **New** button.
2. On the **General** tab enter the values according to Table 22 (on page 154).
3. Proceed to the **Mechanical** tab.

Instead of entering the model parameters in this tab sheet, we will run the cyclic accumulation and optimisation tool. This procedure consists of three steps.

Click the **Mechanical** tab and click the **Cyclic accumulation and optimisation tool** option in the side window as shown in Figure 136 (on page 155).

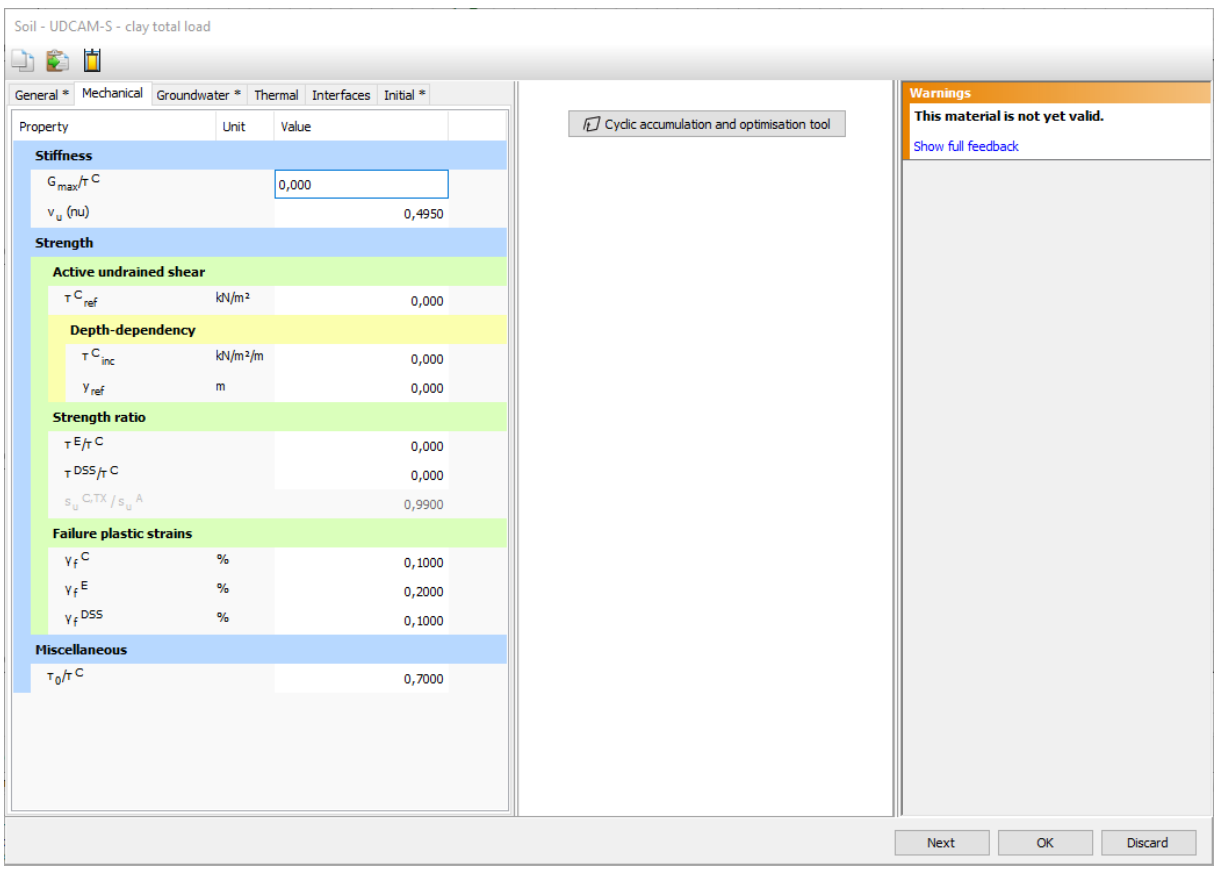

Figure 136: Cyclic accumulation and optimisation tool

A new window opens shown in Figure 137 (on page 156):

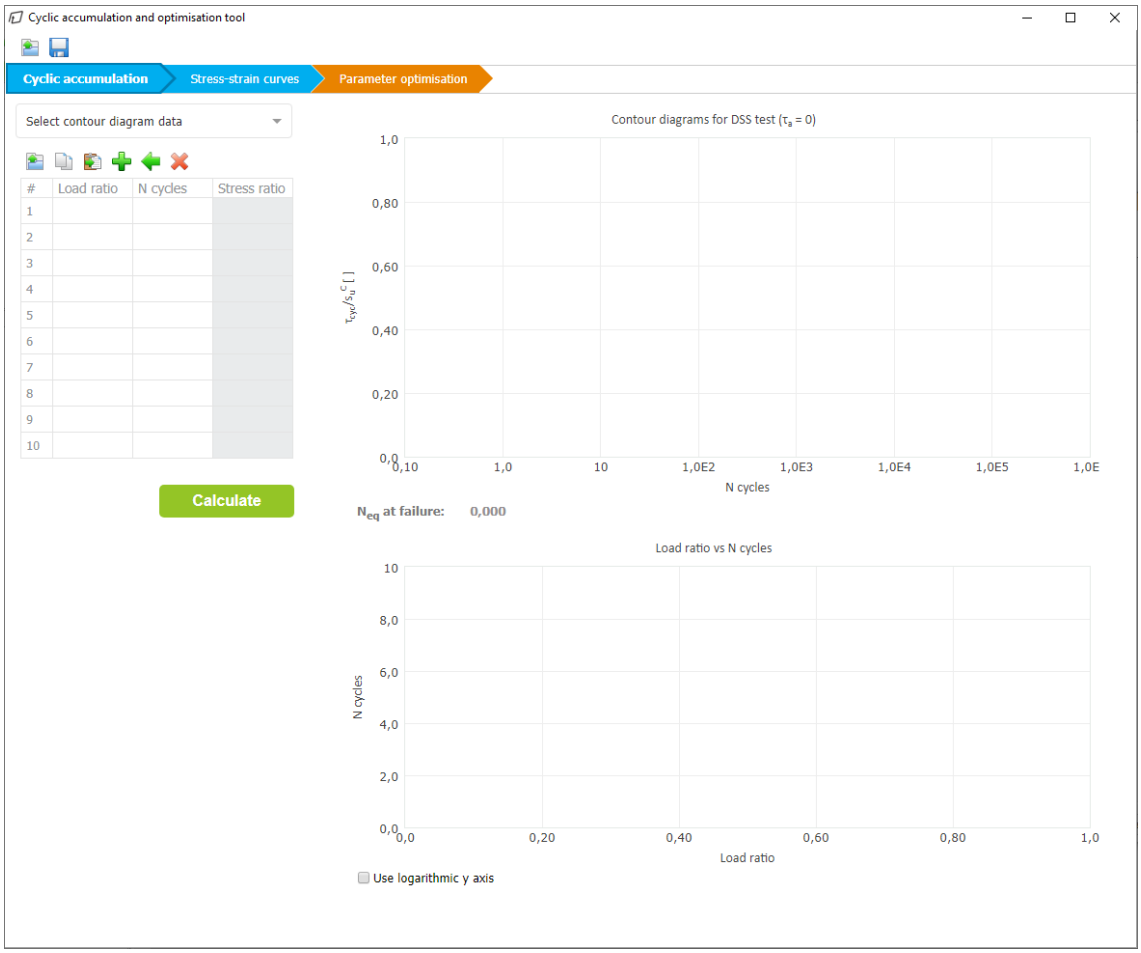

Figure 137: Cyclic accumulation tool window

The three steps of the cyclic accumulation and optimisation procedure are represented by the three modes (**Cyclic accumulation**, **Stress-strain curves** and **Parameter optimisation**) in the window.

Cyclic accumulation

The purpose of this step is to determine the equivalent number of undrained cycles of the peak load, N_{eq}, for a given soil contour diagram and load distribution.

The following storm composition data will be used as shown in Table 23 (on page 156):

Table 23: Composition of cyclic vertical load for a 6-hour design storm

#	Load ratio	N cycles
1	0.02	2371

#	Load ratio	N cycles
2	0.11	2877
3	0.26	1079
4	0.40	163
5	0.51	64
6	0.62	25
7	0.75	10
8	0.89	3
9	1.0	1

1. Select an appropriate contour diagram from **Select contour diagram data** in the **Cyclic accumulation** tab. In this case, select **Drammen clay, OCR = 4**.

   Note: For more information about contour diagrams, see Andersen (2015) [3] and Reference Manual PLAXIS 2D , Cyclic accumulation and optimisation tool.

2. The load ratios and number of cycles from the storm composition can be entered in the empty table. The storm composition is given in Table 23 (Jostad, Torgersrud, Engin & Hofstede, 2015) [4] as the cyclic vertical load normalized with respect to the maximum cyclic vertical load (Load ratio) and the number of cycles (N cycles). It is here assumed that the cyclic shear stress history in the soil is proportional to the maximum cyclic vertical load of the footing. The table should be entered such that the smallest load ratio is at the top and the highest load ratio is at the bottom.

   Note: The design storm is a load history that is transformed into parcels of constant cyclic load. Each parcel corresponds to a number of cycles at a constant amplitude determined from the time record of the load component. See Reference Manual, Cyclic accumulation and optimisation tool, for more information.

   When you've entered the load parcels in the table, the **Load ratio vs N cycles** graph will show a graphic representation of the data. For the data given here and the logarithmic scale turned on, the resulting graph is shown in Figure 138 (on page 158).

[3] Andersen, K.H. (2015). Cyclic soil parameters for offshore foundation design, volume The 3rd ISSMGE McClelland Lecture of Frontiers in Offshore Geotechnics III. Meyer (Ed). Taylor & Francis Group, London, ISFOG 2015. ISBN 978-1-138-02848-7.

[4] Jostad, H.P., Torgersrud, Ø., Engin, H.K., Hofstede, H. (2015). A fe procedure for calculation of fixity of jack-up foundations with skirts using cyclic strain contour diagrams. City University London, UK.

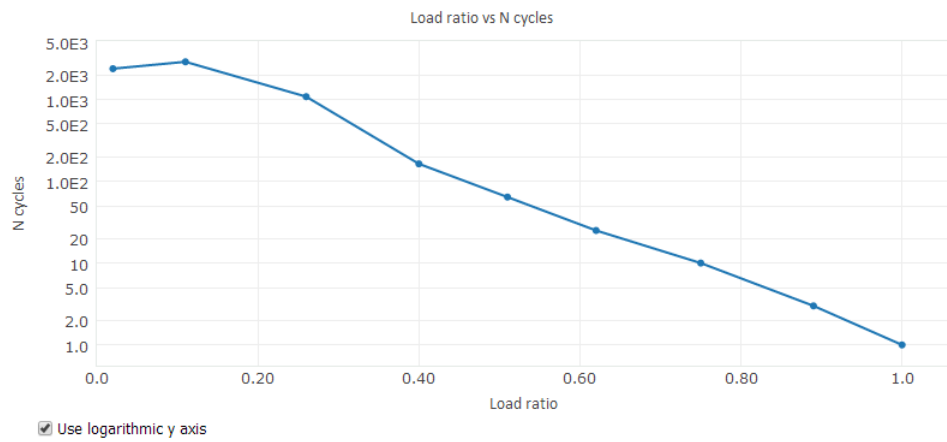

Figure 138: Load ratio vs N cycles graph (logarithmic scale)

3. Click **Calculate** to calculate the equivalent number of cycles N_{eq}.
   The selected contour diagram is plotted together with the shear stress history for a scaling factor where the soil fails (here defined at 15% shear strain) at the last cycle (Figure 139 (on page 158)) and the loci of end-points of the stress history for different scaling factors. The calculated equivalent number of cycles corresponds to the value on the x-axis at the last point of the locus of end-points and is equal to 6.001.

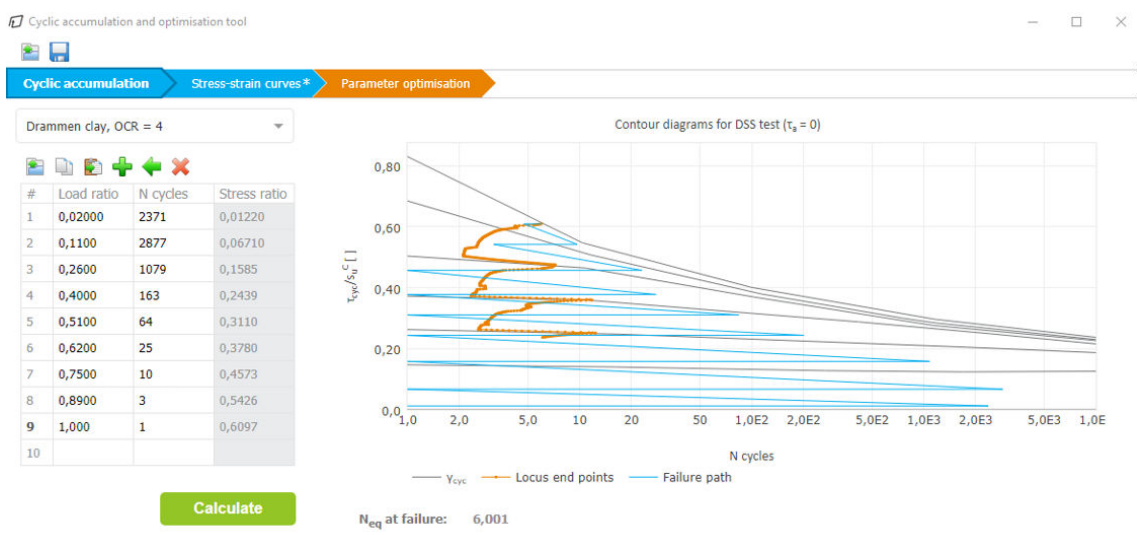

Figure 139: Cyclic accumulation in PLAXIS 2D

Stress-strain curves

The purpose of this tab is to obtain non-linear stress-strain curves for a given (calculated) N_{eq} and given cyclic over average shear stress ratio (here taken equal to the ratio between cyclic and average vertical load during the storm).

1. Go to the **Stress-strain curves** tab.

2. For the N_{eq} determination, keep the default option **From cyclic accumulation**. The calculated equivalent number of cycles is adopted from the previous tab.
3. Keep the **Soil behaviour** as **Anisotropic**, and the **Scaling factor**, **DSS** and **Scaling factor**, **TX** as 1.

Note:

- Cyclic strength can be scaled based on available soil specific cyclic strength.
- If the plasticity index and/or water content of the soil is different from Drammen clay, the cyclic strength can be scaled by applying a scaling factor different from 1 (see Andersen, 2015 [5] for details).

4. Set the cyclic to average shear stress ratio for DSS, triaxial compression and triaxial extension, describing the inclination of the stress path, to appropriate values. In this example, the following input values are selected to obtain strain compatibility at failure, i.e. the same cyclic and average shear strain for the different stress paths at failure.
   a. cyclic to average ratio for DSS $(\Delta\tau_{cyc}/\Delta\tau_a)^{DSS} = 1.1$,
   b. triaxial compression $(\Delta\tau_{cyc}/\Delta\tau_a)^{TXC} = 1.3$ and
   c. extension $(\Delta\tau_{cyc}/\Delta\tau_a)^{TXE} = -6.3$
5. Select the load type as, **Total load** for this first material.
   DSS and triaxial contour diagrams are plotted together with stress paths described by the cyclic to average ratios (Figure 140 (on page 160)). Notice that the shear stresses are normalised with respect to the static undrained shear strength in compression. The extracted stress-strain curves are plotted below the contour diagrams.
6. Click **Calculate** to produce the corresponding normalised stress-strain curves below the contour diagrams. See Figure 140 (on page 160) for the outcome.

[5] Andersen, K.H. (2015). Cyclic soil parameters for offshore foundation design, volume The 3rd ISSMGE McClelland Lecture of Frontiers in Offshore GeotechnicsIII. Meyer (Ed). Taylor & Francis Group, London, ISFOG 2015. ISBN978-1-138-02848-7.

Figure 140: Stress-strain curves for total load

Parameter optimisation

The purpose of the optimisation is to obtain a set of parameters for the UDCAM-S model.

The parameter ranges and the results you will see after the optimisation are shown in Table 24 (on page 160):

Table 24: Parameter ranges and results after optimization

Parameter	Name	Min value	Max value	Optimised value	Unit
Ratio of the initial shear modulus to the degraded shear strength at failure in triaxial compression	G_{ur} / τ^C	400.0	480.0	420.4	-
Shear strain at failure in triaxial compression	γ_f^C	6.0	8.0	6.431	%

Parameter	Name	Min value	Max value	Optimised value	Unit
Shear strain at failure in triaxial extension	γ_f^E	5.0	8.0	7.873	%
Shear strain at failure in direct simple shear	γ_f^{DSS}	8.0	12.0	11.97	%
Ratio of the cyclic compression shear strength over the undrained static compression shear strength	$\tau^C / S_u{}^C$	1.14	1.16	1.152	-
Ratio of the cyclic DSS shear strength over the undrained static compression shear strength	$\tau^{DSS} / S_u{}^C$	0.89	0.91	0.9051	-
Ratio of the cyclic extension shear strength over the undrained static compression shear strength	$\tau^E / S_u{}^C$	0.62	0.64	0.6208	-
Reference degraded shear strength at failure in the triaxial compression test	$\tau^C{}_{ref}$	-	-	149.7	-
Reference depth	y_{ref}	-	-	0.000	m
Increase of degraded shear strength at failure in the triaxial compression test with depth	$\tau^C{}_{inc}$	-	-	0.000	kN/m^2/m
Ratio of the degraded shear strength at failure in the triaxial extension test to the degraded shear strength in the triaxial compression test	τ^E / τ^C	-	-	0.5389	-
Initial mobilisation of the shear strength with respect to the degraded TXC shear strength	τ^0 / τ^C	-	-	2.332E-3	-
Ratio of the degraded shear strength at failure in the direct simple shear test to the degraded shear strength in the triaxial compression test	τ^{DSS} / τ^C	-	-	0.7858	-

Use the following steps to calculate the optimised values.

1. Click the **Parameter optimisation** tab.
2. Enter the parameters of the clay in the **Static properties**. Set $s_u{}^C{}_{ref}$ to 130.0 and K_0 determination to **Manual** and set K_0 to 1.0.
3. Propose minimum and maximum values for the parameters listed in Table 24 (on page 160).

Note:

In the optimisation, set minimum and maximum values of τ^C / $S_u{}^C$, τ^{DSS} / $S_u{}^C$, and τ^E / $S_u{}^C$ close to the results from the strain interpolation if one wants to keep these values.

Calculate G_{max} / τ^C by dividing G_{max} from soil properties with results for (τ^C / $S_u{}^C$) · $S_u{}^C$.

Set the minimum and maximum values close to this value.

4. Click **Calculate** to obtain optimised parameters (Figure 141 (on page 162) and column Optimised value of Table 24 (on page 160)).

   After a few seconds, the optimal values are shown in the corresponding column in the Parameter ranges table. Based on these values, the optimised parameters are calculated and listed in the right-hand side of the table as shown in Figure 141 (on page 162)

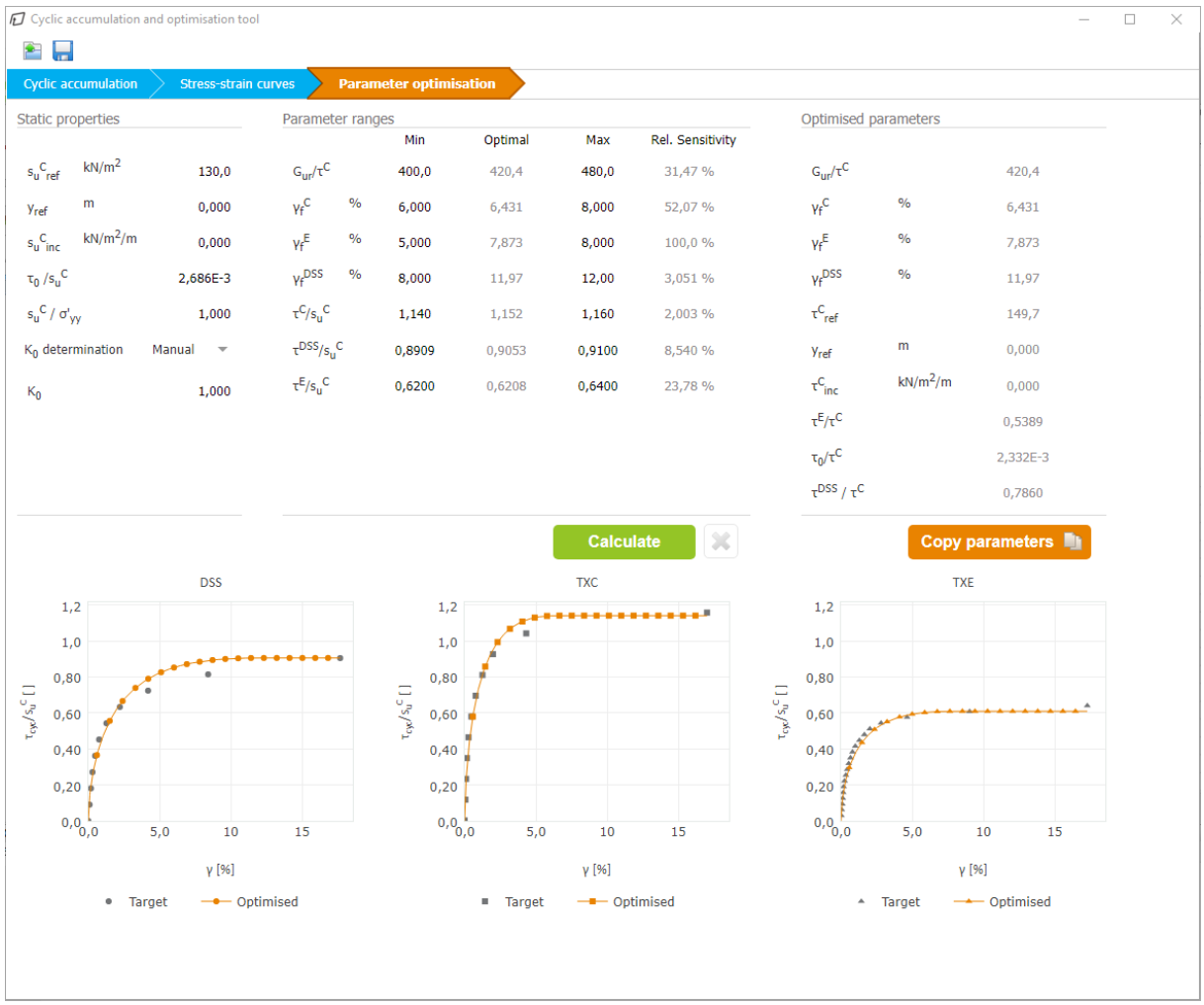

Figure 141: Optimised parameters for total load

The resulting stress-strain curves from test simulations with the UDCAM-S model using the optimised parameters are shown together with the target points from the contour diagrams.

5. When the calculation has finished, save the application state of the Cyclic accumulation and optimisation tool. The saved data will be used when creating another material. To save the application state, press the **Save** button at the top of the window. Save the state under the file name `optimised_total.json`.
6. Copy the optimised material parameters: Press the **Copy parameters** button and go back to the **Soil-UDCAM-S** window describing the material.
7. Click the **Paste material** button .
   The values in the **Mechanical** tab are replaced with the new values as shown in Figure 142 (on page 163) .

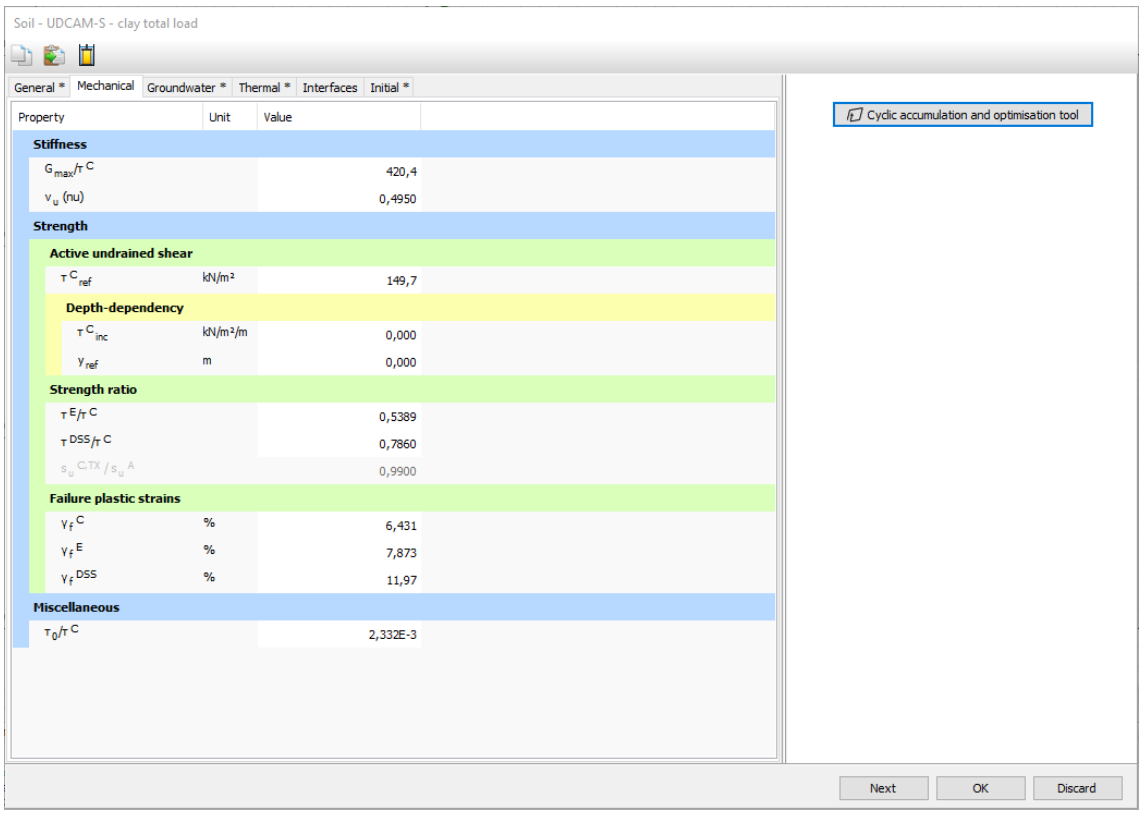

Figure 142: Copy parameters into Clay total material

8. Go to the **Initial** tab and set K_0 to 1 by setting K_0 determination to Manual, check $K_{0,x} = K_{0,z}$ (default) and set $K_{0,x}$ to 1.
9. Click **OK** to close the created material.
10. Assign the **Clay - total load** material set to the soil layer in the borehole.

10.5.2 Material: Clay - cyclic load

Create a material for the second clay. Some information from the *Clay - total load* material will be reused. The optimisation of the parameters has to be recalculated though, based on other conditions.

The parameter ranges and the results you will see after the optimisation are shown in Table 25 (on page 164):

Table 25: Parameter ranges and results after optimisation

Parameter	Name	Min value	Max value	Optimised value	Unit
Ratio of the initial shear modulus to the degraded shear strength at failure in triaxial compression	G_{max} / τ^C	700.0	800.0	703.2	-
Shear strain at failure in triaxial compression	γ_f^C	1.0	3.0	2.966	%
Shear strain at failure in triaxial extension	γ_f^E	1.0	3.0	2.699	%
Shear strain at failure in direct simple shear	γ_f^{DSS}	1.0	3.0	2.946	%
Ratio of the cyclic compression shear strength over the undrained static compression shear strength	$\tau^C / S_u{}^C$	0.66	0.67	0.6667	-
Ratio of the cyclic DSS shear strength over the undrained static compression shear strength	$\tau^{DSS} / S_u{}^C$	0.47	0.49	0.4787	-
Ratio of the cyclic extension shear strength over the undrained static compression shear strength	$\tau^E / S_u{}^C$	0.57	0.59	0.5790	-
Reference degraded shear strength at failure in the triaxial compression test	$\tau^C{}_{ref}$	-	-	86.67	-
Reference depth	y_{ref}	-	-	0.000	m
Increase of degraded shear strength at failure in the triaxial compression test with depth	$\tau^C{}_{inc}$	-	-	0.000	$kN/m^2/m$
Ratio of the degraded shear strength at failure in the triaxial extension test to the degraded shear strength in the triaxial compression test	τ^E / τ^C	-	-	0.8684	-

Parameter	Name	Min value	Max value	Optimised value	Unit
Initial mobilisation of the shear strength with respect to the degraded TXC shear strength	τ^0 / τ^C	-	-	0.000	-
Ratio of the degraded shear strength at failure in the direct simple shear test to the degraded shear strength in the triaxial compression test	τ^{DSS} / τ^C	-	-	0.7181	-

Use the following steps to calculate the optimised values.

1. Copy the **Clay - total load** material.
2. Enter `Clay - cyclic load` for the identification.
3. Go to the **Mechanical** tab.
   Like for the first material, also here the parameters will be determined using the **Cyclic accumulation and optimisation tool**.
4. Click the **Cyclic accumulation and optimisation tool** button on the **Mechanical** tab to open the tool.
5. Click the **Open file** button and choose the application state `optimised_total.json` that was saved after optimisation of the first material.
   All tabs will be filled with data.
6. Leave the **Cyclic accumulation** tab as it is.
7. Go to the **Stress-strain curves** tab, set load type to **Cyclic load**.
8. Press **Calculate** and let the calculation finish.
   The stress-strain curves are shown in Figure 143 (on page 166):

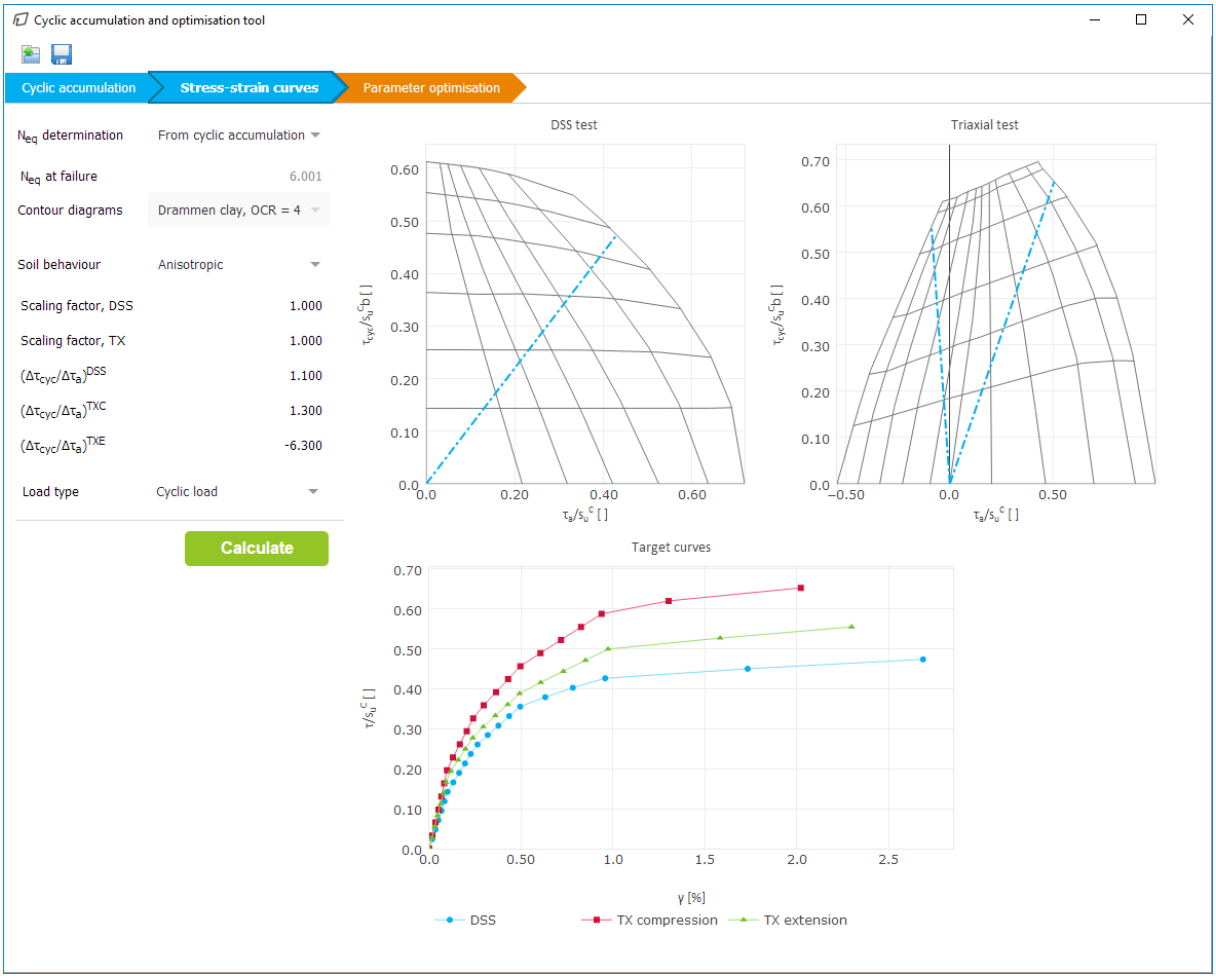

Figure 143: Stress-strain curves for cyclic load

9. Go to the **Parameter optimisation** tab. Accept the notification about resetting the optimisation tab to get updated values.
10. Make sure that $s_u{}^C{}_{ref}$ is set to 130.0 and set K_0 determination to Automatic.
11. Modify the minimum and maximum values for the **Parameter ranges**, see Table 25 (on page 164) for values.
12. Click **Calculate** to get the optimised parameters.
    The optimised parameters are shown in the Figure 144 (on page 167) and are also listed in the column 'Optimised value' in Table 25 (on page 164).

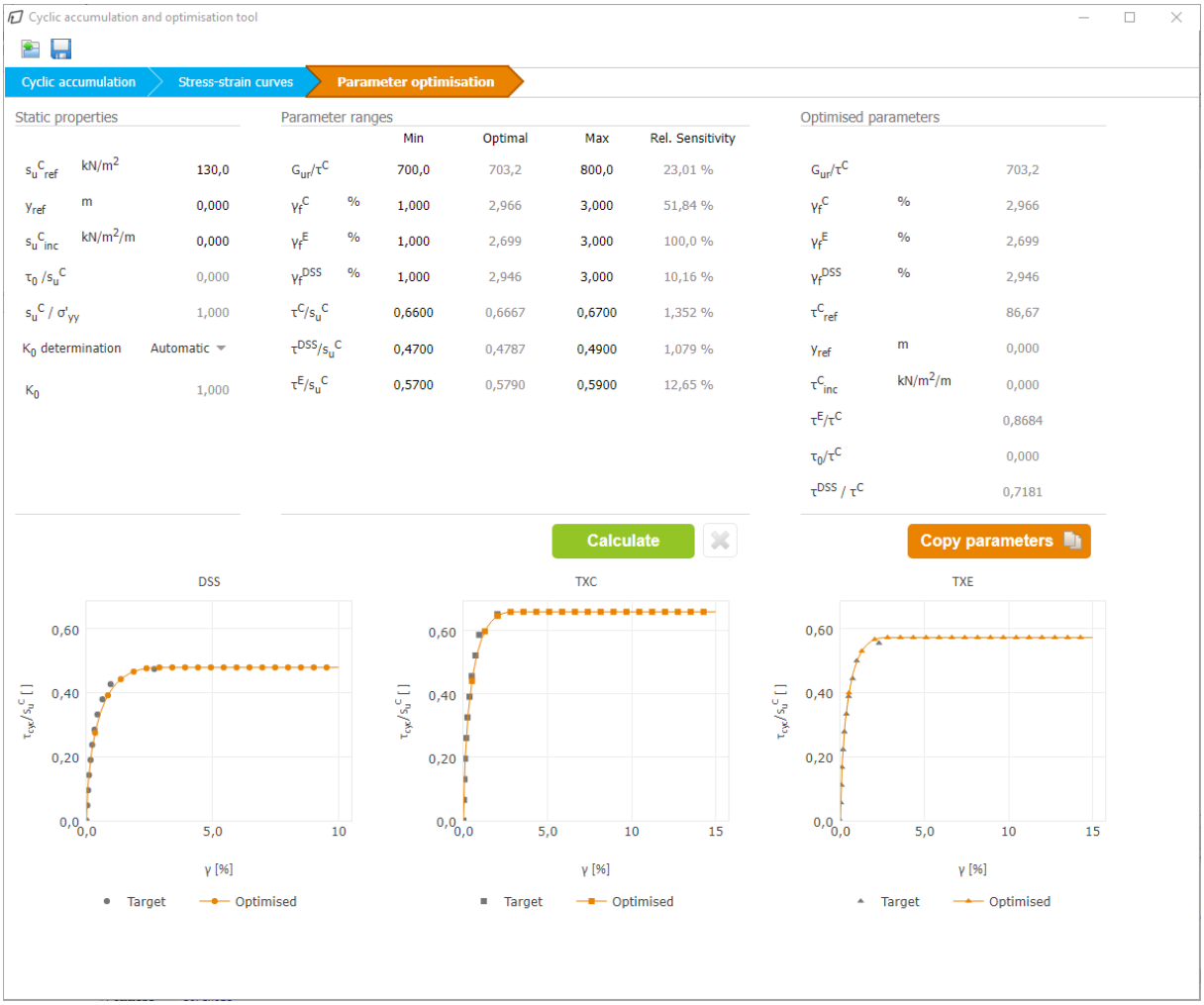

Figure 144: Optimised parameters for cyclic load

13. Save the application state under the file name `optimised_cyclic.json`.
14. Copy the optimised material parameters: Click the **Copy parameters** button and go back to the **Soil-UDCAM-S** window.
15. Click the **Paste material** button .
    The values in the **Mechanical** tab are replaced with the new values.
16. Click **OK** to close the created material.

10.5.3 Material: Concrete

Create a new material for the concrete foundation.

1. Choose **Soil and interfaces** as the **Set** type and click the **New** button.

2. Enter `Concrete footing` for the **Identification** and select **Linear elastic** as the **Material model**.
3. Set the **Drainage type** to **Non-porous**.
4. Enter the properties of the material:
   a. a unit weight of 24 kN/m^3,
   b. Young's modulus of $30x10^6$ kN/m^2 and
   c. a Poisson's ratio of 0.1.
5. Click **OK** to close the created material.
6. Click **OK** to close the **Material sets** window.

10.6 Define the structural elements

The concrete foundation and interfaces have to be defined.

10.6.1 Define the concrete foundation

1. Click the **Structures** tab to proceed with the input of structural elements in the Structures model.
2. Select the **Create soil polygon** feature in the side toolbar and click on (0.0, 0.0), (11.0, 0.0), (11.0, -1.0) and (0.0, -1.0).

Note: Do not yet assign the **Concrete footing** material to the polygon.

10.6.2 Define the interfaces

Create an interface to model the interaction of the foundation and the surrounding soil. Extend the interface half a meter into the soil. Make sure the interface is at the outer side of the footing (inside the soil). The interface is created in two parts.

1. Click **Create interface** to create the upper part from (11.0, -1.0) to (11.0, 0.0), Figure 146 (on page 170).
2. Click **Create interface** to create the lower part (between foundation and soil) from (11.0, -1.5) to (11.0, -1.0), Figure 146 (on page 170).
3. The upper part interface (between the foundation and the soil) is modeled with a reduced strength of 30%.
   a. Make a copy of the **Clay - total load** material and name it `Clay - total load - interface` .
   b. Reduce the interface strength by setting R_{inter} to 0.3 as shown in Figure 145 (on page 168) and

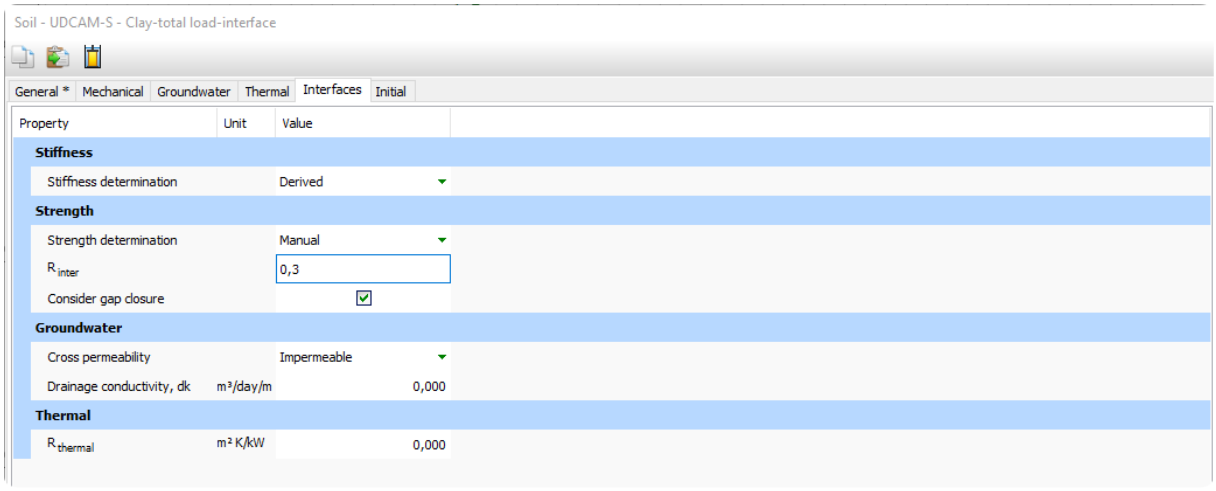

Figure 145: Clay-Total load interface

c. Assign this to the upper part of the interface.

4. For Phase 3 (Calculate vertical cyclic stiffness), another material with reduced strength is needed.

a. Make a copy of the **Clay - cyclic load material** and name it `Clay - cyclic load - interface`.

b. Reduce the interface strength by setting R_{inter} to 0.3.

c. Do not assign this yet. It will be assigned when defining Phase 3.

5. For the interface material extended into the soil, full soil strength is applied (R_{inter} = 1.0), as implicitly defined in the original clay material **Clay - total load**. Keep the default setting **Material mode**: From adjacent soil. The geometry of the model is shown in Figure 146 (on page 170):

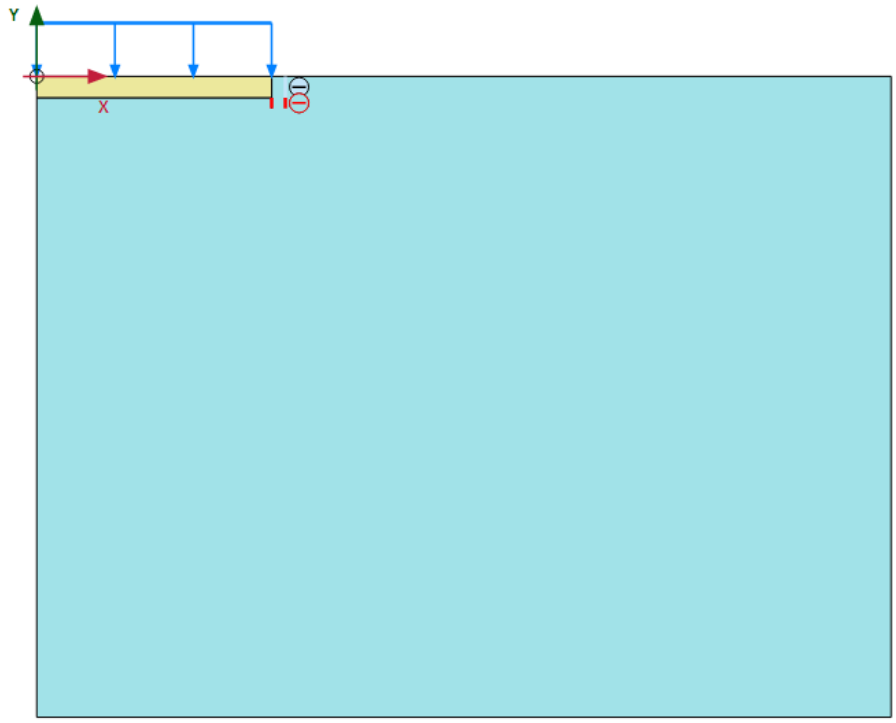

Figure 146: Geometry of the model

10.6.3 Define a vertical load

In order to calculate the cyclic vertical capacity and stiffness, a vertical load is applied at the top of the foundation.

1. Define a distributed load by selecting **Create line load** and click (0.0, 0.0) and (11.0, 0.0).
2. In the **Selection explorer** set the value of $q_{y,start,ref}$ to -1000 kN/m/m.

10.7 Generate the mesh

1. Proceed to the **Mesh mode** .
2. Click the **Generate mesh** button in the side toolbar. For the **Element distribution** parameter, use the option **Medium** (default).
3. Click the **View mesh** button to view the mesh as shown in Figure 147 (on page 171).

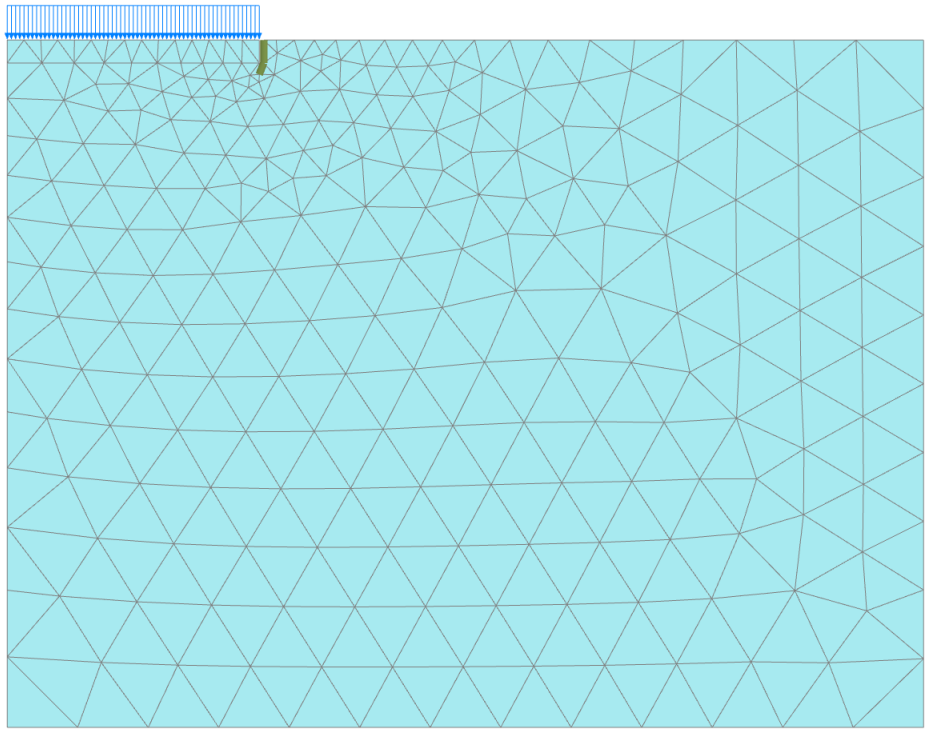

Figure 147: The generated mesh

4. Click the **Close** tab to close the Output program.

10.8 Define and perform the calculation

The calculation consists of the following phases:

- In the Initial phase, the initial stress conditions are generated by the **K0 procedure**, using the default values.
- In Phase 1 the footing is activated by assigning the **Concrete** material to the corresponding polygon. The interfaces are also activated.
- In Phase 2 the total cyclic vertical bearing capacity and stiffness are calculated.
- In Phase 3 the cyclic vertical bearing capacity and stiffness are computed.

10.8.1 Initial phase

1. Proceed to **Staged construction mode** .
2. In the **Phases explorer** double-click the initial phase.
3. Make sure that **Calculation type** is set to K0 procedure.
4. Click OK to close the **Phases** window.

10.8.2 Phase 1: Footing and interface activation

1. Click the **Add phase** button to create a new phase.
2. Phase 1 starts from the Initial phase.
3. Activate the footing by assigning the **Concrete footing** material to the corresponding polygon.
4. Activate the interfaces as well.

10.8.3 Phase 2: Cyclic Vertical Bearing capacity and stiffness

In Phase 2 the total cyclic vertical bearing capacity and stiffness are calculated. The vertical bearing capacity is obtained by increasing the vertical load (stress) until failure. The stiffness is calculated as the force divided by the displacement.

1. Click the **Add phase** button to create a new phase.
2. Phase 2 starts from Phase 1.
3. In the **Phases** window go to the **Deformation control parameters** subtree and select the **Reset displacements to zero** option and **Reset small strain**.
4. Activate the line load.

10.8.4 Phase 3: Calculate vertical cyclic stiffness

In Phase 3, which also starts from Phase 1, the vertical cyclic stiffness is calculated by activating the **Clay - cyclic load material**. The vertical bearing capacity is obtained by increasing the vertical load (stress) until failure.

1. Click the **Add phase** button to create a new phase.
2. In the **Phases** window set the **Start from phase** to Phase 1.
3. Go to the **Deformation control parameters** subtree and select the **Reset displacements to zero** option and **Reset small strain**. Close this window.
4. Replace the soil material with the **Clay - cyclic load**.
5. Assign the material **Clay - cyclic load - interface** material to the upper part of the interface. The material mode of the lower part of the interface remains **From adjacent soil**.
6. Make sure the line is activated.

The calculation definition is now complete.

10.8.5 Execute the calculation

Before starting the calculation it is recommended to select nodes or stress points for a later generation of load-displacement curves or stress and strain diagrams.

To do this, follow these steps:

1. Click the **Select points for curves** button in the side toolbar.
   The connectivity plot is displayed in the Output program and the **Select points** window is activated.
2. Select a node at the bottom of the footing (0.0, 0.0). Close the **Select points** window.
3. Click on the **Update** tab to close the Output program and go back to the Input program.
4. Click the **Calculate** button to calculate the project.

10.9 Results

10.9.1 Total load cyclic vertical bearing capacity

Applied vertical stress (load): q_y = -1000 kN/m^2

Failure at: q_y = 719.1 kN/m^2(Figure 148 (on page 173))

Total vertical bearing capacity: $V_{cap} = q_y \cdot \text{Area} = 719.1\ \text{kN/m}^2 \cdot \pi \cdot (11\ \text{m})^2 = 273.35\ \text{MN}$

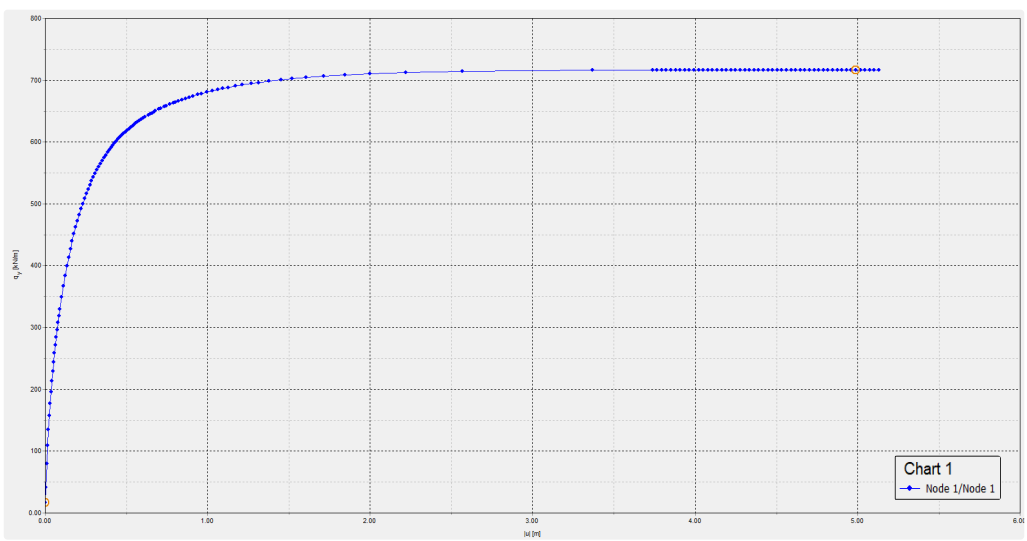

Figure 148: Load displacement curve for total load

For comparison, the static vertical bearing capacity (using the static undrained shear strength) is found to be 228.1 MN. The reason for the larger vertical bearing capacity is that the shear strengths increase due to the

higher strain rate during wave loading, compared to the value obtained from standard monotonic laboratory tests, and this effect is larger than the cyclic degradation during the storm.

10.9.2 Cyclic load cyclic vertical bearing capacity

Applied vertical stress (load): q_y = -1000 kN/m^2

Failure at: q_y = 458.1 kN/m^2(Figure 149 (on page 174))

Total vertical bearing capacity:

$V_{cap} = q_y \cdot \text{Area} = 458.1\ \text{kN/m}^2 \cdot \pi \cdot (11\ \text{m})^2 = 174.14\ \text{MN}$

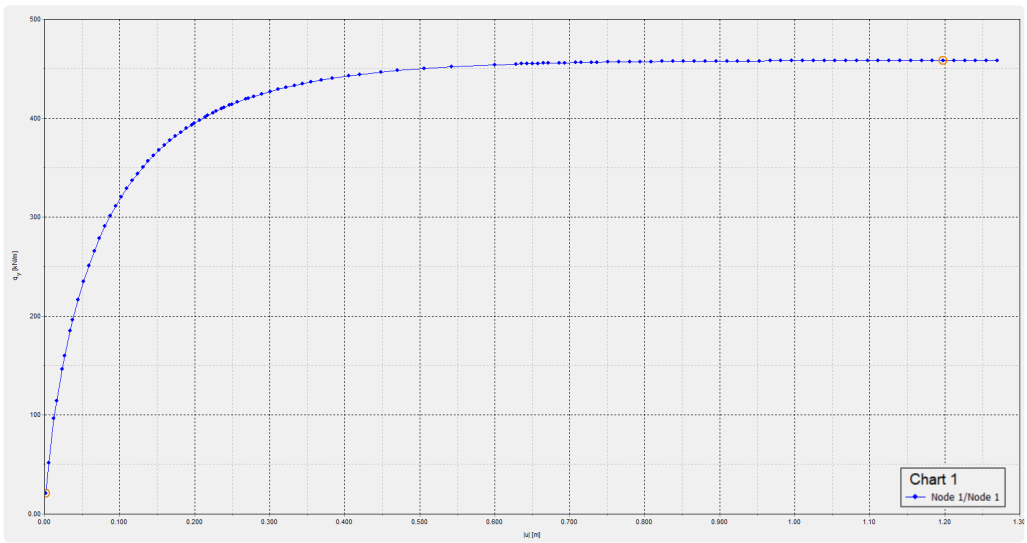

Figure 149: Load displacement curve for cyclic load

10.9.3 Vertical stiffness

The vertical stiffness (accounting for cyclic loading) is calculated as $k_y = F_y / u_y$ for both the total and the cyclic component. The total vertical displacement includes accumulated vertical displacements during the storm. Load versus stiffness is shown in the following Figure 150 (on page 175):

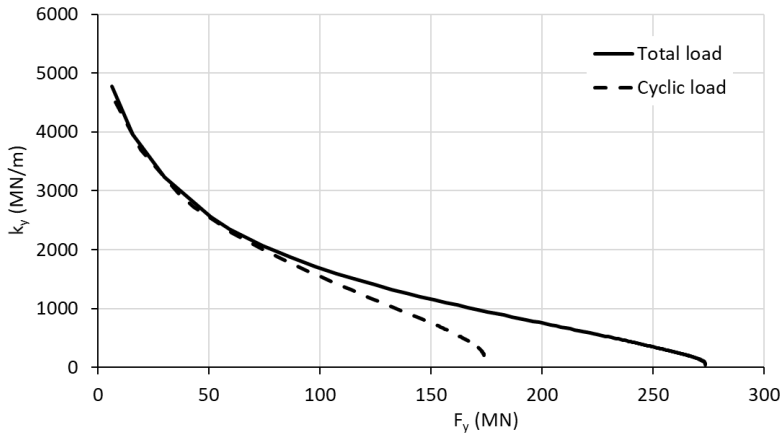

Figure 150: Vertical load versus stiffness for total and cyclic load components