

2D Consolidation under a Strip Footing

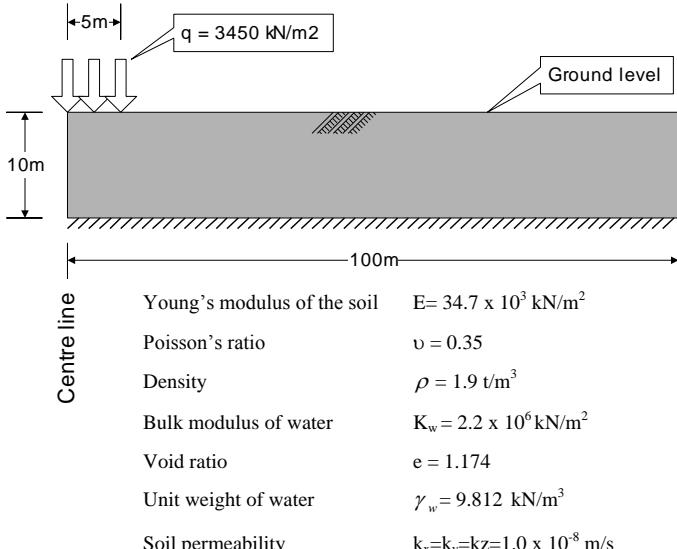
For LUSAS version:	17.0
For software product(s):	Any Plus version.
With product option(s):	Nonlinear, Dynamic.
Note: The example exceeds the limits of the LUSAS Teaching and Training Version.	

Description

The pore water pressure dissipation and settlement in a soil following the application of a distributed load is to be investigated.

Horizontal displacement at the left edge is restrained to model the symmetrical boundary condition. Vertical displacement at the base of the soil is restrained as the soil rests on solid rock.

The pore pressure at ground level is prescribed to zero.



Units of kN, m, t, s, C are used throughout.

Objectives

The required output from the analysis consists of:

- Settlement at the centre of the footing with time.
- Pore pressure distribution immediately after application of the load (undrained response)
- Pore water pressure dissipation with time at the centre of the footing

Keywords

2D, Plane Strain, Consolidation, Pore Water Pressure, Time Stepping, Nonlinear, Transient, Settlement, Two Phase Materials, Default Assignments, Graphs

Associated Files



- pwp_modelling.vbs** carries out the modelling of the example.

Modelling

Running LUSAS Modeller

For details of how to run LUSAS Modeller see the heading *Running LUSAS Modeller* in the Examples Manual Introduction.



Note. This example is written assuming a new LUSAS Modeller session has been started. If continuing from an existing Modeller session select the menu command **File>New** to start a new model file. Modeller will prompt for any unsaved data and display the New Model dialog.

Creating a new model

- Enter a File name of **pwp**
- Use the default User-defined working folder.
- Ensure an Analysis type of **Structural** is set.
- Select an Analysis Category of **2D plane strain**
- Set Model units of **kN,m,t,s,C**
- Leave the Timescale units as **Seconds**
- Select a Startup template of **2D Plane Stress**.

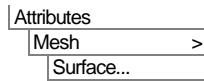
- Ensure the Layout grid is set as **None**
- Enter a Title of **Consolidation under a Strip Footing**
- Click the **OK** button.



Note. The Undo button may be used to correct a mistake. The undo button allows any number of actions since the last save to be undone.

Mesh Definition

Since this analysis requires the modelling of pore water pressure, plane-strain two phase elements will be used.



- Select **Plane strain two phase, Quadrilateral, Quadratic** elements. Ensure the **Regular mesh** option is selected with **Automatic divisions** so that Modeller uses the mesh divisions assigned to each line.
- Give the attribute the name **Plane Strain Two Phase** and click the **OK** button to add the mesh attribute to the  Treeview.
- In the  Treeview click on the mesh attribute **Plane Strain Two Phase** with the right-hand mouse button and select the **Set Default** option. This will ensure all newly created surfaces will be assigned the elements defined in this mesh attribute.

Material Properties

For consolidation analysis both the elastic and two-phase soil properties need to be defined. The overall 'equivalent' bulk modulus of the soil is related to the bulk modulus of the pore fluid and the bulk modulus of the solid soil particles by the formula:

$$\frac{1}{Ke} = \frac{n}{Kf} + \frac{(1-n)}{Ks} \approx \frac{n}{Kf}$$

Where

Ke is the equivalent bulk modulus of the soil

Kf is the bulk modulus of the pore fluid

Ks is the bulk modulus of the solid soil particles

n is the porosity of the soil

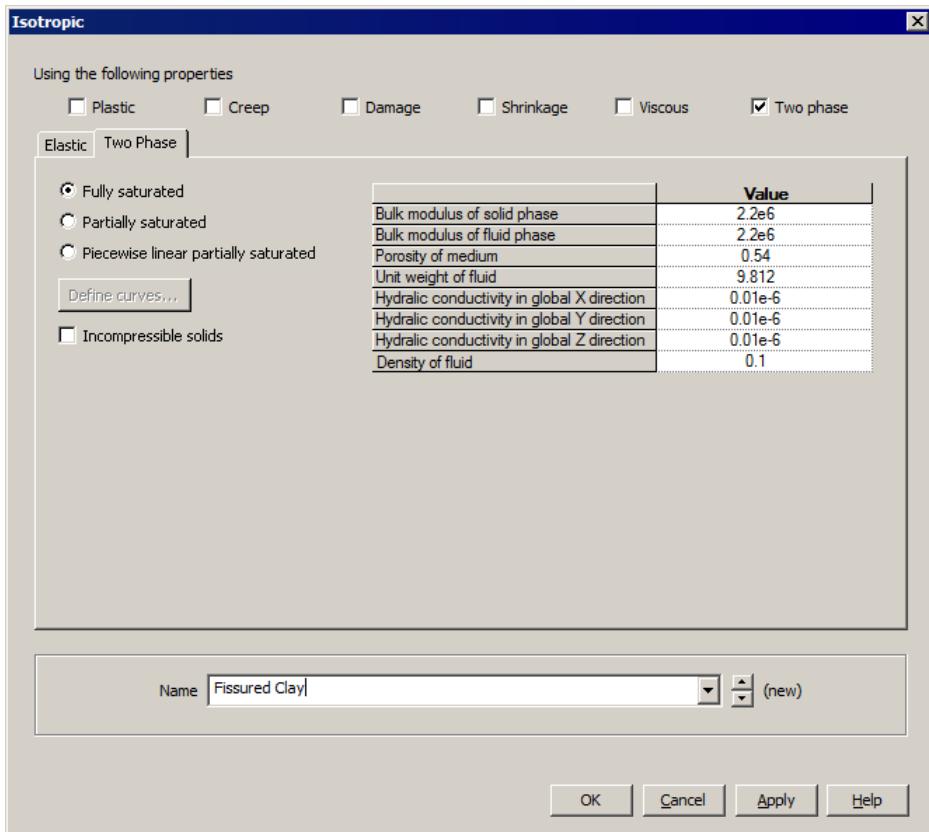
The porosity of the soil is related to the void ratio by the formula:

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$$\text{Porosity } n = \frac{e}{1+e} = 0.54$$

Attributes
Material >
Isotropic...

- Enter the isotropic material properties for the soil as Young's Modulus **34.7E3**, Poisson's Ratio **0.35** and Mass density **1.9**
- Click on the **Two phase** check box at the top right-hand corner of the dialog.



- For a **Fully saturated condition** enter the properties as shown in the dialog above.



Note. For the purposes of this example and to comply with a corresponding test case the undrained bulk modulus of the soil is set to be the same as that of the pore fluid.

- Enter the attribute name as **Fissured Clay** and click the **OK** button to add the attribute to the Treeview.

- In the  Treeview click on the attribute **Fissured Clay** with the right-hand mouse button and select the **Set Default** option. This will ensure all newly created features will be assigned the properties defined in this material attribute.

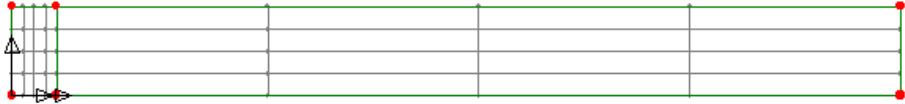
Feature Geometry

Geometry
Surface >
By Coords...

 Enter coordinates of **(0, 0)**, **(5, 0)**, **(5, 10)** and **(0, 10)** to define the soil under the load. Use the Tab key to move to the next entry field on the dialog. When all coordinates have been entered click the **OK** button.

Geometry
Surface >
By Coords...

 Enter the coordinates of **(5, 0)**, **(100, 0)**, **(100, 10)**, **(5, 10)** to define the remainder of the soil.

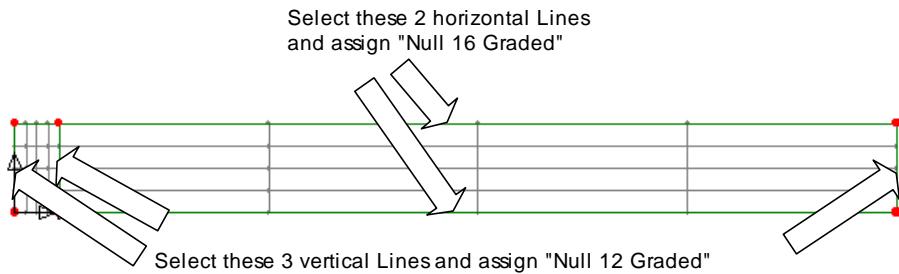


Mesh Grading

Attributes
Mesh >
Line...

- Define a Line mesh with element type **None** and **16** divisions.
- Select the **Spacing** button.
- Choose the **Uniform transition** option and set the **Ratio of first to last element** to **0.1**
- Click **OK** to accept the spacing properties.
- Give the attribute name as **Null 16 Graded** and click the **Apply** button to add the attribute to the  Treeview and keep the dialog active.
- Define a Line mesh with **12** divisions.
- Select the **Spacing** button.
- Enter the **Uniform transition** option and set the **Ratio of first to last element** to **5**
- Click **OK** to accept the spacing properties.
- Give the attribute name as **Null 12 Graded** and click **OK** to add the attribute to the  Treeview.

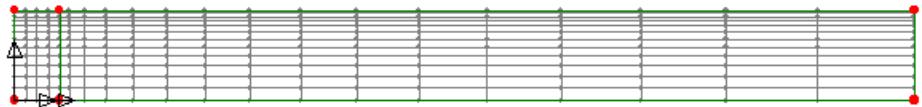
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- Select the horizontal lines of the larger surface as shown and assign the mesh attribute **Null 16 Graded**
- Select all the vertical lines as shown (Use the **Shift** key to add to the initial selection) and assign the mesh attribute **Null 12 Graded**



Note. If the mesh is graded with the smaller elements at the wrong end of a line reverse the line by selecting the line, and using the **Geometry>Line>Reverse** menu. The end result should be a mesh that looks like this:



Supports

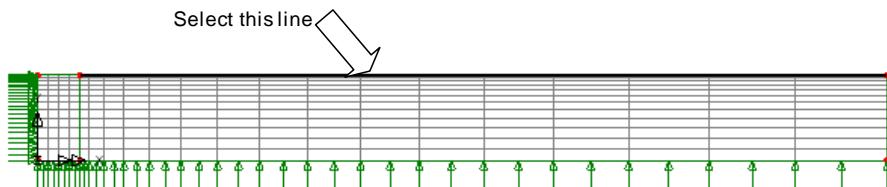
Define a support to prescribe zero pore pressure.

- Click on the option to make the Pore pressure **Fixed**
- Enter the attribute name as **Fixed PWP** and click the **OK** button.

Assign the supports to the model.

- Select the vertical Line on the left-hand side of the model and drag and drop the support attribute **Fixed in X** from the  Treeview onto the selection. With the **Assign to lines** option selected click **OK** to assign the support attribute to **All analysis loadcases**
- Select the 2 horizontal Lines representing the base of the soil and drag and drop the support attribute **Fixed in Y** from the  Treeview onto the selection. With the **Assign to lines** option selected click **OK** to assign the support attribute to **All analysis loadcases**

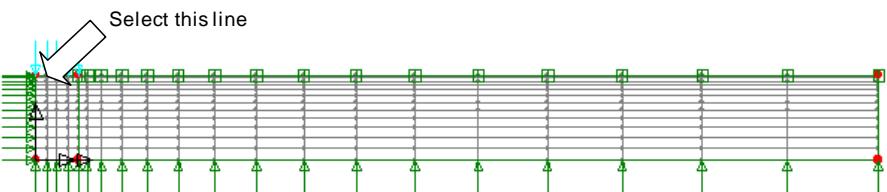
- Select the Line at ground level on the right-hand side of the model (see image) and drag and drop the support attribute **Fixed PWP** from the  Treeview onto the selection. With the **Assign to lines** option selected click **OK** to assign the support attribute to **All analysis loadcases**



Loading

Attributes
Loading...

- Select the **Face** option and click **Next**
- Enter loading of **3450** in the **y Direction**
- Enter the attribute name of **Distributed Load** and click the **Finish** button.
- Select the top line on the left-hand side of the model and drag and drop the **Distributed Load** attribute onto the selection. With the **Assign to lines** option selected click **OK** to assign the loadcase attribute to **Loadcase 1**.



Analysis Control

With this consolidation problem an automatic time stepping procedure is adopted. This is because consolidation is a typical diffusion process in which the field changes rapidly at the start of the process before settling down to a steady state condition a considerable time after the initial load is applied. The automatic time stepping procedure enables the time step to be modified so that the small time steps required at the start of the problem can be increased as the analysis progresses. In some cases the overall response time can be orders of magnitude larger than the initial time step.

The initial time step is important since the early variations in pore pressure must be accurately accounted for. Vermeer and Verruijt suggest the following criteria for determining the initial time step where Δh is the minimum distance between nodes.

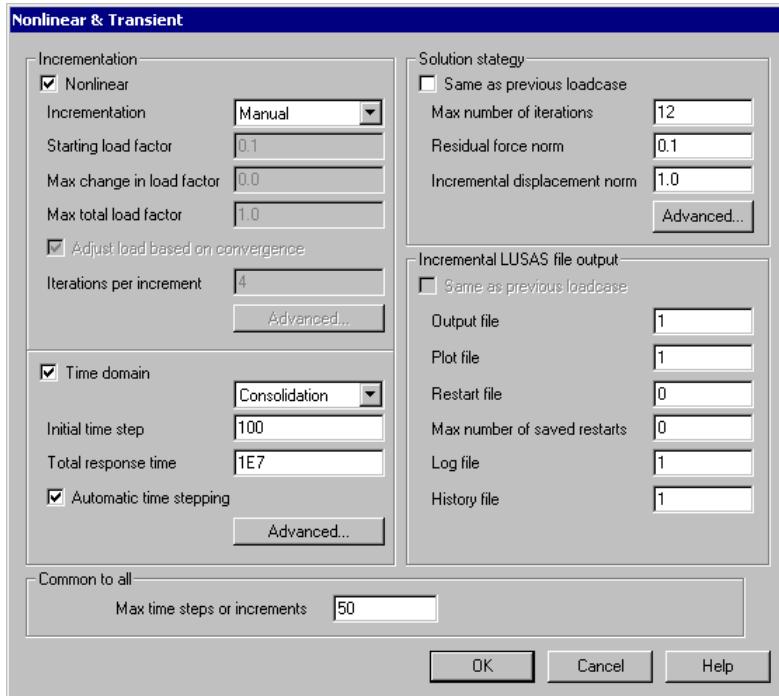
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$$\Delta t \geq \frac{\gamma_w}{6Ek} (\Delta h)^2 = \frac{9.812}{6 \times 34.7E3 \times 1E-8} \times 0.14^2 \approx 100 \text{ secs}$$



Note. The distance between two nodes can be determined by selecting the two nodes and then picking the **Utilities>Mesh>Distance between Nodes** entry.

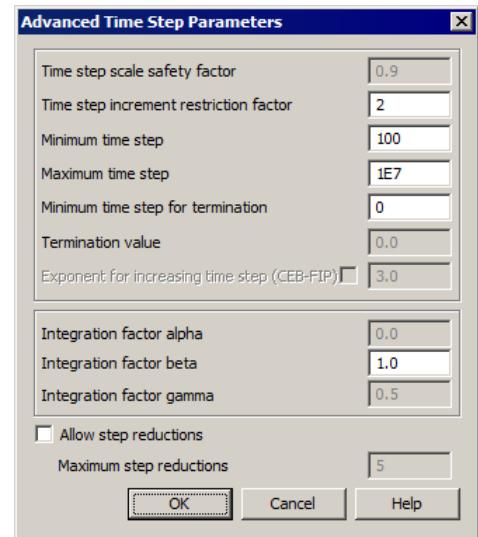
- In the Treeview expand **Analysis 1** then right-click on **Loadcase 1** and select **Nonlinear & Transient** from the **Controls** menu.



In the Incrementation section:

- Select the **Nonlinear** option and choose **Manual** incrementation.
- Select the **Time domain** option and chose **Consolidation** from the drop down list.
- Enter an **Initial time step** of **100**
- Select the **Automatic time stepping** option.
- Select the **Advanced** button in the Time domain section of the dialog.

- On the Advanced time step parameters dialog set the **Time step increment restriction factor** to **2**
- Set the **Minimum time step** to **100**
- Set the **Maximum time step** to **1E7**
- Set the **Minimum time step for termination** to **0**
- Click **OK** to return to the Nonlinear and Transient control dialog.
- On the Nonlinear and Transient control dialog set **Max time steps or increments** to **50**
- Click **OK** to set the loadcase control.



Saving the model



 Save the model file.

Running the Analysis

 Open the **Solve Now** dialog. Ensure **Analysis 1** is selected and press **OK** to run the analysis.

A LUSAS Datafile will be created from the model information. The LUSAS Solver uses this datafile to perform the analysis.

If the analysis is successful...

Analysis loadcase results are added to the  Treeview.

In addition, 2 files will be created in the Associated Model Data directory where the model file resides:



-  **pwp.out** this output file contains details of model data, assigned attributes and selected statistics of the analysis.
-  **pwp.mys** this is the LUSAS results file which is loaded automatically into the Treeview to allow results processing to take place.

If the analysis fails...

If the analysis fails, the output file will provide information relating to the nature of the error encountered. Any errors listed in the output file should be fixed in LUSAS Modeller before saving the model and re-running the analysis.

Rebuilding a Model

If it proves impossible for you to correct the errors reported a file is provided to enable you to re-create the model from scratch and run an analysis successfully.



❑ **pwp_modelling.vbs** carries out the modelling of the example.



Start a new model file. If an existing model is open Modeller will prompt for unsaved data to be saved before opening the new file.

- Enter the file name as **pwp**
- To recreate the model, select the file **pwp_modelling.vbs** located in the **\<LUSAS Installation Folder>\Examples\Modeller** directory.



Rerun the analysis to generate the results.

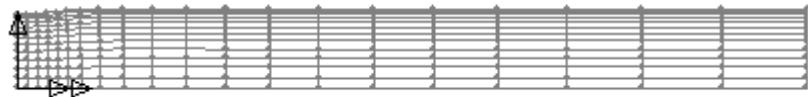
Viewing the Results

Loadcase results can be seen in the  Treeview. For a nonlinear analysis the last solver results time step is set active by default.

- If present, turn off the **Geometry**, **Mesh** and **Attributes** layers in the  Treeview.

Settlement

- In the  Treeview, right-click on the first load increment **Time Step 0** and select the **Set Active** option to view results immediately after the loading is applied.
- Click the **Deformations** button in the  Treeview and select the **Specify factor** option. Specify a factor of **1** and click **OK** to visualise the deformed mesh for the first time step.



A graph of the deformation over time will be created using the graph wizard.

- Zoom into the left-hand side of the model and select the node on the centre line at the centre of the footing.
- With the **Time history** option selected click **Next**

Utilities
Graph Wizard...

Firstly define the data to be used for the X axis.

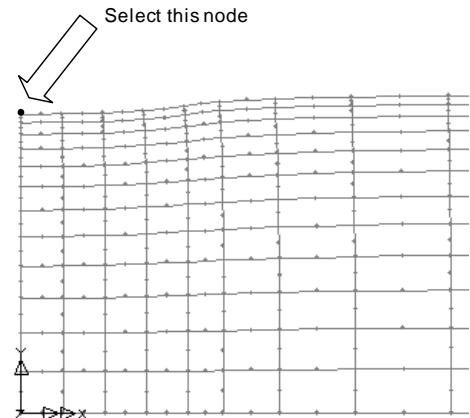
- Selected the **Named** option and click **Next**
- Select **Response Time** from the drop down list and click **Next**

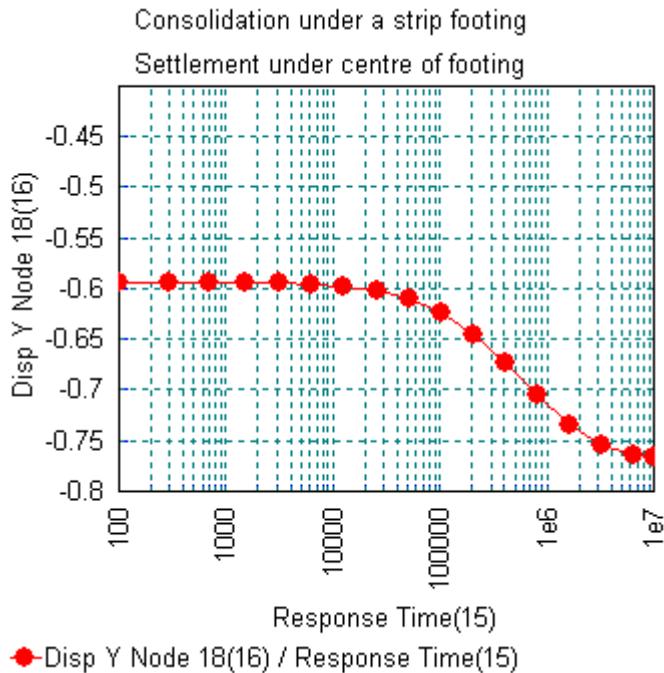
Secondly define the data for the Y axis.

- With the **Nodal** option selected and click **Next**
- Select **Displacement** from the Entity drop down list and **DY** from the Component drop down list.
- The selected node number will appear in the **Specified single node** drop down list. Click **Next**

For the X Scale enter **Manual** values of minimum **100** and maximum **10e6** respectively.

- Select the **Use logarithmic scale** option.
- Title the graph as **Settlement under centre of footing**
- Click **Finish** to display the graph of settlement over time under the centre of the strip footing.





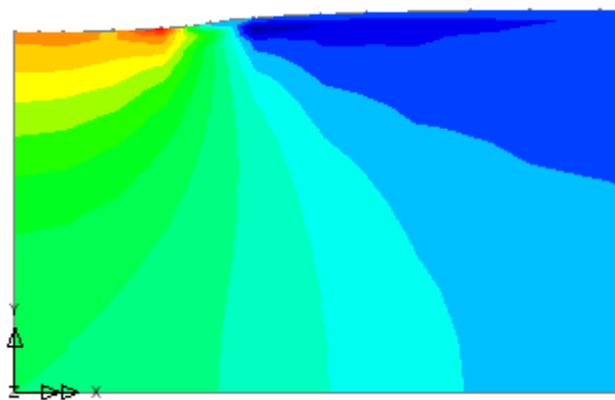
Close the graph window

Maximise the graphics window.

Pore water pressure

The distribution of pore pressure is to be shown using contours.

- With **Time Step 0** set active in the Treeview, and with no features selected, click the right-hand mouse button in a blank part of the view window and select **Contours** to add the contours layer to the Treeview.
- Select **Displacement** from the Entity drop down list and **PRES** from the component drop down list.
- Select the **Contour Range** tab and set the **Interval** to **250**
- Click the **OK** button to display contours of the undrained pore pressure distribution (Time step 0) immediately after the loading is applied.



Note. The dissipation of pore water pressure over time may be observed by creating an animation of the contour display.

- To observe the distribution of pore water pressure at a particular time after the application of loading activate the appropriate time step from the Treeview by selecting the time step with the right-hand mouse button and choosing the **Set Active** option.

The dissipation of pore water pressure under the footing is to be presented on a graph.

- Select the node on the centreline under the footing as before.
- With the **Time history** option selected click **Next**

Utilities
Graph Wizard...

Firstly define the data to be used for the X axis:

- Selected the **Named** option and click **Next**
- Select **Response Time** from the drop down list and click **Next**

Secondly define the data for the Y axis:

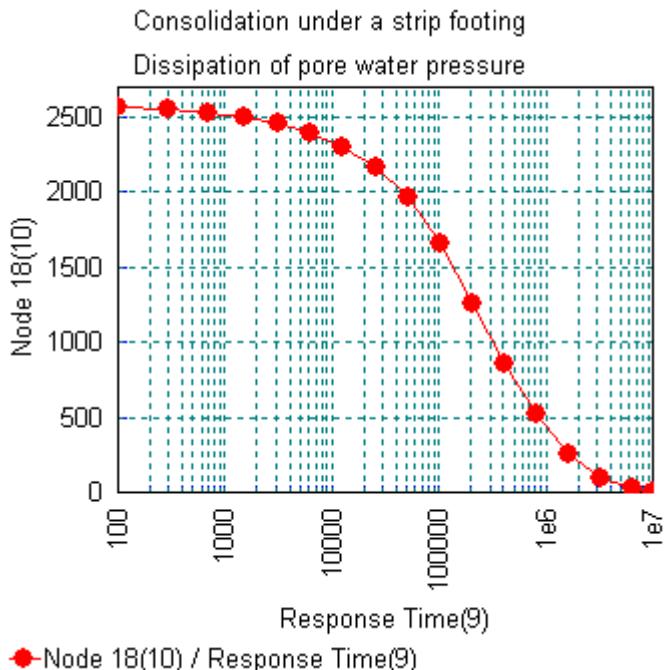
- With the **Nodal** option selected and click **Next**
- Select **Displacement** from the Entity drop down list and **PRES** from the Component drop down list.
- The extent to be graphed will be set to **Specified single node** and the node selected will be seen in the Specify node field. Click **Next**

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- For the X Scale ensure that **Manual** values of minimum **100** and maximum **10e6** respectively are used.
- Select the **Use Logarithmic scale** option
- For the Y Scale leave the values as the defaults.
- Title the graph as **Dissipation of pore water pressure**
- Click **Finish** to display the dissipation of pore water pressure over time under the centre of the strip footing.

Graph showing Dissipation of pore water pressure (Node 18(10)) versus Response Time(9). The Y-axis is logarithmic, ranging from 0 to 2500. The X-axis is logarithmic, ranging from 100 to 1e6. The data points show a rapid initial dissipation followed by a slow, nearly linear decrease on the log-log scale.

Response Time(9)	Node 18(10)
100	2500
200	2500
400	2500
800	2500
1600	2500
3200	2500
6400	2500
12800	2500
25600	2500
51200	2500
102400	2500
204800	2500
409600	2500
819200	2500
1638400	2500
3276800	2500
6553600	2500
13107200	2500
26214400	2500
52428800	2500
104857600	2500
209715200	2500
419430400	2500
838860800	2500
1677721600	2500
3355443200	2500
6710886400	2500
13421772800	2500
26843545600	2500
53687091200	2500
107374182400	2500
214748364800	2500
429496729600	2500
858993459200	2500
1717986918400	2500
3435973836800	2500
6871947673600	2500
13743895347200	2500
27487790694400	2500
54975581388800	2500
109951162777600	2500
219902325555200	2500
439804651110400	2500
879609302220800	2500
1759218604441600	2500
3518437208883200	2500
7036874417766400	2500
14073748835532800	2500
28147497671065600	2500
56294995342131200	2500
112589990684262400	2500
225179981368524800	2500
450359962737049600	2500
900719925474099200	2500
1801439850948198400	2500
3602879701896396800	2500
7205759403792793600	2500
14411518807585887200	2500
28823037615171774400	2500
57646075230343548800	2500
11529215046068709600	2500
23058430092137419200	2500
46116860184274838400	2500
92233720368549676800	2500
184467440737099353600	2500
368934881474198707200	2500
737869762948397414400	2500
1475739525896794828800	2500
2951479051793589657600	2500
5902958103587179315200	2500
11805916207174358630400	2500
23611832414348717260800	2500
47223664828697434521600	2500
94447329657394869043200	2500
188894659314789738086400	2500
377789318629579476172800	2500
755578637259158952345600	2500
1511157274582357904691200	2500
3022314549164715809382400	2500
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12089258196658863237529600	2500
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48357032786635452950118400	2500
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3169126504704941043789568102400	2500
6338253009409882087579136204800	2500
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50706024075279056700633089638400	2500
101412048150558113401266179276800	2500
202824096301116226802532358553600	2500
405648192602232453605064717107200	2500
811296385204464907210128434214400	2500
1622592770408929814420256868428800	2500
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103845937306171508122884399579443200	2500
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265845599503790640794580069233740800	2500
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6968982765670800498218381970176168352000	2500
1393796553134160099643676394035233664000	2500
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1115037242507328079714941153228186912000	2500
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4460148970029312318859764612912747648000	2500
8920297940058626637719529225825495296000	2500
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467680106237810108263667954035167081730048000	2500
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187072042495124043305467801614066832692192000	2500
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245199067539208986041331697731584557166624000	2500
490398135078417972082663395463169114333248000	2500
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4417107160520837908756215154910358568137979200000	2500
88342143210416758175124303088207171362759584000	



Close the graph window.



 Maximise the graphics window.

As the pore water dissipates the load is carried by the soil. The increase in effective stress in soil can be observed on a graph of effective stress against response time.

- Ensure the node on the centreline under the footing still selected
- With the **Time history** option selected click **Next**

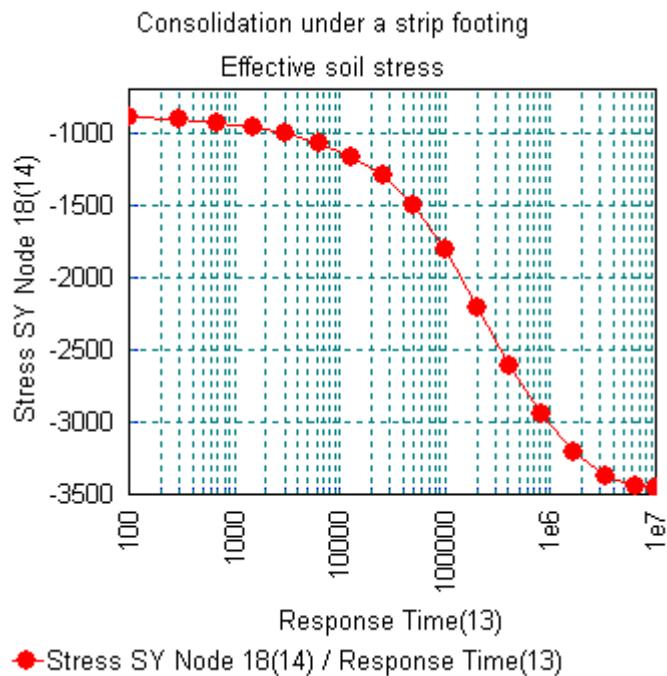
Firstly define the data to be used for the X axis

- Select the **Named** option and click **Next**
- Select **Response Time** from the drop down list and click **Next**

Secondly define the data for the Y axis

- With the **Nodal** option selected and click **Next**
- Select **Stress - Plane Strain** from the Entity drop down list and **SY** from the Component drop down list.

- The extent to be graphed will be set to **Specified single node** and the node selected will be seen in the Specify node field. Click **Next**
- For the X Scale ensure that **Manual** values of minimum **100** and maximum **10e6** respectively are used.
- Select the **Use Logarithmic scale** option.
- For the Y Scale leave the values as the defaults.
- Title the graph as **Effective soil stress**
- Click **Finish** to display the graph of the effective soil stress over time under the centre of the strip footing.



This completes the example.

2D Consolidation under a Strip Footing
