

8 CYCLIC VERTICAL CAPACITY AND STIFFNESS OF CIRCULAR UNDERWATER FOOTING

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 $10 \text{ kN}/\text{m}^3$ 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 $s_u^c = 130 \text{ kPa}$. 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) assuming that the behaviour is representative of the actual clay. The soil properties and footing geometry are shown in Figure 8.1.

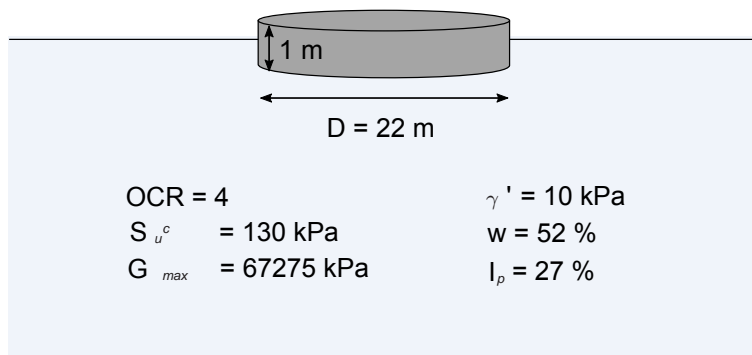


Figure 8.1 Properties of the soil and footing

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.

8.1 INPUT

To create the geometry model, follow these steps:

8.1.1 GENERAL SETTINGS

1. Start the Input program and select *Start a new project* from the *Quick select* dialog box.
2. In the *Project* tab sheet of the *Project properties* window, enter an appropriate title.
3. In the *Model* tab sheet make sure that
 - *Model* is set to *Axisymmetry* and that
 - *Elements* is set to *15-Noded*.
4. Define the limits for the soil contour as
 - $x_{min} = 0.0$ and $x_{max} = 40.0$
 - $y_{min} = -30.0$ and $y_{max} = 0$.

8.1.2 DEFINITION OF SOIL STRATIGRAPHY

The sub-soil layers are defined using a borehole.

- Create a borehole at $x = 0$. The *Modify soil layers* window pops up.
- Create a single soil layer with top level at 0.0 m and bottom level at -30.0m as shown in Figure 8.2.
- 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.

In the borehole column specify a value of -50,00 for *Head*.

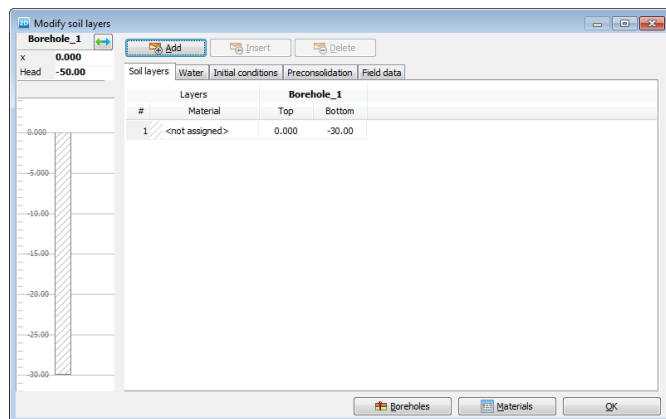


Figure 8.2 Soil layer

8.1.3 DEFINITION OF MATERIALS

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.

Material: Clay - total load

- Create a new soil material data set: Choose *Soil and interfaces* as the *Set type* and click the *New* button.
- On the *General* tab enter the values according to Table 8.1

Table 8.1 Material properties

| Parameter | Name | Clay - total load | Unit |
|---------------------------------------|-----------------------|-------------------|-------------------|
| Identification name | <i>Identification</i> | Clay - total load | - |
| Material model | <i>Model</i> | UDCAM-S | - |
| Type of material behaviour | <i>Type</i> | Undrained(C) | - |
| Soil unit weight above phreatic level | γ_{unsat} | 10 | kN/m ³ |

- Proceed to the *Parameters* 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 *Cyclic accumulation and optimisation tool* button on the *Parameters* tab, see Figure 8.3. A new window opens as shown in Figure 8.4.

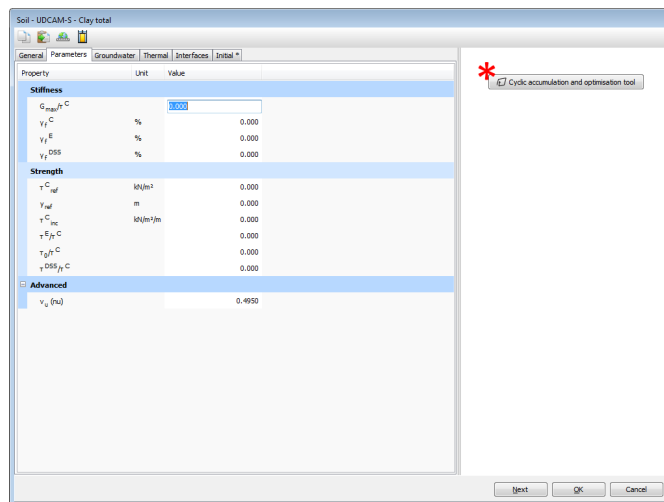


Figure 8.3 Cyclic accumulation and optimisation tool

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

1. Cyclic accumulation



Figure 8.4 Cyclic accumulation tool window

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.

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

Hint: For more information about contour diagrams, see Andersen (2015) and Section 6.1.4.

- 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 8.2 (Jostad, Torgersrud, Engin & Hofstede, 2015) 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.

Hint: 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 Section 6.1.4 of the Reference Manual 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, it will look like Figure 8.5.

- 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

Table 8.2 Composition of cyclic vertical load for a 6-hour design storm

| # | Load ratio | N cycles |
|---|------------|----------|
| 1 | 0.02 | 2371 |
| 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 |

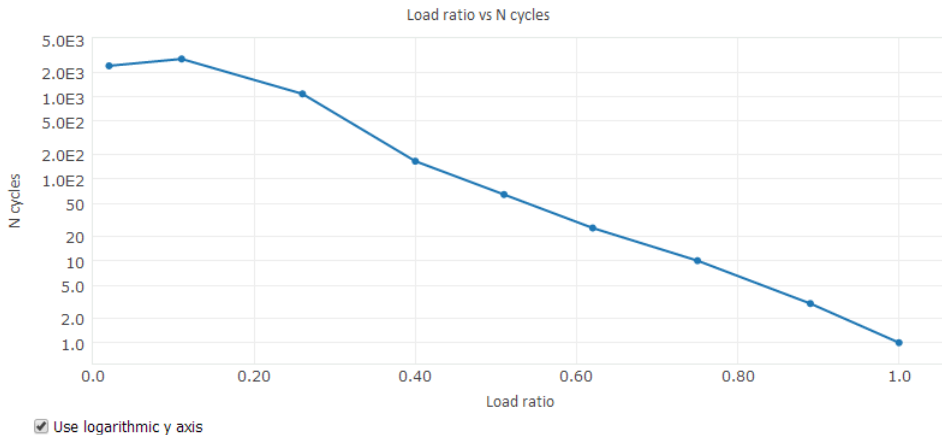


Figure 8.5 Load ratio vs N cycles graph (logarithmic scale)

the last cycle (Figure 8.6) 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.

2. 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).

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

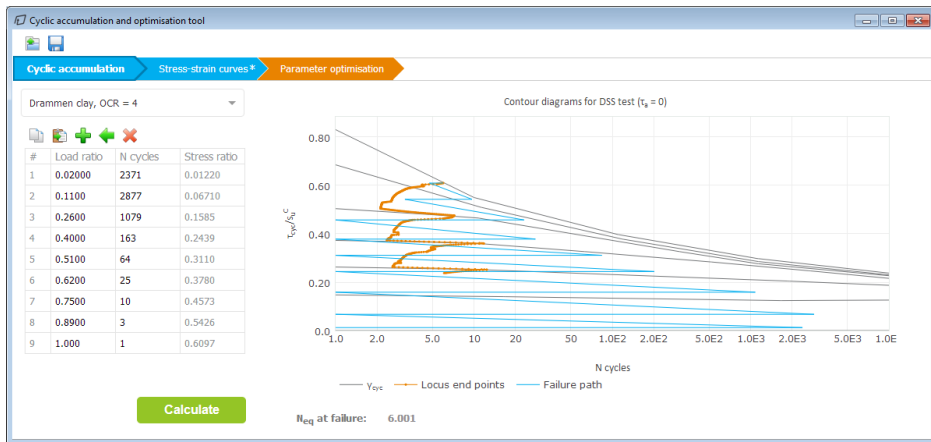


Figure 8.6 Cyclic accumulation in PLAXIS

Hint: 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) for details).

- 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.
 - cyclic to average ratio for DSS $(\Delta\tau_{cyc}/\Delta\tau)^{DSS} = 1.1$,
 - triaxial compression $(\Delta\tau_{cyc}/\Delta\tau)^{TxC} = 1.3$ and
 - extension $(\Delta\tau_{cyc}/\Delta\tau)^{TxE} = -6.3$
- Select the load type of interest, *Total load case* is selected for this first material. DSS and triaxial contour diagrams are plotted together with stress paths described by the cyclic to average ratios Figure 8.7. 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.
- Press *Calculate* to produce the corresponding normalised stress-strain curves below the contour diagrams. See Figure 8.7 for the outcome.

3. Parameter optimisation

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

- Click the *Parameter optimisation* tab.
- Enter the parameters of the clay in the *Static properties*. Set $s_{U ref}^C$ to 130.0 and K_0 determination to *Manual* and set K_0 to 1.0.

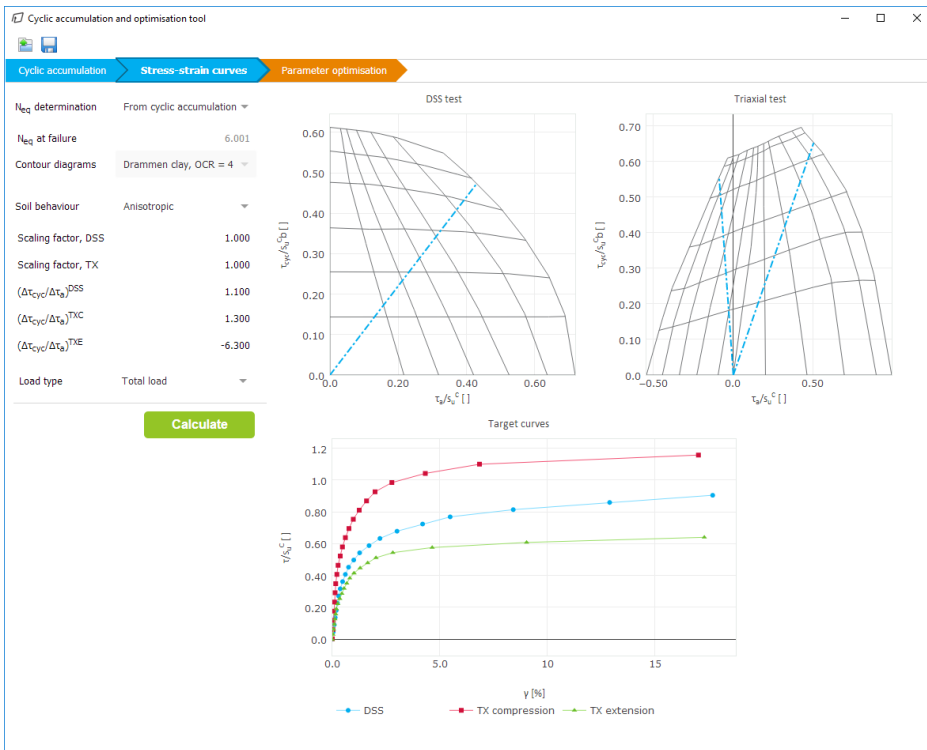


Figure 8.7 Stress-strain curves for total load

- Propose minimum and maximum values for the parameters listed below *Parameter ranges*, see (Table 8.3) for values.

Hint: 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 $(\tau^C / S_u^C) * S_u^C$. Set the minimum and maximum values close to this value.

- Click *Calculate* to obtain optimised parameters (Figure 8.8 and column 'Optimised value' of Table 8.3).


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 table.

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.

- 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.

Table 8.3 Parameter ranges and calculation results for optimisation (total load)

| 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 | 400.0 | 480.0 | 420.4 | - |
| Shear strain at failure in triaxial compression | γ_f^C | 6.0 | 8.0 | 6.431 | % |
| 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 | τ^C/S_u^C | 1.14 | 1.16 | 1.152 | - |
| Ratio of the cyclic DSS shear strength over the undrained static compression shear strength | τ^{DSS}/S_u^C | 0.89 | 0.91 | 0.9051 | - |
| Ratio of the cyclic extension shear strength over the undrained static compression shear strength | τ^E/S_u^C | 0.62 | 0.64 | 0.6208 | - |
| Reference degraded shear strength at failure in the triaxial compression test | τ_{ref}^C | - | - | 149.7 | - |
| Reference depth | y_{ref} | - | - | 0.000 | m |
| Increase of degraded shear strength at failure in the triaxial compression test with depth | τ_{inc}^C | - | - | 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 | - |

- Buttons/Input/ButtonSaveFile.png 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`.
- Copy the optimised material parameters: Press the *Copy parameters* button and go back to the *Soil-UDCAM-S* window describing the material.
 Press the *Paste material* button, and the values in the *Parameters* tab are replaced with the new values, see Figure 8.9.
- 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.
- Click *OK* to close the created material.
- Assign the *Clay - total load* material set to the soil layer in the borehole.

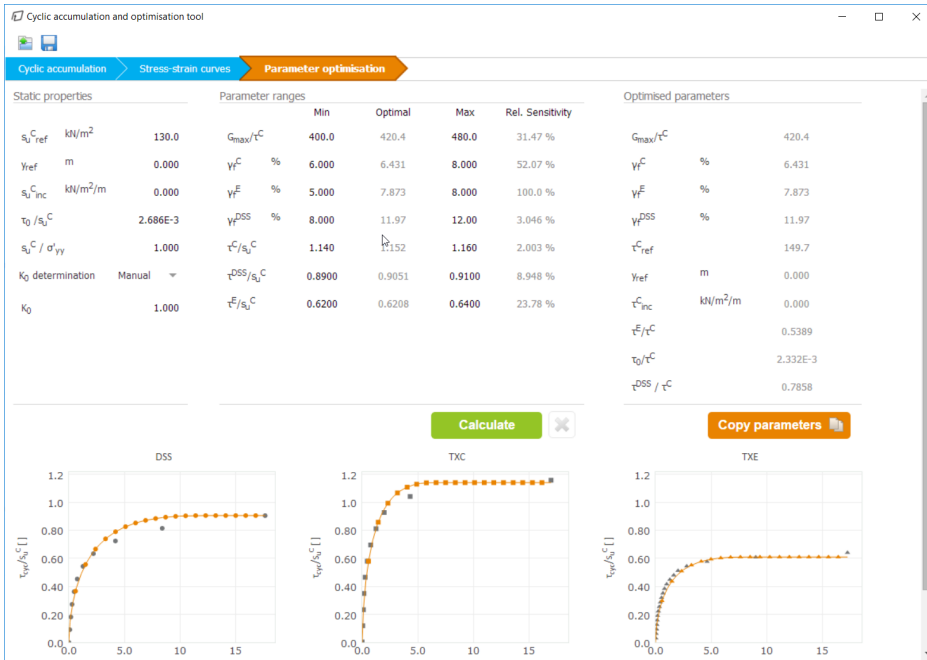


Figure 8.8 Optimised parameters for total load

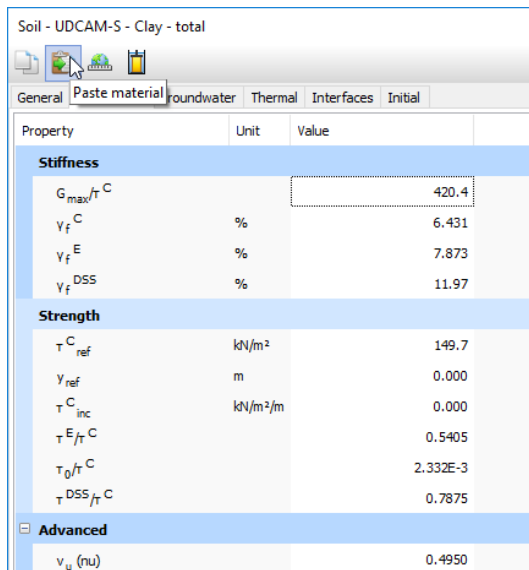


Figure 8.9 Copy parameters into Clay total material

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.

- Copy the *Clay - total load* material.
- Enter "Clay - cyclic load" for the identification.
- Go to the *Parameters* tab. Like for the first material, also here the parameters will be determined using the Cyclic accumulation and optimisation tool. Click the *Cyclic accumulation and optimisation tool* button on the *Parameters* tab to open the tool.



Click the *Open file* and choose the application state `optimised_total.json` that was saved after optimisation of the first material. All tabs will be filled with data.

The *Cyclic accumulation* tab is left as is.

- Go to the *Stress-strain curves* tab, set load type to *Cyclic load*.
- Press *Calculate* and let the calculation finish. The stress-strain curves are shown, see Figure 8.10.
- Go to the *Parameter optimisation* tab.

Accept the notification about resetting the optimisation tab to get updated values.

- Make sure that $s_{U\ ref}^C$ is set to 130.0 and set K_0 determination to Automatic.
- Modify the minimum and maximum values for the *Parameter ranges*, see Table 8.4 for values.
- Click *Calculate* to get the optimised parameters. The optimised parameters are shown in Figure 8.11 and listed in the column 'Optimised value' in Table 8.4.
- Save the application state under the file name `optimised_cyclic.json`.
- Copy the optimised material parameters: Press the *Copy parameters* button and go back to the *Soil-UDCAM-S* window.



Press the *Paste material* button, and the values in the *Parameters* tab are replaced with the new values.

- Click *OK* to close the created material.

Material: Concrete

Create a new material for the concrete foundation.

- Choose *Soil and interfaces* as the *Set* type and click the *New* button.
- Enter "Concrete footing" for the *Identification* and select *Linear elastic* as the *Material model*.
- Set the *Drainage type* to Non-porous.
- Enter the properties of the layer:
 - a unit weight of 24 kN/m³,
 - Young's modulus of 30E6 kN/m² and

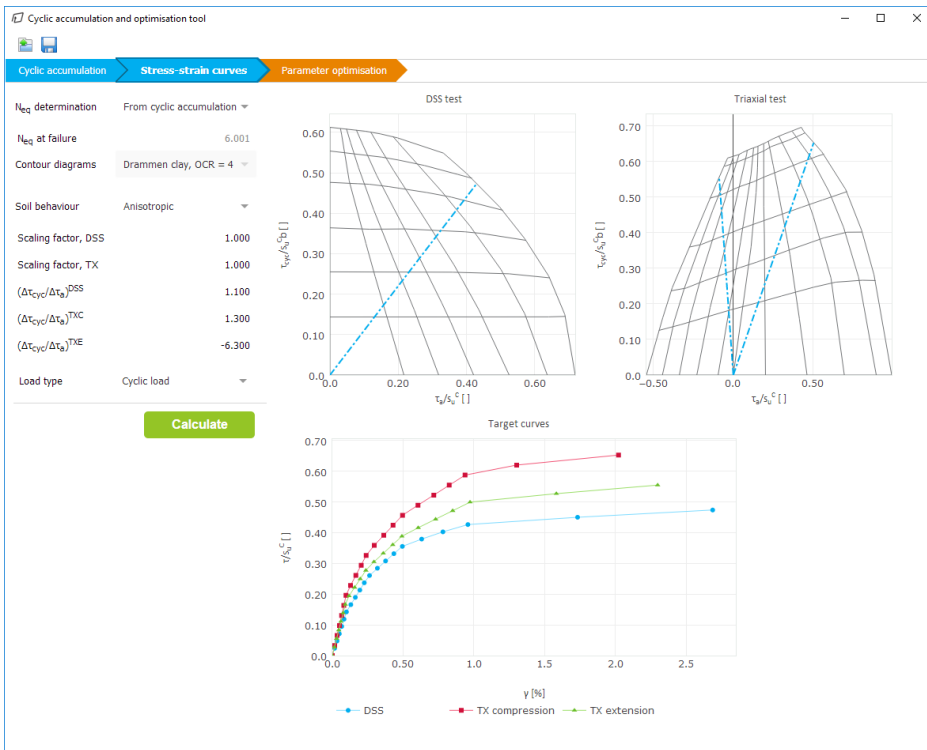


Figure 8.10 Stress-strain curves for cyclic load

- a Poisson's ratio of 0.1.
 - Click *OK* to close the created material.
- Click *OK* to close the Material sets window.

Table 8.4 Parameter ranges and calculation results for optimisation (cyclic load)

| 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 | τ^C/S_u^C | 0.66 | 0.67 | 0.6667 | - |
| Ratio of the cyclic DSS shear strength over the undrained static compression shear strength | τ^{DSS}/S_u^C | 0.47 | 0.49 | 0.4787 | - |
| Ratio of the cyclic extension shear strength over the undrained static compression shear strength | τ^E/S_u^C | 0.57 | 0.59 | 0.5790 | - |
| Reference degraded shear strength at failure in the triaxial compression test | τ_{ref}^C | - | - | 86.67 | - |
| Reference depth | y_{ref} | - | - | 0.000 | m |
| Increase of degraded shear strength at failure in the triaxial compression test with depth | τ_{inc}^C | - | - | 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 | - |
| 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 | - |

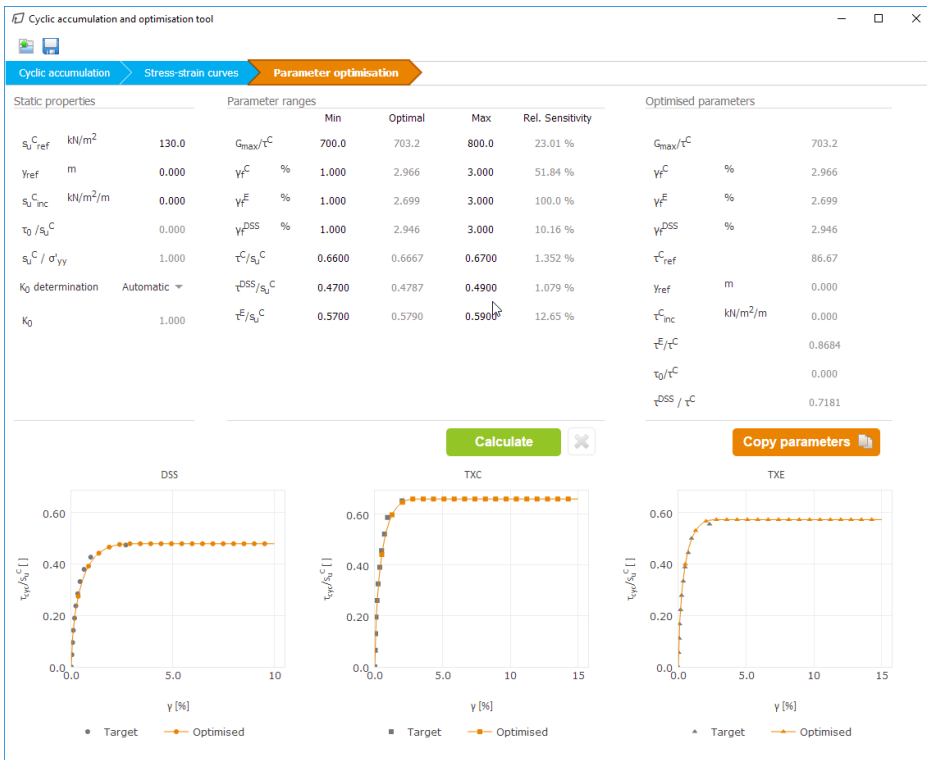


Figure 8.11 Optimised parameters for cyclic load

8.1.4 DEFINITION OF STRUCTURAL ELEMENTS

Define the concrete foundation.

- Click the *Structures* tab to proceed with the input of structural elements in the Structures model.
- 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.

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.
- Click *Create interface* to create the upper part from (11.0, -1.0) to (11.0, 0.0), Figure 8.13.
- Click *Create interface* to create the lower part (between foundation and soil) from (11.0, -1.5) to (11.0, -1.0), Figure 8.13.
- The upper part interface (between the foundation and the soil) is modeled with a reduced strength of 30%.

Make a copy of the *Clay - total load* material and name it "Clay - total load - interface". Reduce the interface strength by setting R_{inter} to 0.3 and assign this to the upper part of the interface.

- For Phase 3 (Calculate vertical cyclic stiffness), another material with reduced strength is needed. Make a copy of the *Clay - cyclic load material* and name it "Clay - cyclic load - interface". Reduce the interface strength by setting R_{inter} to 0.3. Do not assign this yet. It will be assigned when defining Phase 3.

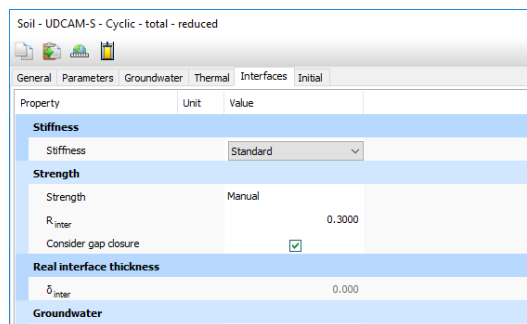


Figure 8.12 Soil definition: Reduced strength material

- 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.

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.

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

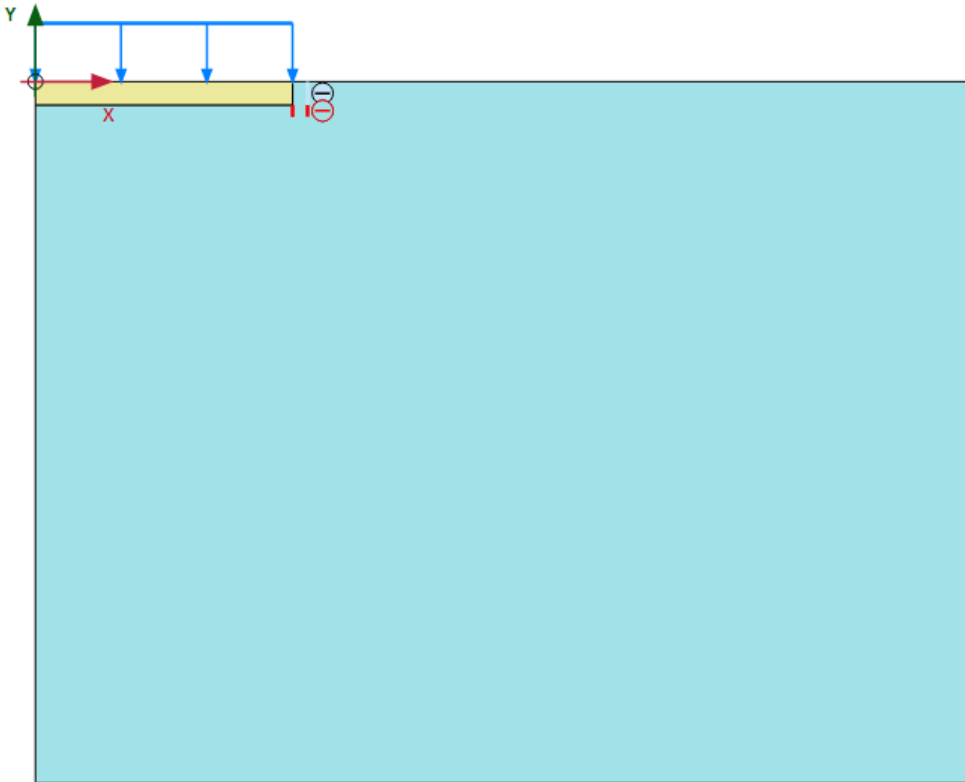




Figure 8.13 Geometry of the model

8.2 MESH GENERATION

- Proceed to the *Mesh* mode.
-  Generate the mesh. Use the default option for the *Element distribution* parameter (*Medium*).
-  View the generated mesh. The resulting mesh is shown in Figure 8.14.
- Click on the *Close* tab to close the Output program.

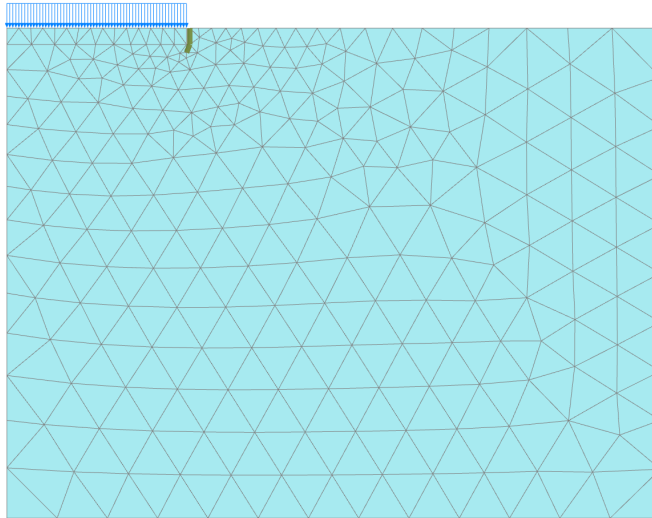


Figure 8.14 The generated mesh

8.3 CALCULATIONS

The calculation consists of three 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.

Initial phase:

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

Phase 1: Footing and interface activation



Add a new phase.

- Phase 1 starts from the Initial phase.
- Activate the footing by assigning the *Concrete footing* material to the corresponding polygon.
- Activate the interfaces as well.

Phase 2: 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.

 Add a new phase.

- Phase 2 starts from Phase 1.
- In the *Phases* window go to the *Deformation control parameters* subtree and select the *Reset displacements to zero* option and *Reset small strain*.
- Activate the line load.


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.

 Add a new phase.

- In the *Phases* window set the *Start from phase* to Phase 1.
- Go to the *Deformation control parameters* subtree and select the *Reset displacements to zero* option and *Reset small strain*. Close this window.
- Replace the soil material with the *Clay - cyclic load*.
- 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*.
- Activate the line load.

The calculation definition is now complete. 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:

-  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.
- Select a node at the bottom of the footing (0.0, 0.0). Close the *Select points* window.
- Click on the *Update* tab to close the Output program and go back to the *Input* program.

 Calculate the project.

8.4 RESULTS

Total load cyclic vertical bearing capacity

Applied vertical stress (load): $q_y = -1000 \text{ kN/m}^2$

Failure at: $q_y = 719.1 \text{ kN/m}^2$ (Figure 8.15)

Total vertical bearing capacity:

$$V_{cap} = q_y * Area = 719.1 \text{ kN/m}^2 * \pi * (11 \text{ m})^2 = 273.35 \text{ MN}$$

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

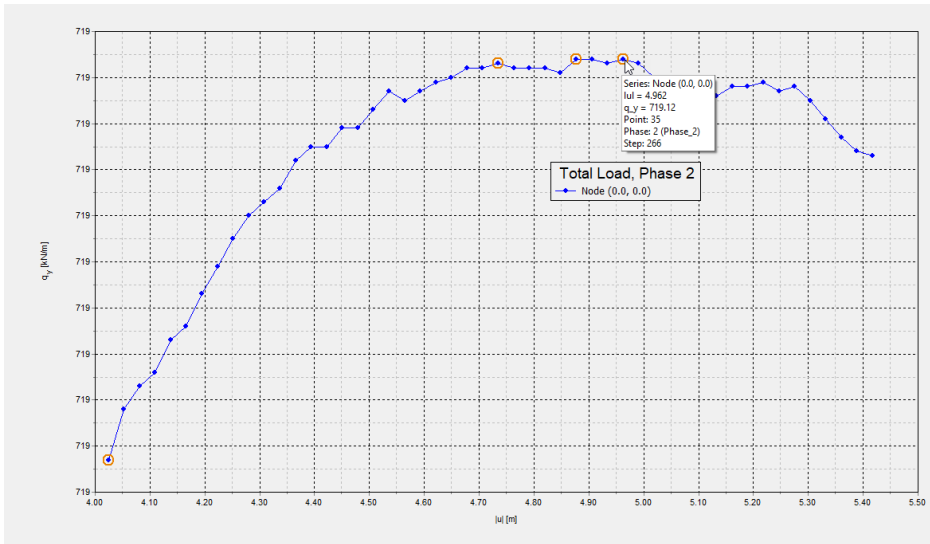


Figure 8.15 Load displacement curve for total load

is larger than the cyclic degradation during the storm.

Cyclic load cyclic vertical bearing capacity

Applied vertical stress (load): $q_y = - 1000 \text{ kN/m}^2$

Failure at: $q_y = 458.1 \text{ kN/m}^2$ (Figure 8.16)

Total vertical bearing capacity:

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

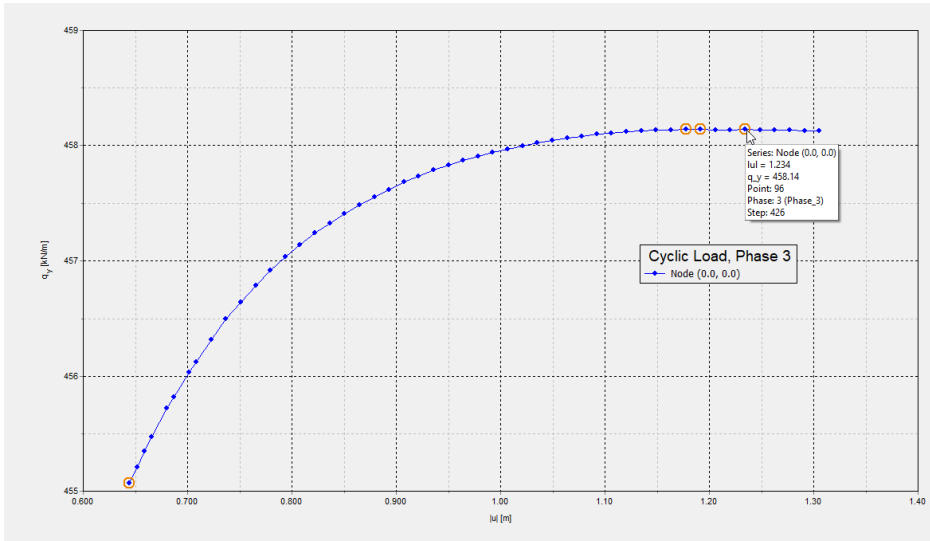


Figure 8.16 Load displacement curve for cyclic load

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 Figure 8.17.

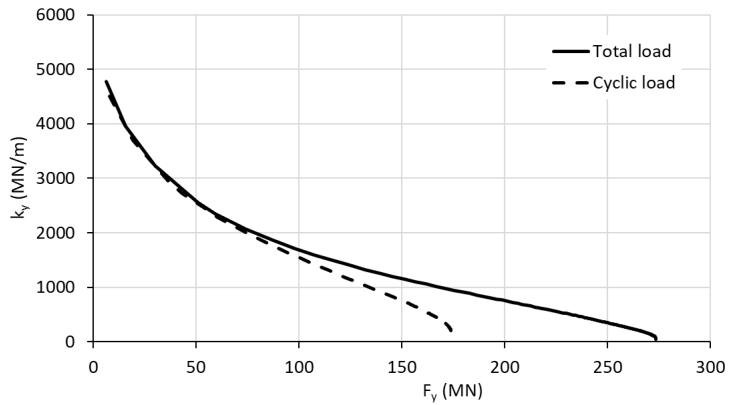


Figure 8.17 Vertical load versus stiffness for total and cyclic load components