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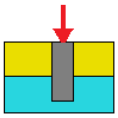

User Manual for PileLAT

A Program for Single Piles under Lateral Loading

Innovative Geotechnics

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Chapter 1. Introduction

PileLAT is a finite-element based program that analyses the behaviour of single piles mainly under lateral loading based on p-y curves for various soils and rocks. PileLAT is powerful and easy to use. It is a useful tool for pile design and analysis by both structural and geotechnical engineers. Some of the important features and benefits are summarised as follows:

- Standard window-style dialogs, push buttons, drop menus, list boxes, EXCEL-like data grid cells, slide bars, radio buttons, check boxes and toolbars can be accessed in the program;
- Automatic generation of nonlinear soil resistance p-y curves for various soil types such as cohesive soils, cohesionless soils and rocks. Soil resistance (p-y) curves for each node can be viewed, copied and printed. There is no need to specify the node locations before the analysis for accessing the p-y curve information. Once the analysis is completed successfully, p-y curves for all the nodes are automatically available to the user;
- Both static and cyclic behaviour of soils can be considered. The user can input the cycle number of the cyclic load;
- Pile batter and sloping ground surface can be modelled through an interactive dialogue where the geometry of the pile batter and ground surface slope can be graphically updated and viewed by the user with moving the relevant slide bars;
- An interactive graphical presentation of pile and soil layer geometry is provided. Important changes in the input data such as pile length, the number of soil layers, soil layer name, soil layer thickness, soil layer color, p-y model type, water table position, certain soil parameters and pile loading will be automatically updated in the graph. It is very convenient for the user to visually view the input change;
- P-multipliers can be defined by the user for each soil layer to consider the potential pile group effects for closely-spaced piles. The user also can use this option to purposely reduce the resistance of some soil layers if required;
- Multiple pile segments with different user-defined elastic bending stiffness or plastic bending moments can be specified by the users;
- An interactive dialogue is available to the user to specify the distributed loading along the pile length and the user can see the locations of the nodes with the applied loading. Free-field soil lateral displacement loading along the pile length can be considered by the program at the specified node locations. Distributed horizontal shear forces and bending moments can be specified by the user at the node positions;
- Various boundary conditions at the pile head can be considered by the program. Those boundary conditions include free head, rigid head, partially restrained head with elastic rotational spring, specified deflection with the applied bending moment and specified deflection and rotation.
- Different pile section types such as circular section, rectangular section, steel H-section, steel pipe section, octagonal section and user-defined section can be selected by the user. Driven piles or bored piles / drilled shafts can be selected by the user. The load settlement curve at the pile head will be determined by the program based on the input axial loading and the selected pile installation type. API recommendations

will be adopted for driven piles and FHWA recommendations will be used for bored piles / drilled shaft in PileLAT. More advanced options are available in PileAXL for the pile settlement analysis under axial loading.

- Load-settlement curve can be generated by the program for the specified axial loading at the pile head. Preliminary estimations on the ultimate shaft resistance, ultimate end bearing resistance and ultimate axial pile capacity are carried out by the program and the preliminary results are shown on the load-settlement curve graph.
- Automatic generation of load deflection curves such as horizontal load vs top deflection, bending moment vs top deflection and maximum bending moment vs top deflection once the analysis is successfully completed;
- A well-designed result output dialog is provided for the user to view all the relevant results graphically. Switching among different results is very straightforward. All the analysis results along the pile length are presented together with the soil layer geometry. Therefore, the analysis results within each soil layer can be viewed by the user conveniently from the graph of the results.
- Detailed analysis results are presented in EXCEL-like format and can be easily selected and copied into the third-party program such as EXCEL for further processing;

Chapter 2. Start the new file

When PileLAT program is started, the following dialog (Figure 2-1) will firstly appear, which enables the user to choose (1) Start a new project or (2) Open an existing project.

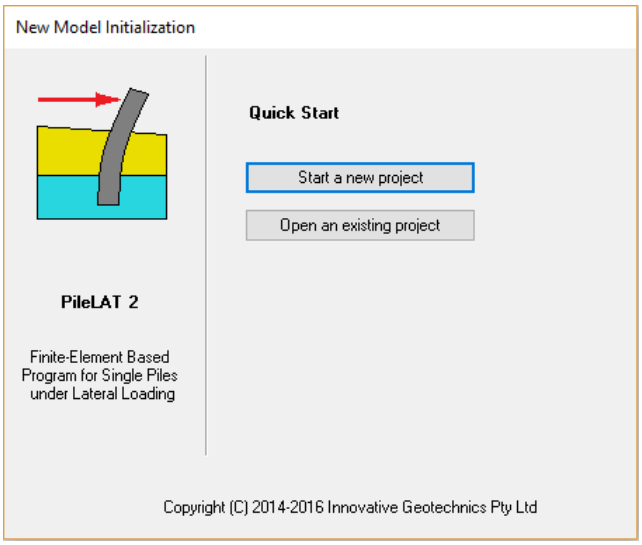


Figure 2-1 Project start dialog in PileLAT

Once the option of "**Start a new project**" is selected, a default new project with two soil layers is automatically created. The default file name is "Newfile.LAT". The corresponding file path is shown on the top title bar of the program. The ground profile and general program interface is loaded and shown in Figure 2-2.

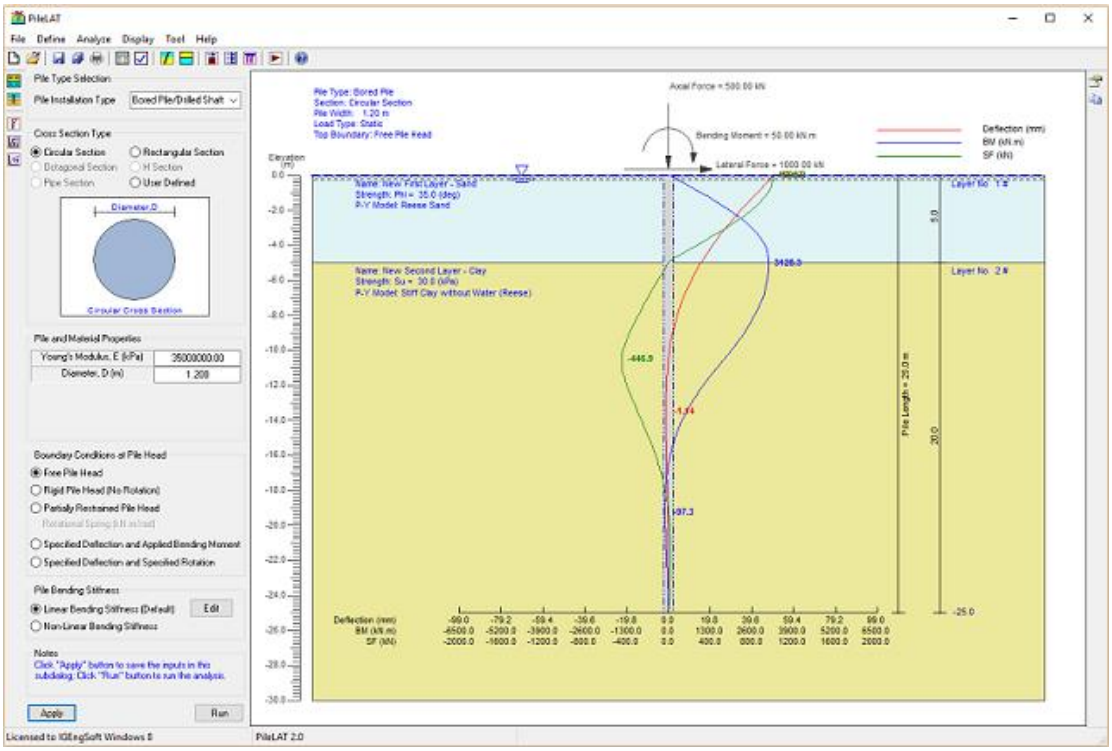


Figure 2-2 General layout of the program interface for PileLAT

If "**Open an existing project**" button is clicked, then the file selection dialog will be invoked as shown in Figure 2-3 where the user will be able to open the existing PileLAT analysis file with the file type of LAT.

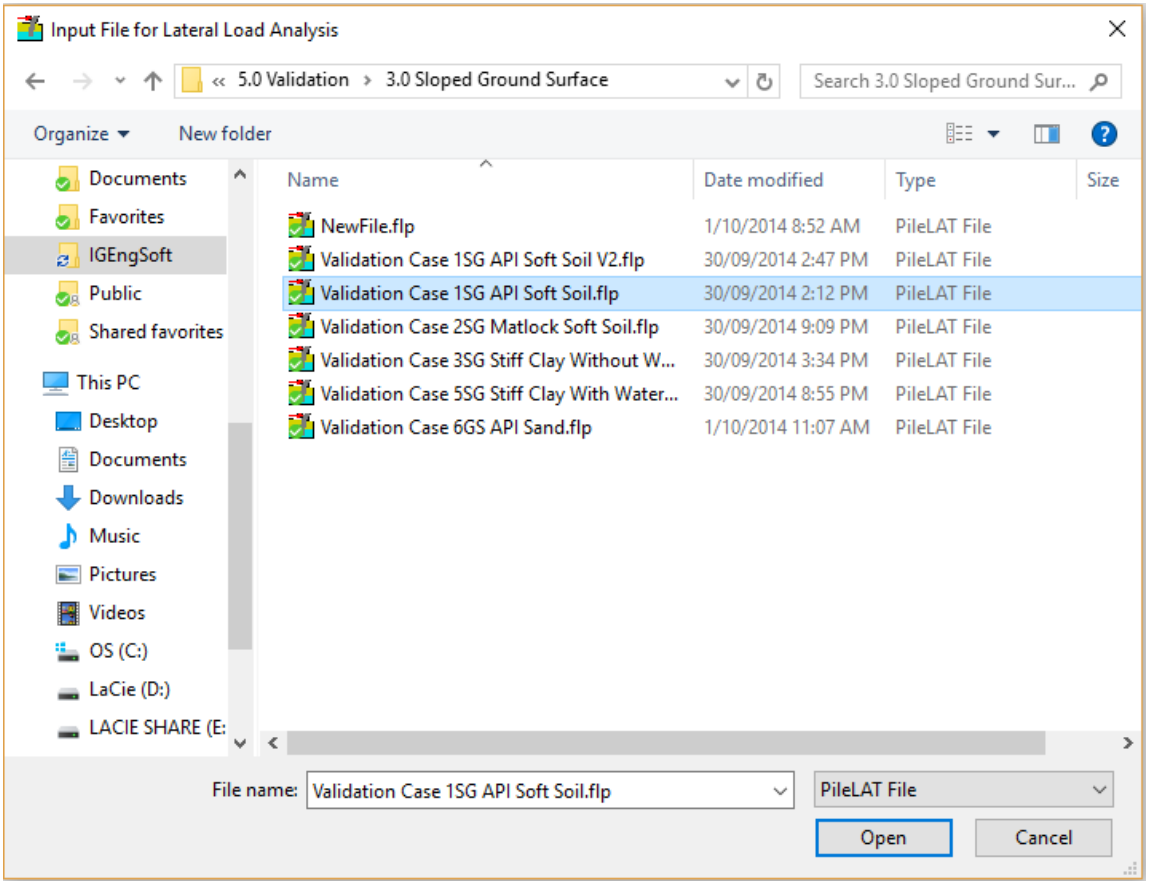


Figure 2-3 Analysis file selection dialog for PileLAT

Chapter 3. Project Title Information Input

The project title information can be input by the users with clicking the “Title” icon from the toolbar or clicking “Project Title” menu item from the main “Define” menu of the program. Figure 3-1 shows the general layout of “Title” dialog. The following information can be input by the user for the project:

- Project Title;
- Job Number;
- Design Engineer;
- Client; and
- Description.

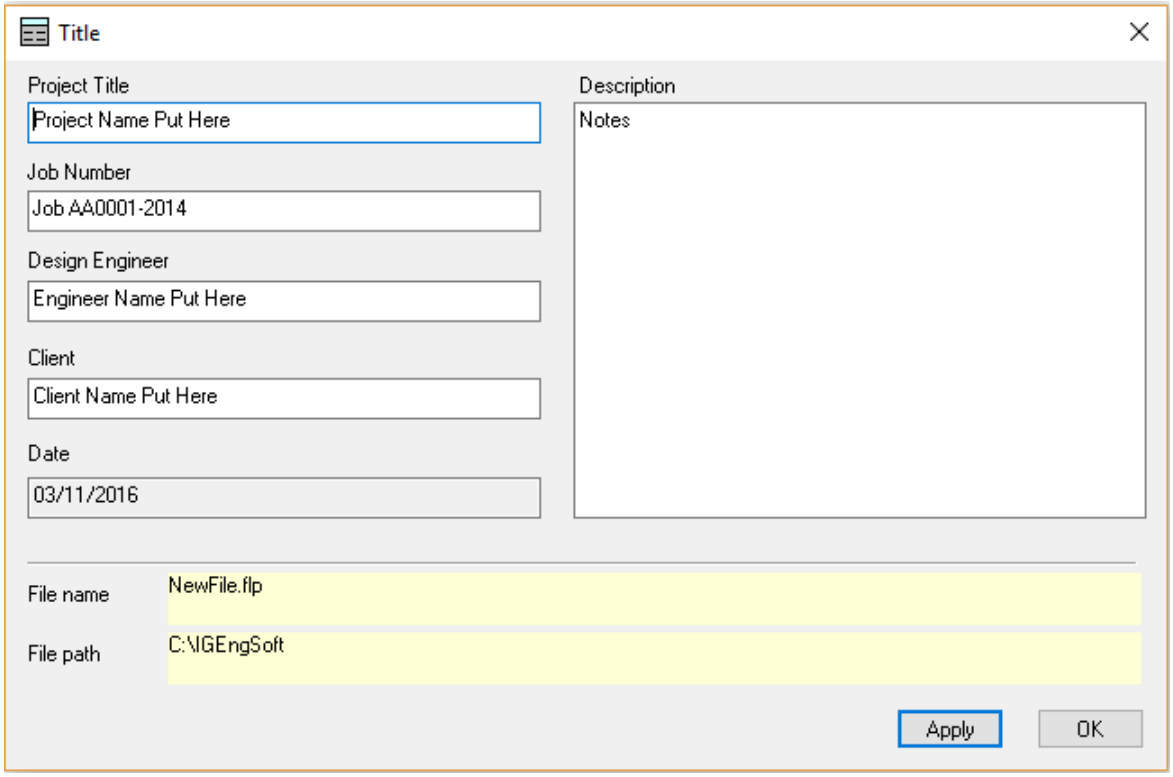


Figure 3-1 General layout of “Project Title” Dialog

The following items are created by the program for the user’s reference and cannot be changed by the user from this dialog:

- Date – the creation date of the project file. The date will also be updated when the project file is changed and saved.
- File name – the name of the analysis file; and

- File path – the directory path of the program.

Chapter 4. Analysis Option Input

Various analysis options can be input by the users with clicking the “Analysis Option” icon from the toolbar or clicking “Analysis Option” menu item from the main “Define” menu of the program. Figure 4-1 shows the general layout of “Analysis Option” dialog. This dialog provides the user with different analysis options as described below for two main groups: (1) “Control Parameters” Group and (2) "Units of Input and Analyses" group.

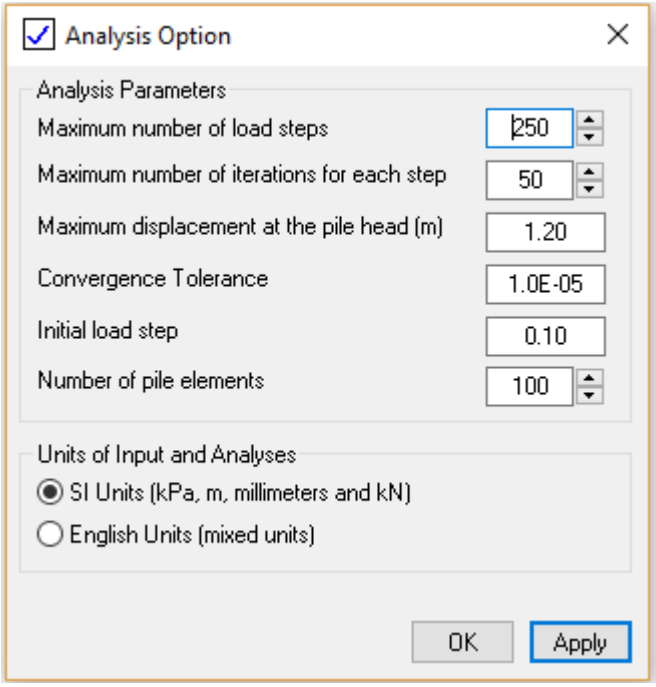


Figure 4-1 General Layout of Analysis Option Dialog for PileLAT

"Control Parameters" group lists 6 main control parameters for the finite element analysis:

- Maximum number of load step: This allows the user to change/update the maximum load steps used in the analysis. The minimum value is 100 and maximum value is 500. The default value is 100. Depending on the nonlinearity of the problem, this value may need to be increased by the user for convergence.
- Maximum number of iterations for each step: This is the maximum iteration number at each load step used in the analysis. The minimum value is 30 and maximum value is 300. The default value is 30. Depending on the nonlinearity of the problem, this value may need to be increased by the user for convergence.
- Maximum displacement at the pile head: This is the maximum lateral displacement allowed by the program at the pile head. If the specified value is exceeded, the analysis will be terminated and no result outputs will be provided as this usually means that the pile fails under the current loading conditions.
- Convergence Tolerance: This is the convergence tolerance used to determine whether the equilibrium conditions are achieved under the current loading conditions. The default value is 1.0E-05 and it shall be changed with cautions if required. The accuracy of the solutions will be in question if this value is too

high. On the other hand, the analysis will have convergence problem if this value is set to unnecessary small value in numerical analysis.

- Initial load step: This is the initial load step used in the analysis and the default value is 0.1.
- Number of pile elements: This is the number of pile elements used in the analysis. The pile length will be equally divided into elements with the specified number.

"Units of Input and Analyses" group provides two unit options in the program.

- SI Units: This is to select SI Units in the program. It the default option in the program.
- English Units: This is to select English Units in the program.

Chapter 5. Pile Properties Input

The inputs for the pile properties including different installation and cross section types can be accessed from the sub-dialog at the left side of the main program interface as shown in the figure below.

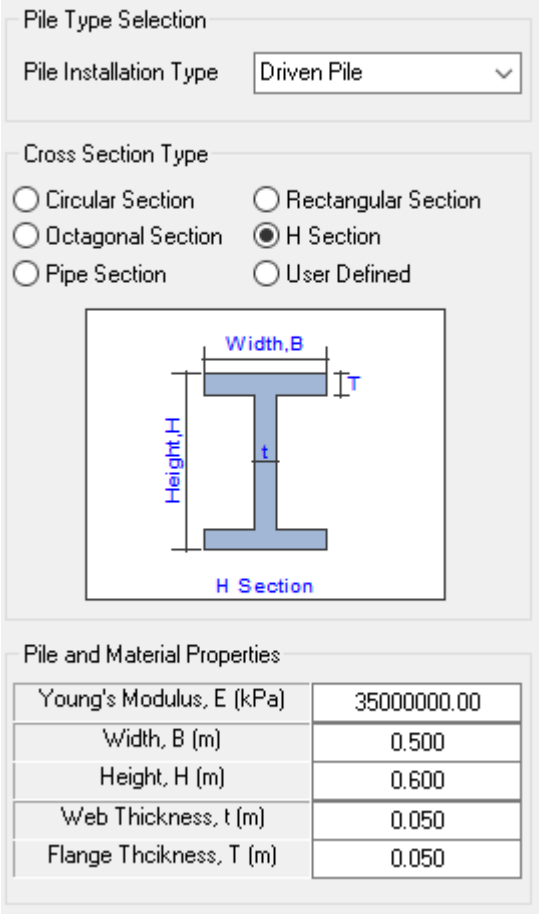


Figure 5-1 General Layout of Pile Type and Cross Section Dialog

Both driven and bored piles are supported by PileLAT and the following cross section types can be used in the pile capacity and settlement analysis:

Driven Piles:

- Circular Section;
- Rectangular Section;
- Octagonal Section;
- H Section;
- Pipe Section; and
- User-defined Section

Bored Piles or Drilled Shaft:

- Circular Section;
- Rectangular Section; and
- User-defined Section

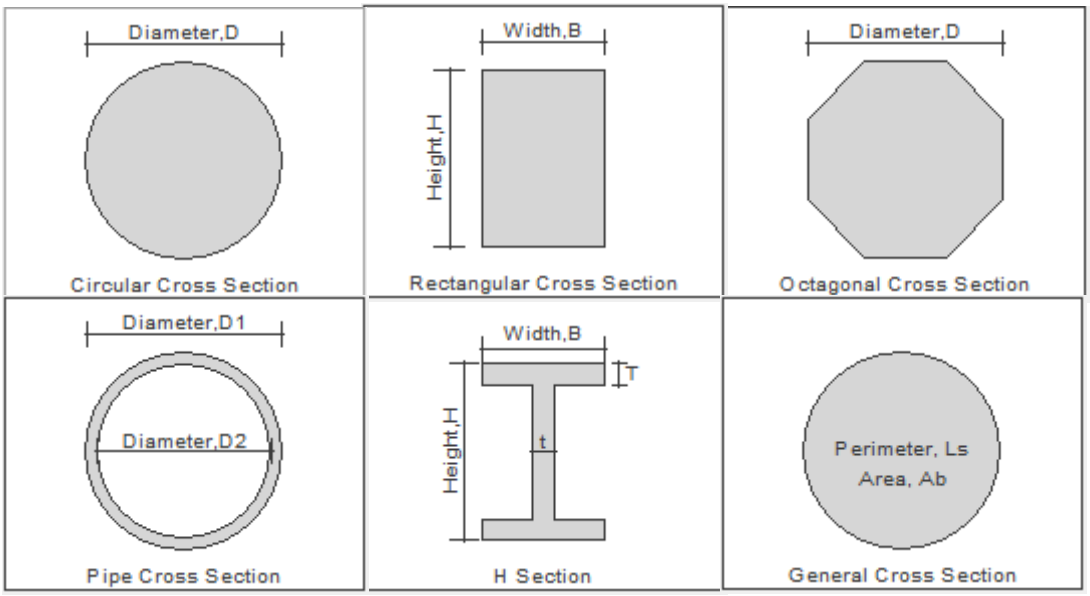


Figure 5-2 Cross Section Types in PileLAT

Note that the rectangular section for bored piles or drilled shafts enable the users to analyse the barrette piles which are usually adopted for large axial loads.

Chapter 6. Pile Top Boundary Conditions

Various pile top boundary conditions are available in PileLAT and the users can access those options from the dialog at the left side of the main program interface as shown in the figure below.

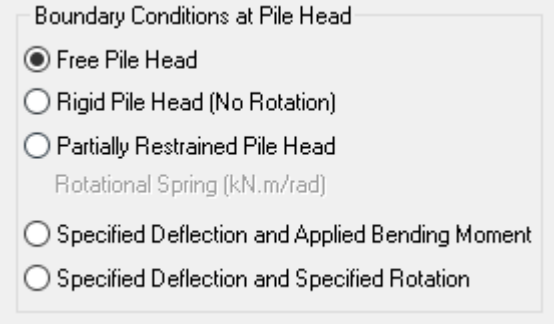


Figure 6-1 Cross Section Types in PileLAT

The following five different options can be adopted by the user for the pile top boundary condition as shown in Figure 6-1:

- Option 1: Free Pile Head. Pile head is free to move laterally and rotate. Usually, pin or hinge connections are assumed between pile cap and piles.
- Option 2: Rigid Pile Head. Pile head can move laterally but cannot rotate. Moment will be generated at the pile head.
- Option 3: Partially Restrained Pile Head. Rotational spring value needs to be provided in the unit of moment per unit slope.
- Option 4: Specified Deflection and Applied Bending Moment.
- Option 5: Specified Deflection and Specified Rotation.

Chapter 7. Pile Bending Stiffness

PileLAT provides the users with two different options for pile bending stiffness (Figure 7-1) as below:

- Linear Bending Stiffness Option (Default). This is a default option. This option enables the user to adopt different pile segments with different bending stiffness in the analysis. The maximum pile segment number currently allowed in the program is 10. By default, the pile segment number is 1, the segment length is the pile length and the elastic bending stiffness value is based on the section properties and material stiffness.
- Non-Linear Bending Stiffness Option. With this option, the user can adopt different plastic bending moment capacity for different pile segments in the analysis. Each pile segment can be assigned a different plastic bending moment capacity to model the nonlinear behaviour of piles under bending. The maximum pile segment number currently allowed in the program is 10.

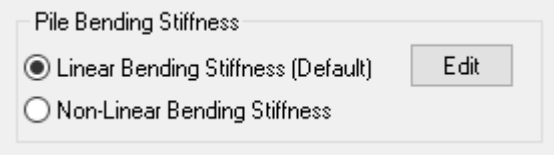


Figure 7-1 Pile bending stiffness options in PileLAT

The following dialog for bending stiffness input is shown (Figure 7-2) once the "Edit" button is pressed when the option of “Linear Bending Stiffness (Default)” is active in Figure 7-1.

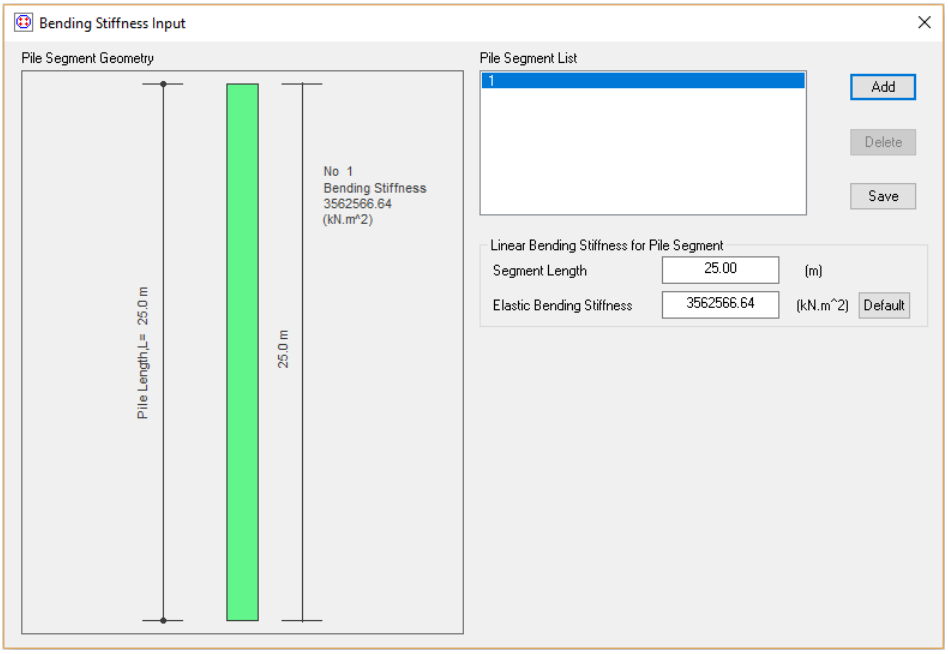


Figure 7-2 Linear Bending Stiffness Option in PileLAT

For each option, the pile segment length, elastic bending stiffness or plastic bending moment can be changed or edited. Pile segments can be added or deleted through "Add" and "Delete" Button. Pressing "Save" button after any change will enable the latest pile segment input details to be shown on the figure. Clicking each pile segment no in "Pile Segment List" selection box will highlight the selected pile segment on the figure.

Noted that if the total length of all segments is different from the pile length entered in "Pile Length" dialog, then the pile length value on the "Pile Length" dialog will be automatically changed and updated to the total length of all segments from this dialog.

If “Non-linear Bending Stiffness” option is selected as shown in Figure 7-3, then non-linear bending stiffness input information can be provided by the user through pressing the “Non-Linear Bending Stiffness” button.

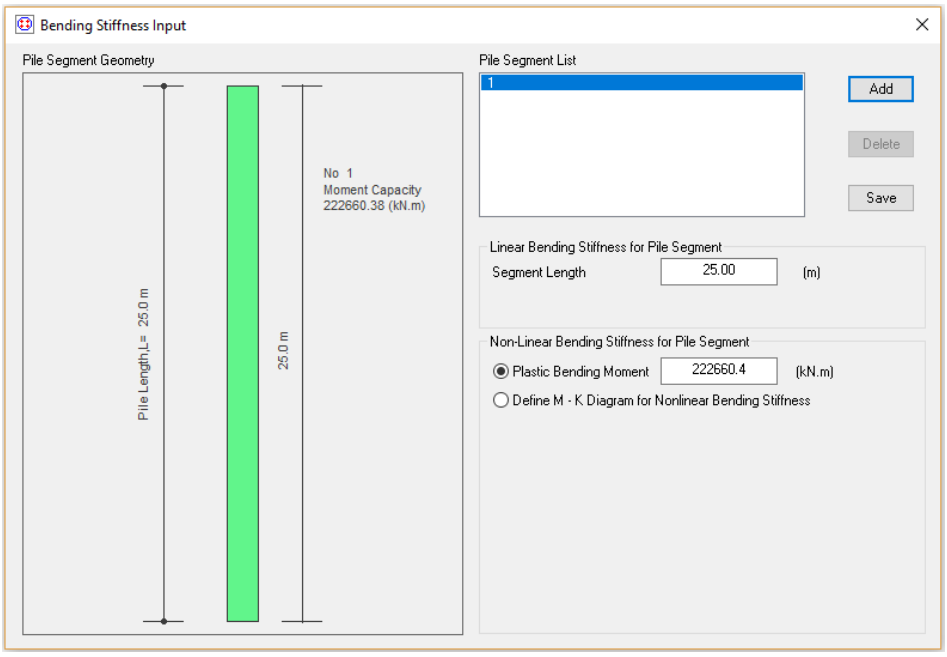


Figure 7-3 Non-Linear Bending Stiffness Option in PileLAT

Chapter 8. Pile Length

The pile length input can be accessed by clicking “Pile Length” item under “Define” main menu or clicking “Pile Length” icon on the toolbar. The invoked dialog allows the user to input the pile length, Pile Top Level, Pile Batter and Ground Surface Angle.

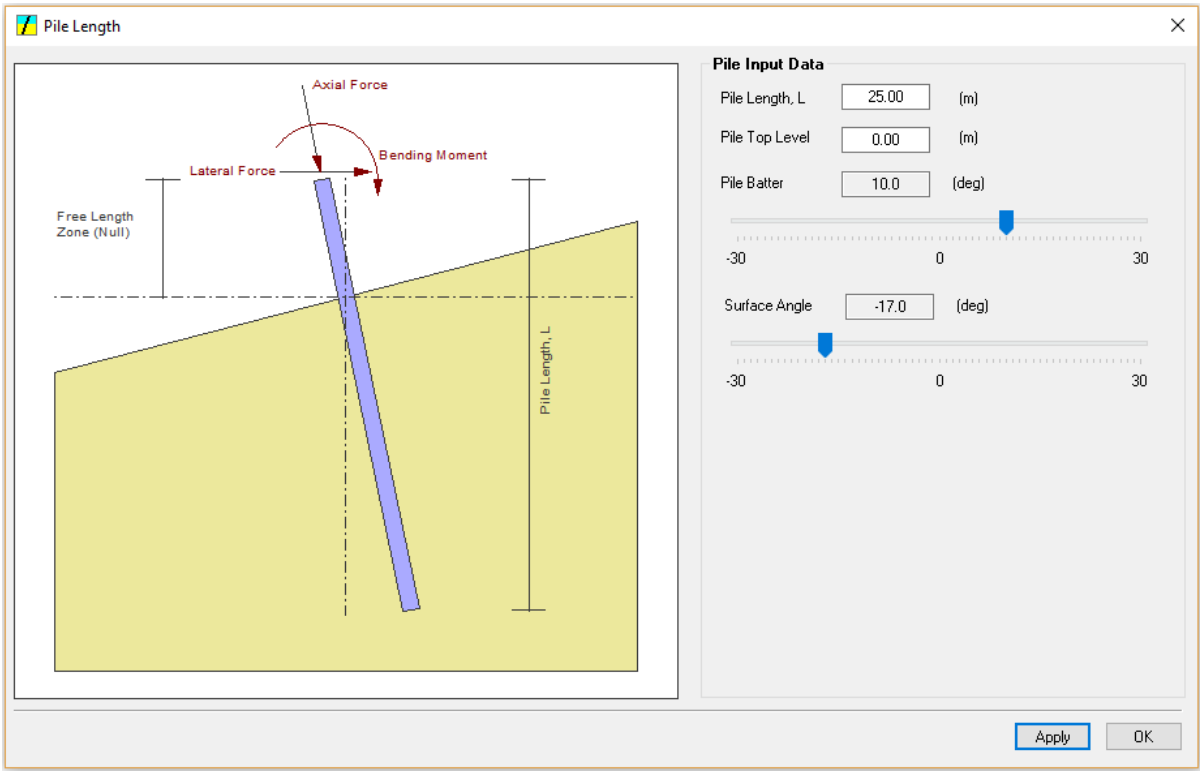


Figure 8-1 General Layout of Pile Length Input Dialog

The pile batter and ground surface angle are selected by the user through moving the corresponding slide bars. The minimum is -30 degree and the maximum is 30 degree. The increment is 0.5 degree and it is believed that this should be accurate enough for most engineering projects.

PileLAT provides a unique interactive input (as shown in Figure 8-1) of Pile Batter and Ground Surface Angle with moving the sliding bars. The dialog figure will be automatically updated to reflect any change in Pile Batter and Ground Surface Angle.

Free length portion of the pile as shown in the figure is denoted as "Free Length Zone (Null)". This can be achieved by specifying a "Null" material layer at the ground surface with the layer thickness equal to the cantilever length or free length.

Chapter 9. Soil Layers and Properties Input

PileLAT offers an innovative and straightforward interactive way to create multiple soil layers with various relevant parameters in the program. Soil layer input dialog can be invoked through clicking "Soil Layers and Properties" item under "Define" menu or clicking "Soil Layers and Properties" icon from the toolbar.

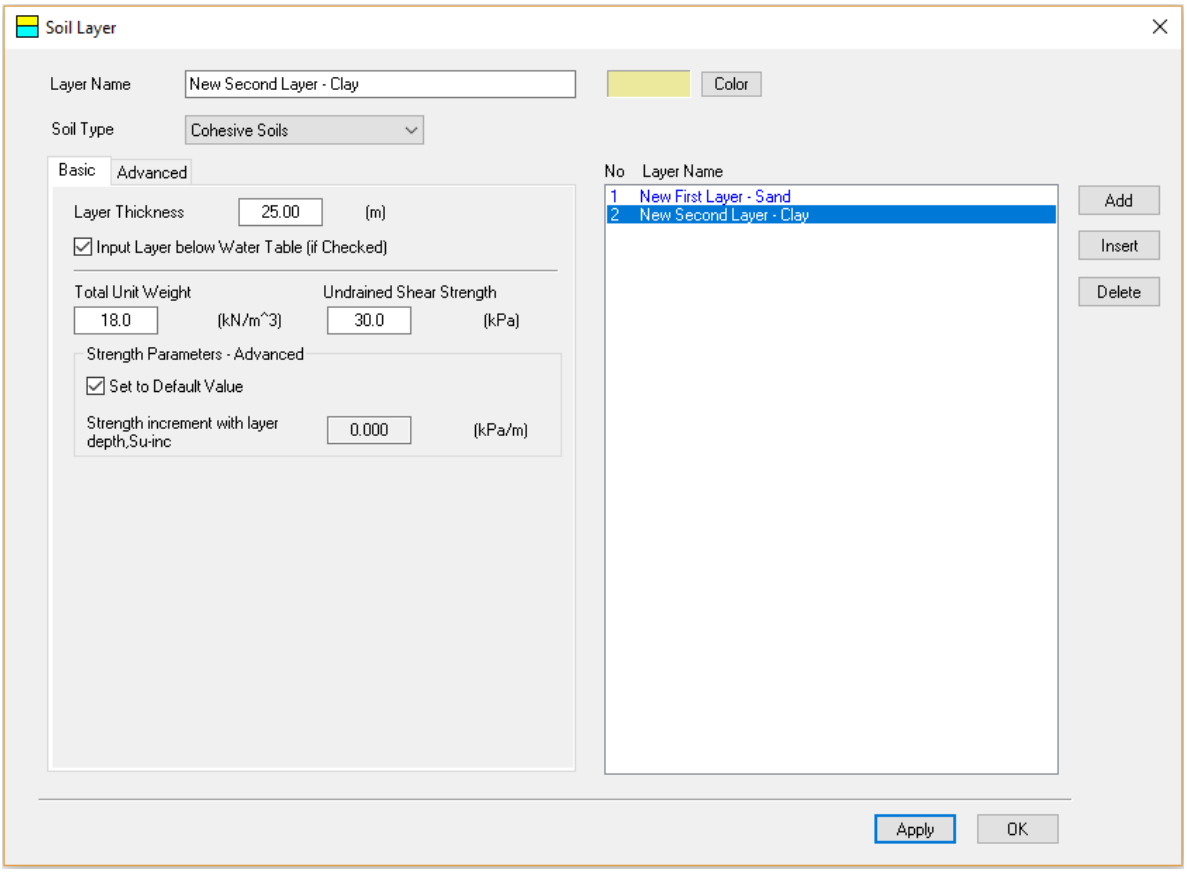


Figure 9-1 General Layout of Soil Layer Input Dialog

Soil layers can be added, inserted or deleted through "Add", "Insert" and "Delete" buttons. The layer colour also can be adjusted or updated by clicking "Colour" button. In the current version, maximum 50 soil layers can be defined by the user. Layer name also can be defined by the user through text input. The available material types from “Soil Layers and Properties” input dialog include: (1) Null material; (2) Cohesive soils; (3) Cohesionless soils and (4) Rocks.

For each material type, different P-Y models can be selected through "Advanced" tab except for Null materials which are mainly used to model the pile cantilever (free length) section above or below water. In another word, free length or cantilever pile length is defined through adopting a soil layer with Null material properties at the ground surface. Once "Null Material" type is selected, the "Advanced" tab will be disabled.

Input of soil layers and properties mainly consists of two parts:

(1) Basic soil parameters on "Basic" Tab such as soil layer thickness, total unit weight, groundwater status (above or below ground water table), undrained shear strength for cohesive soils, effective friction angle for cohesionless soils and unconfined compressive strength for rocks. For cohesive soils and rocks, the strength increment with the layer depth also can be specified through "Strength Parameters - Advanced" option. The

strength increment is automatically set to zero if the default option is selected.

(2) Advanced soil parameters related to different P-Y models on "Advanced" Tab.

The available P-Y models depend on the soil type which the user select and are listed below for different soil types:

- Cohesive Soils: Soft clay (API), Soft clay (Matlock), Stiff clay without water (Reese), Modified stiff clay without water, Stiff clay with water (Reese), Elastic-plastic model and Elastic model.
- Cohesionless Soils: Sand (API), Sand (Reese), Liquefied sand, Elastic-plastic model and Elastic model.
- Rock: Weak rock (Reese), Strong rock, Massive rock, Weak rock (Fragio), Elastic-plastic model and Elastic model.

Detailed descriptions about those P-Y models adopted by PileLAT are presented in Appendix A.

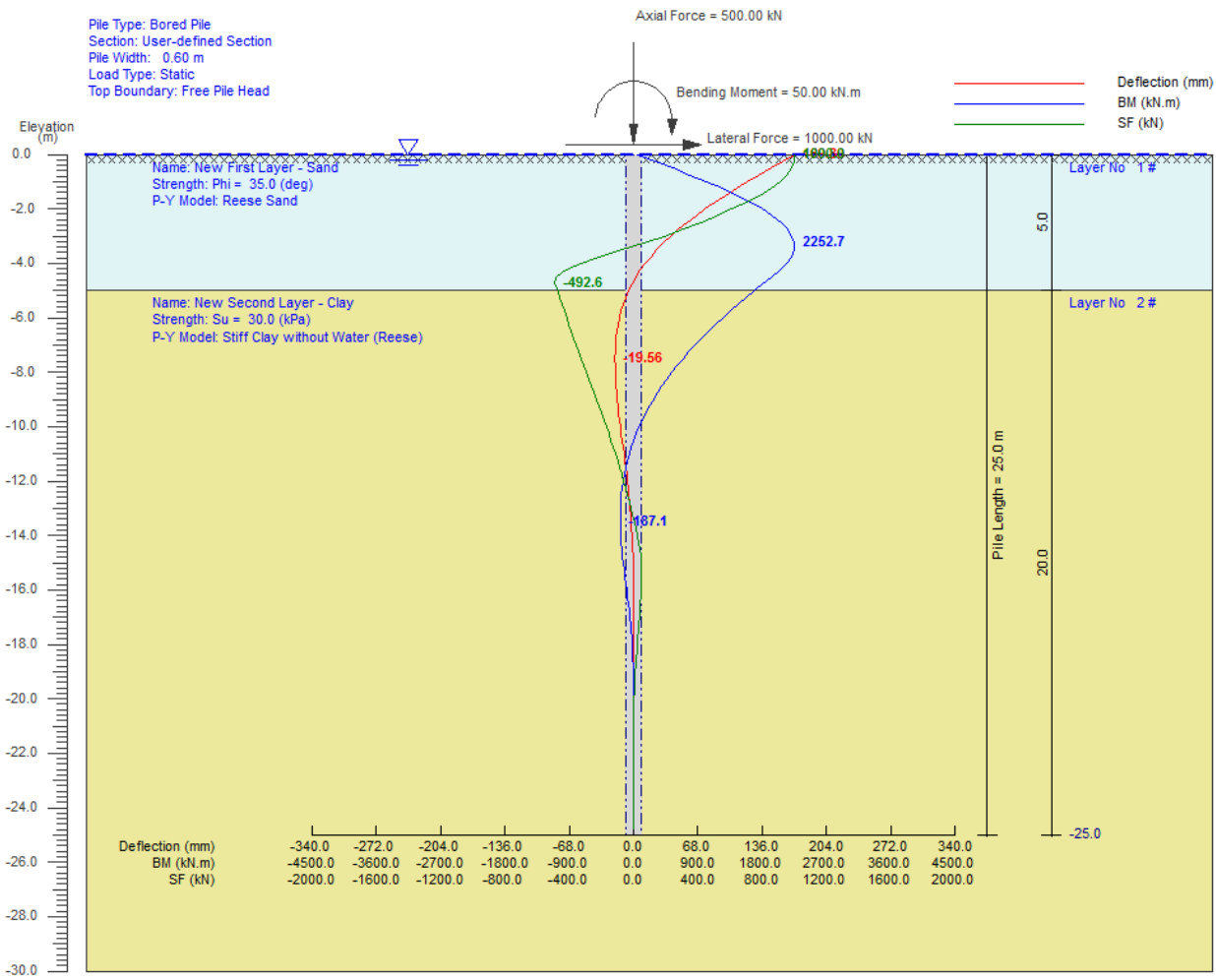


Figure 9-2 Typical Ground Profile with Analysis Results after Soil Layer Input

Clicking different layer within the layer list will display the corresponding basic parameter. The program will save the input parameters into the internal memory when the “OK” or “Apply” button at the bottom or “X” button at the top right corner is pressed. The ground profile will be automatically updated once the soil layer input is updated and saved. If “Copy Graph” item under the “File” menu is clicked or the “Copy to Clipboard”

toolbar button on the right side of the program interface is pressed, then the input ground profile can be copied into the clipboard and then pasted into the report if required. A sample of the copied ground profile graph with the analysis results is shown in Figure 9-2.

The users can use “Display Option” dialog as shown in Figure 9-3 to select or deselect display items: (1) General input information and (2) Analysis results for the ground profile plot.

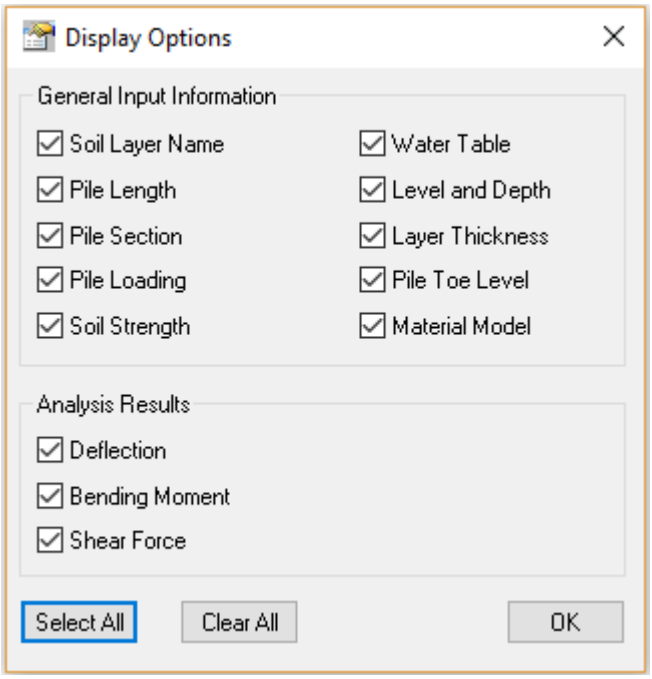


Figure 9-3 Display Options for Ground Profile in PileLAT

Chapter 10. Pile Head Load Input

The dialog for the pile head loading input can be invoked by clicking "Pile Top Loading" option under "Define" menu or "Pile Top Loading" icon from the toolbar. Axial force, horizontal shear force and bending moment at the pile head can be input from the user.

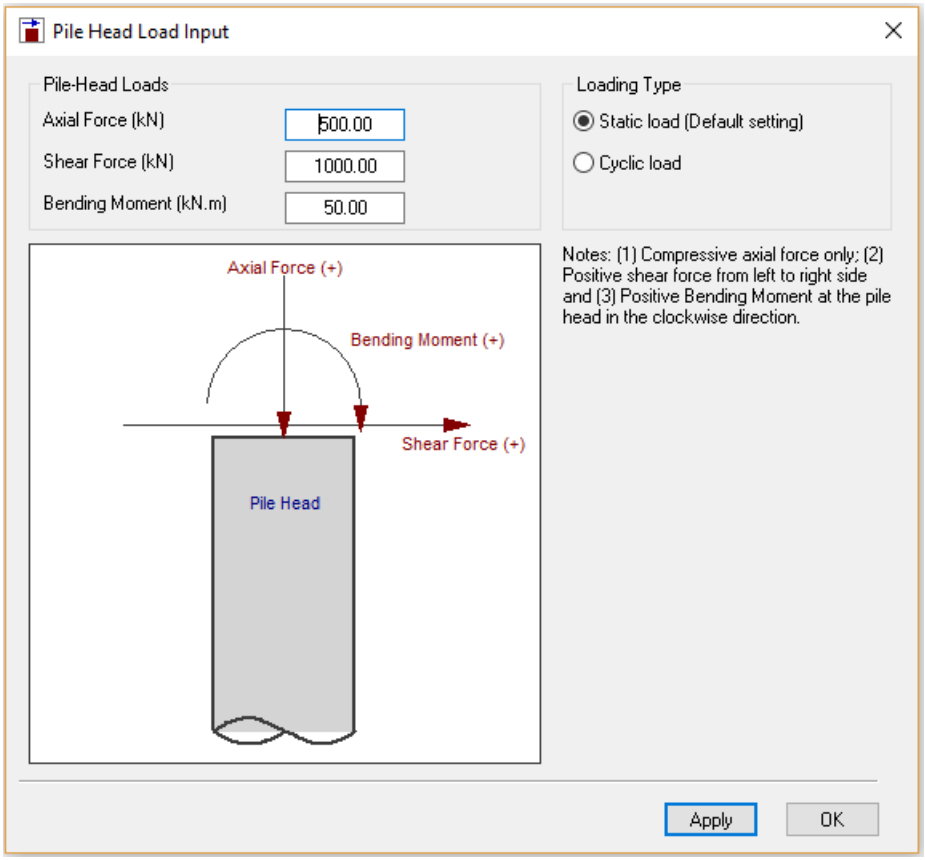


Figure 10-1 Pile Head Load Input Dialog in PileLAT

Note that only compressive axial force is considered in PileLAT and no tension force is allowed. Horizontal shear force from the left to right side is defined as positive and bending moment in the clockwise direction is defined as positive.

For the additional loads along the pile shaft such as distributed shear force and bending moment or soil movement loading, the user need to go to "Distributed Load" option to define those additional loads. This will be explained in the other sections.

If the user wants to carry out the cyclic load analysis, then the option of “Cyclic Load” can be selected within the loading type.

Chapter 11. Distributed Load Input

Distributed Load Option can be invoked by clicking "Distributed Load" option under Define Menu or clicking "Distributed Load" icon from the toolbar. Figure 11-1 shows the “Distributed Load Input” dialog. The default selection is “No Distributed Loads” option. If the “User-defined Distributed Lateral Loads” option is selected, then distributed horizontal shear force, bending moment, and displacement can be input by the users.

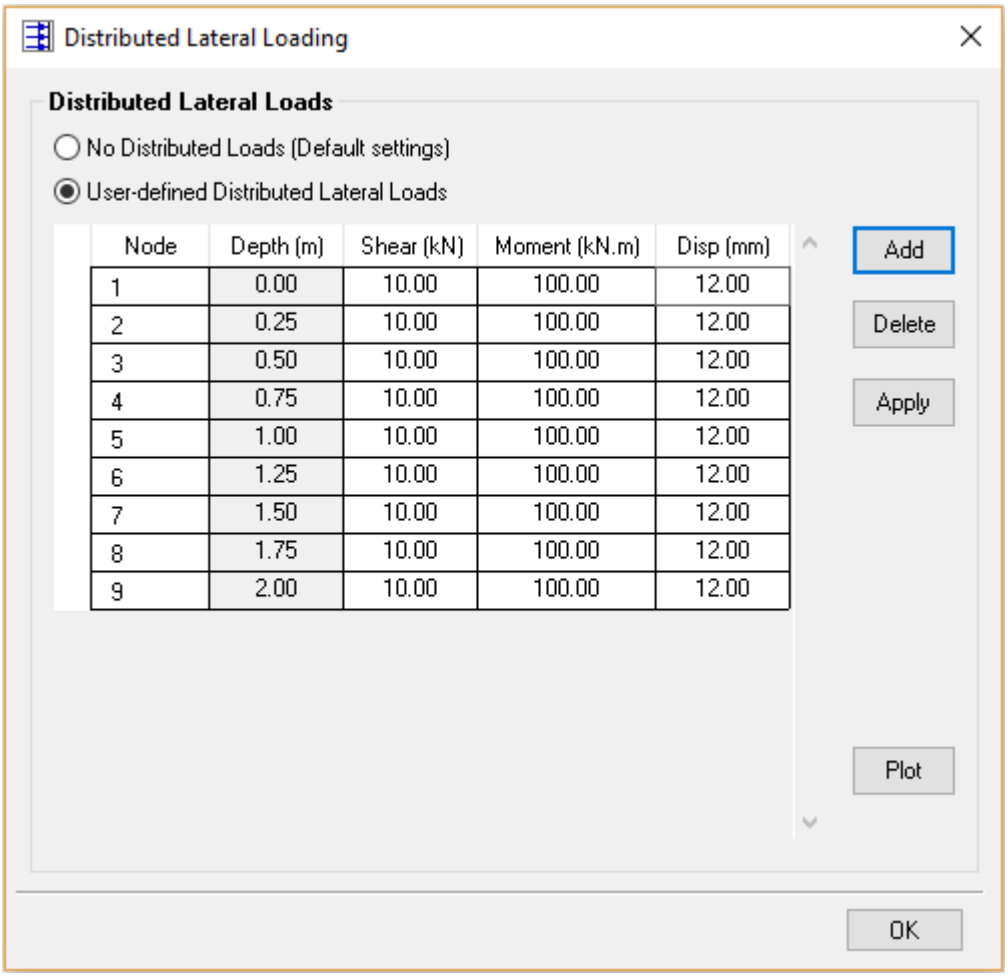


Figure 11-1 Distributed lateral Loads Input Dialog in PileLAT

Specific node number can be selected through the drop menu under the "Node" column. The "Depth" column shows the depth of the node point below the pile head and this column is not editable. Distributed load can be added or deleted through "Add" and "Delete" buttons on the right side. Pressing "Apply" button after input will save the input to the analysis file.

PileLAT provides the users with the option of viewing the distributed loads or displacements after input and this is achieved through pressing “Plot” button on the right bottom side of the dialog.

Distributed shear forces and bending moments will be displayed in the solid arrows and distributed displacement loads are shown in the dash-dot arrows (Figure 11-2). Soil layers with the specified layer colours and boundaries are also displayed in the graph to help the user to know the relative position of the nodes to

the soil layers.

Four display options are provided in PileLAT to enable the users to show or hide the information related to the distributed loads along the pile length such as (1) Node number, (2) Shear force, (3) Bending moment and (4) Displacement.

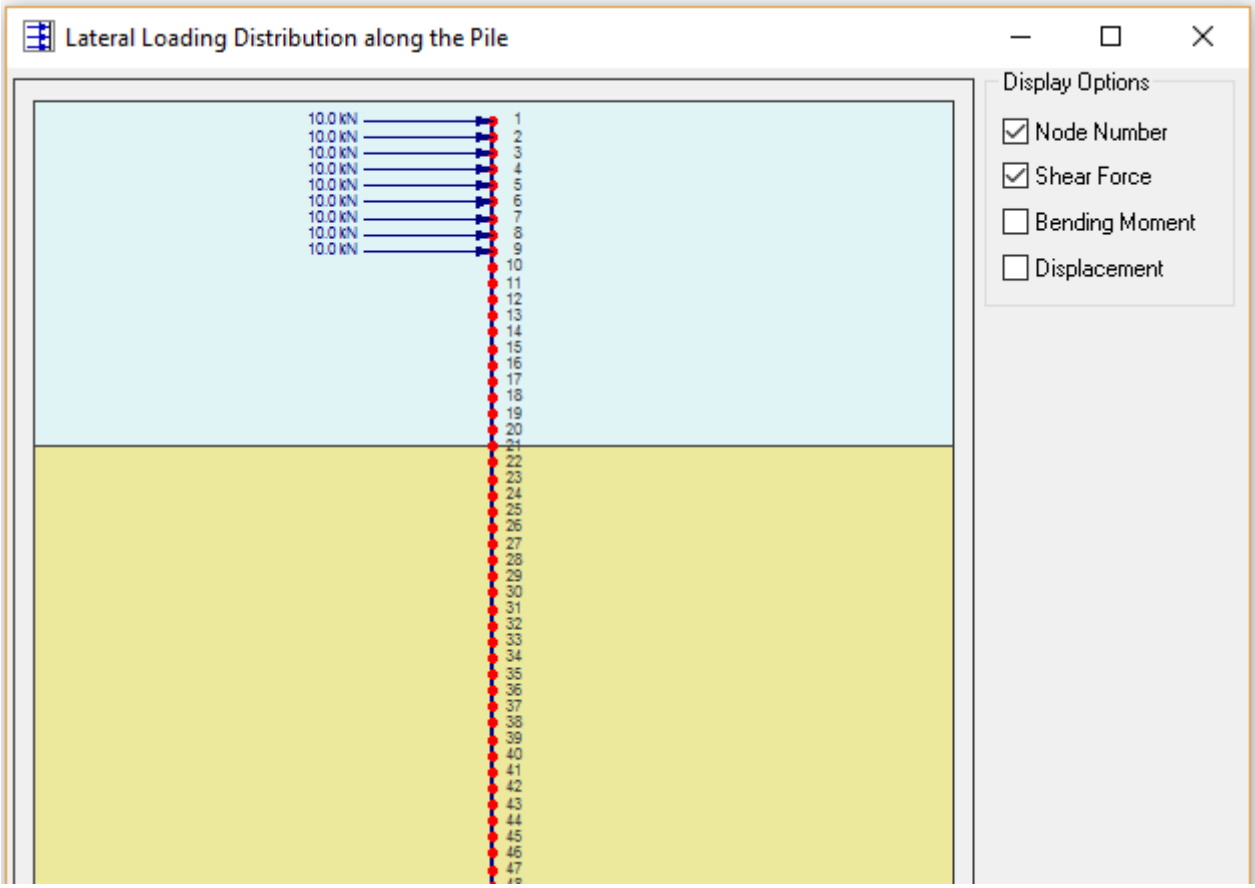


Figure 11-2 Distributed lateral Loads Input Dialog in PileLAT

Chapter 12. Pile Group Effect

In PileLAT, it is very straightforward to specify the P-Multipliers for each soil layer to consider the potential pile group effects. The dialog for the group effect input option can be invoked by clicking "Group Effect" option under "Define" menu or clicking “Group Effect” icon from the toolbar.

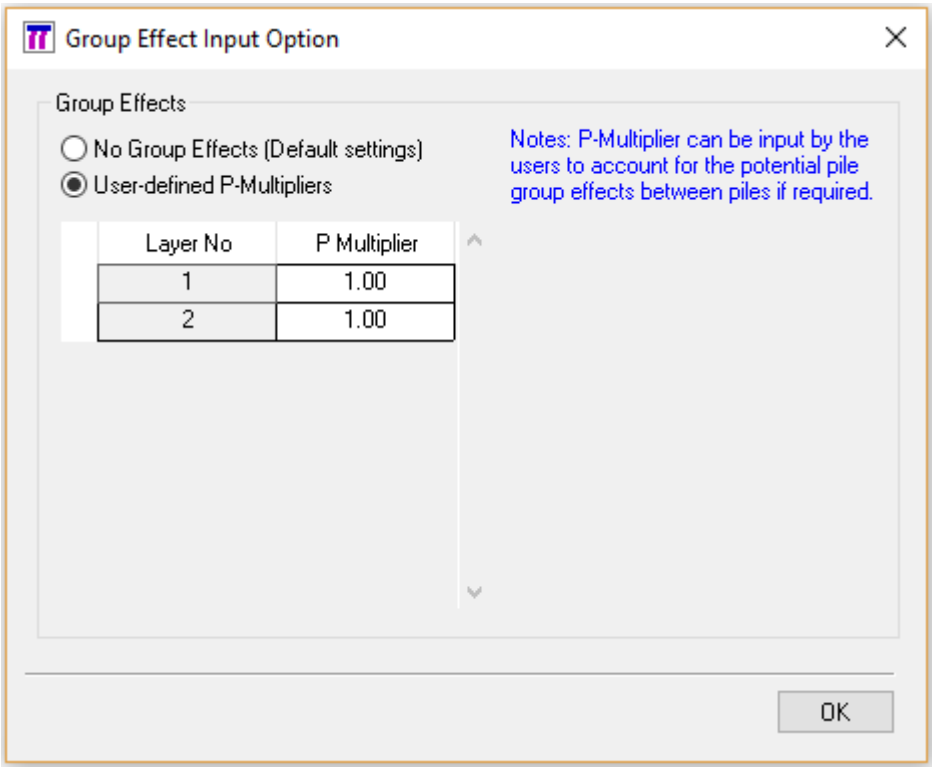


Figure 12-1 P-Multipliers Input Dialog in PileLAT

Two options are available to the users: (1) No Group Effects (Default settings) and (2) Manual settings where the users can specify the P-Multipliers for each soil layer to consider the potential pile group effects.

If the "User-defined P-Multipliers" option is selected, the input table as shown in Figure 12-1 will appear which allows the user to input the specific P-Multipliers for each soil layer. The default value for each layer is 1.0.

Chapter 13. Reviewing Soil Layer Input Parameters

PileLAT provides the user with the option of reviewing soil layer input parameters. Soil layer input summary dialog can be invoked through clicking "Soil Layer Input Summary" option under "Define" menu or "Soil Layer Input Summary" icon from the left toolbar. The invoked summary table is shown in Figure 13-1 which enables the user to review the detailed soil layer parameter inputs into the analysis and spot the input errors if any.

Soil Layer Input Parameter Summary

No	Layer Parameters	Layer No 1	Layer No 2
1	Layer Type Parameter	3	2
2	Layer Type Name	Cohesionless Soil	Cohesive Soil
3	Layer Color	16184544	10283244
4	Layer Name	New First Layer - Sand	New Second Layer - Clay
5	Layer Thickness (m)	5.0	25.0
6	Water State	1	1
7	P-Y Model Parameter	32	23
8	P-Y Model Name	Reese Sand	Stiff Clay without Water - Reese
9	Total Unit Weight (kN/m^3)	17.0	18.0
10	Undrained Shear Strength (kPa)	-	30.0
11	Effective Friction Angle (deg)	35.0	-
12	Unconfined Compressive Strength (MPa)	-	-
13	Strength Increment with Depth (kPa or MPa/m)	-	0.0
14	Strain Factor, Eps50	-	0.010
15	Empirical Constant, J	-	0.250
16	Initial Subgrade Modulus (kN/m^3), Ki	20373.2	-
17	Young's Modulus (kPa), E	-	-
18	Increment of Young's Modulus (kPa/m), dE	-	-
19	Poisson's Ratio, v	-	-
20	Modulus of Subgrade Reaction(kN/m/m), Kh	-	-
21	Increment of Modulus of Subgrade Reaction (kN/m^3), dKh	-	-
22	Strain Factor for Weak Rock, Epsm	-	-
23	Initial Weak Rock Mass Modulus, Eir (kPa)	-	-
24	RQD	-	-
25	Intact Rock Material Constant, mi	-	-
26	GSI	-	-

Row 1 Column 1

Figure 13-1 Soil layer input summary table for an example

Chapter 14. Reviewing Pile Input Parameters

Pile input summary table can be viewed through clicking "Pile Input Summary" option under "Define" menu or pressing "Pile Input Summary" from the left toolbar. It summaries the values of pile input parameters from the user. Multiple columns for different pile segments can be shown if more than one pile segment is used. The dialog as shown in Figure 14-1 enables the users to review the input parameters related to the pile type, section type, section dimension, material stiffness, top connection conditions, bending stiffness and pile batter.

Pile Input Parameter Summary

No	Pile Parameters	Pile Segment No 1
1	Pile Type	Bored Pile / Drilled Shaft
2	Section Type	Circular Section
3	Pile Diameter (m)	1.200
4	Section Width (m)	-
5	Section Height (m)	-
6	Web Thickness (m)	-
7	Flange Thickness (m)	-
8	External Diameter (m)	-
9	Internal Diameter (m)	-
10	Pile Segment Length (m)	25.000
11	Gross Section Area (m^2)	1.131
12	Section Perimeter (m)	3.770
13	Moment of Inertia (m^4)	0.10178762
14	Pile Material Stiffness (kPa)	35000000.00
15	Pile Batter (Degree)	0.00
16	Ground Surface Angle (Degree)	0.00
17	Pile Top Boundary	Free Pile Head
18	Rotational Spring (kN.m/rad)	-
19	Nonlinear Bending	No
20	Bending Stiffness (kN.m^2)	3562566.64
21	Plastic Bending Moment (kN.m)	-

Row 1 Column 1

Figure 14-1 Pile input summary table for an example

Chapter 15. Run Analysis

Running the analysis file with the input parameters created from the previous steps can be invoked by clicking "Run Analysis" option under "Analyze" menu or clicking “Run Analysis” icon from the top toolbar. The invoked running message dialog as shown in Figure 15-1 details the analysis information and the analysis result status.

The warning messages if any will be displayed under the progress bar to show the likely cause of the problem. Clicking "OK" button will close the dialog and the user will be able to access the various analysis results if the analysis run is successful. Otherwise, the user will need to review the input file to find out why the analysis cannot be successfully completed.

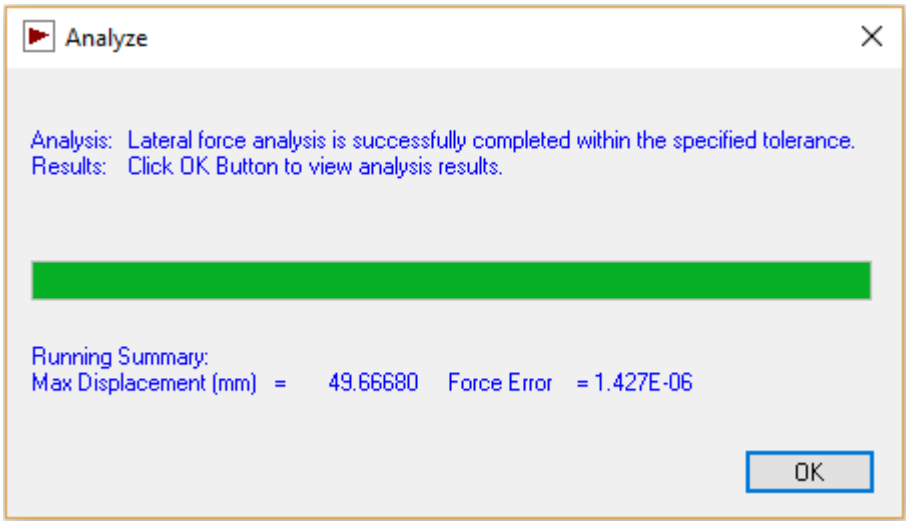


Figure 15-1 Run Analysis Message Box for an example

Chapter 16. Viewing Analysis Results

PileLAT provides an easy way to access various detailed analysis results through "Analysis Results" Output Dialog as shown in Figure 16-1. The User can view almost all analysis results plotted against the pile length. Clicking the corresponding radio button enables the User to switch different analysis result plots conveniently. Soil layers with the specified layer colours and boundaries are also shown in the graph to help the user to know the relative position of the results to the soil layers.

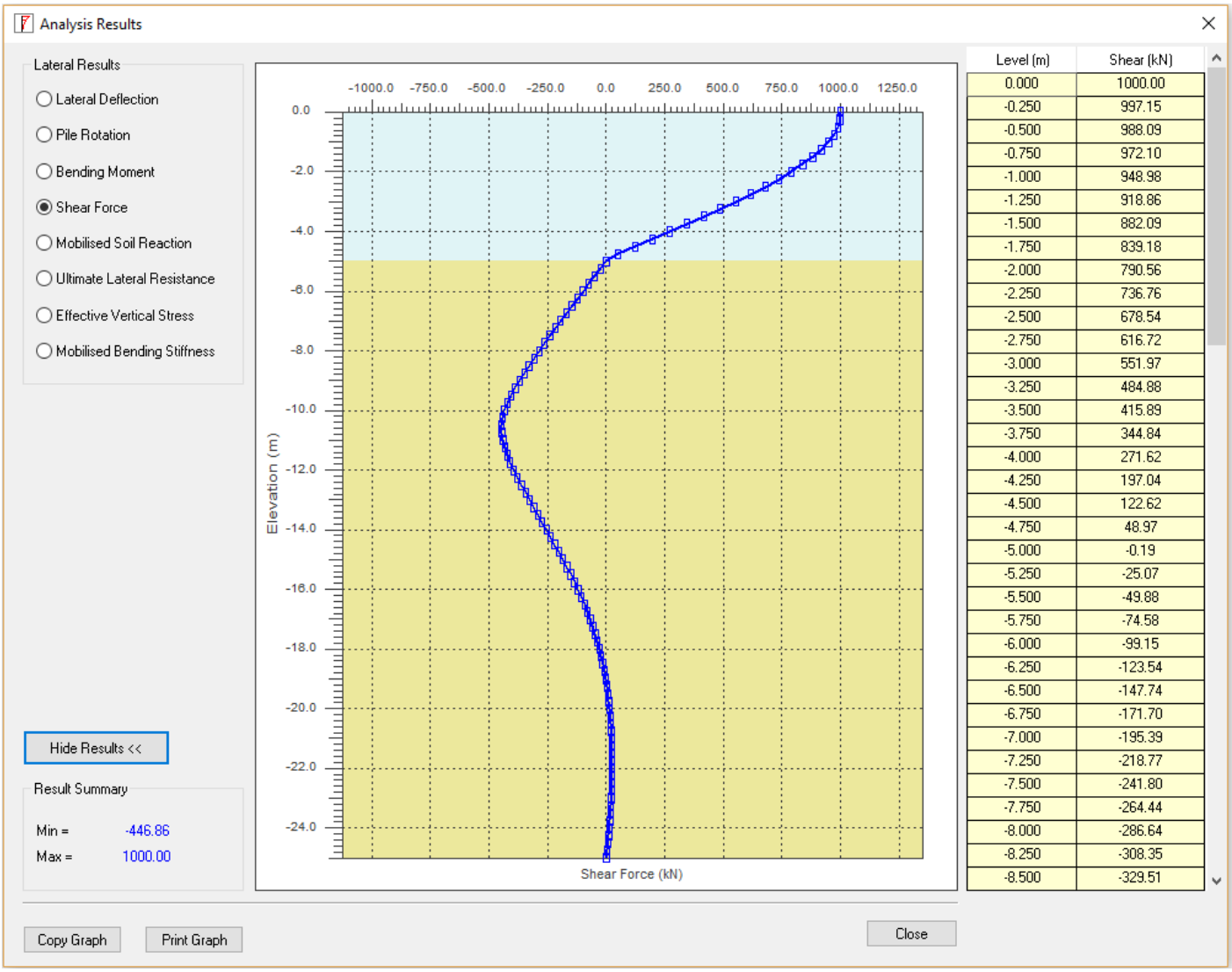


Figure 16-1 Analysis Results Dialog of PileLAT

This “Analysis Results” Output Dialog can be invoked by clicking “Analysis Results” icon from the left toolbar and the analysis results which are available for viewing from this dialog include:

- Distribution of the lateral displacement with the pile length;
- Distribution of the pile rotation with the pile length;
- Distribution of the bending moment with the pile length;

- Distribution of the shear force with the pile length;
- Distribution of the mobilised soil reaction with the pile length;
- Distribution of the ultimate lateral resistance with the pile length;
- Distribution of the effective vertical stress with the pile length;
- Distribution of the mobilised bending stiffness with the pile length;

The above results can also be viewed by clicking the corresponding items under the "Display" menu. In addition to the plotting results, PileLAT also provides the detailed analysis results in the excel-like table format if "Display Results" button is pressed. It is convenient for the user to go through each analysis result at different depths. The tabulated results can be also easily copied into the third-party software for further process if required.

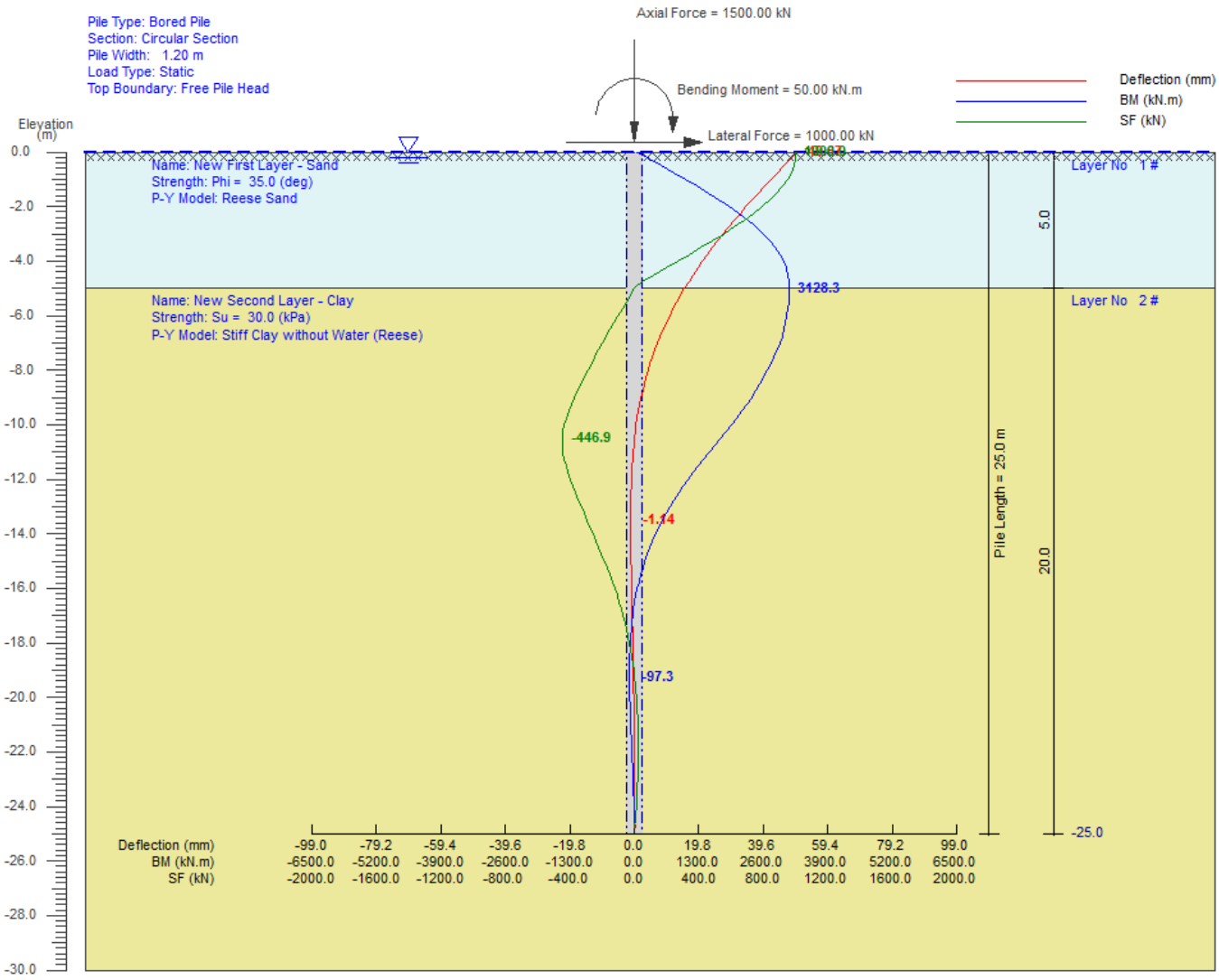


Figure 16-2 Analysis results plotted with the ground profile

Apart from viewing the results through Analysis Results Dialog, the important analysis results such as deflection, shear and bending moment are also plotted within the ground profile in the main interface of the program as shown in Figure 16-2.

PileLAT enables the user to copy or print the relevant detailed results on the graph. This can be done by clicking “Copy Graph” or “Print Graph” on the bottom of the “Analysis Results” Dialog. The copied graph can be easily pasted into the third-party application for reporting purpose. A sample of the copied and pasted result graph is shown in Figure 16-3 for an example.

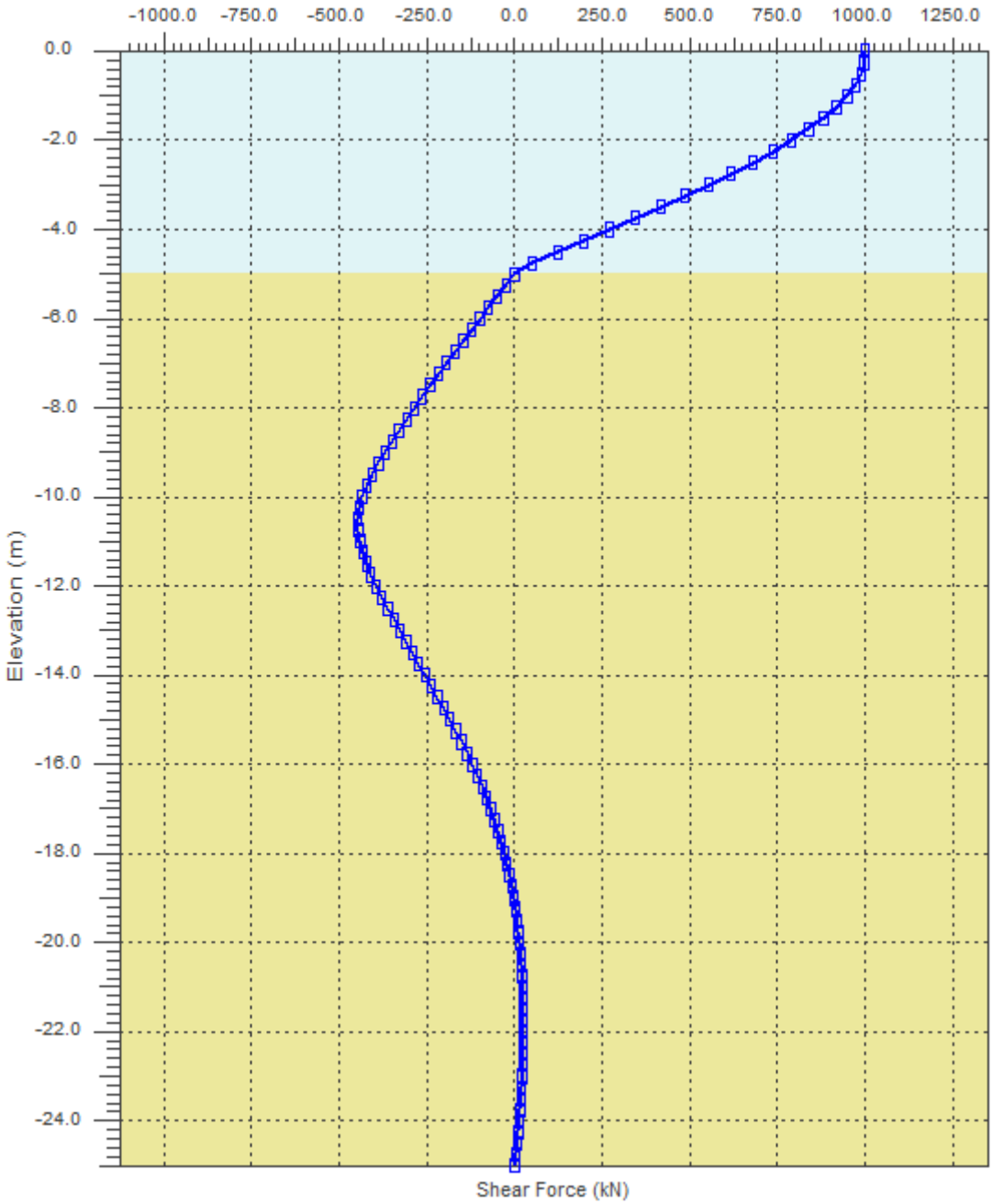


Figure 16-3 Copied result graph (Shear Force) for an example

Chapter 17. Viewing P-Y Curves

In PileLAT, once the analysis is successfully completed, the user can access the various analysis results. The dialog for p-y curve plot can be invoked by clicking the "p-y Curve Plot" option under "Display" menu or “p-y Curve Plot” from the toolbar.

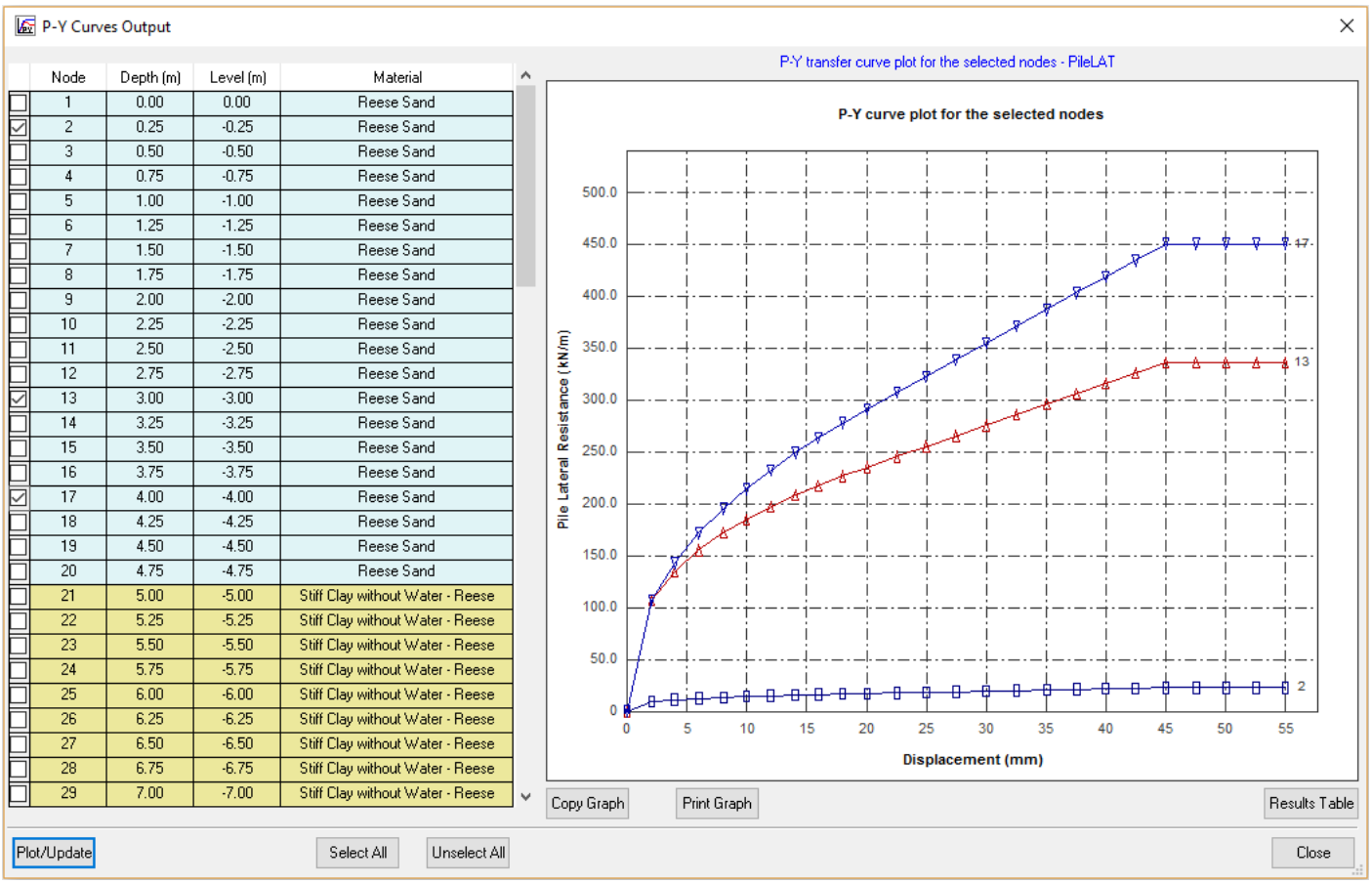


Figure 17-1 “p-y Curve Plot” dialog for an example

p-y curves for all the nodes can be selected and viewed by the user through p-y Curve Plot Dialog as shown in Figure 17-1. Plot or update the p-y curve plots can be done through the following steps:

- Step 1: Tick the check box for the pile node number where you want to view the results. Note that multiple node points can be selected;
- Step 2: Click the "**Plot/Update**" button at the bottom of the table to update the p-y curve plots.

For each node point listed in the table, other relevant information such as Depth, Level, and p-y model type are also displayed for the user's information. The background colour of row in the table follows the colour of the soil layer.

If required, detailed p-y curve results can be accessed through clicking the button of "Results Table" under the summary table. A new window with gird-type outlook as shown in Figure 17-2 will be invoked with "y" lateral displacement (mm or inch) and "p" mobilised soil reaction (kN/m or lbf/in) for the selected node

points along the pile length.

P-Y Curve Results Table

Y (mm) for Node 2	Pu (kN/m) for Node 2	Y (mm) for Node 13	Pu (kN/m) for Node 13	Y (mm) for Node
0.00	0.00	0.00	0.00	0.00
2.04	9.19	2.04	107.13	2.04
3.96	11.00	3.96	134.61	3.96
6.00	12.30	6.00	155.30	6.00
8.04	13.31	8.04	171.76	8.04
9.96	14.11	9.96	184.90	9.96
12.00	14.84	12.00	197.14	12.00
14.04	15.48	14.04	208.09	14.04
15.96	16.02	15.96	217.48	15.96
18.00	16.55	18.00	226.67	18.00
20.04	17.04	20.04	235.20	20.04
22.56	17.62	22.56	245.39	22.56
24.96	18.17	24.96	255.10	24.96
27.48	18.75	27.48	265.29	27.48
30.00	19.33	30.00	275.49	30.00
32.52	19.91	32.52	285.68	32.52
35.04	20.49	35.04	295.87	35.04
37.56	21.07	37.56	306.07	37.56
39.96	21.62	39.96	315.77	39.96
42.48	22.20	42.48	325.97	42.48
45.00	22.78	45.00	336.16	45.00
47.52	22.78	47.52	336.16	47.52
50.04	22.78	50.04	336.16	50.04
52.56	22.78	52.56	336.16	52.56
54.96	22.78	54.96	336.16	54.96

Row 1 Column 1

Figure 17-2 Tabulated p-y Curve results for an example

PileLAT enables the user to copy or print the relevant results on the graph. This can be done by clicking “Copy Graph” or “Print Graph” on the bottom of the “Analysis Results” Dialog. The copied graph can be easily pasted into the third-party application for reporting purpose as shown in Figure 17-3.

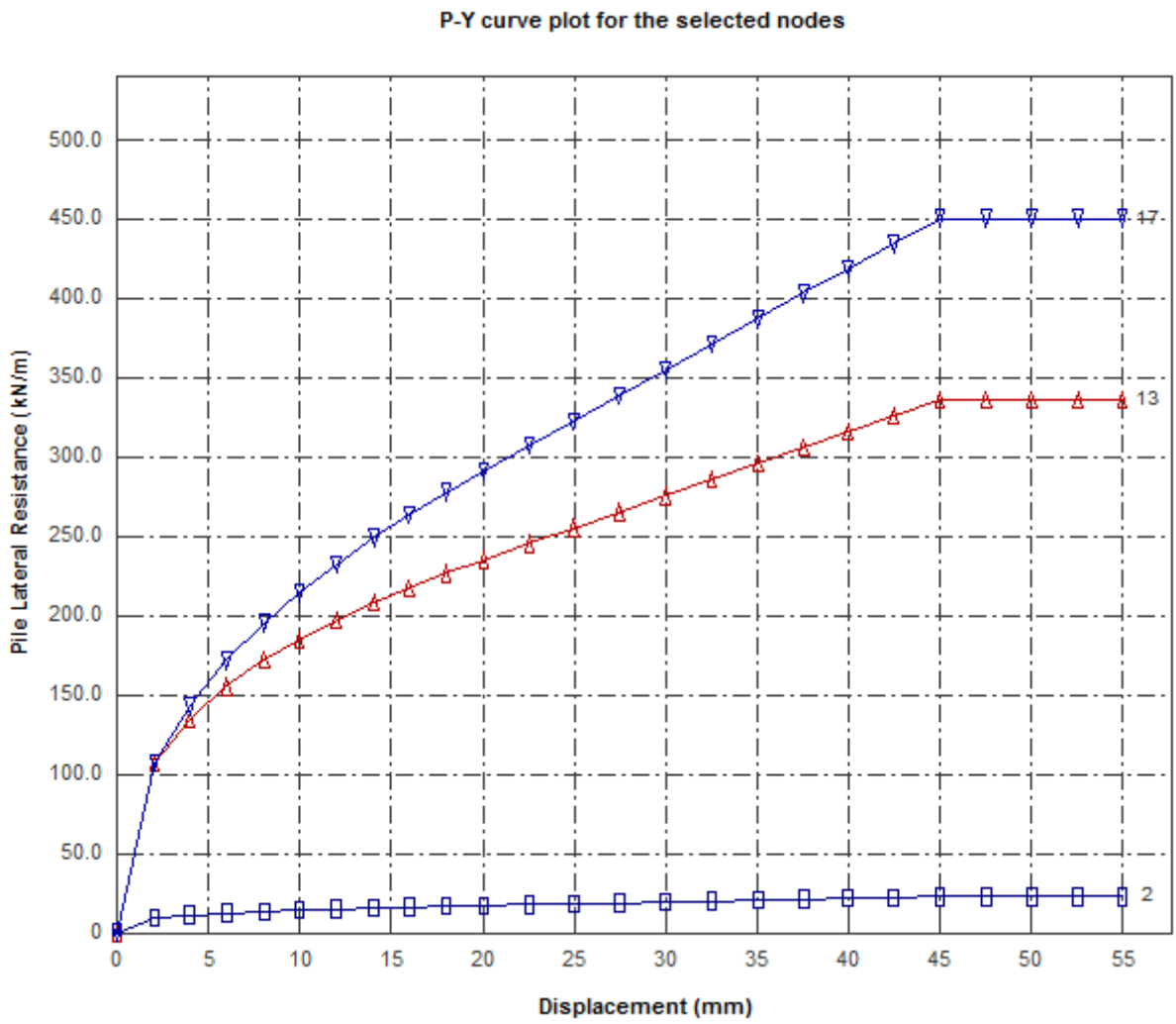


Figure 17-3 Copied p-y curves graph for an example

Chapter 18. Viewing Load Deflection Plot for Pile Head

In addition to p-y curves, the user also can access different types of load deflection curves (H-Y Curves) at the pile head once the analysis is successfully completed in PileLAT. The dialog for H-Y curve plot can be invoked by clicking the "H-Y Curve Plot" option under "Display" menu or “H-Y Curve Plot” from the toolbar on the left side of the main program interface.

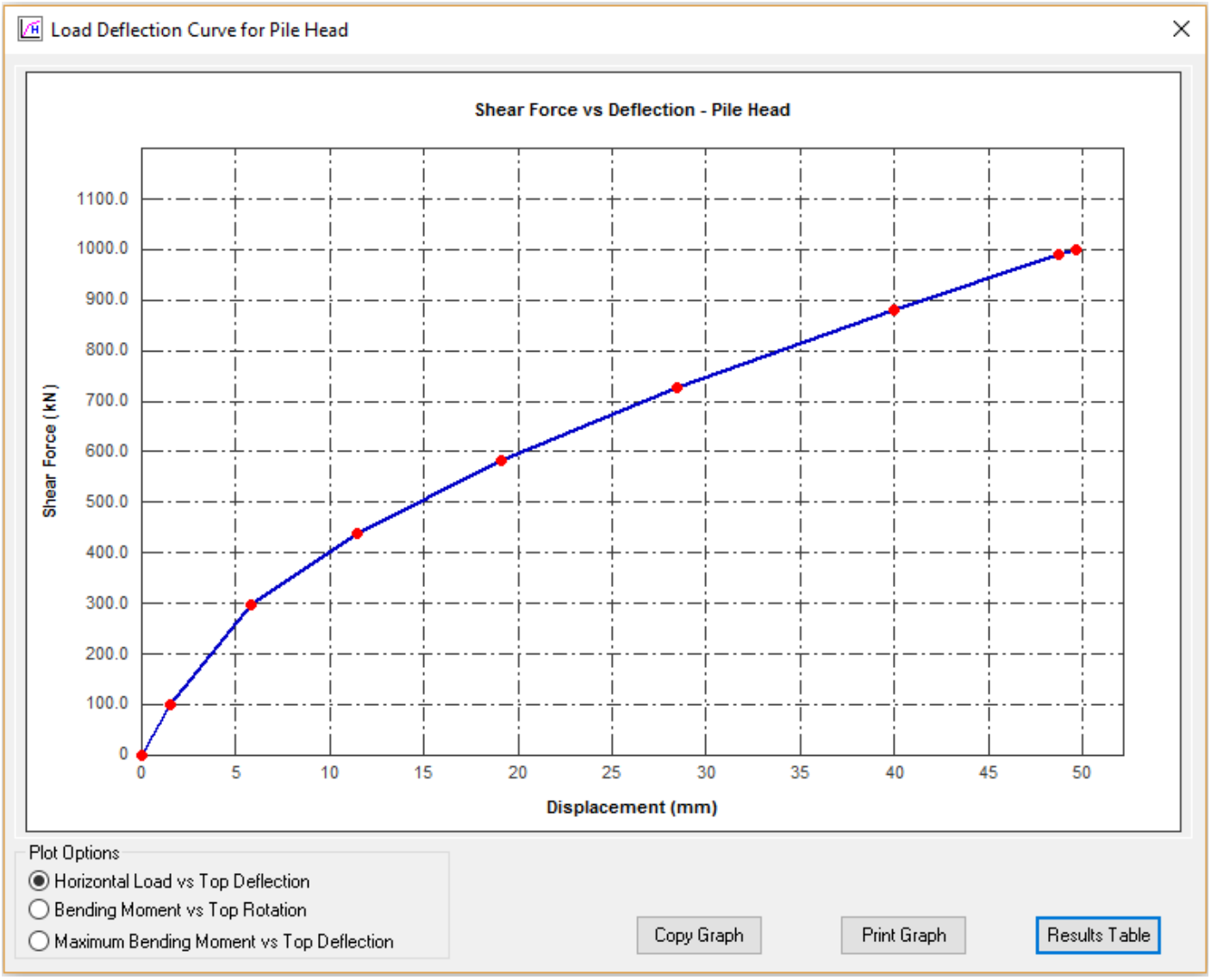


Figure 18-1 Load deflection curve plot dialog

The first option is “Horizontal Load vs Top Deflection” which shows the relationship between the horizontal load and the resulted lateral deflection at the pile head.

The second option is "Bending Moment vs Top Rotation" which shows the relationship between the mobilised bending moment and pile rotation at the pile head. Noted this plot depends on the applied bending moment at the pile head. If the applied bending moment at the pile head is zero, then only a

horizontal line at the bottom is present.

The third option is “Maximum Bending Moment vs Top Deflection” which shows the relationship between the mobilised maximum bending moment and the lateral deflection at the pile head. This option is very useful when the nonlinear bending stiffness option is adopted in the analysis.

If required, the tabulated results as shown in Figure 18-2 for the load and deflection curves at the pile head will be presented in the Excel-like table format through clicking the button of "Results Table" under the graph.

Pile Top Load Deflection Curve Results Table

Top Deflection (mm)	Top Lateral Load (kN)	Top Bending (kN.m)	Top Rotation (Rad)	Maximum Bending (kN.m)
0.00	0.00	0.00	0.000E+00	0.00
1.56	100.00	5.00	-3.723E-04	217.18
5.85	297.54	14.88	-1.302E-03	723.85
11.48	438.14	21.91	-2.310E-03	1169.92
19.12	583.47	29.17	-3.549E-03	1660.03
28.48	727.95	36.40	-4.953E-03	2167.57
40.00	881.40	44.07	-6.582E-03	2711.36
48.75	989.06	49.45	-7.773E-03	3089.59
49.63	999.56	49.98	-7.892E-03	3126.71
49.67	1000.00	50.00	-7.897E-03	3128.25

Row 1 Column 1

Figure 18-2 Tabulated H-Y Curve results

PileLAT also enables the user to copy or print the relevant results on the graph. This can be done by clicking “Copy Graph” or “Print Graph” on the bottom of “Load Deflection Curve for Pile Head” dialog. The copied graph can be easily pasted into the third-party application for reporting purpose. A sample of the copied and pasted result graph is shown in Figure 18-3 for this example.

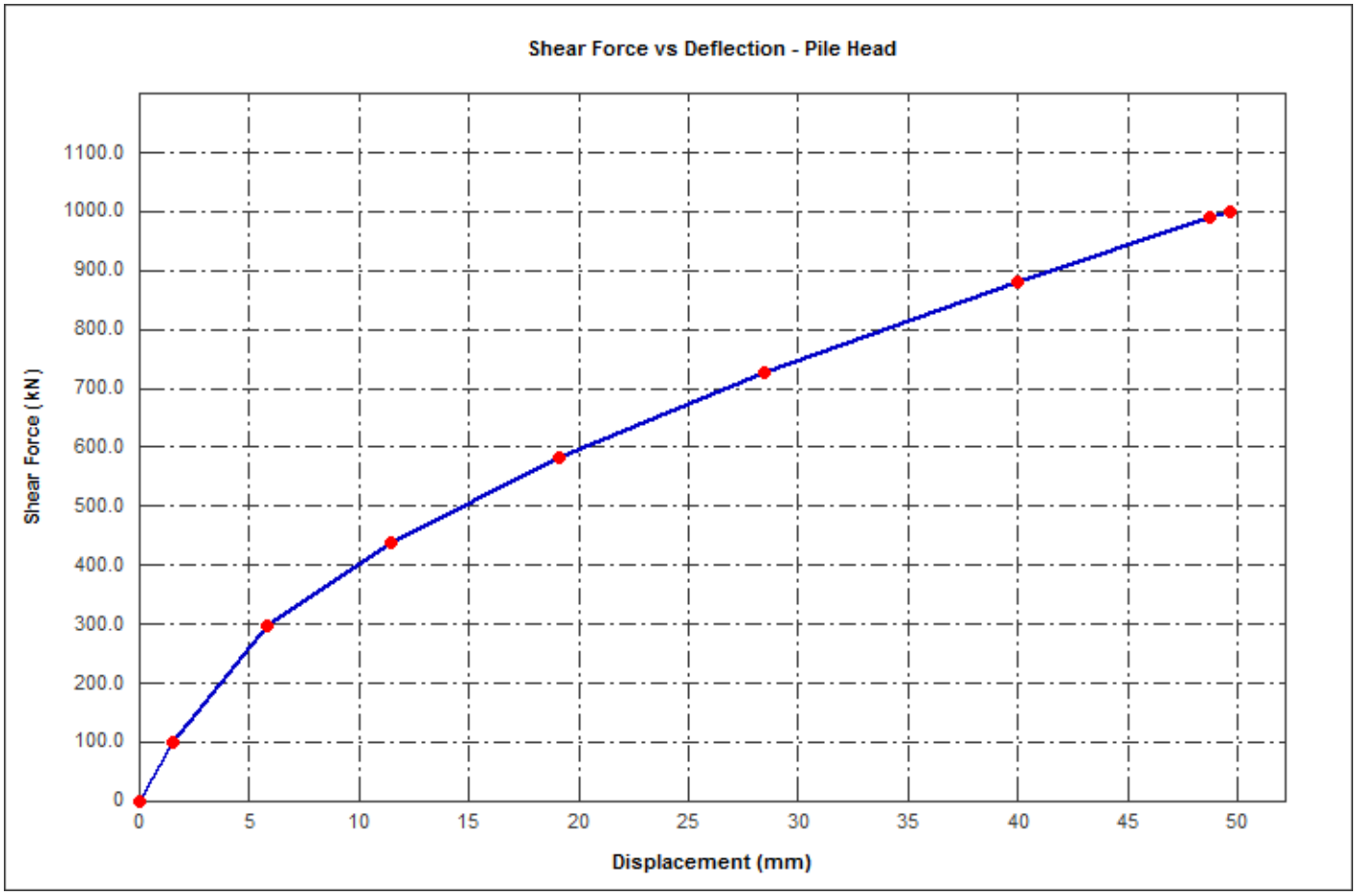


Figure 18-3 Copied H-Y Curve Plot

Chapter 19. Pile Axial Load Settlement Curves

PileLAT predicts the pile settlement under compressive axial loading at the pile head. This unique feature is very useful. It enables the users to estimate the axial load settlement curve at the pile head when lateral force analysis is carried out without the need to set up a separate analysis file for pile settlement analysis. The only additional input is the axial load at the pile head.

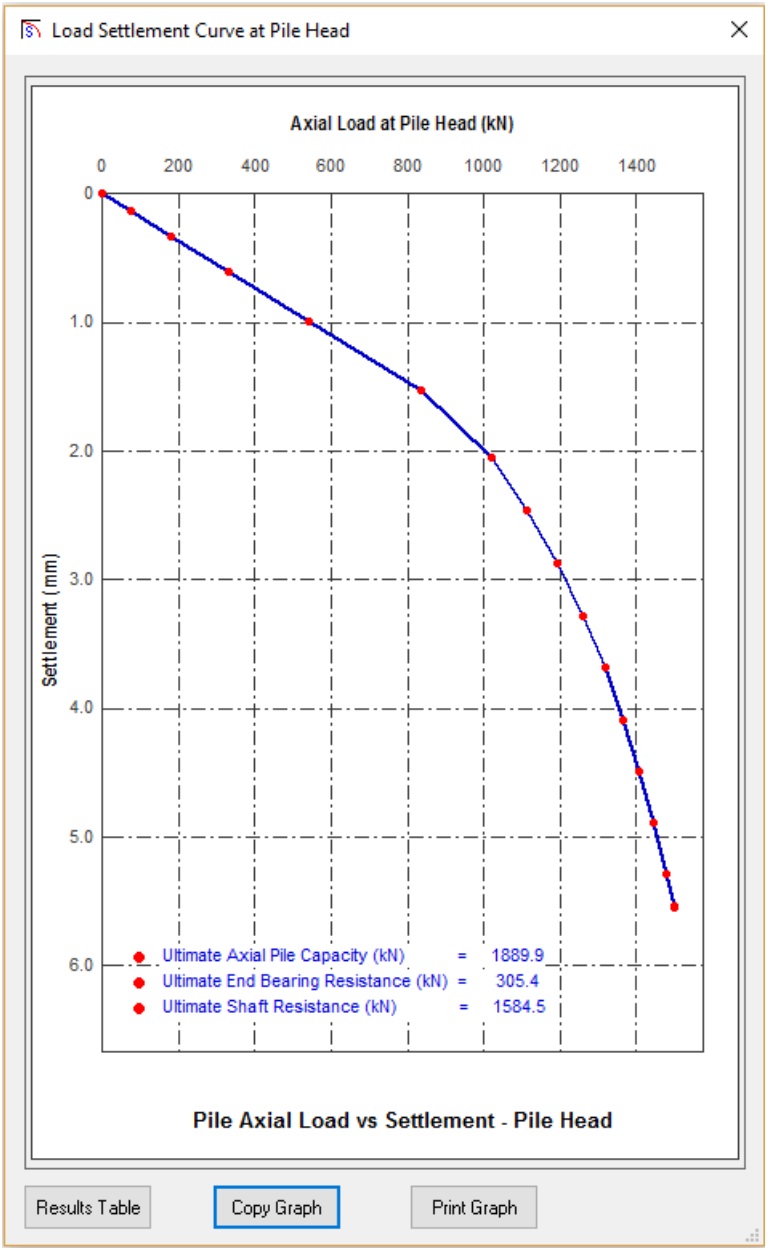


Figure 19-1 "Axial Load Settlement Curve" dialog

Load transfer t-z and q-w curves are automatically generated based on the pile installation type and soil type. For driven piles, t-z and q-w curves based on the recommendations of API (2002) are adopted for both

cohesive and cohesionless (granular) soils. For bored piles or drilled shafts, t-z and q-w curves are based on the recommendations from Reese and O'Neill (1987) for both cohesive and cohesionless (granular) soils. For rock, t-z curve recommended by O'Neill and Hassan (1994) is adopted. Elastic-plastic model is adopted for q-w response at the pile toe. Detailed approaches to calculate the ultimate shaft resistance and ultimate end bearing resistance for different types of soils are briefly reviewed and summarised in the Appendix B.

Detailed pile axial capacity and settlement analysis with more options can be carried out by PileAXL which has more advanced features. The dialog for pile settlement curve plot can be invoked by clicking the "Axial Load Settlement Curve" option under "Tool" menu.

Figure 19-1 shows the "Axial Load Settlement Curve" dialog. Load-settlement curve is generated by the program for the specified axial loading at the pile head. Preliminary estimations on the ultimate shaft resistance, ultimate end bearing resistance and ultimate axial pile capacity are carried out by the program and the preliminary results are shown on the load-settlement curve graph.

If required, the tabulated results as shown in Figure 19-2 for the load and settlement curve at the pile head will be presented in the Excel-like table format through clicking the button of "Results Table" under the graph.

Axial Load Settlement Results

Settlement (mm)	Axial Load (kN)
0.000	0.00
0.136	75.00
0.329	181.07
0.601	331.07
0.986	543.20
1.531	837.74
2.051	1019.06
2.463	1114.78
2.872	1193.95
3.278	1260.57
3.682	1317.41
4.085	1366.44
4.486	1409.15
4.886	1446.66
5.286	1479.87
5.528	1498.21
5.551	1499.94
5.552	1500.00

Row 1 Column 1

Figure 19-2 Tabulated axial load settlement curve results

PileLAT also enables the user to copy or print the axial load settlement curve results on the graph. This can be done by clicking "Copy Graph" or "Print Graph" on the bottom of "Load Deflection Curve for Pile Head" dialog. The copied graph can be easily pasted into the third-party application for reporting purpose. A sample

of the copied and pasted result graph is shown in Figure 19-3 for this example.

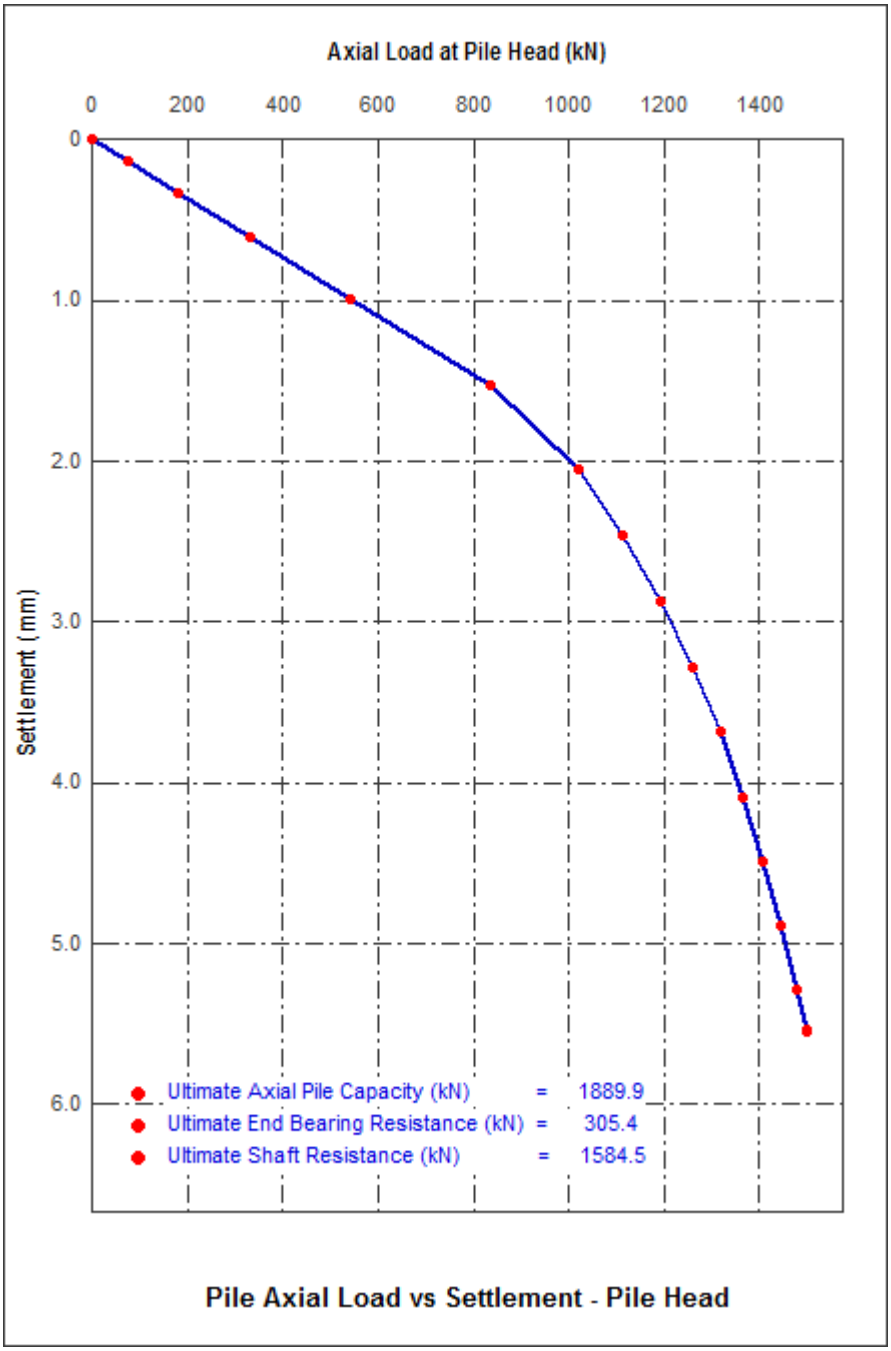


Figure 19-3 Copied axial load pile settlement curve

APPENDICES

Appendix A. P-Y curves for lateral force analysis

A.1 Soft clay (Matlock) model

P-Y curves for soft clay with water based on the method established by Matlock (1970) are shown below for both static and cyclic loading conditions.

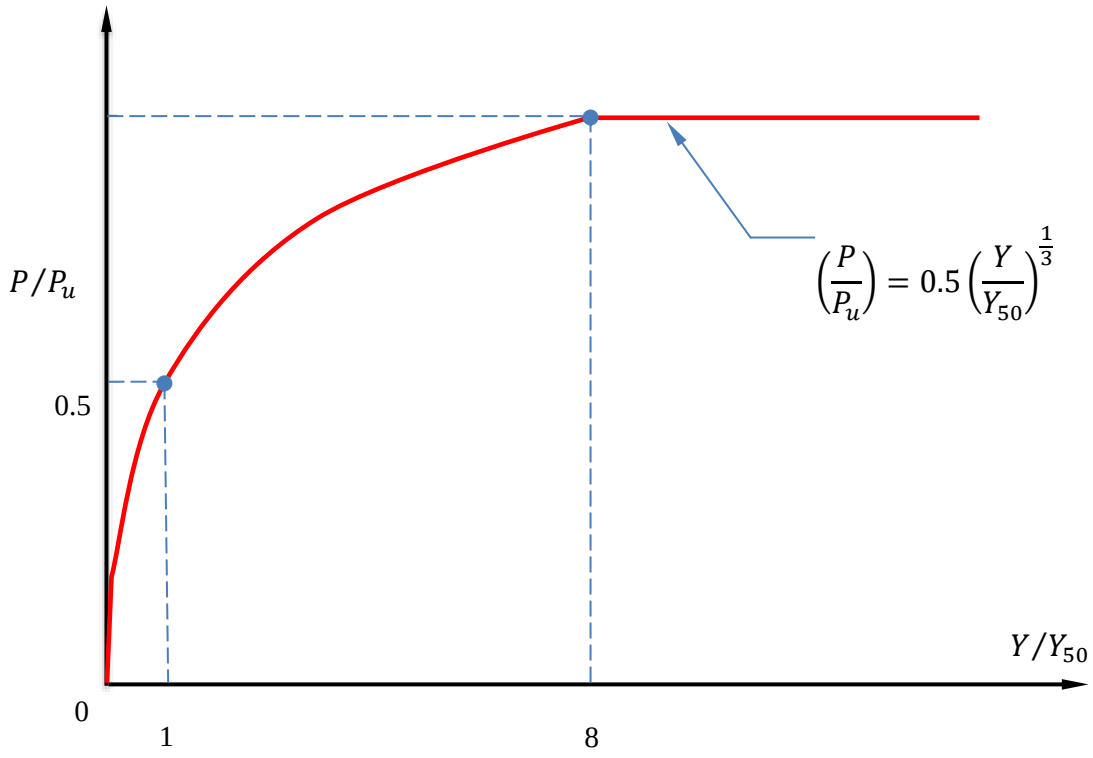


Figure A.1-1 P-Y curve for soft clay (Matlock) model under static loading condition

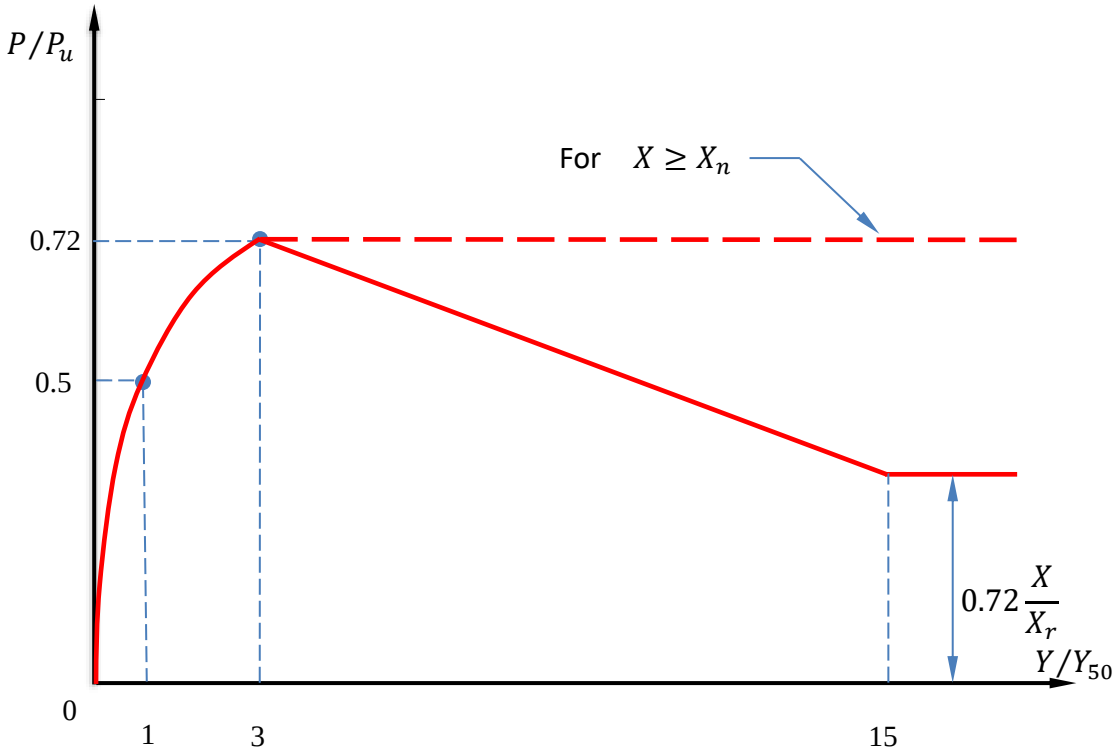


Figure A.1-2 P-Y curve for soft clay (Matlock) model under cyclic loading condition

The ultimate resistance (Pu) of soft clay increases with the depth and the smaller of the values based on the following relationships is adopted:

$$P_u = c_u D\left(3 + \frac{\gamma'}{c_u}X + J\frac{X}{D}\right) \qquad \text{for} \quad X \leq X_R \qquad \text{(A.1-1)}$$

$$P_u = 9c_u D \qquad \text{for} \quad X \geq X_R \qquad \text{(A.1-2)}$$

Where:

P_u = ultimate soil resistance per unit length

c_u = undrained shear strength

σ'_n = vertical effective stress

D = pile diameter

J = dimensionless empirical constant (0.5 for soft clays and 0.25 for medium clay). In PileLAT 2, the default value of 0.25 is adopted.

X = depth below soil surface

X_R = transition depth where both equations produce the same value.

The reference displacement Y_{50} is calculated by the equation below:

$$Y_{50} = 2.5\varepsilon_{50}D \qquad \text{(A.1-3)}$$

where ε_{50} is the strain at one-half the maximum stress for an undrained tri-axial compression test. If no direct laboratory data is available, the following recommended values of ε_{50} are adopted in PileLAT for clays:

Table A.1-1 Recommendation values for Strain Factor of clays

Undrained Shear Strength (kPa)	Strain Factor, ε_{50}
≤ 24	0.02
24 ~ 48	0.01
48 ~ 96	0.007
96 ~ 200	0.005
≥ 200	0.004

The following figure shows the default P-Y parameter input for soft clay (Matlock) model in PileLAT.

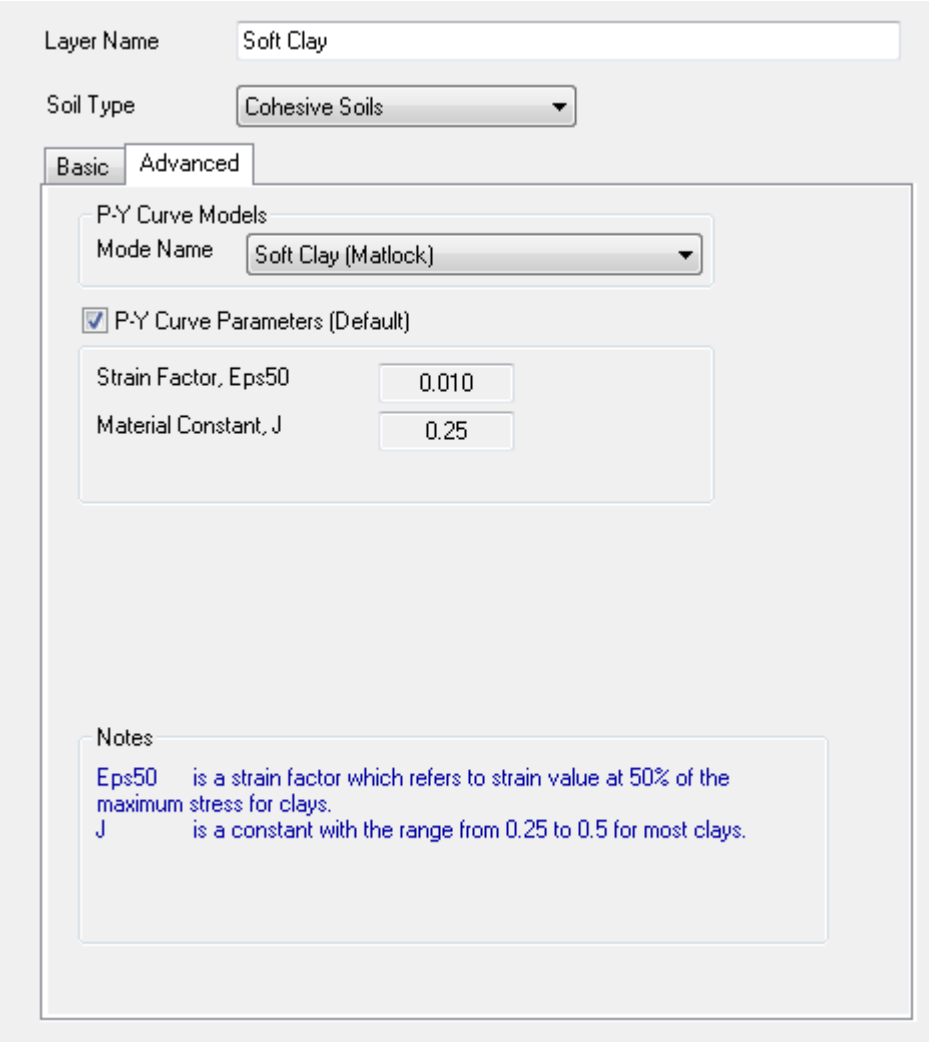


Figure A.1-3 P-Y parameter input dialog for soft clay (Matlock) model in PileLAT

A.2 API Soft clay – (API 2000)

Soft clay also can be modelled by the method recommended in API RP2A 21st Edition (2000), where the ultimate resistance (Pu) of soft clay is determined in the same way as Matlock (1970). The only difference is that the piece-wise curves are used as shown in the figures below for both static and cyclic loading conditions.

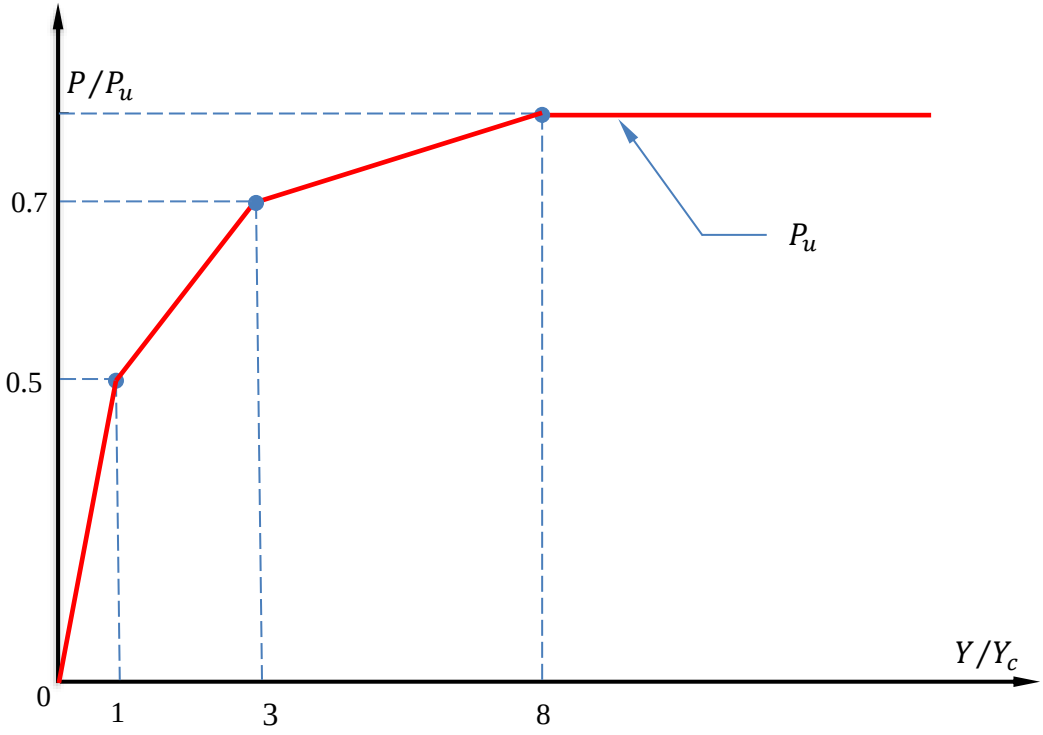


Figure A.2-1 P-Y curve for soft clay (API) model under static loading condition

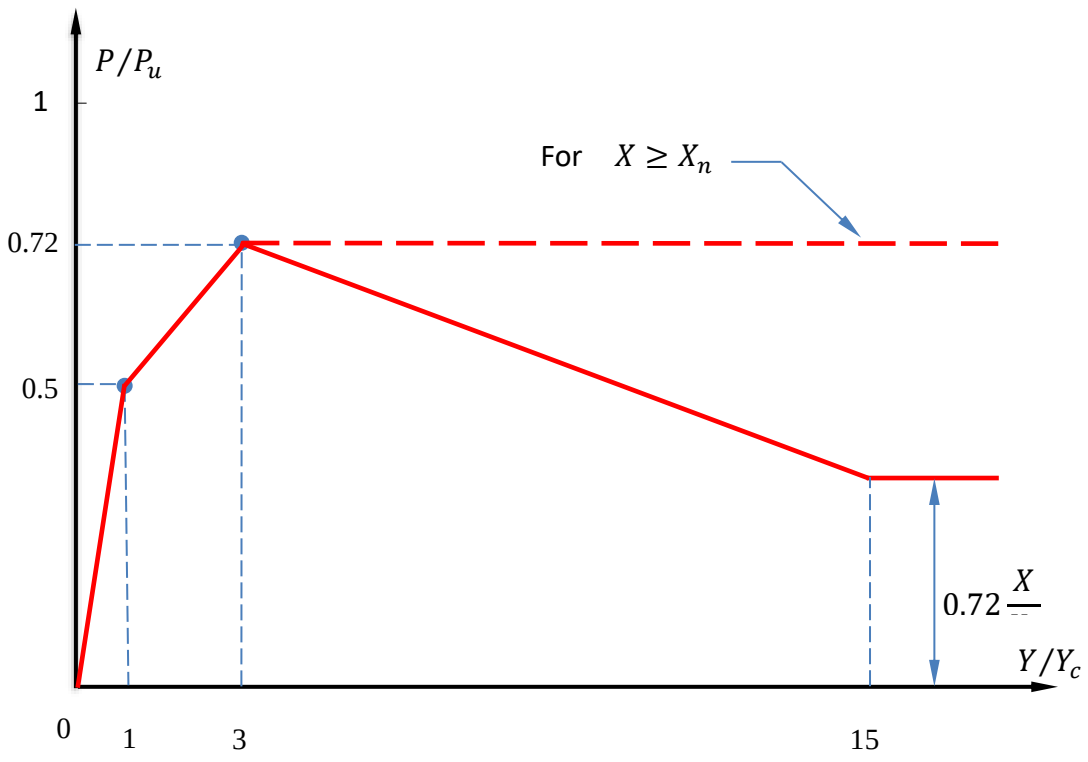


Figure A.2-2 P-Y curve for soft clay (API) model under cyclic loading condition

The reference displacement Y_c is calculated by the equation below:

$$Y_c = 2.5\varepsilon_{50}D \qquad \text{(A-4)}$$

where ε_{50} is the strain at one-half the maximum stress for an undrained tri-axial compression test and is based on the recommendations in Table A.1-1.

The following figure shows the default P-Y parameter input for soft clay (API) model in PileLAT 2.

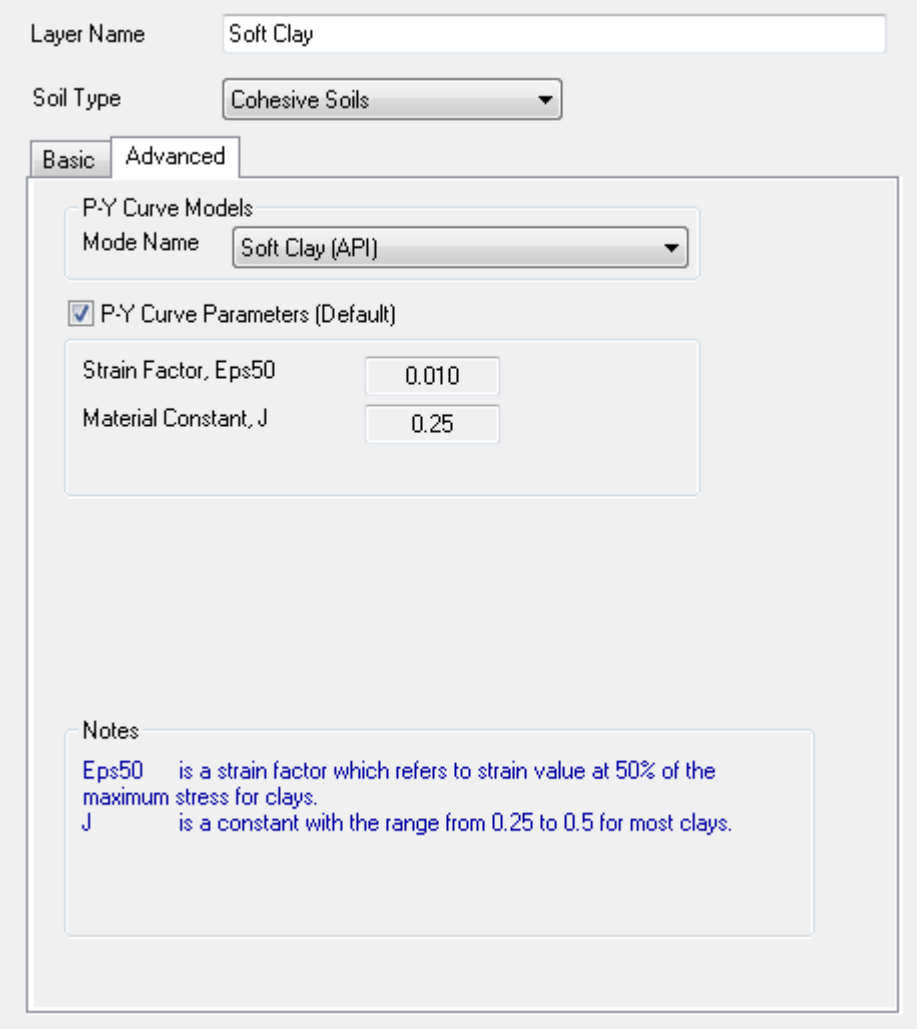


Figure A.2-3 P-Y parameter input dialog for soft clay (API) model in PileLAT

A.3 Stiff Clay without Water - (Welch and Reese 1972)

The following figures show the P-Y curves for stiff clay without water based on Welch and Reese (1972).

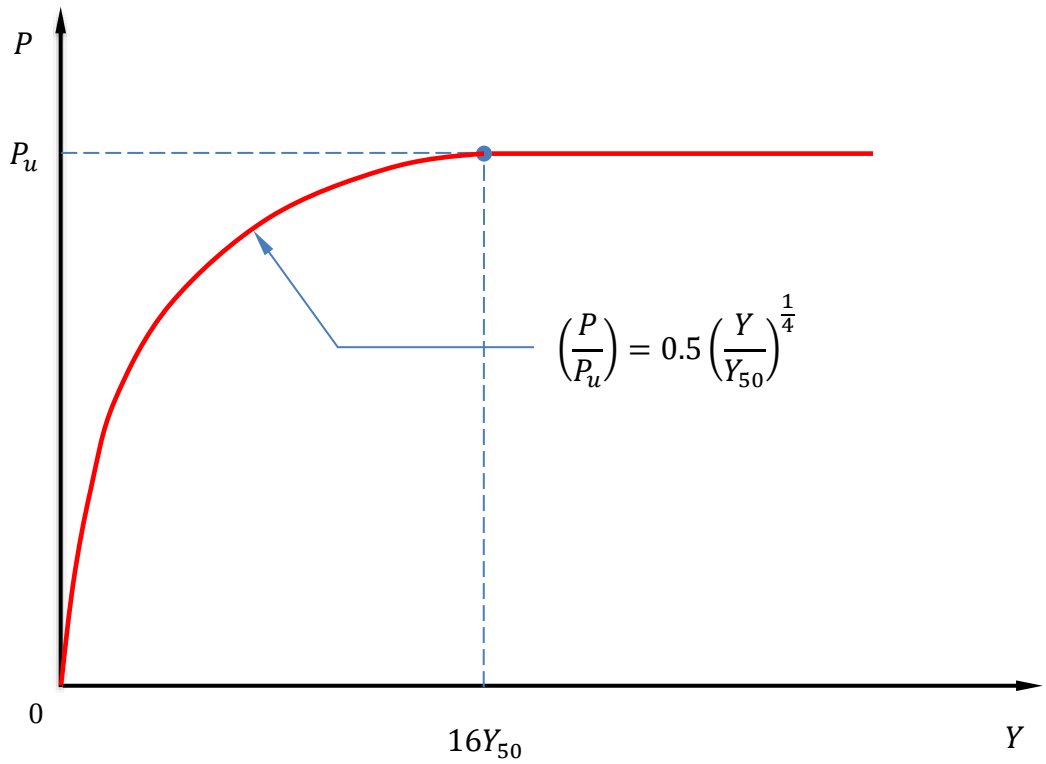


Figure A.3-1 P-Y curve for stiff clay without water model under static loading condition

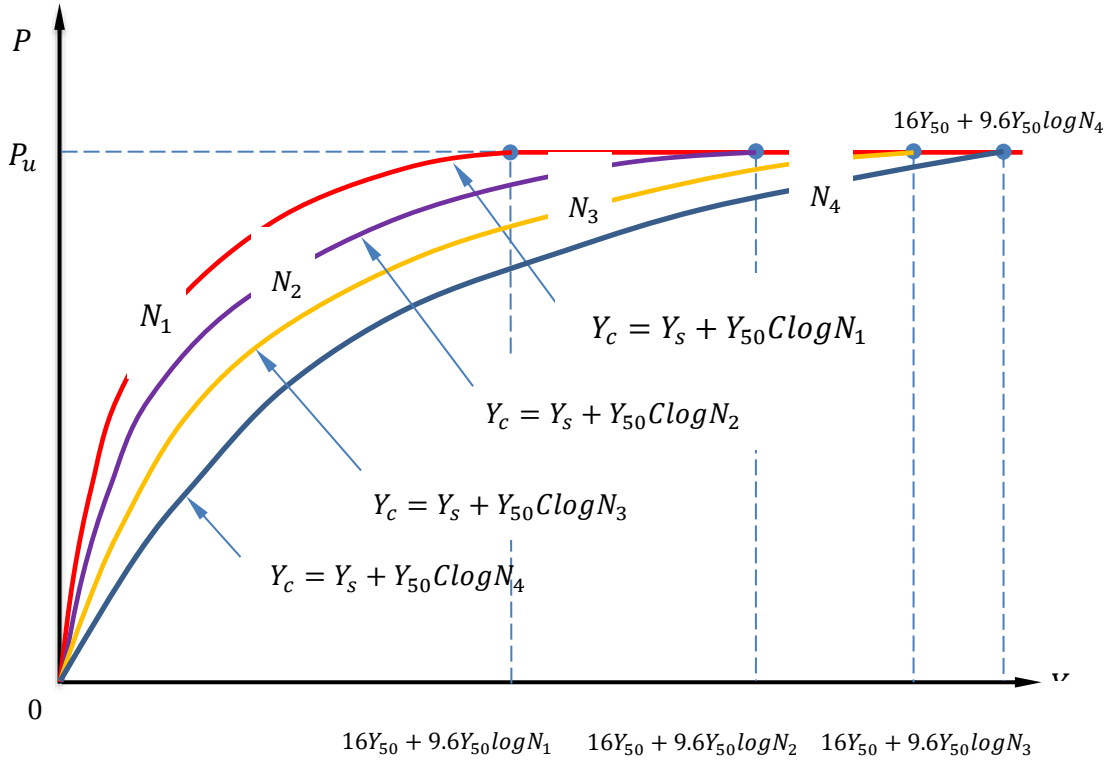


Figure A.3-2 P-Y curve for stiff clay without water model under cyclic loading condition

The ultimate soil resistance per unit length of pile, Pu and the reference displacement Y_{50} is determined by the procedure as described in Appendix A.1.

The following figure shows the default P-Y parameter input for stiff clay without water model in PileLAT.

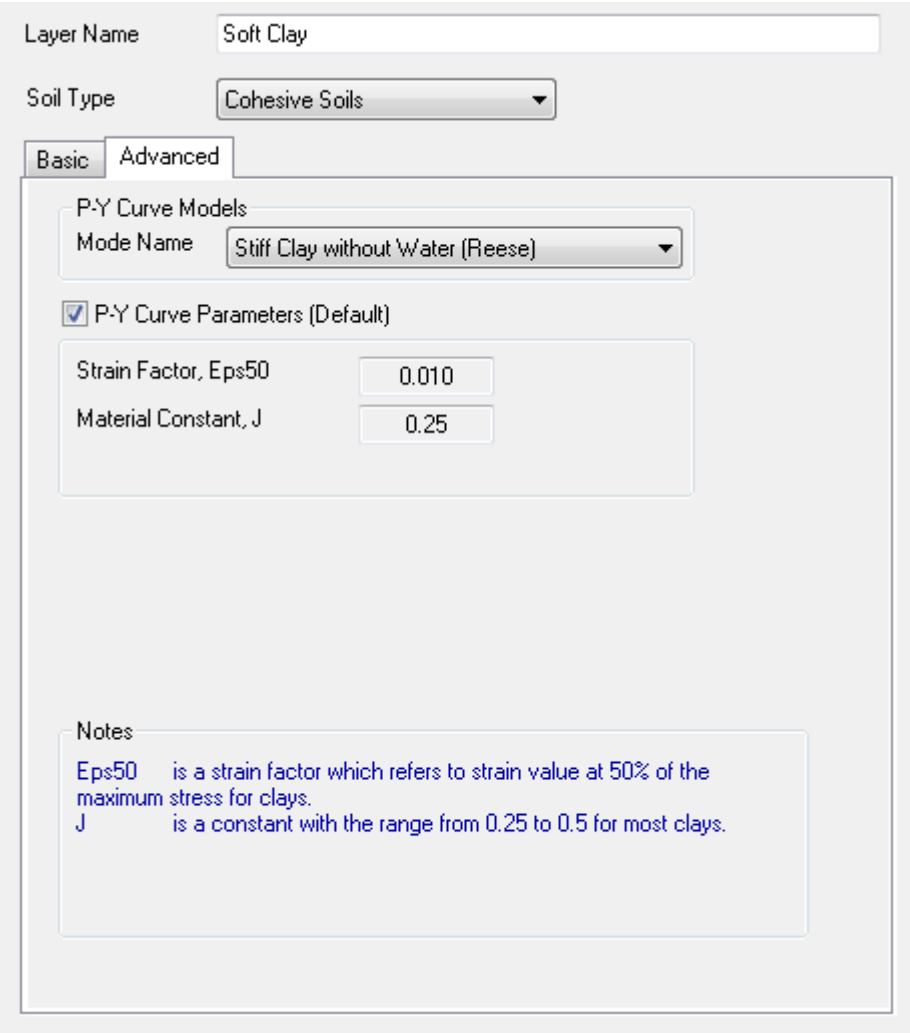


Figure A.3-3 P-Y parameter input dialog for stiff clay without water model in PileLAT

A.4 Stiff Clay without Water with initial subgrade modulus

This model is similar to stiff clay without water based on the method by Welch and Reese (1972) except for that the initial slope follows the recommendations on the model of stiff clay with water by Reese et al. (1975). The initial straight-line portion of the P-Y curve is calculated by multiplying the depth, X by Ks. The values of Ks are determined based on the values of undrained shear strength as follows (Reese and Van Impe, 2001):

Table A.4-1 Recommended on the initial slope of the p-y curve for stiff clay

Ks (MN/m3)	Undrained shear strength (kPa)		
	50 ~ 100	100 ~ 200	300 ~ 400
Static Loading	135	270	540
Cyclic Loading	55	110	217

The following figures show the P-Y curves for the stiff clay with initial modulus based on the recommendation of Brown (2002).

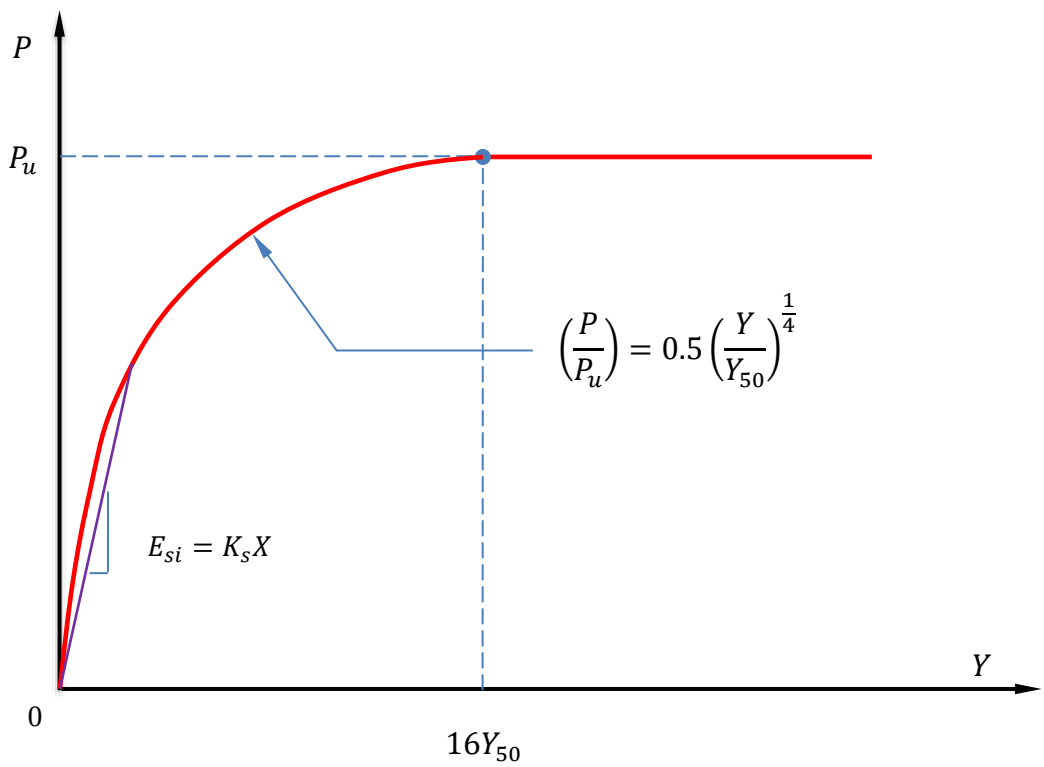


Figure A.4-1 P-Y curve for the stiff clay with initial modulus model under static loading condition

The following figure shows the default P-Y parameter input for the modified stiff clay without water model in PileLAT.

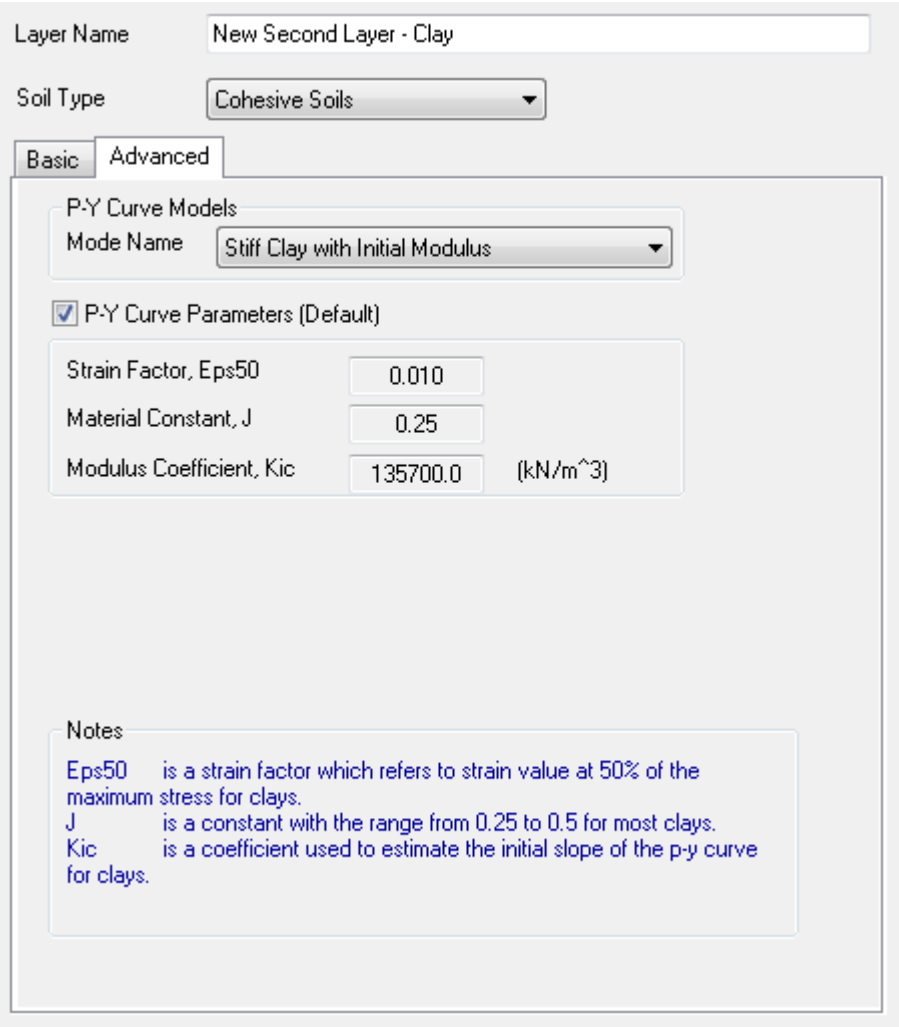


Figure A.4-2 P-Y parameter input dialog for the stiff clay with initial modulus model in PileLAT

A.5 Stiff Clay without Water – Reese et al. (1975)

P-Y curves for stiff clay with water are based on the method established by Reese et al. (1975). The ultimate resistance (Pc) of stiff clay with water is calculated based on the equations as follows:

$$P_{cs} = 2c_a D + \gamma' DX + 2.83 c_a X \quad \text{(A.5-1)}$$

$$P_{cd} = 11 c_u D \quad \text{(A.5-2)}$$

$$P_c = \min(P_{cs}, P_{ct}) \quad \text{(A.5-3)}$$

where:

P_{cs} = ultimate soil resistance per length for stiff clay with water near the ground surface

P_{cd} = ultimate soil resistance per length for stiff clay with water at deep depth

c_a = average undrained shear strength over the calculation depth

c_u = undrained shear strength

γ' = effective soil unit weight

D = pile diameter

X = depth below soil surface

The initial straight-line portion of the P-Y curve is calculated by multiplying the depth, X by Ks. The values of Ks are determined based on the values of undrained shear strength as follows (Reese and Van Impe, 2001) as shown in Table A.4-1.

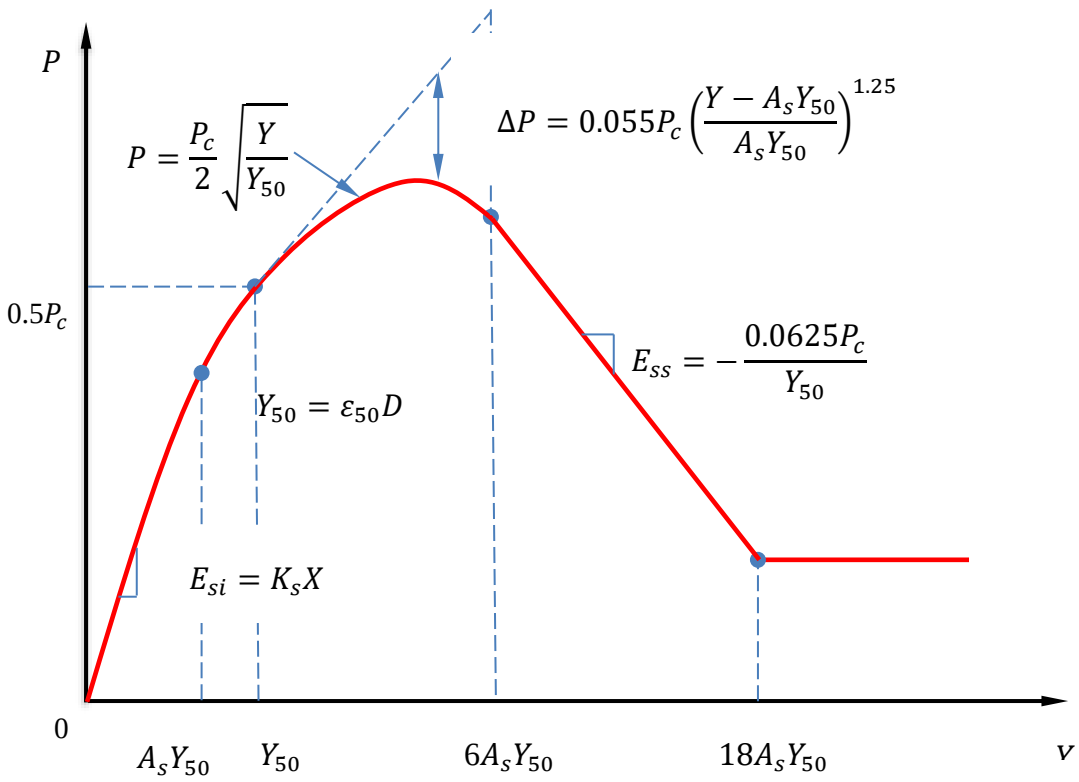


Figure A.5-1 P-Y curve for the stiff clay with water model under static loading condition

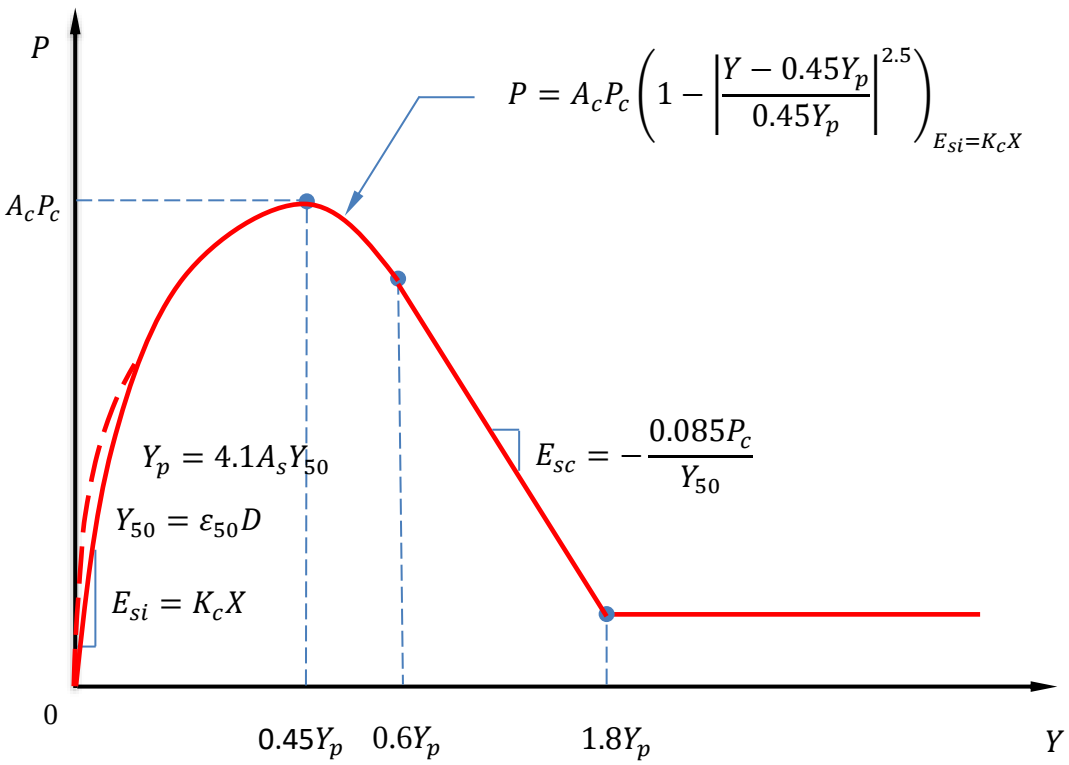


Figure A.5-2 P-Y curve for the stiff clay with water model under cyclic loading condition

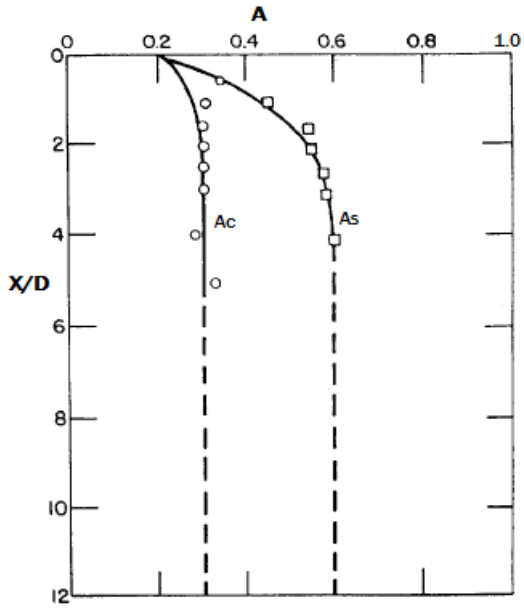


Figure A.5-3 Variation of As and Ac parameters with the depth for the stiff clay with water model

Figures A.5-1 and A.5-2 show the P-Y curves for the stiff clay with water model under both static and cyclic loading conditions. Y_{50} and Y_p are calculated by the following equations:

$$Y_{50} = \varepsilon_{50} D \qquad \text{(A.5-4)}$$

$$Y_p = 4.1 A_s Y_{50} \qquad \text{(A.5-5)}$$

where the strain factor ε_{50} is based on the Table A.1-1. The parameters, As and Ac can be determined from Figure A.5-3.

The following figure shows the default P-Y parameter input for the stiff clay with water model in PileLAT.

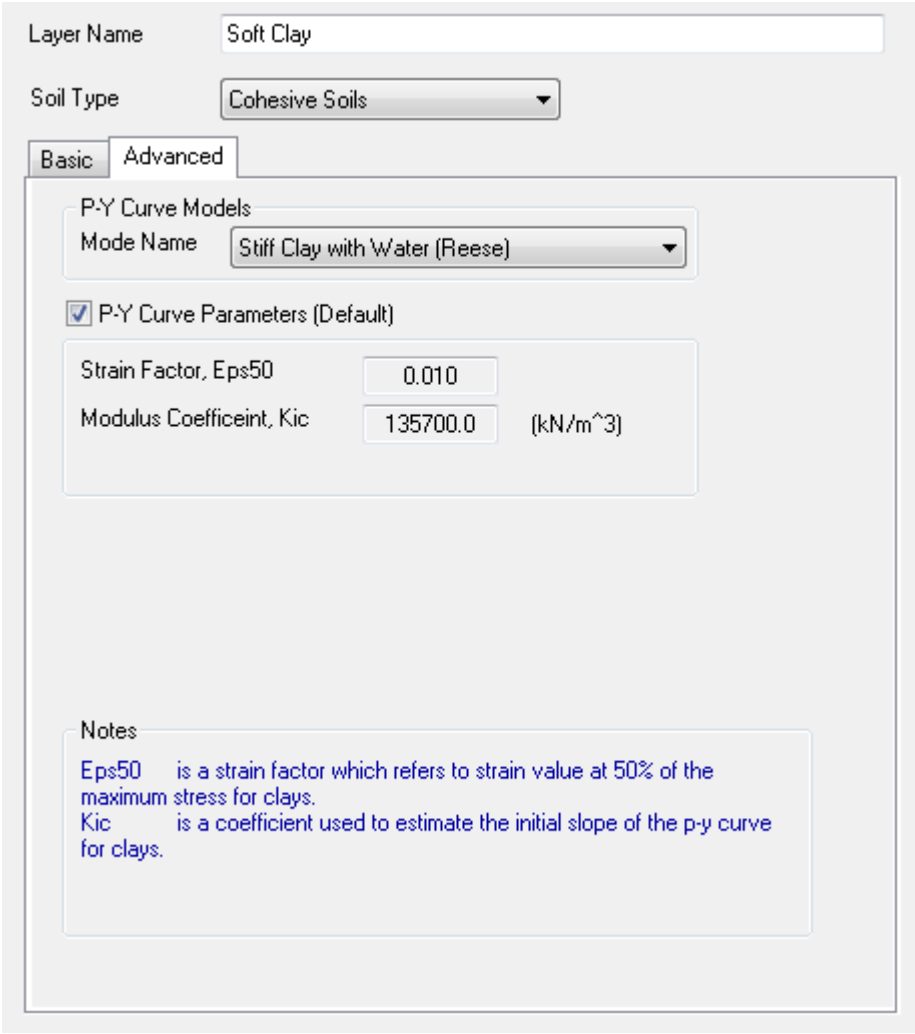


Figure A.5-4 P-Y parameter input dialog for the stiff clay with water model in PileLAT

A.6 API Sand - API (2000)

For API Sand model (API 2000), the ultimate lateral bearing capacity for sand at shallow depth is calculated as:

$$P_{us} = (C_1 X + C_2 D)\gamma' X \qquad \text{(A.6-1)}$$

$$P_{ud} = C_3 D \gamma' X \qquad \text{(A.6-2)}$$

where:

P_{us} = ultimate resistance at the shallow depth;

P_{ud} = ultimate resistance at the deep depth;

γ' = effective soil weight

X = depth

C_1, C_2, C_3 = coefficients determined from Figure A.6-2 of the API RP2A 21st Edition

D = Pile Diameter

P-Y curves for API Sand under both static and cyclic loading conditions are shown in the figure below.

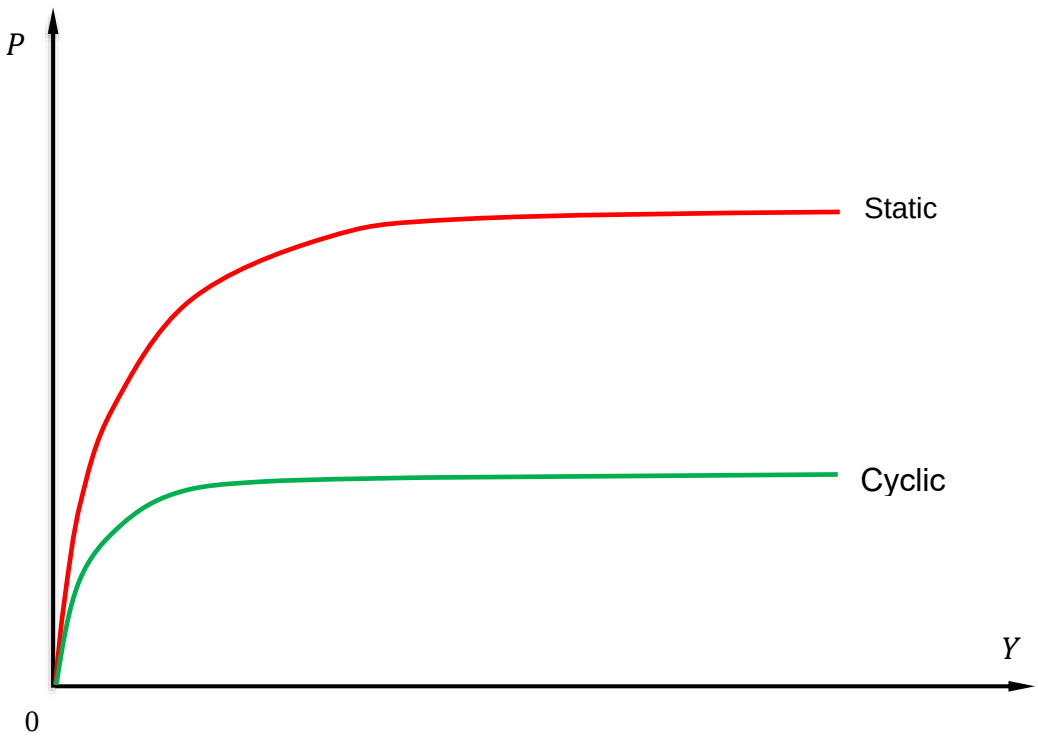


Figure A.6-1 P-Y curve for API Sand model under both static and cyclic loading condition

The lateral soil resistance-deflection (P-Y) relationship is described by:

$$P = AP_u tanh\left[\frac{KD}{AP_u}y\right] \qquad \text{(A.6-3)}$$

where:

P = actual lateral resistance

A = Factor to account for cyclic or static loading conditions (0.9 for cyclic loading, $\max(3.0 - 0.8\mathrm{H}/\mathrm{D}, 0.9)$ for static loading)

K = initial modulus of subgrade reaction determined from Figure 6.8.7-1 of the API RP2A 21st Edition

Y = lateral deflection

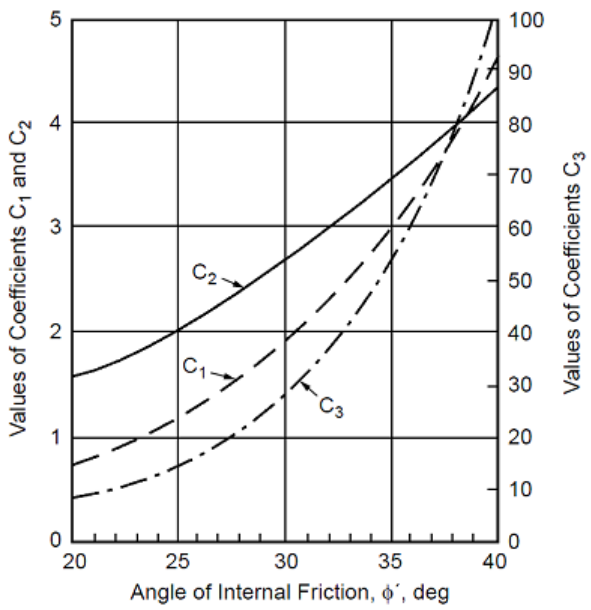


Figure A.6-2 Variation of C1, C2 and C3 with the friction angle for API sand model (after API 2000)

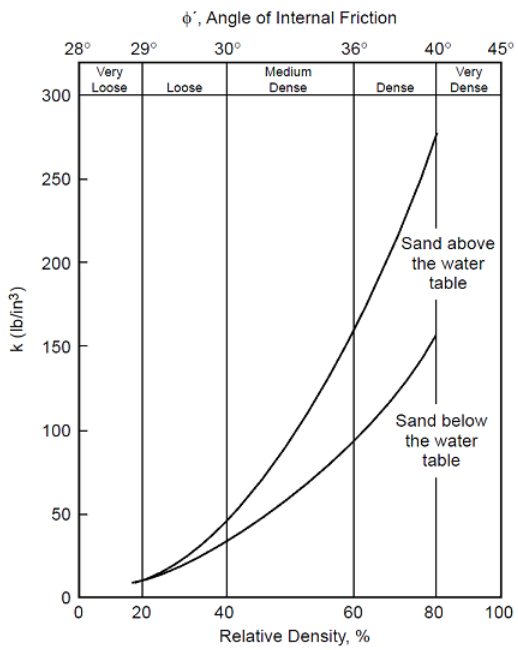


Figure A.6-3 Variation of initial modulus of subgrade with the friction angle for API sand model (after API 2000)

The following figure shows the default P-Y parameter input for API Sand model in PileLAT.

Figure A.6-4 P-Y parameter input dialog for the API Sand in PileLAT

A.7 Reese Sand – Reese et al. (1974)

P-Y curves for sand based on Reese et al. (1974) for both static and cyclic loading conditions are shown in the figure below.

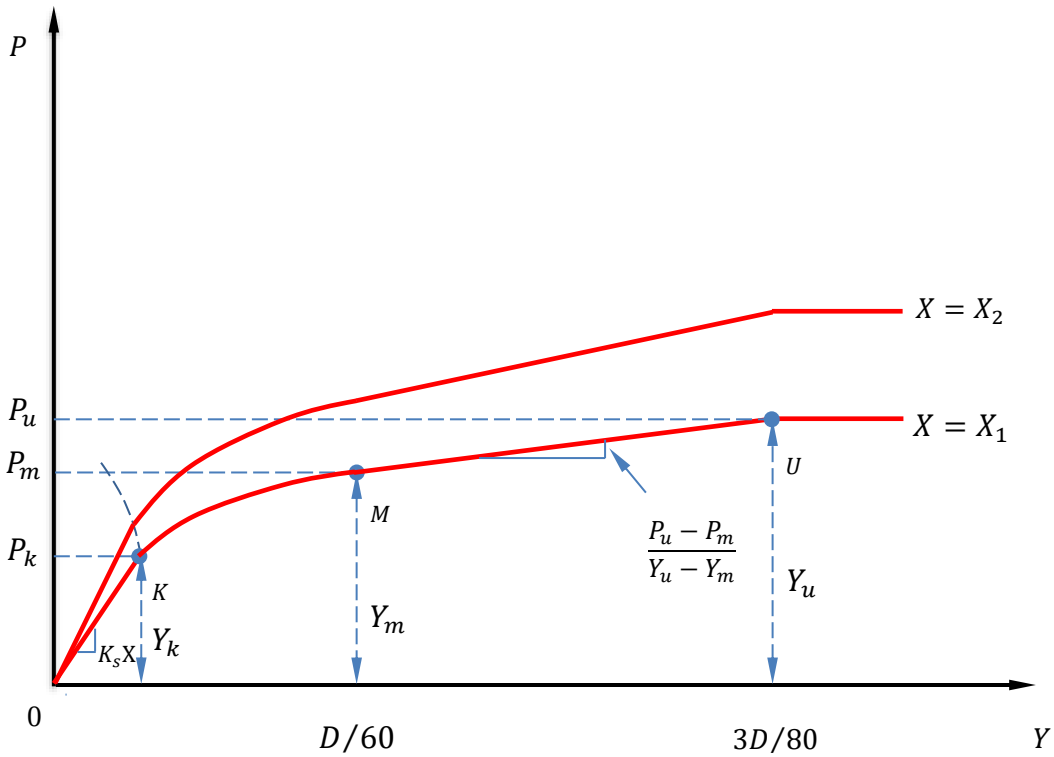


Figure A.7-1 P-Y curve for Reese Sand model under both static and cyclic loading condition

The ultimate resistance of sand varies from a value determined by equation (A.7-1) at shallow depths to a value determined by equation (A.7-2) at deep depths. The depth of transition (X_t) is determined by comparing the value of each equation at the specified depths.

The ultimate resistance of sand at the shallow depths is determined according to:

$$P_{st} = \gamma X \left[\frac{K_0 X \tan\varphi' \sin\beta}{\tan(\beta - \varphi')\cos\alpha} + \frac{\tan\beta}{\tan(\beta - \varphi')}(D + X\tan\beta\tan\alpha) + K_0 \tan\beta\,(\tan\varphi' \sin\beta - \tan\alpha) - K_a D \right] \quad \text{(A.7-1)}$$

and the ultimate resistance of sand at deep depths is determined according to:

$$P_{sd} = \gamma X D \{K_a[(\tan\beta)^8 - 1] + K_0 \tan\varphi' \,(\tan\beta)^4\} \quad \text{(A.7-2)}$$

where:

X = depth below soil surface

K_0 = coefficient of earth pressure at rest

φ' = angle of internal friction of sand

$$\beta = 45^\circ + \frac{\varphi'}{2}$$

$$\alpha = \frac{\varphi'}{2}$$

$$K_a = \left[\tan\left(45^\circ - \frac{\varphi'}{2}\right)\right]^2$$

D = pile diameter

$P_s = \min(P_{st}, P_{sd})$

$P_u = A_s P_s$ or $P_u = A_c P_s$

$P_m = B_s P_s$ or $P_m = B_c P_s$

The empirical parameters As, Ac, Bs and Bc can be determined through the following figures.

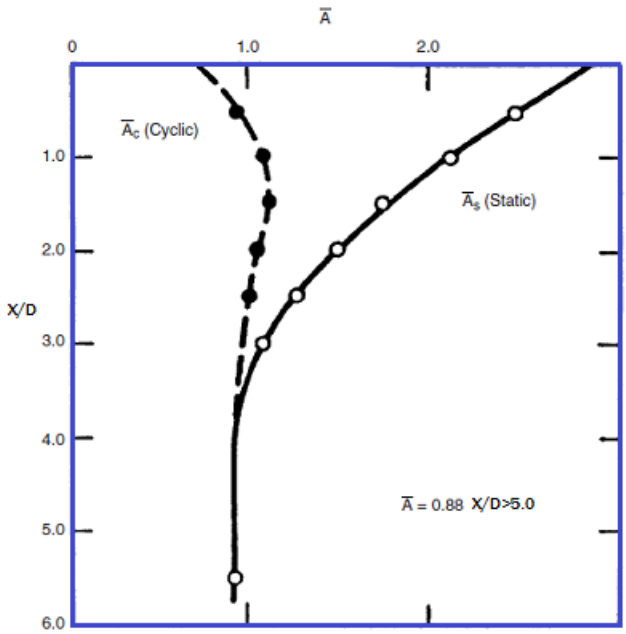


Figure A.7-2 Variation of As and Ac with the depth for Reese sand model (After Reese at al. 1974)

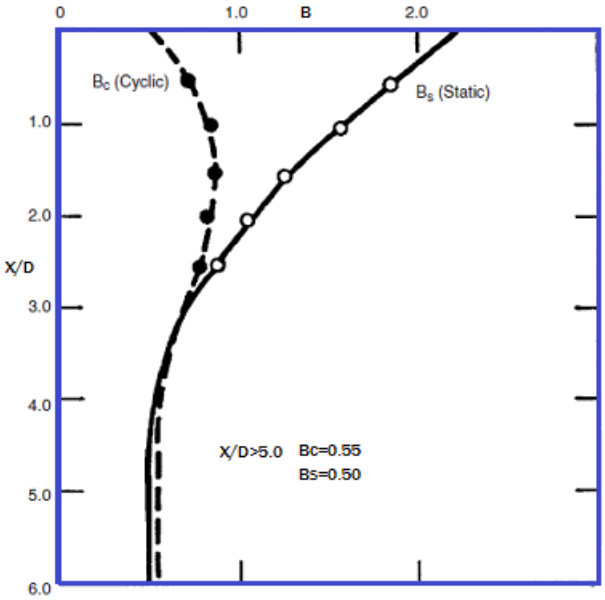


Figure A.7-3 Variation of Bs and Bc with the depth for Reese sand model (After Reese et al. 1974)

The following figure shows the default P-Y parameter input for Reese Sand model in PileLAT.

Figure A.7-4 P-Y parameter input dialog for the Reese Sand in PileLAT

A.8 Liquefied Sand – Rollins et al. (2005)

P-Y curves for liquefied sand is based on the works of Rollins et al. (2005) and is shown in the figure below. No additional advanced soil parameter inputs are required for this soil model. The program will automatically calculate the P-Y response during the analysis.

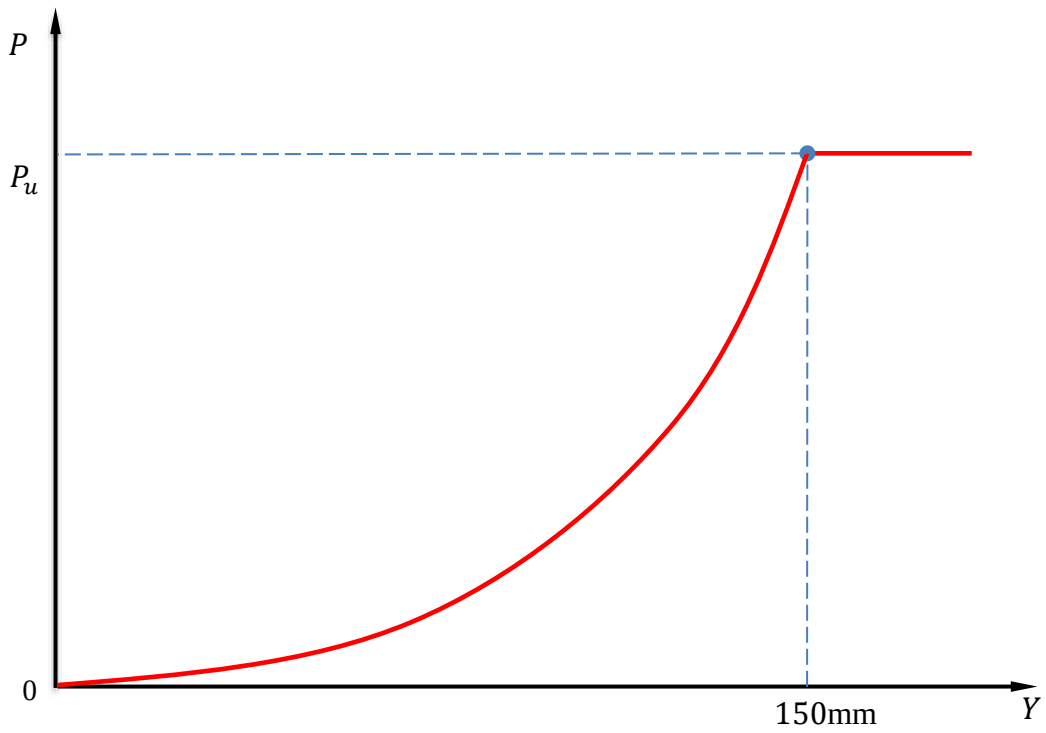


Figure A.8-1 P-Y curve for Liquefied Sand

The following equations are used to produce the curve:

$$P_{0.3m} = A(By)^C \leq 15 \;\; kN/m \qquad \text{(A.8-1)}$$

$$P_d = 3.81 \ln|D| + 5.6 \qquad \text{for 0.3 m < D < 2.6 m} \qquad \text{(A.8-2)}$$

$$P = P_{0.3m} P_d \qquad \text{(A.8-3)}$$

$$A = 3\times10^{-7}(X+1)^{6.05} \qquad \text{(A.8-4)}$$

$$B = 2.80(X+1)^{0.11} \qquad \text{(A.8-5)}$$

$$C = 2.85(X+1)^{-0.41} \qquad \text{(A.8-6)}$$

Note that it could be possible that the maximum value of P is reached when the lateral deflection is less than 150 mm.

A.9 Weak Rock – Reese (1997)

P-Y curves for weak rock are calculated using the method established by Reese (1997) and shown in the figure below.

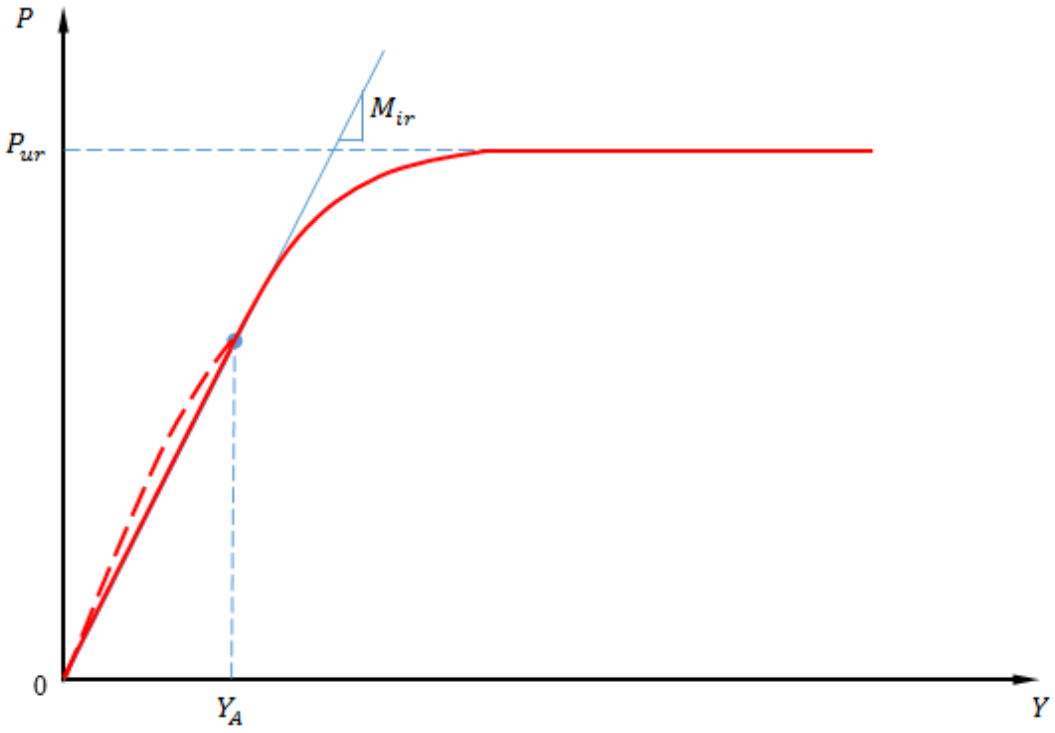


Figure A.9-1 P-Y curve for Weak Rock – Reese (1997)

The ultimate resistance of weak rock is determined according to the following equations:

$$P_{ur} = \alpha_r Q_{ur} D \left(1 + 1.4\frac{X_r}{D}\right) \quad \text{(For } 0 \le X_r \le 3D\text{)} \qquad \text{(A.9-1)}$$

$$P_{ur} = 5.2\alpha_r Q_{ur} D \quad \text{(For } X_r \ge 3D\text{)} \qquad \text{(A.9-2)}$$

where P_{ur} is ultimate soil resistance per unit length; α_r is the strength reduction factor; Q_{ur} is the unconfined compressive strength of rock; D = pile diameter and X_r = depth below rock surface.

The lateral resistance-deflection (P-Y) relationship for weak rock is represented by a three-segment curve. The relationship is described by:

$$P = M_{ir}Y$$

For $Y \leq Y_A$ (A.9-3)

$$P = \frac{P_{ur}}{2}\left(\frac{Y}{Y_m}\right)^{0.25}$$

For $Y \geq Y_A$ and $P \leq P_{ur}$ (A.9-4)

$$P = P_{ur}$$

For $Y \geq 16Y_m$ (A.9-5)

Y_A can be found by solving the following equation:

$$Y_A = \left[\frac{P_{ur}}{2(Y_m)^{0.25}M_{ir}}\right]^{1.333} \quad \text{(A.9-6)}$$

The initial modulus / slope of the P-Y curve, M_{ir}can be determined by:

$$M_{ir} = k_{ir}E_m \quad \text{(A.9-7)}$$

Where E_m is the rock mass modulus and k_{ir} is a dimensionless factor calculated by:

$$k_{ir} = 100 + \frac{400Xr}{3D}$$

(For $0 \leq X_r \leq 3D$) (A.9-8)

$$k_{ir} = 500$$

(For $X_r \geq 3D$) (A.9-9)

The parameter Y_m can be determined by:

$$Y_m = \varepsilon_{rm}D \quad \text{(A.9-10)}$$

where ε_{rm} is a dimensionless constant and normally ranges from 0.0005 to 0.00005 in the analysis.

The required input parameters for Weak Rock (Reese) model are shown in the figure below on the “advanced” page of the soil layer input dialog:

Eps-rm, which is ε_{rm}- dimensionless constant ranging from 0.00005 to 0.0005;

Em, which is rock mass modulus. The default value of Em is determined by the method of

Rowe and Armitage (1984): $E_m = 215\sqrt{\sigma_c}$ (MPa) where σ_c is the unconfined compressive strength of rock;

RQD, which is rock quality designation parameter and varies between 0 and 100%;

Em-inc, which is the rock mass modulus increment rate with the layer depth.

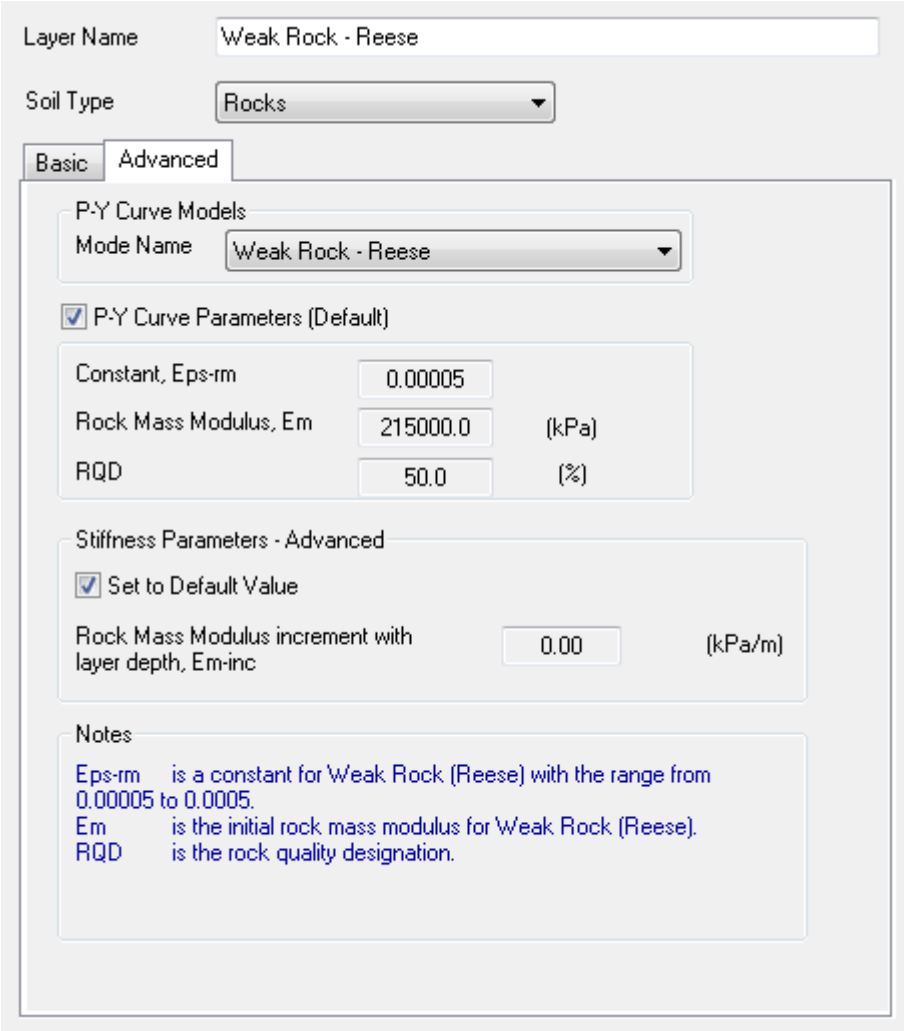


Figure A.9-2 P-Y parameter input dialog for the Weak Rock in PileLAT

A.10 Strong Rock – Tunner (2006)

P-Y curves for strong rock are calculated using the method by Turner (2006) and are shown in the figure below.

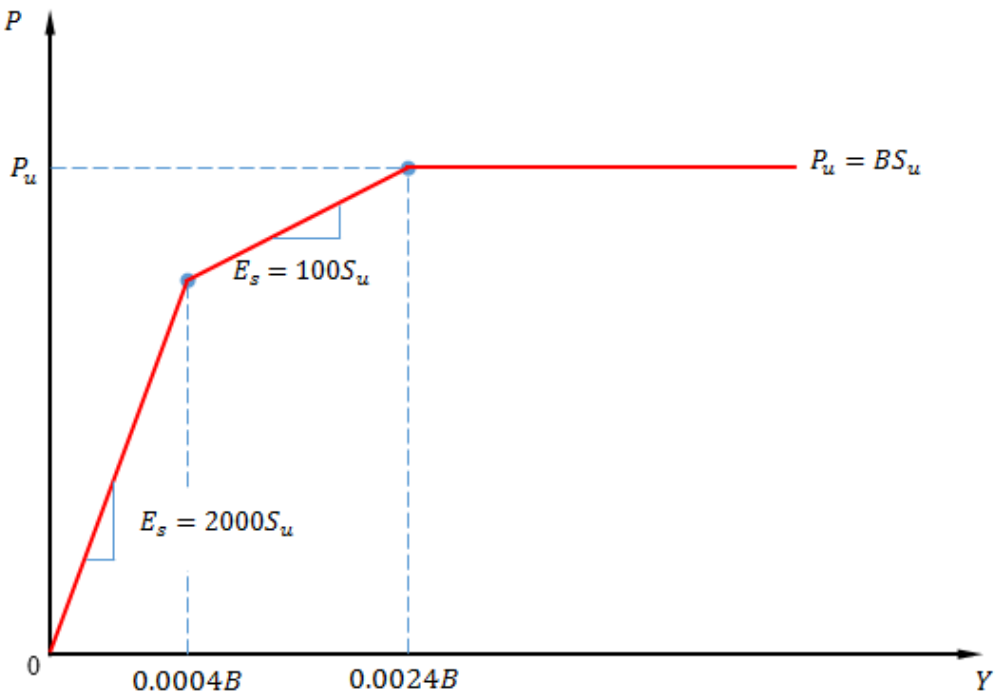


Figure A.10-1 P-Y curve for Strong Rock

The ultimate resistance of strong rock is given by the following equation:

$$P_u = BS_u$$

where B is the pile diameter and $\mathrm{S_u}$ is the half of the unconfined compressive strength of the strong rock.

A.11 Massive Rock – Liang et al. (2009)

P-Y curves for massive rock are calculated using the method by Liang et al. (2009) and are shown in the figure below.

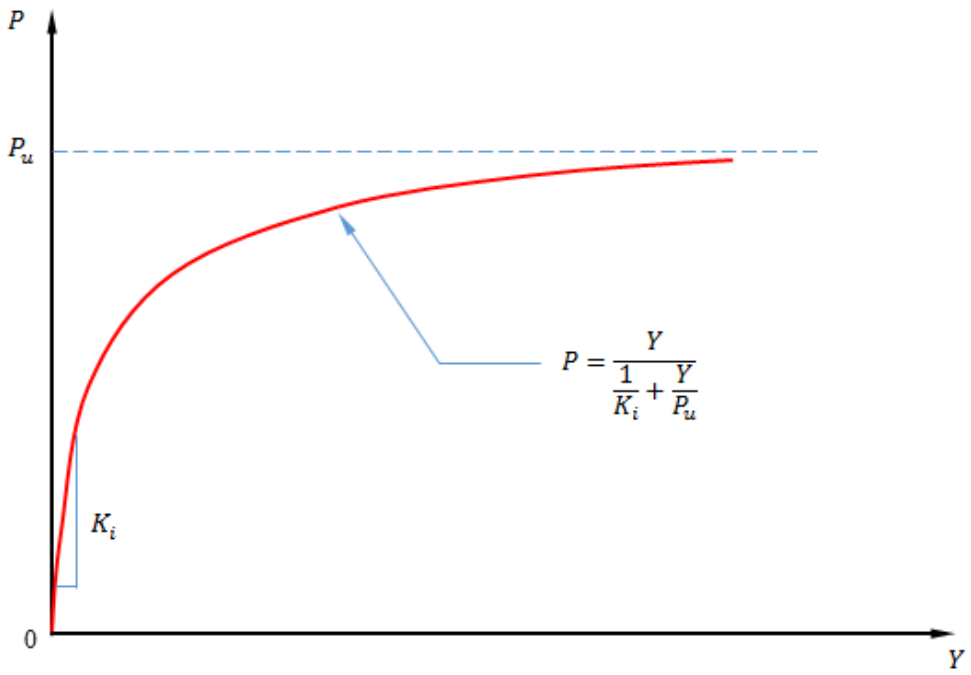


Figure A.11-1 P-Y curve for Massive Rock

The ultimate resistance of massive rock at the shallow depth is given by the following equations:

$$P_{us} = 2C_1 \cos\theta \sin\beta + C_2 \sin\beta - 2C_4 \sin\theta - C_5$$

$$C_1 = H \tan\beta \sec\theta \left(c' + K_o \sigma'_{v0} \tan\emptyset' + \frac{H}{2} K_o \gamma' \tan\emptyset'\right)$$

$$C_2 = C_3 \tan\emptyset' + c'(D \sec\beta + 2H \tan\beta \sec\beta \tan\theta)$$

$$C_3 = \frac{D \tan\beta\,(\sigma'_{vo} + H\gamma') + H(\tan\beta)^2 \tan\theta(2\sigma'_{v0} + H\gamma') + c'(D + 2H \tan\beta \tan\theta) + 2C_1 \cos\beta \cos\theta}{\sin\beta - \tan\emptyset' \cos\beta}$$

$$C_4 = K_0 H \tan\beta \sec\theta \left(\sigma'_{v0} + \frac{\gamma' H}{2}\right)$$

$$C_5 = \gamma' K_a (H - z_0) D$$

$$\beta = 45° + \frac{\emptyset'}{2}$$

$$\theta = \frac{\emptyset'}{2}$$

$$K_a = tan^2\left(45° - \frac{\emptyset'}{2}\right)$$

$$K_0 = 1 - \sin\emptyset'$$

$$z_0 = \frac{2c'}{\gamma'\sqrt{K_a}} - \frac{\sigma'_{v0}}{\gamma'}$$

where c' is the effective cohesion, $\emptyset'$ is the effective friction angle, γ' is the effective unit weight and D is the pile diameter/width.

The ultimate resistance of massive rock at the deep depth is given by the following equations:

$$P_u = \left(\frac{\pi}{4}P_L + \frac{2}{3}\tau_{max} - P_a\right)D$$

$$P_a = K_a\sigma'_v - 2c'\sqrt{K_a}$$

$$\tau_{max} = 0.45\sqrt{\sigma_c}$$

where σ'_v is the effective overburden pressure at the deep depth and σ_c is the unconfined compressive strength of rock mass.The lesser of those ultimate resistance values will be adopted in the analysis.

The initial slope of the P-Y curve, Ki can be determined by the following equation:

$$K_i = E_m\left(\frac{D}{D_{ref}}\right)e^{-2\upsilon}\left(\frac{E_pI_p}{E_mD^4}\right)^{0.284}$$

Where E_m is the rock mass modulus, D is the pile diameter, E_pI_p is the bending stiffness of the pile, D_{ref} is the reference pile diameter which is equal to 0.305 m and υ is Poisson's ratio of the pile.

The effective strength parameters of massive rock, c' and ϕ' are determined using the Hoek-Brown strength criterion as follows in the program:

$$\emptyset' = 90° - \sin^{-1}\left(\frac{2\tau}{\sigma'_1 - \sigma'_3}\right)$$

$$c' = \tau - \sigma_n \tan\emptyset'$$

$$\sigma_n' = \sigma_3' + \frac{(\sigma_1' - \sigma_3')^2}{2(\sigma_1' - \sigma_3') - 0.5 m_b \sigma_c}$$

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_b \frac{\sigma_3'}{\sigma_c} + s \right)^a$$

where m_b, s and a are material constants of rock and determined by the following method in PileLAT 2:

For GSI>25 which represents rock masses of good to reasonable quality

$$m_b = \exp\left(\frac{GSI - 100}{28}\right) m_i$$

$$s = exp\left(\frac{GSI - 100}{9}\right)$$

$$a = 0.5$$

For GSI<25 which represents rock masses of very poor quality

$$m_b = \exp\left(\frac{GSI - 100}{28}\right) m_i$$

$$s = 0$$

$$a = 0.65 - \frac{GSI}{200}$$

The required input parameters for massive rock model in PileLAT are as follows:

Em, which is rock mass modulus. The default value of Em is determined by the method of Rowe and Armitage (1984): $E_m = 215\sqrt{\sigma_c}$ (MPa) where σ_c is the unconfined compressive strength of rock;

Mi, Intact rock constant which depends on the rock type and normally ranges from 4 to 33;

GSI, Geological strength index;

Em-inc, which is the rock mass modulus increment rate with the layer depth.

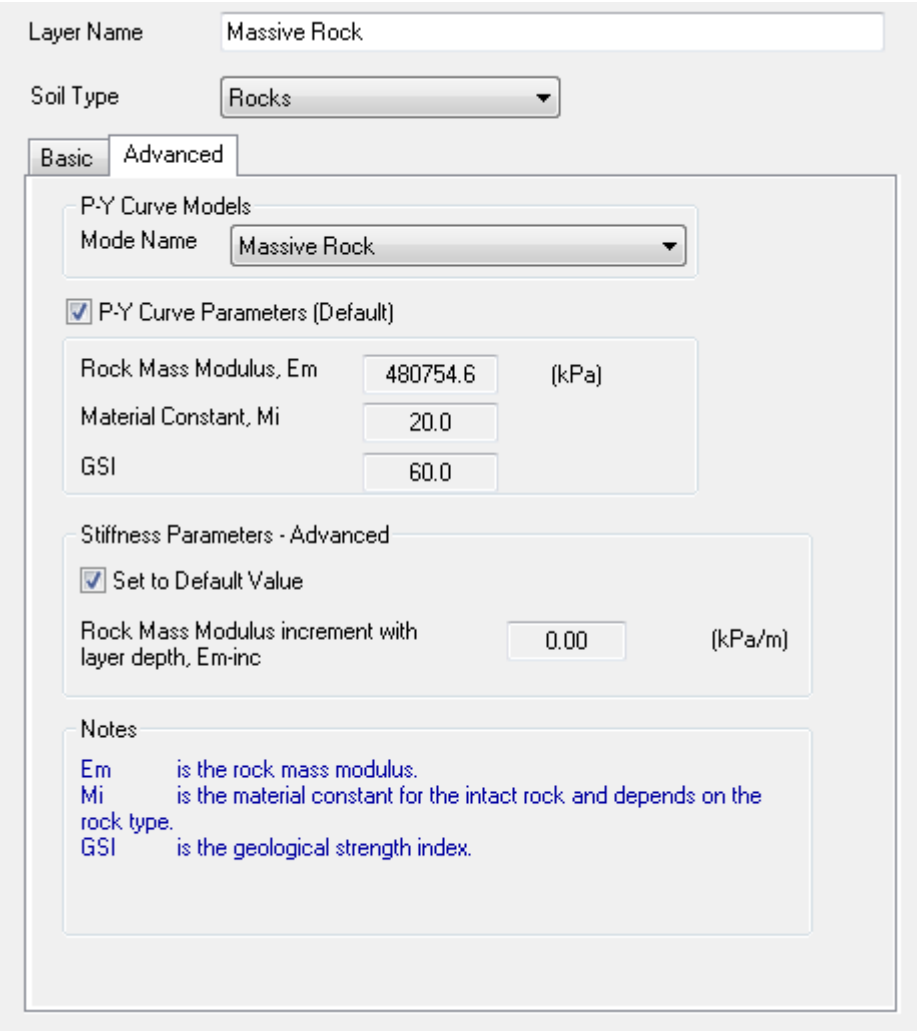


Figure A.11-2 P-Y parameter input dialog for the Massive Rock in PileLAT

A.12 Calcareous Rock – Fragio et al. (1985)

P-Y curves for calcareous are calculated using the method by Fragio et al. (1985) and are shown in the figure below.

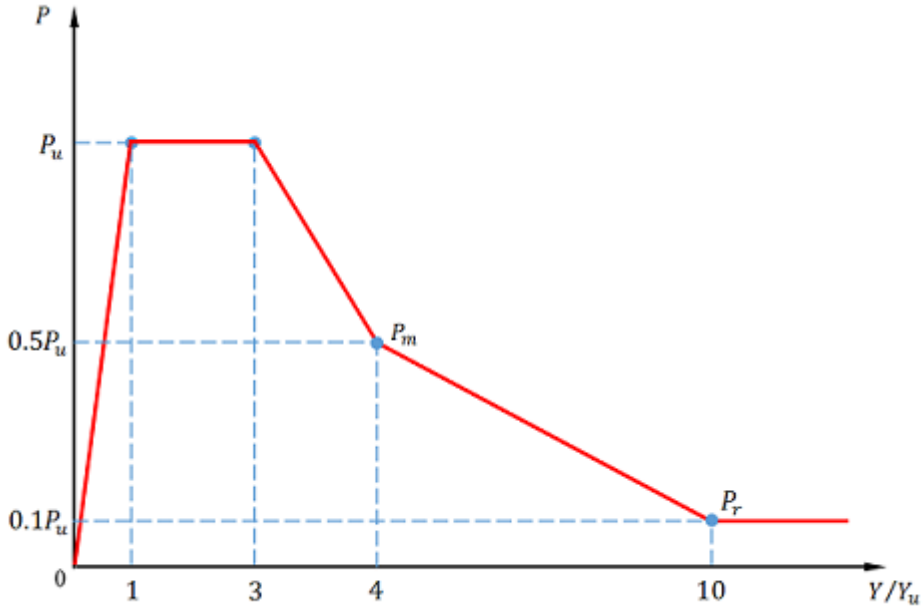


Figure A.12-1 P-Y curve for calcareous rock near the ground surface

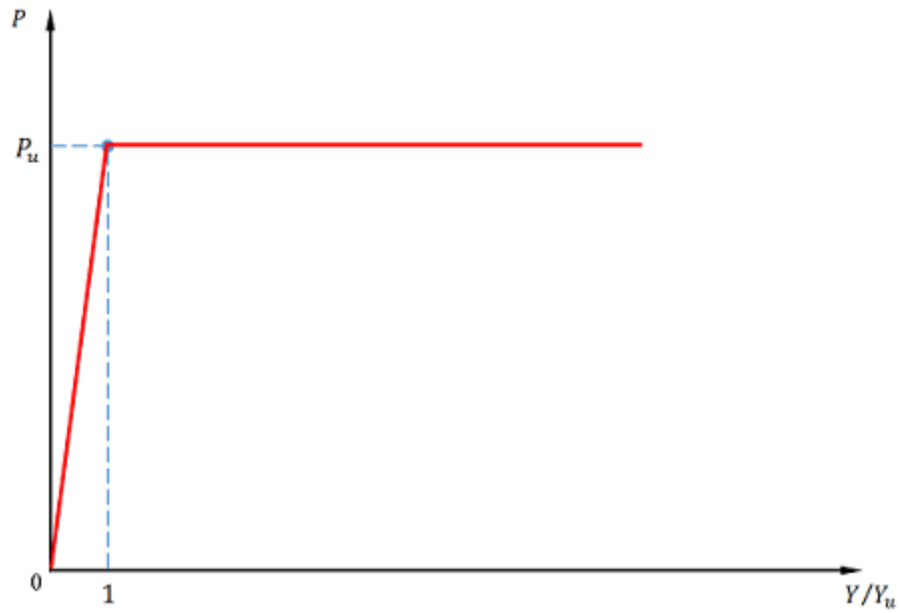


Figure A.12-2 P-Y curve for calcareous rock below the transition depth

Ultimate lateral resistance of calcareous rock, Pu is determined as follows:

Near the ground surface:

$$P_u = 3\sigma_s \qquad \text{(A.12-1)}$$

Below the transition depth:

$$P_u = 9\sigma_s \qquad \text{(A.12-2)}$$

where σ_s is the rock mass strength and is assumed to be 10% of the unconfined compressive strength of rock according to the recommendation of Fragio et al. (1985).

The following figure shows the variation of strength with the depth. The transition depth is assumed to be 6 pile diameter.

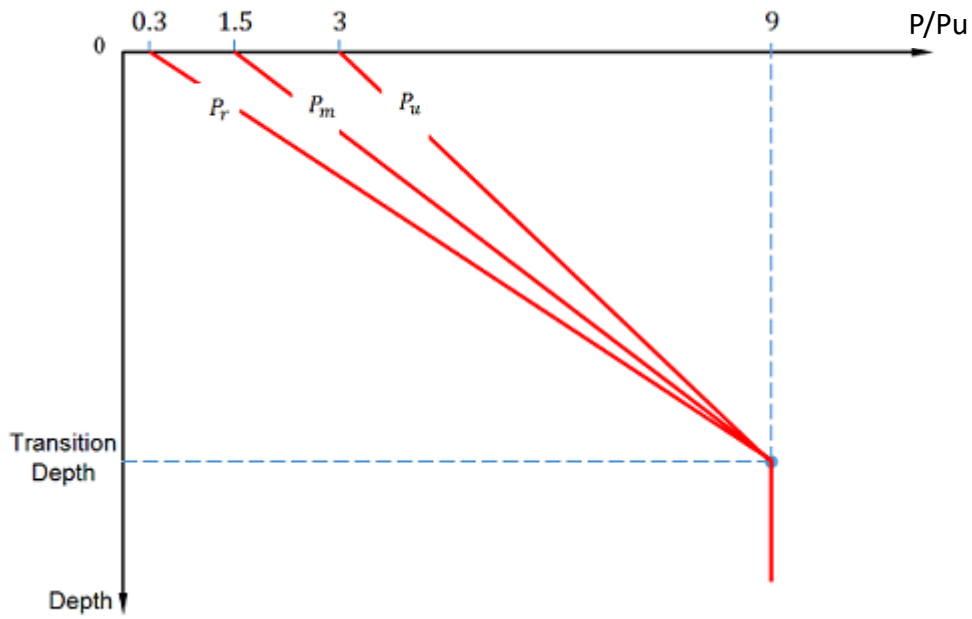


Figure A.12-3 Variation of the lateral resistance with the depth

The reference displacement Yu is determined with the following equation:

$$Y_u = \frac{P_u D}{Ks} \qquad \text{(A.12-3)}$$

$$K_s = \left(\frac{0.65}{D}\right)\left(\frac{E_s D}{E_p I_p}\right)^{1/12}\left(\frac{E_s}{1-\upsilon^2}\right) \qquad \text{(A.12-4)}$$

where D is pile diameter, K_s is soil subgrade modulus, E_s is soil's Young's Modulus, υ is soil's Poisson's ratio and $E_p I_p$ is elastic bending stiffness of pile.

The required input parameters for massive rock model on the advanced page of the layer input in PileLAT 2 are as follows:

Em, which is rock mass modulus. The default value of Em is determined by the method of Rowe and Armitage (1984): $E_m = 215\sqrt{\sigma_c}$ (MPa) where σ_c is the unconfined compressive strength of rock;

Mur, Poisson's Ratio for the rock. The default value is 0.25;

Em-inc, which is the rock mass modulus increment rate with the layer depth.

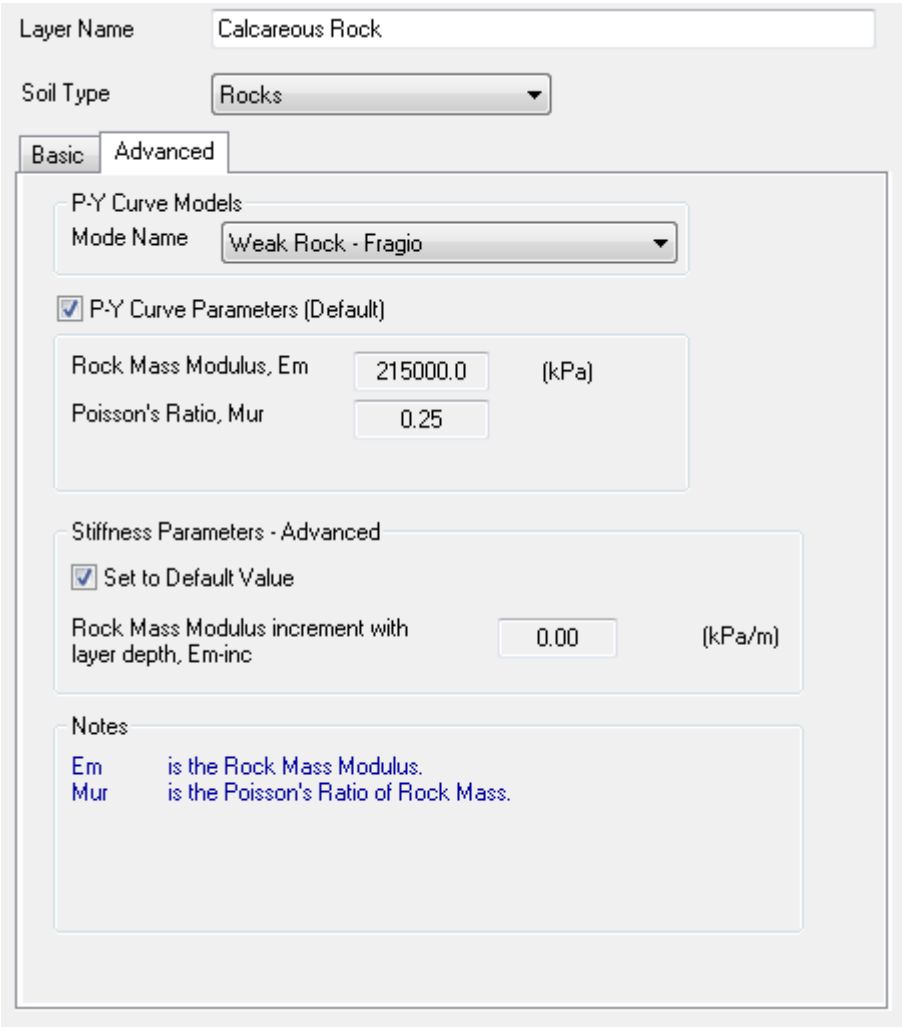


Figure A.12-4 P-Y parameter input dialog for the Weak Rock – Fragio in PileLAT

A.13 Elastic-Plastic Model for soils and rocks

P-Y curve of Elastic-Plastic model for both soils and rocks is shown in the figure below:

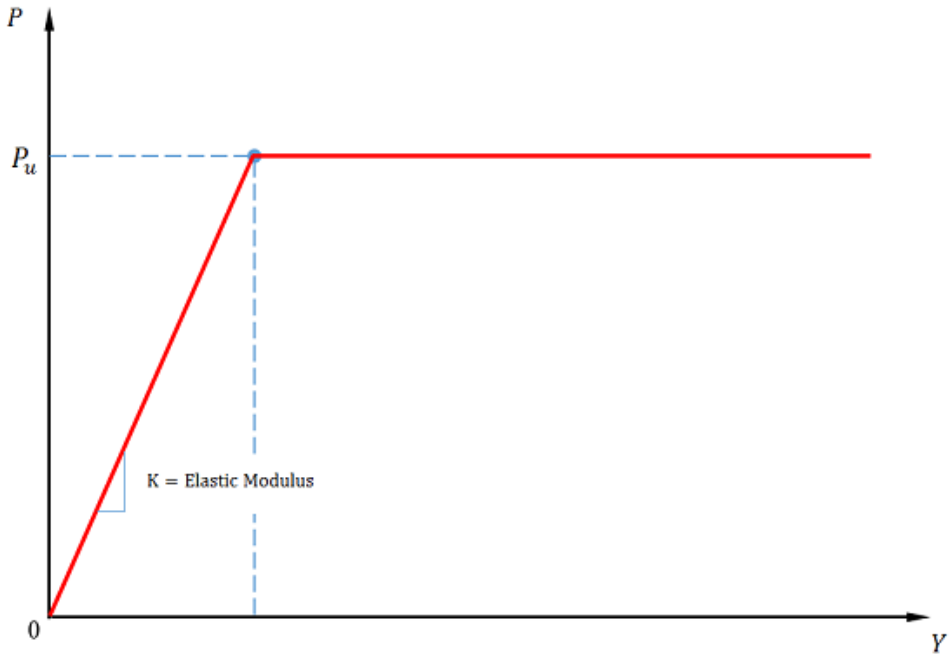


Figure A.13-1 P-Y parameter input dialog for the Elastic-Plastic Model

Ultimate lateral resistance Pu is determined based on the material type as detailed below:

- Cohesive soils - API clay model with the provided undrained shear strength value;
- Granular soils – Reese sand model with the provided effective friction angle value; and
- Rock – Weak rock (Reese) model with the provided unconfined compressive strength value and RQD of 0.

The linear portion of the P-Y curve, K is determined with the following equation:

$$K = \left(\frac{0.65}{D}\right)\left(\frac{E_s D}{E_p I_p}\right)^{1/12}\left(\frac{E_s}{1-\upsilon^2}\right) \qquad \text{(A.13-1)}$$

where D is pile diameter, K is soil subgrade modulus, E_s is soil's Young's Modulus, υ is soil's Poisson's ratio and $E_p I_p$ is elastic bending stiffness of pile.

The required input parameters for Elastic-Plastic model on the advanced page of the soil layer input dialog in PileLAT are as follows:

Es, which is Young's modulus of soils or rocks;

Mur, Poisson's Ratio of soils or rocks. The default value is 0.3;

E-inc, which is the increment of Young's modulus with the layer depth.

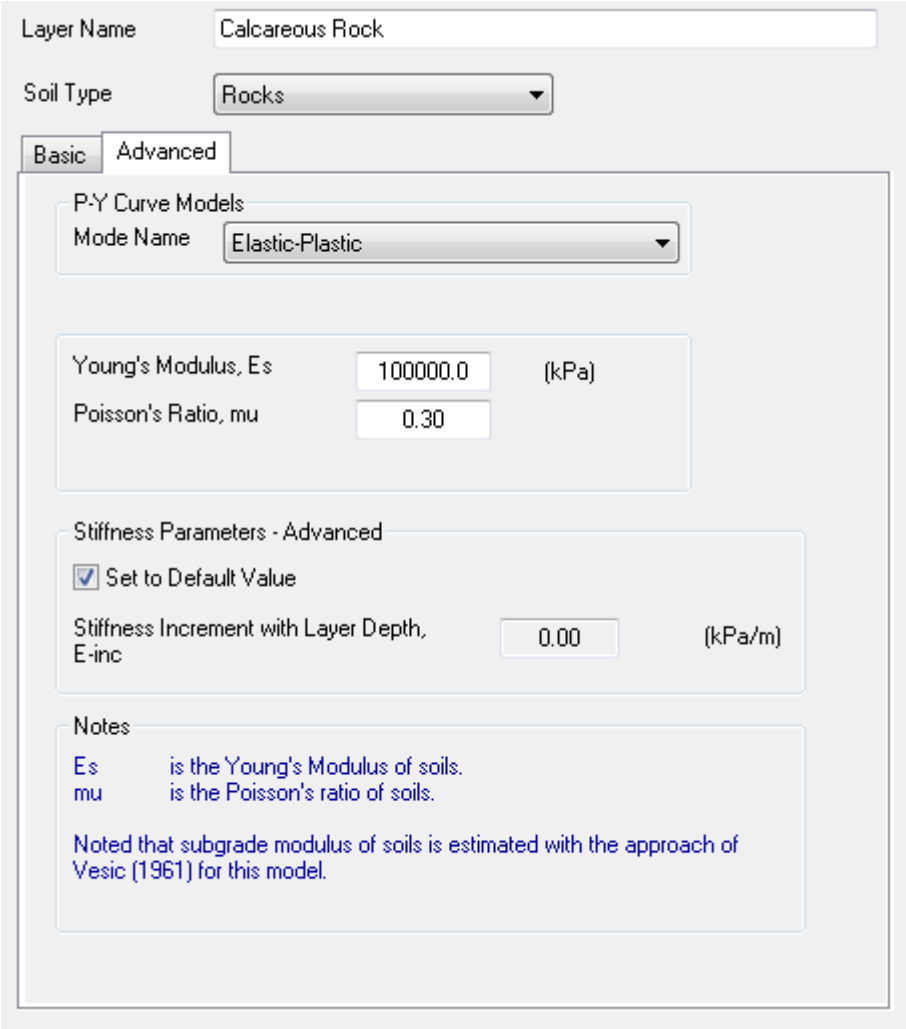


Figure A.13-2 P-Y parameter input dialog for the Elastic-Plastic Model in PileLAT

A.14 Elastic Model for soils and rocks

Elastic model in PileLAT 2 adopts the subgrade modulus to calculate the response of soils/rocks under the lateral deformation.

$$K_h = \frac{P}{y} \qquad \text{(A.14-1)}$$

where K_h is the subgrade modulus with the unit of kN/m/m, P is the force per length along the pile with the unit of kN/m and y is the lateral displacement with the unit of m.

Note that K_h is different from the coefficient of subgrade modulus, k_h which has the unit of kN/m^3. The relationship between the subgrade modulus K_h and the coefficient of subgrade modulus k_h can be expressed by the following equation:

$$K_h = k_h D \qquad \text{(A.14-2)}$$

where D is the pile diameter/width.

The required input parameters for Elastic Model on the advanced page of the soil layer input dialog in PileLAT 2 are as follows:

Kh, which is the subgrade modulus;

Kh-inc, which is the increment of the subgrade modulus with the layer depth.

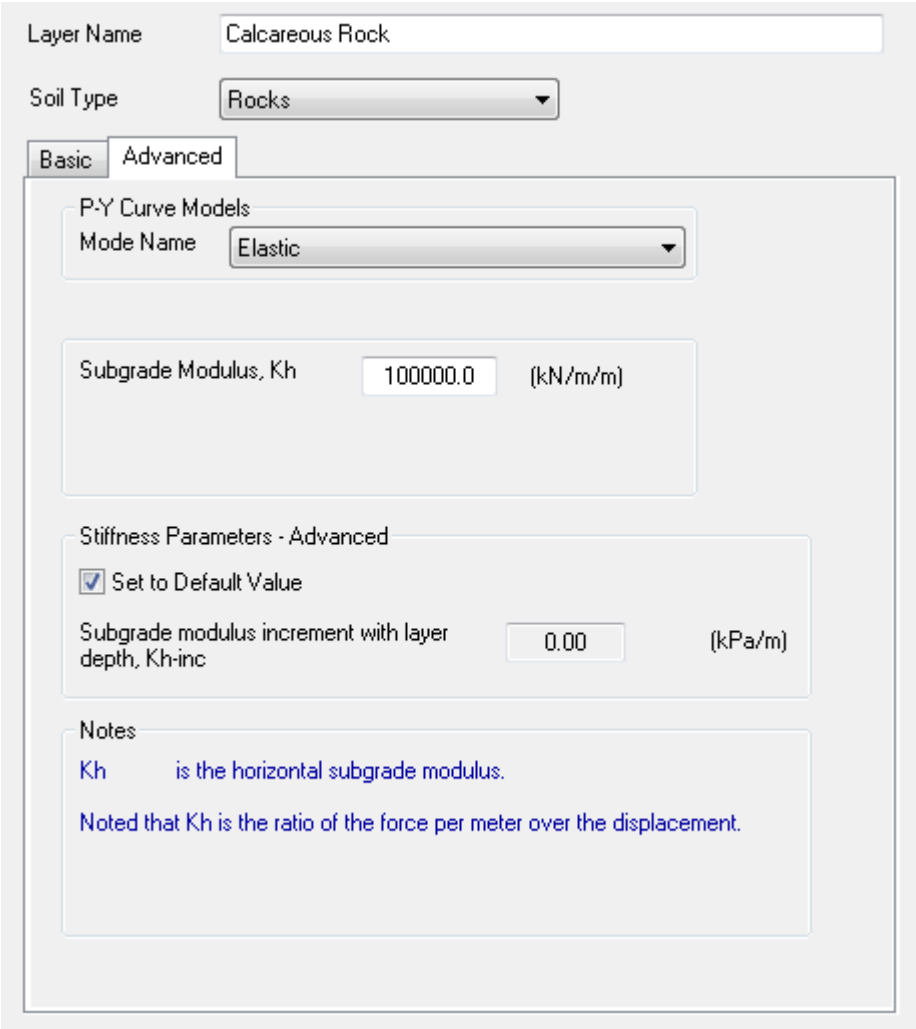


Figure A.14-1 P-Y parameter input dialog for the Elastic Model in PileLAT

Appendix B. t-z and q-w curves for pile settlement analysis

Appendix B.1 Cohesive Soils

B.1.1 Driven Piles

For the cohesive soils, the following equations as recommended in API (2000) are adopted to calculate the ultimate shaft resistance, f_s and ultimate end bearing resistance, f_b:

$$f_s = \alpha c_u$$

$$\alpha = 0.5\psi^{-0.5} \text{ where } \psi \leq 1.0$$

$$\alpha = 0.5\psi^{-0.25} \text{ where } \psi \geq 1.0$$

$$\psi = c_u / p_o'$$

$$f_b = 9c_u$$

c_u is undrained shear strength and p_o' is effective overburden pressure at the point in question. The following t-z and q-w curves is adopted in PileLAT for the cohesive soils of driven piles.

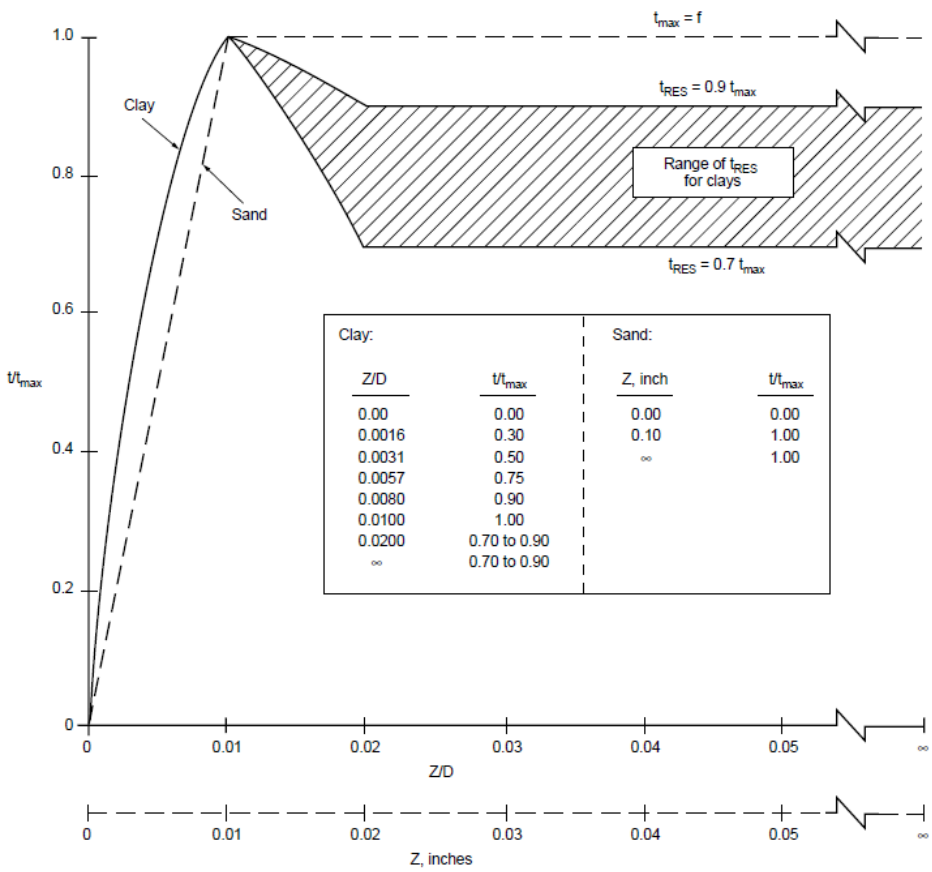


Figure B.1-1 t-z curve adopted for the cohesive soils – driven piles (after API 2000)

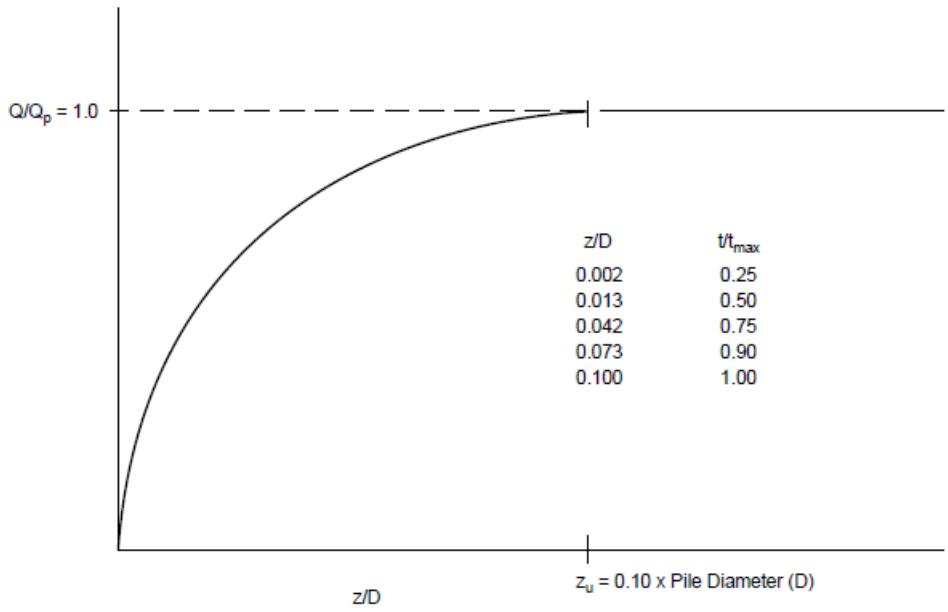


Figure B.1-2 q-w curve adopted for the cohesive soils – driven piles (after API 2000)

B.1.2 Bored Piles

For the cohesive soils, the following equations as recommended in FHWA manual (O'Neill and Reese 1999) are adopted to calculate the ultimate shaft resistance, f_s and ultimate end bearing resistance, f_b:

$$f_s = \alpha c_u$$

$$\alpha = 0.55 \text{ for } c_u/p_a \leq 1.5$$

$$\alpha = 0.55 - 0.1(c_u/p_a - 1.5) \text{ for } 1.5 \leq c_u/p_a \leq 2.5$$

where c_u is undrained shear strength and p_a is the atmospheric pressure.

$$f_b = N_c c_u$$

$$N_c = 6.0\left(1 + 0.2\left(\frac{L}{D}\right)\right)$$

Noted that f_b cannot be greater than 3800 kPa for bored piles within the cohesive soils according to O'Neill and Reese (1999) and N_c cannot be greater than 9.0. The following t-z and q-w curves is adopted in PileLAT for the cohesive soils of bored piles.

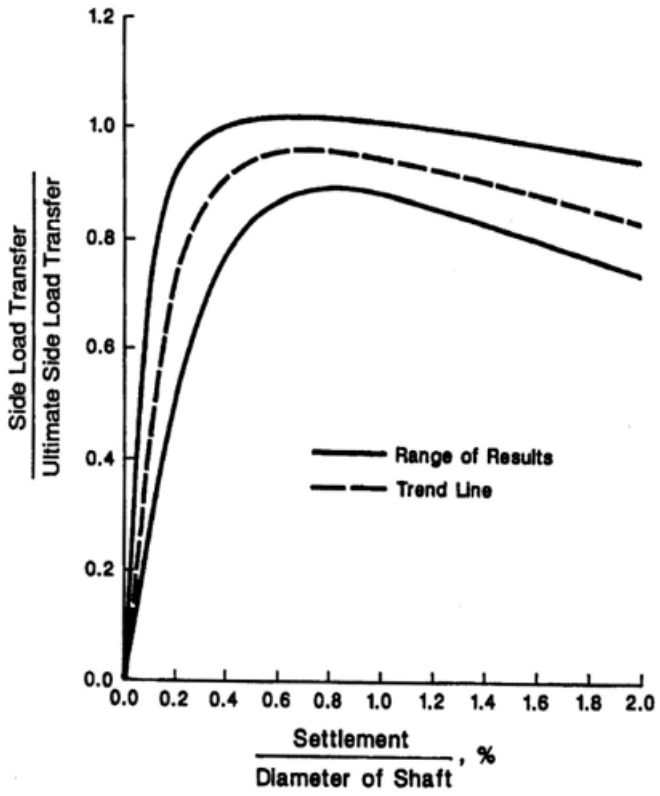


Figure B.1-3 t-z curve adopted for the cohesive soils – bored piles (O'Neill and Reese 1999)

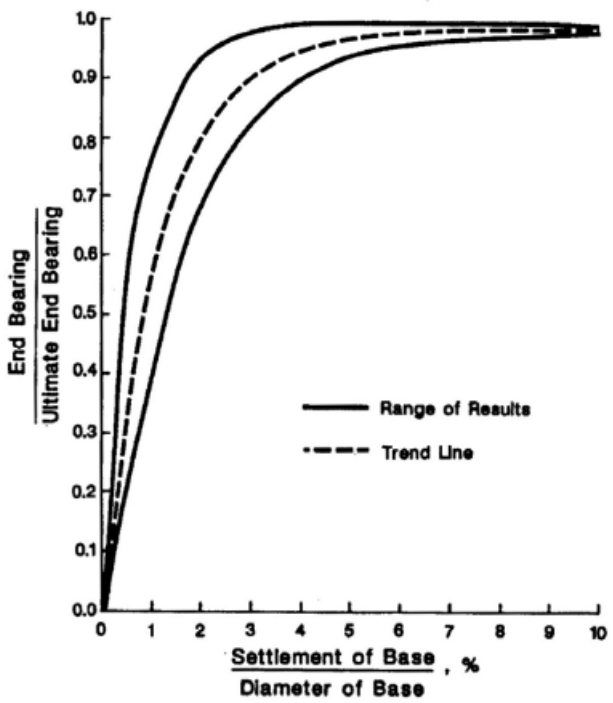


Figure B.1-4 q-w curve adopted for the cohesive soils – bored piles (O'Neill and Reese 1999)

Appendix B.2 Granular Soils

B.2.1 Driven Piles

For the granular soils, the following equations as recommended in API (2000) are adopted to calculate the ultimate shaft resistance, f_s and ultimate end bearing resistance, f_b:

$$f_s = Kp_o \tan\delta$$

$$f_b = N_q p_o$$

where K is the coefficient of lateral pressure and usually assumed to be 0.8 for open-ended pipe pile with unplugged toe or 1.0 for plugged or close end pipes, δ is the friction angle between the soil and pile, N_q is the bearing capacity factor and p_o is the effective overburden pressure.

The following table is adopted in PileLAT 2 for the values of interface friction angle, δ and bearing capacity factor, N_q.

Table B.2-1 Design parameters for cohesionless soils (after API 2000)

Density	Soil Description	Soil-Pile Friction Angle, δ Degrees	Limiting Skin Friction Values kips/ft^2 (kPa)	N_q	Limiting Unit End Bearing Values kips/ft^2 (MPa)
Very Loose	Sand	15	1.0 (47.8)	8	40 (1.9)
Loose	Sand-Silt**				
Medium	Silt				
Loose	Sand	20	1.4 (67.0)	12	60 (2.9)
Medium	Sand-Silt**				
Dense	Silt				
Medium	Sand	25	1.7 (81.3)	20	100 (4.8)
Dense	Sand-Silt**				
Dense	Sand	30	2.0 (95.7)	40	200 (9.6)
Very Dense	Sand-Silt**				
Dense	Gravel	35	2.4 (114.8)	50	250 (12.0)
Very Dense	Sand				

The t-z and q-w curves shown in Figure B.1-1 and Figure B.1-2 are adopted in PileLAT 2 for the granular soils of driven piles.

B.2.2 Bored Piles

For the cohesive soils, the following equations as recommended in FHWA manual (O'Neill and Reese 1999) are adopted to calculate the ultimate shaft resistance, f_s and ultimate end bearing resistance, f_b:

$$f_s = \beta\sigma_z'$$

$$\beta = 1.5 - 0.245z^{0.5} \text{ where } 0.25 \leq \beta \leq 1.5$$

$$f_b = 0 \text{ for } \phi \leq 30^{\circ}$$

$$f_b = 1530 \ kPa \text{ for } 30^{\circ} \leq \phi \leq 36^{\circ}$$

$$f_b = 3830 \ kPa \text{ for } 36^{\circ} \leq \phi \leq 41^{\circ}$$

$$f_b = 4300 \ kPa \text{ for } 41^{\circ} \leq \phi$$

where z is the depth below the ground surface, σ_v' is the effective overburden pressure and ϕ is the effective friction angle of the sand.

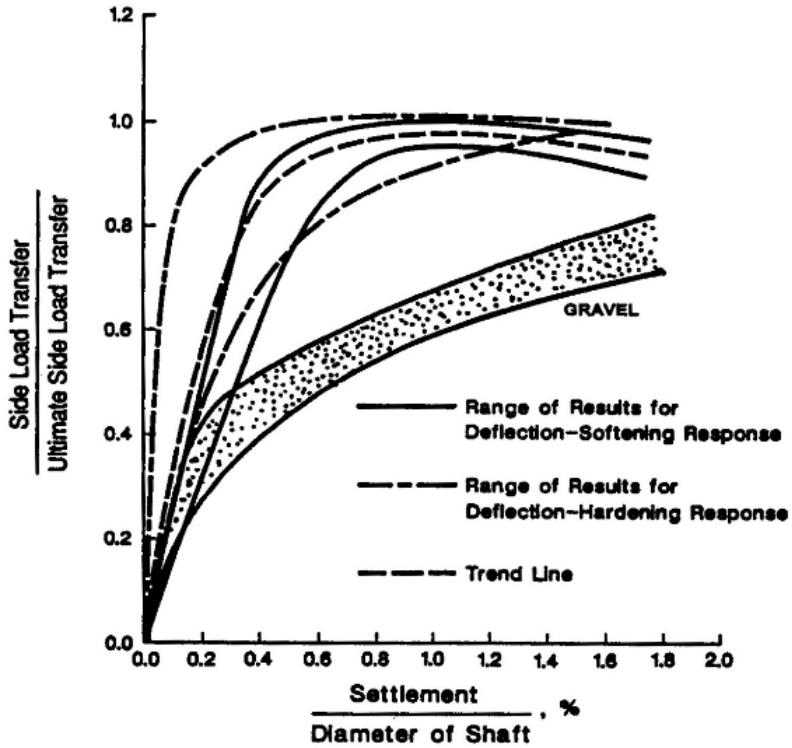


Figure B.2-1 t-z curve adopted for the granular soils – bored piles (O'Neill and Reese 1999)

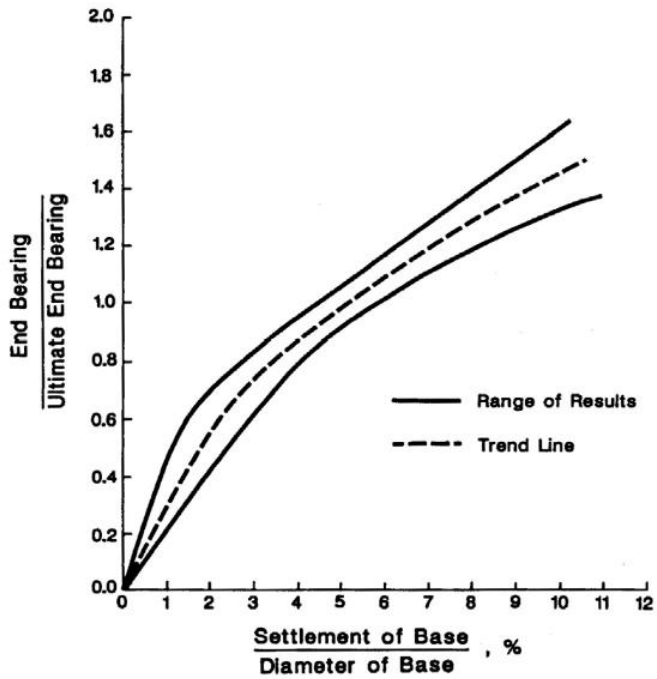


Figure B.2-2 q-w curve adopted for the granular soils – bored piles (O'Neill and Reese 1999)

Appendix B.3 General Rock

Only bored piles are considered for general rock. If the rock material is selected in the lateral analysis for driven pile, then this rock material is automatically converted to an "equivalent" cohesive soil material with high undrained shear strength (half of the unconfined compressive strength) in the pile settlement and axial capacity analysis.

B.3.1 Ultimate Shaft Resistance and End Bearing Resistance

For general rock material in PileLAT, the following equation are adopted to calculate the ultimate shaft resistance, f_s and ultimate end bearing resistance, f_b:

$$f_s = \alpha(\sigma_c)^\beta$$

$$f_b = N_c\sigma_c$$

where α and β are empirical factors determined from the various load tests, σ_c is the unconfined compressive strength of intact rocks in the unit of MPa and N_c is the bearing capacity factor for the rock which is assumed to be 2.5 in PileLAT. Kulhawy et al. (2005) reviewed the database of the currently existing methods of predicting ultimate shaft resistance and suggested that β can be adopted as 0.5 for all practical purposes. As for the empirical factor, α, a value of 0.25 is considered to be close to the lower bound to 90% of the published data for normal rock sockets in PileLAT. More options are available in PileAXL for both empirical parameters where the user would be able to choose the specific value if required.

B.3.2 t-z curve for rock

The following hyperbolic relationship for t-z curve as recommended by O'Neill and Hassan (1994) is adopted in the program to calculate the mobilised shaft resistance f_{s-mob} based on the pile settlement z:

$$f_{s-mob} = \frac{z}{\frac{2.5D}{E_m} + \frac{z}{f_s}}$$

where D is the pile diameter and E_m is the elastic modulus of the rock mass. The following relationship proposed by Rowe and Armitage (1984) is adopted to calculate the elastic modulus of the rock mass based on the unconfined compressive strength of rocks:

$$E_m = 215\sqrt{\sigma_c}$$

B.3.3 q-w curve for rock

According to Pells (1999), for massive and intact rock, the load-displacement behaviour is linear up to bearing pressures of 2 to 4 times the UCS. For jointed rock mass, the load-displacement behaviour is linear up to 0.75 to 1.25 times the UCS. Baguelin (1982) suggested using the following equation for the linear load-displacement relationship for end bearing up to a specific maximum displacement at which the ultimate bearing resistance is mobilised:

$$\sigma_b = s_b \cdot \frac{4E_b}{\pi(1-\upsilon_b{}^2)D} \leq f_b$$

in which E_b is elastic rock modulus at the pile toe; s_b is pile toe displacement; υ_b is Poisson's ratio (0.25 is adopted in the program); D is the pile diameter and σ_b is the mobilised end bearing pressure at the pile toe. This elastic-plastic relationship is adopted in PileLAT.

Appendix C. Examples

C.1 Example 1 - Steel pipe pile driven into soft clay and sand layers

This example involves a single 600 mm diameter steel pipe pile of 25 m long driven through soft clay (15 m thick) and into the medium dense sand. The soft clay layer is 5 m below the water surface. The wall thickness of the steel pipe pile is 20 mm. The undrained shear strength of the soft clay is 35 kPa at the layer top and increases in the rate of 1 kPa/m along the depth. The effective friction angle of medium dense sand is 35 degree.

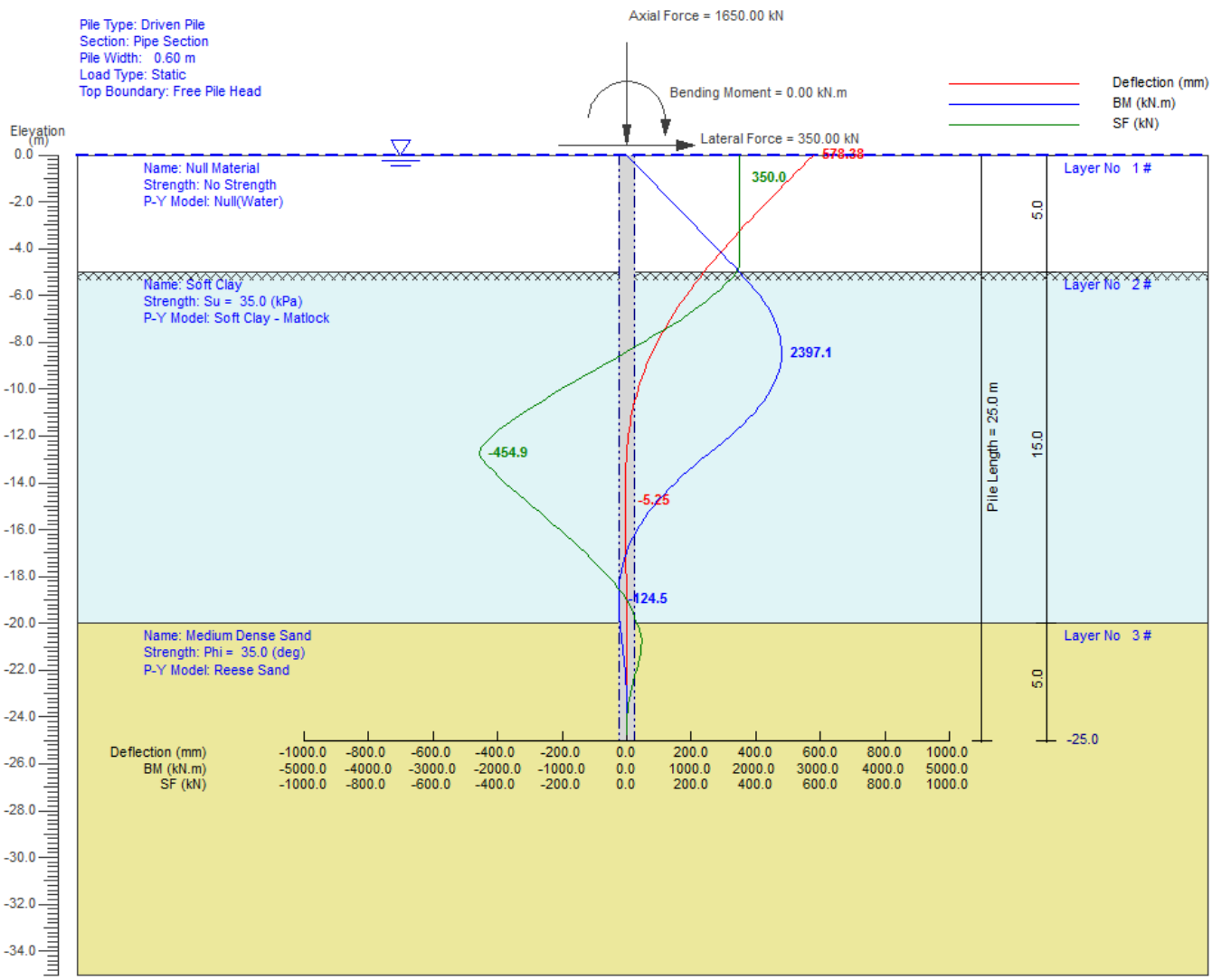


Figure C.1-1 Ground profile with the pile length and loading conditions for Example 1

Forces applied at the pile head are (1) axial force of 1650 kN and (2) lateral force of 350 kN. The bending moment applied at the pile head is 0 in this example. Figure C.1-1 shows the ground profile with the pile length and loading conditions for this example.

Note that the cantilever portion of the pile is modelled with using a layer with “Null” material type in PileLAT program. If the cantilever portion is within the water such as driven piles used for offshore projects, the user

only needs to make sure that this special “Null” layer is under water table in the soil layer input. In this example, since the first 5 m cantilever portion is within the water, the first layer – which is the layer with “Null” material type under the water table. The water table is shown as a thicker blue line in the ground profile as shown in Figure C-1. The distribution of lateral displacement is shown in Figure C.1-2.

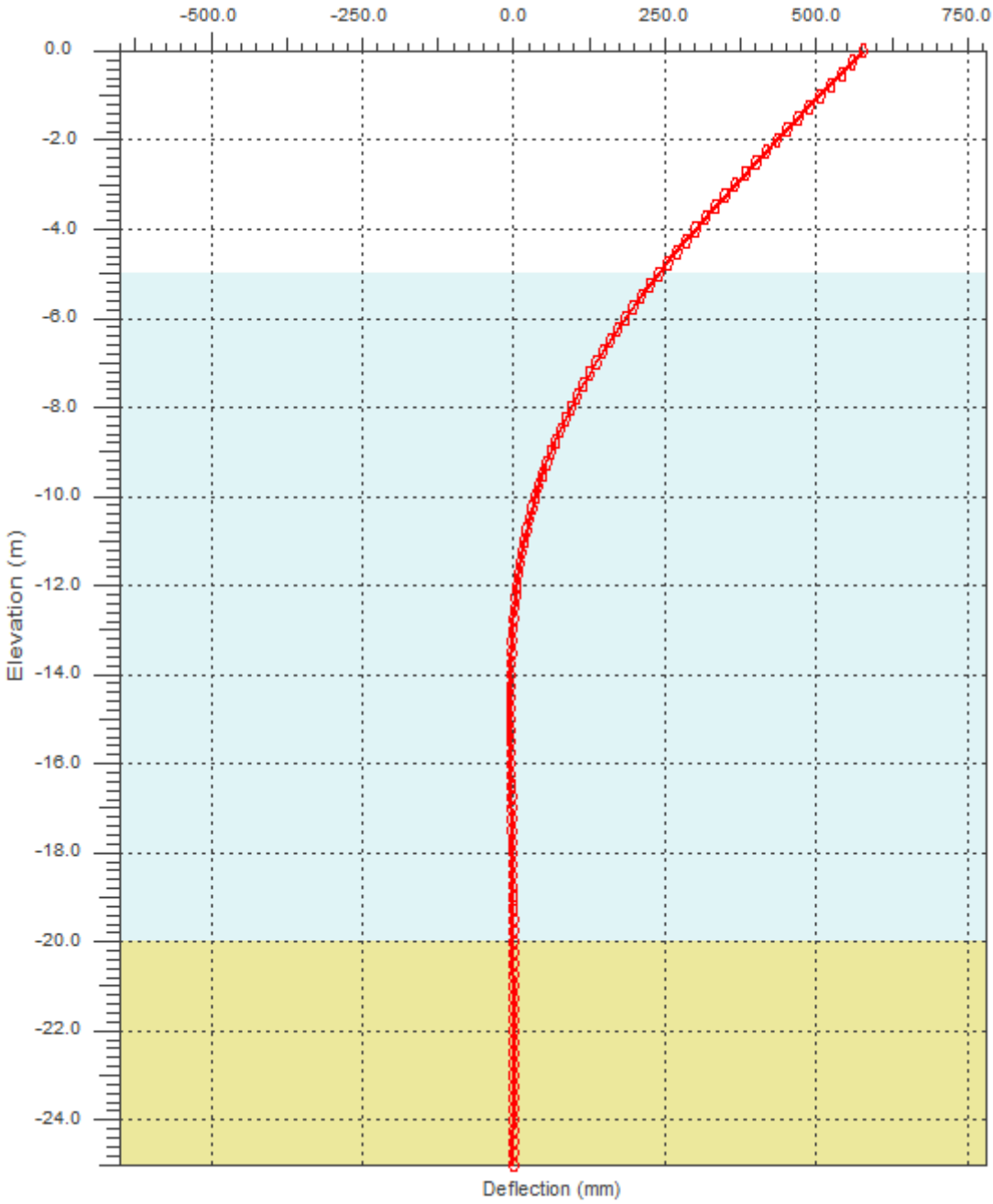


Figure C.1-2 Lateral displacement along the pile with the static load

C.2 Example 2 - Steel pipe pile driven into soft clay and sand layers with cyclic loading

All the other inputs are the same as Example 1 except for that cyclic load with 2000 cycles is adopted instead of the static loads at the pile top. Figure C.2-1 shows the cyclic load setting for the applied force at the pile head. Figure C.2-2 shows the distribution of lateral displacement along the pile for this example.

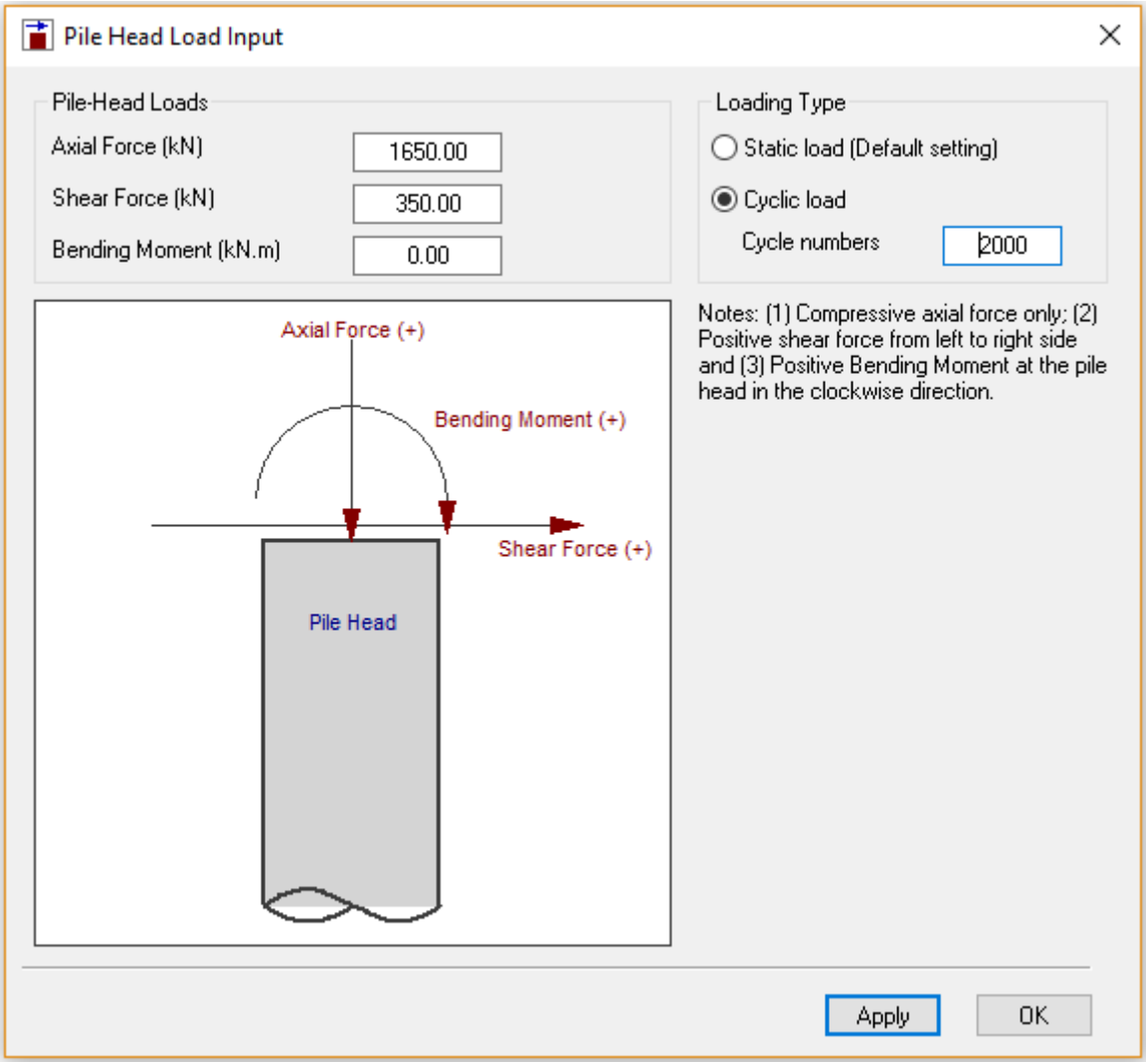


Figure C.2-1 Cyclic load setting for the applied force at the pile head

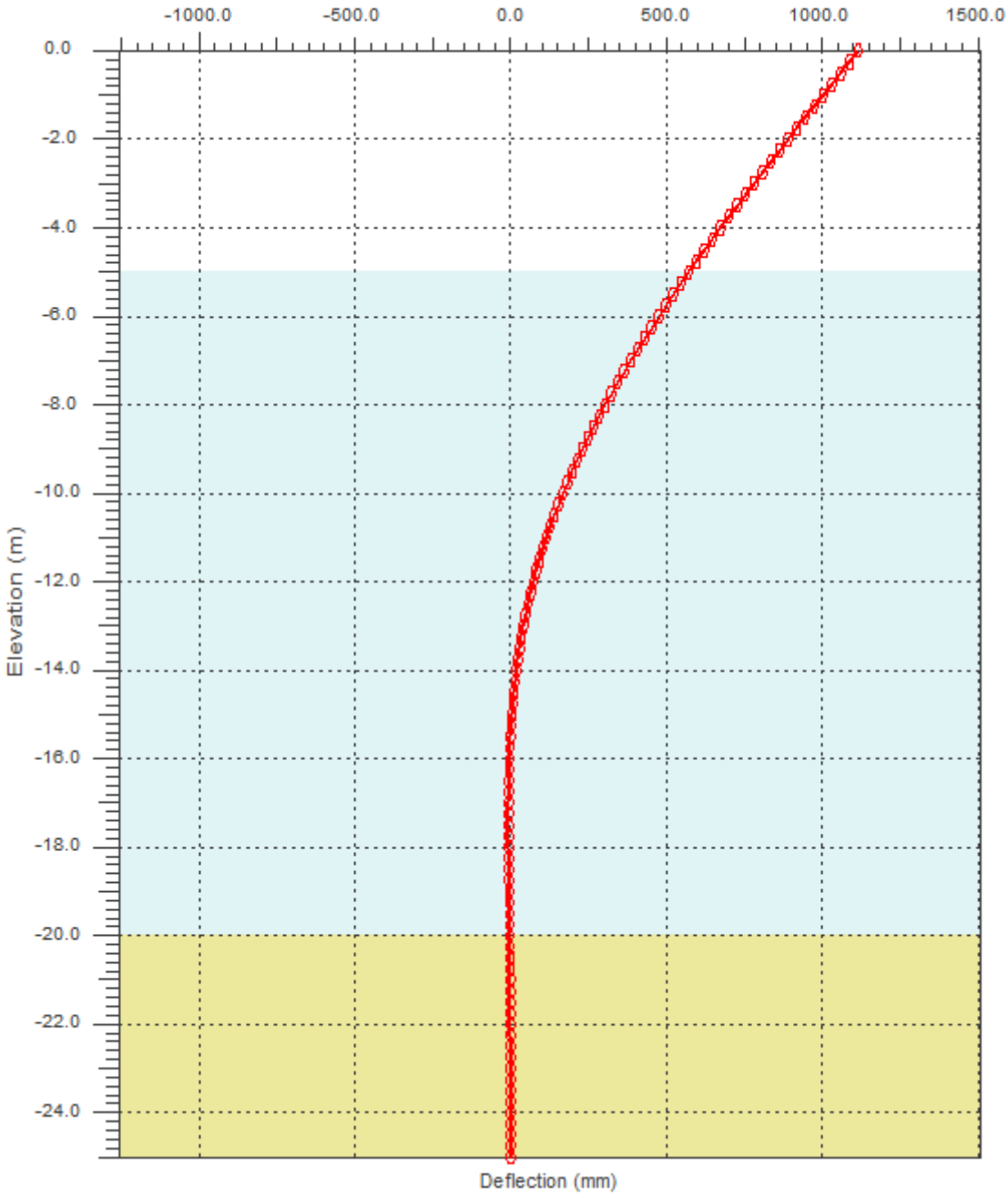


Figure C.2-2 Lateral displacement along the pile with the cyclic load

C.3 Example 3 - Steel pipe pile driven into soft clay and sand layers with sloping ground surface

All the other inputs are the same as Example 1 except for that sloping ground surface is adopted in this example. The surface angle is 15 degree. Figure C.3-1 shows the input of the sloping ground surface for this example. Figure C.3-2 shows the distribution of lateral displacement along the pile for this example.

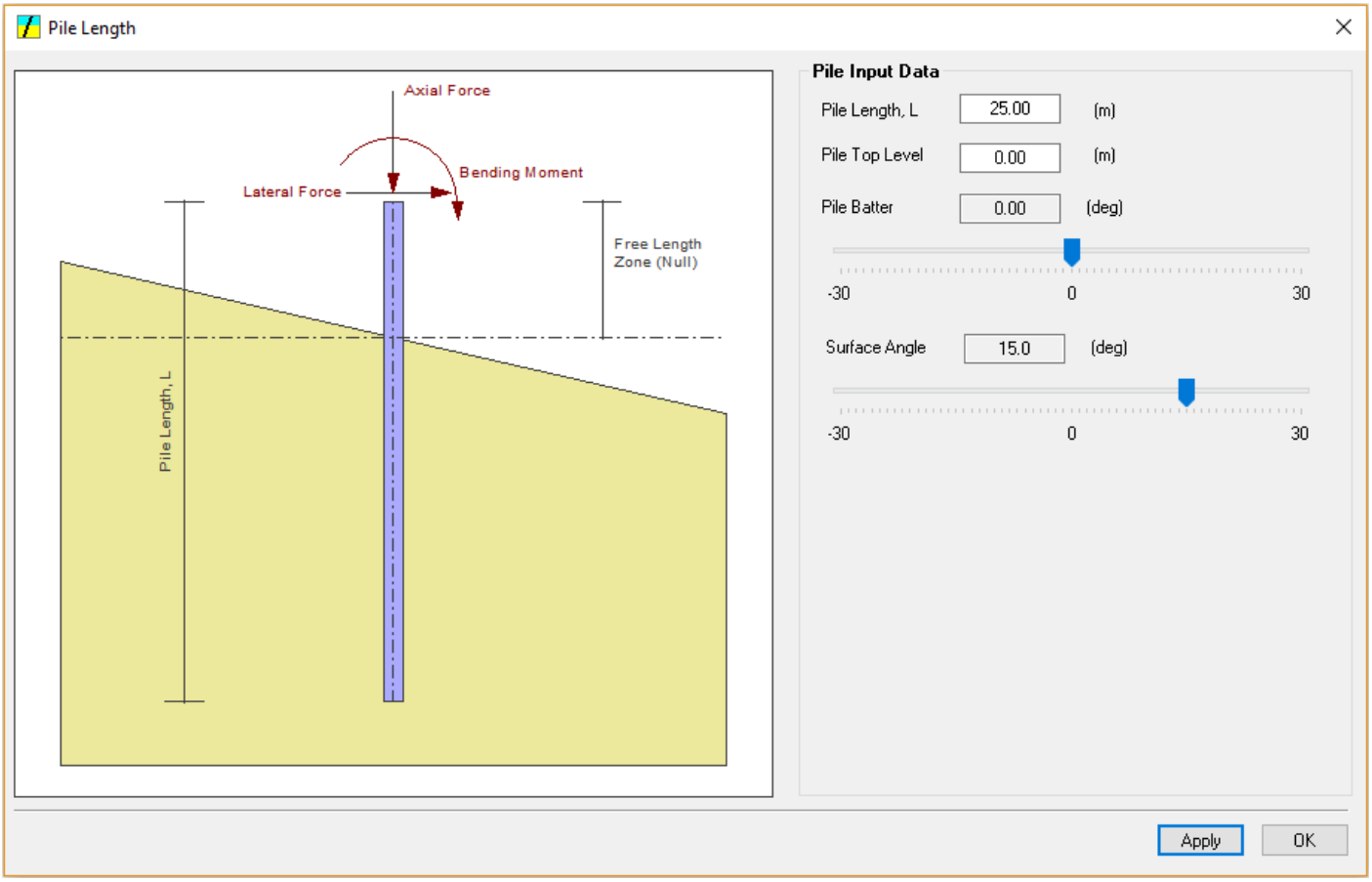


Figure C.3-1 Sloping ground surface (15 degree)

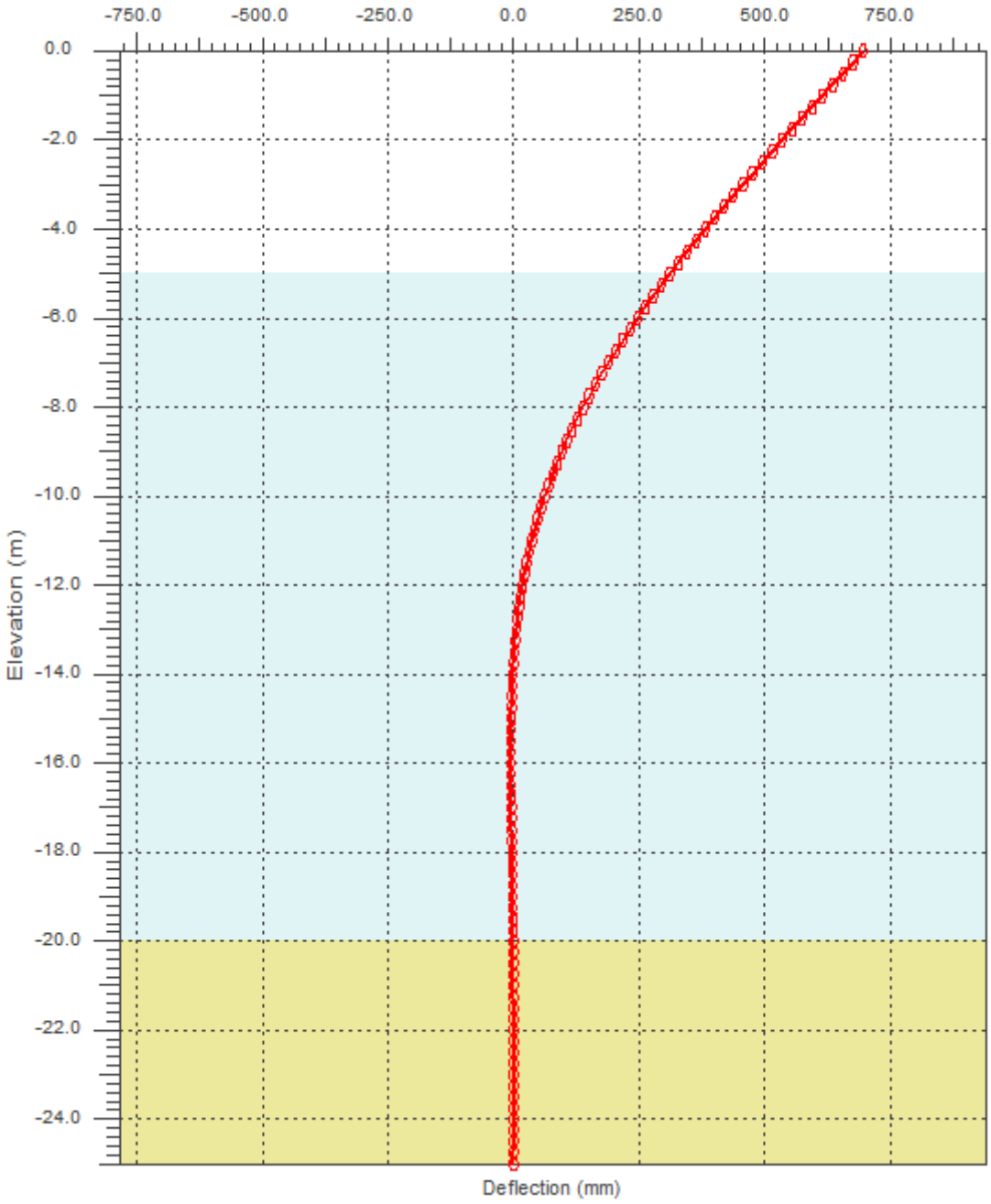


Figure C.3-2 Lateral displacement along the pile for the sloping ground surface

C.4 Example 4 – Bored pile socketed into rock layers

This example involves a 600 mm diameter reinforced concrete bored pile installed through multiple sand and clay layers and socketed into strong rock by 4 m. The pile length is 20 m and the ground water table is about 4.5 m below the ground surface. The ground profile is shown in the table below.

Table C.4-1 Ground profile information for Example 4

Layer No	Layer Name	Layer Thickness (m)	P-Y Model
1	Medium dense to dense sand layer	2	API Sand
2	Stiff clay layer	2.5	Stiff clay without free water (Reese)
3	Soft clay layer	5.0	Soft Clay – Matlock
4	Stiff clay layer	2.0	Stiff Clay with Free Water (Reese)
5	Dense sand Layer	2.0	Reese Sand
6	Very low to low strength rock	2.5	Weak Rock (Reese)
7	Medium to high strength rock	4.0	Strong Rock

Detailed soil layer input parameters are shown in the table below.

Table C.4-2 Summarised soil strength parameters for Example 4

Layer No	Strength Parameters		
	Undrained Shear Strength, s_u (kPa)	Effective Friction Angle, ϕ' (deg)	Unconfined Compressive Strength, UCS (MPa)
1	-	36	-
2*	95	-	-
3	25	-	-
4	100	-	-
5	-	40	-
6	-	-	1.0
7	-	-	10.0

* Undrained shear strength increment rate is 0.5 kPa/m from the layer top for this soil layer.

Both static axial force and lateral force are applied at the pile head. The applied axial force is 11500 kN in compression and the applied lateral force is 500 kN. The bending moment applied at the pile head is 0 in this example. Figure C.4-1 shows the ground profile with the pile length and loading conditions for this example.

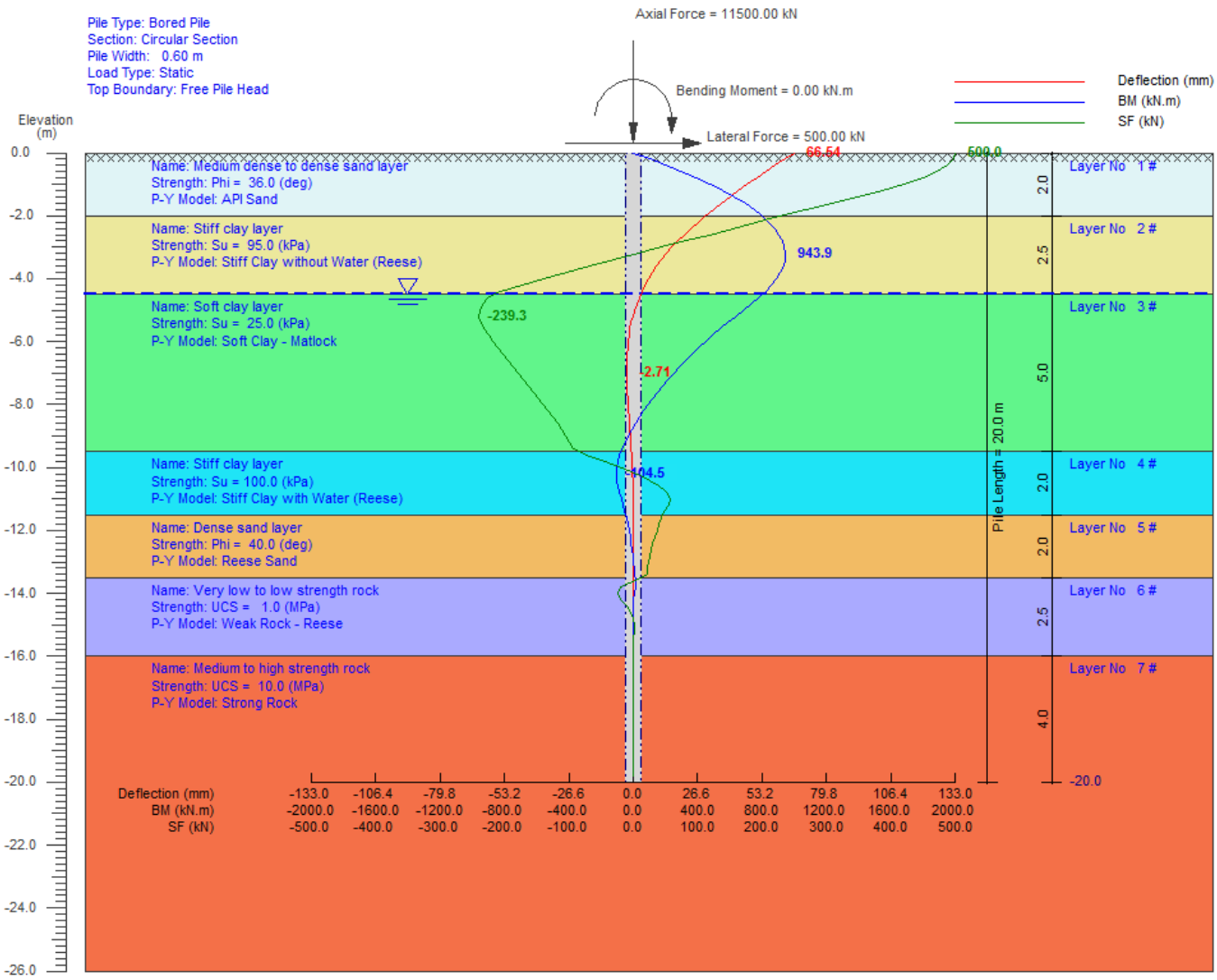


Figure C.4-1 Ground profile with the pile length and loading conditions for Example 4

The distribution of the pile lateral displacement under the applied loading is shown in Figure C.4-2. The load settlement curve at the pile head under the applied axial loading is shown in Figure C.4-3.

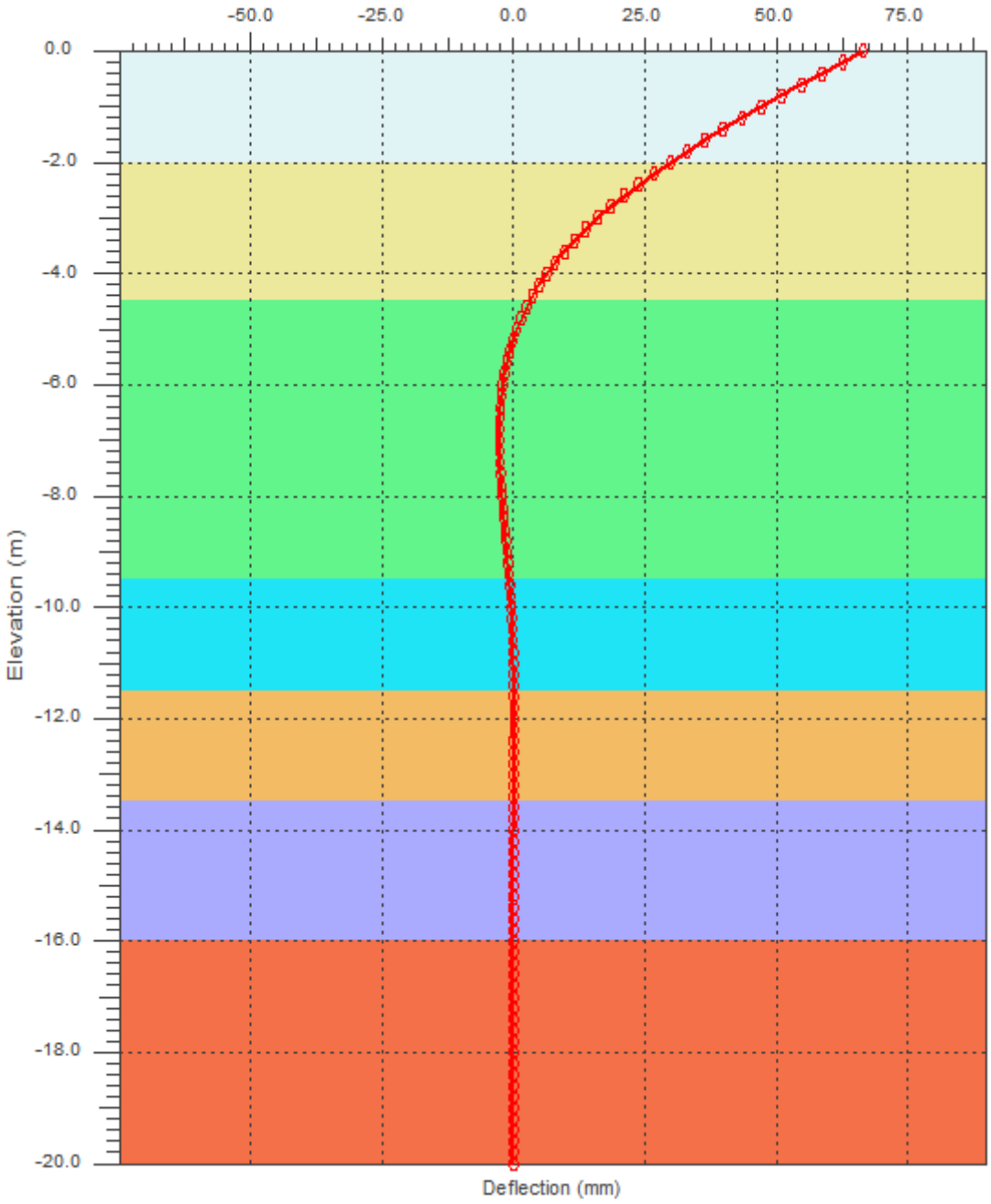


Figure C.4-2 Lateral displacement along the pile for Example 4

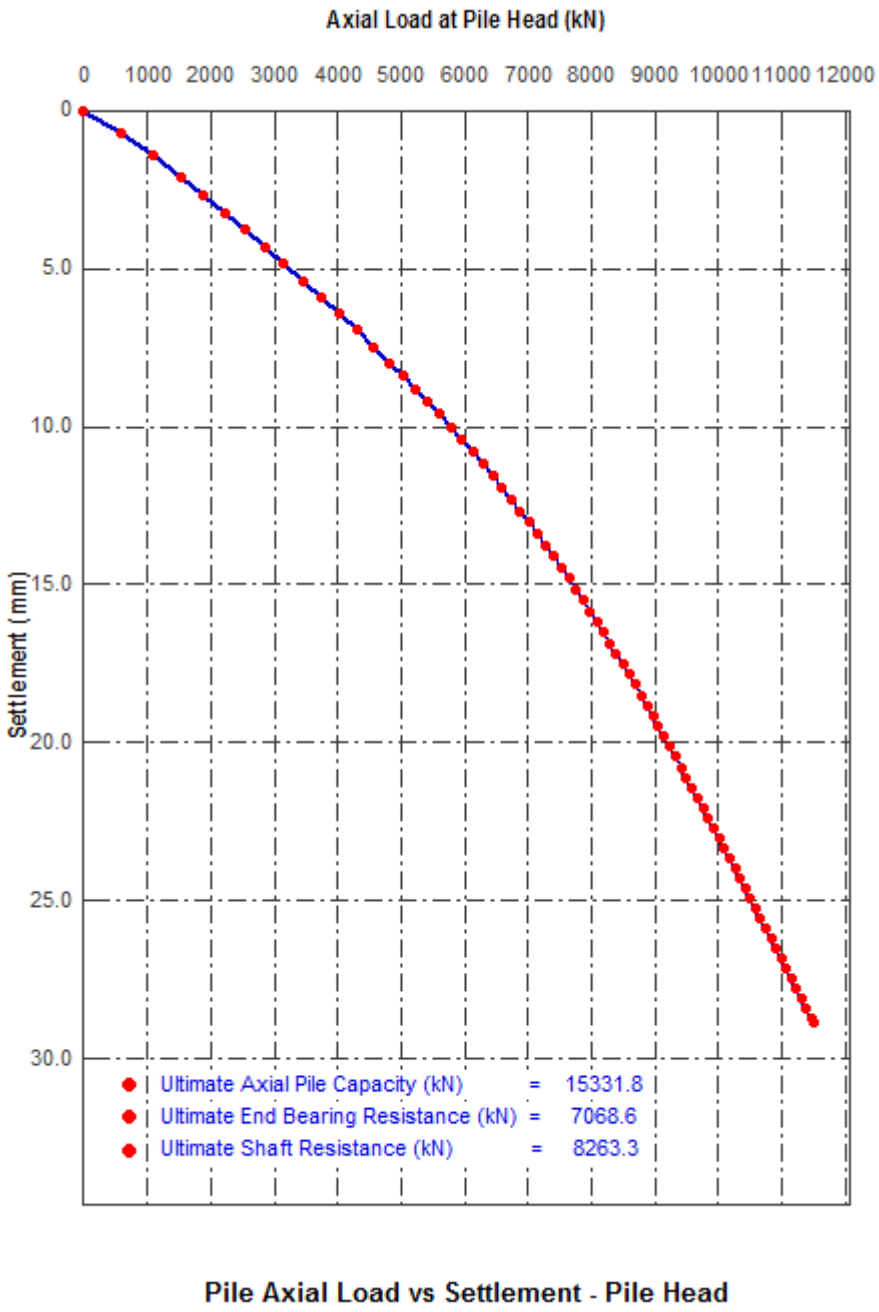


Figure C.4-3 Load settlement curve at the pile head for Example 4

C.5 Example 5 – Driven Steel Pipe Piles under Distributed Displacement Loads along the Pile

This example demonstrates the use of US Units and how the lateral spreading is modelled in PileLAT program through distributed load option. This example involves a steel pipe pile with 48-inch diameter and 1-inch thickness, which is driven into clay and sand layers. The pile length is 50 ft and the ground water table is about 4 ft below the ground surface. The ground profile is shown in the table below.

Table C.5-1 Ground profile information for Example 5

Layer No	Layer Name	Layer Thickness (ft)	P-Y Model
1	Stiff Clay Layer	4	Stiff clay without free water (Reese)
2	Sand Layer	10	Liquefied Sand
3	Stiff Clay Layer	50	Stiff clay with free water (Reese)

Detailed soil layer input parameters are shown in the table below.

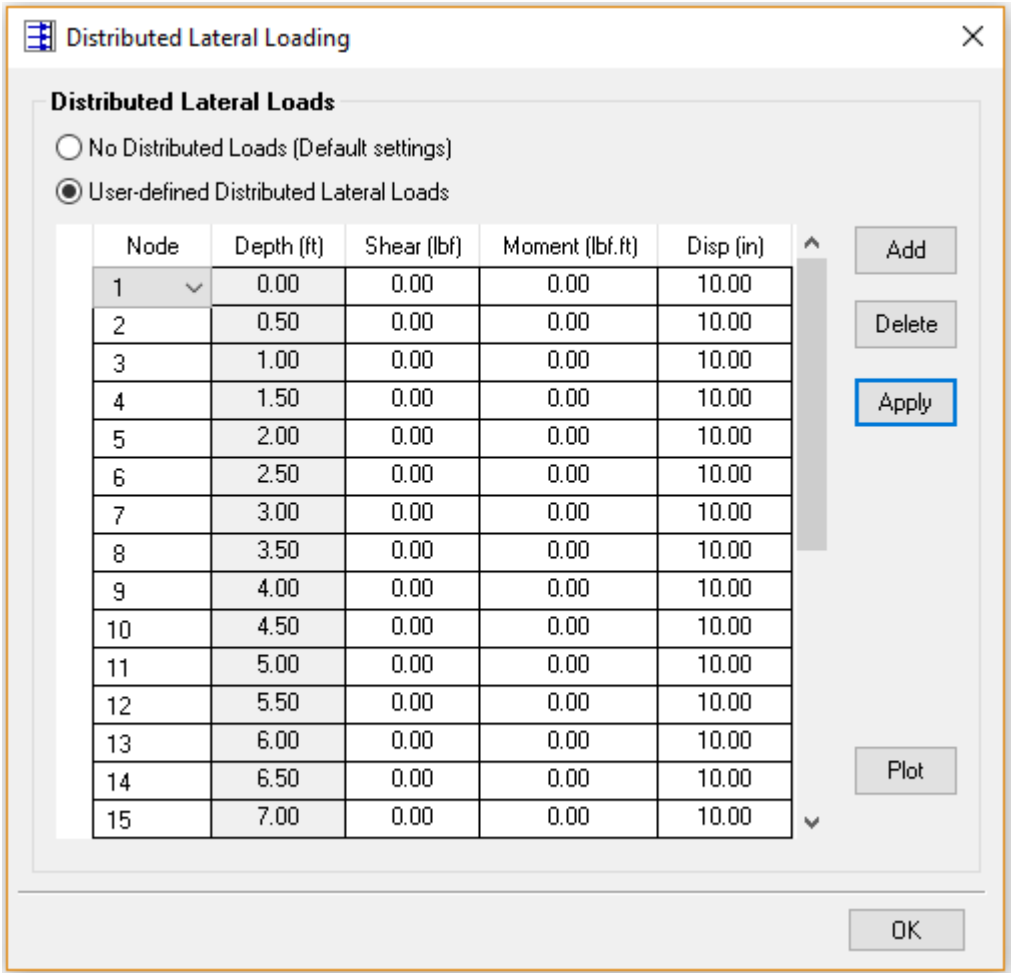
Table C.5-2 Summarised soil strength parameters for Example 5

Layer No	Strength Parameters		
	Undrained Shear Strength, s_u (lbs/ft^2)	Effective Friction Angle, ϕ' (deg)	Unit Weight (lbs/ft^3)
1	1650	-	115
2*	-	-	110
3	1800	-	120

* Undrained shear strength increment rate is 35.3 lbs/ft^2/ft from the layer top for this soil layer.

Static lateral force is applied at the pile head. The applied lateral force at the pile head is 5000 lbf. The bending moment applied at the pile head is 0 in this example. The lateral spreading is modelled with distributed lateral displacement in this example. In PileLAT, the users can input the lateral displacement (lateral spreading) at the node point along the pile length. Figure C.5-1 shows the values of the applied lateral displacement at the node point – 10 inch lateral displacement from Node 1 to 25; 8.5 inch lateral displacement for Node 26, 7.0 inch lateral displacement Node 27 and 3.5 inch lateral displacement for Node 28. This is to model the lateral

spreading within the top stiff clay and liquefied sand layers. Figure C.5-1 shows the dialog of distributed lateral loading for this example.



Node	Depth (ft)	Shear (lbf)	Moment (lbf.ft)	Disp (in)
1	0.00	0.00	0.00	10.00
2	0.50	0.00	0.00	10.00
3	1.00	0.00	0.00	10.00
4	1.50	0.00	0.00	10.00
5	2.00	0.00	0.00	10.00
6	2.50	0.00	0.00	10.00
7	3.00	0.00	0.00	10.00
8	3.50	0.00	0.00	10.00
9	4.00	0.00	0.00	10.00
10	4.50	0.00	0.00	10.00
11	5.00	0.00	0.00	10.00
12	5.50	0.00	0.00	10.00
13	6.00	0.00	0.00	10.00
14	6.50	0.00	0.00	10.00
15	7.00	0.00	0.00	10.00

Figure C.5-1 Distributed Lateral Loading Input for Example 5

Figure C.5-2 shows the graphic display of the input distributed lateral displacement along the pile. Figure C.5-3 shows the analysis results of the pile under lateral loading. Figure C.5-4 shows the p-y curves for the selected nodes No 2 (stiff clay without water) and No 12 (liquefied sand).

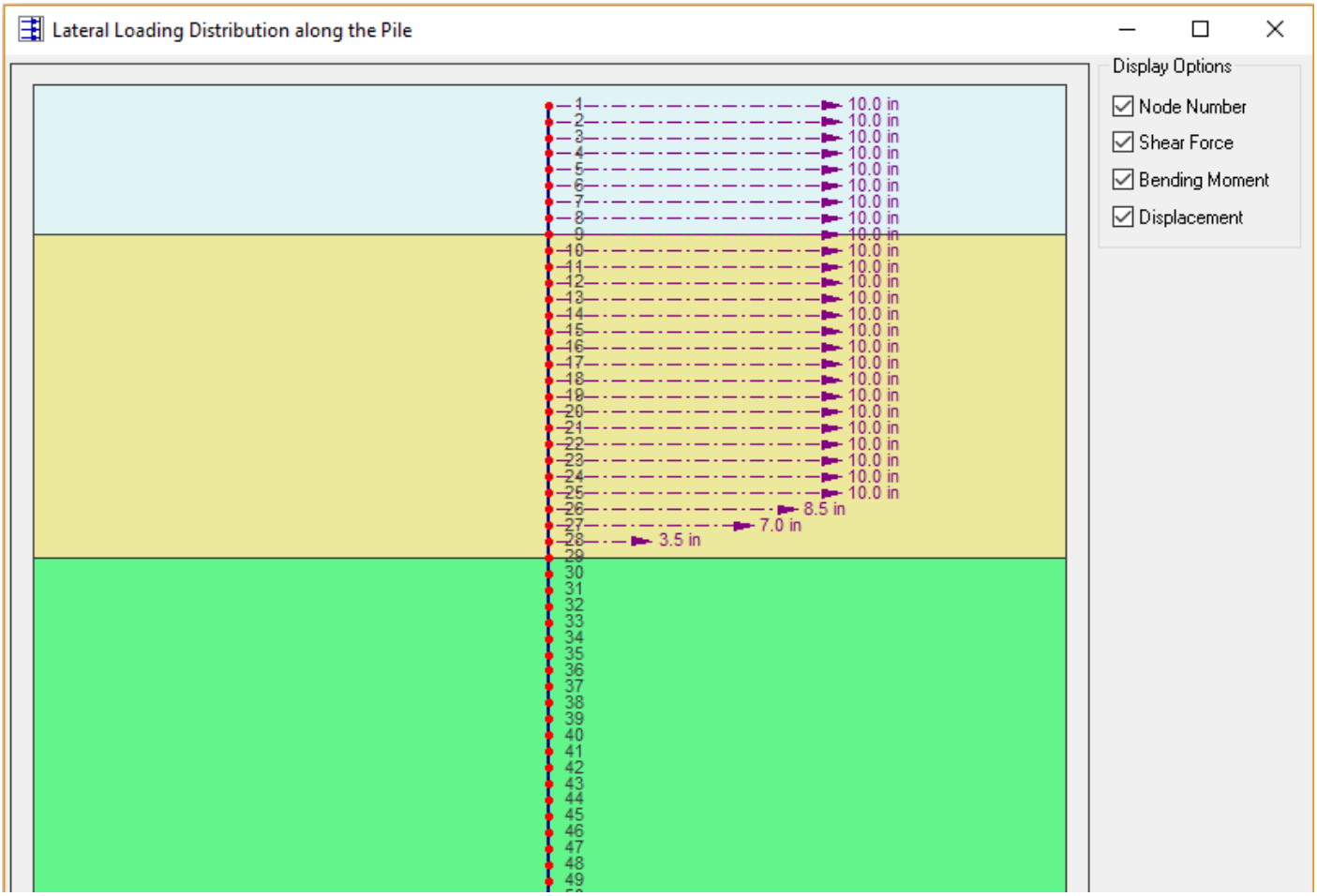


Figure C.5-2 Graphic plot of the distributed displacement along the pile

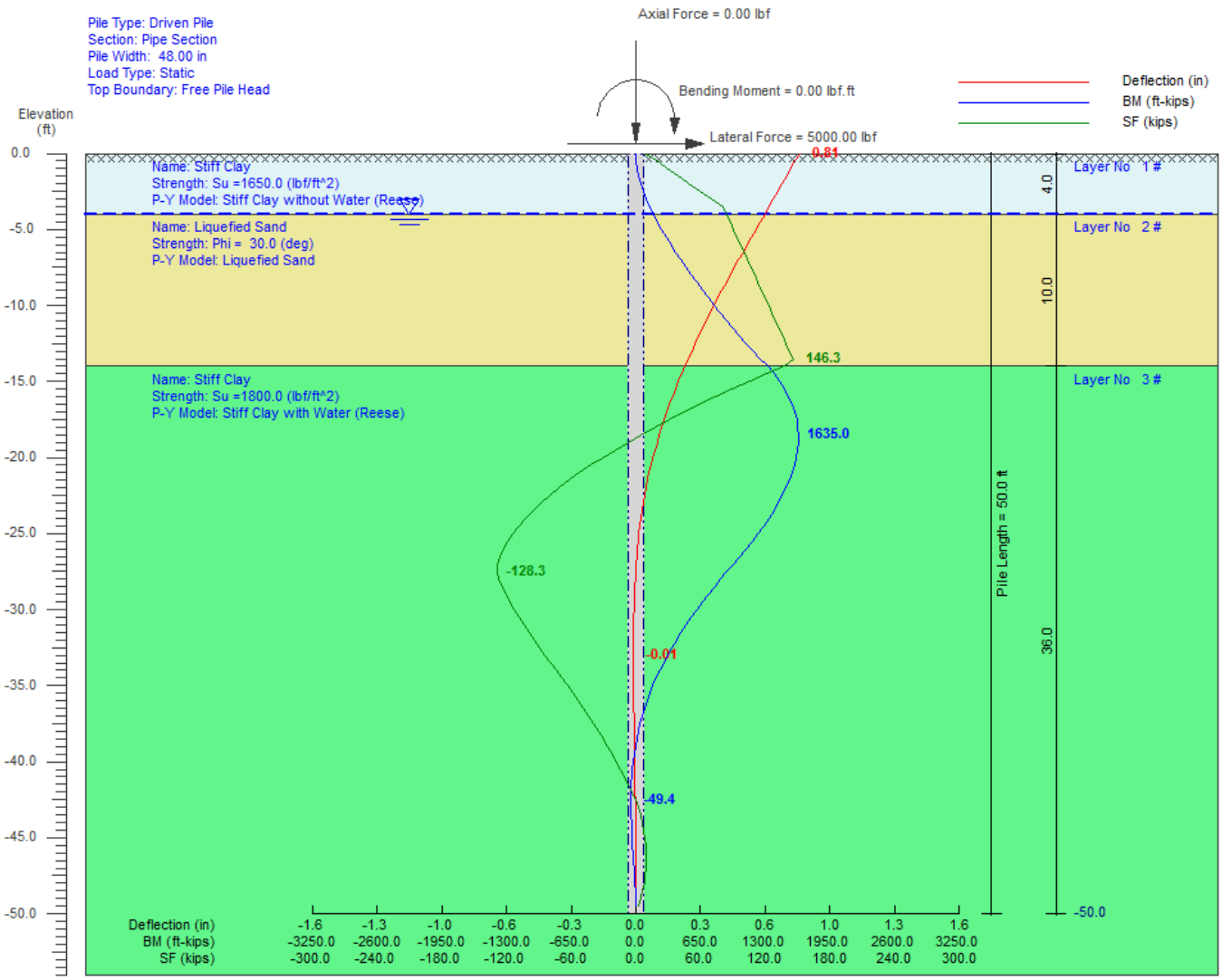


Figure C.5-3 Graphic plot of the analysis results

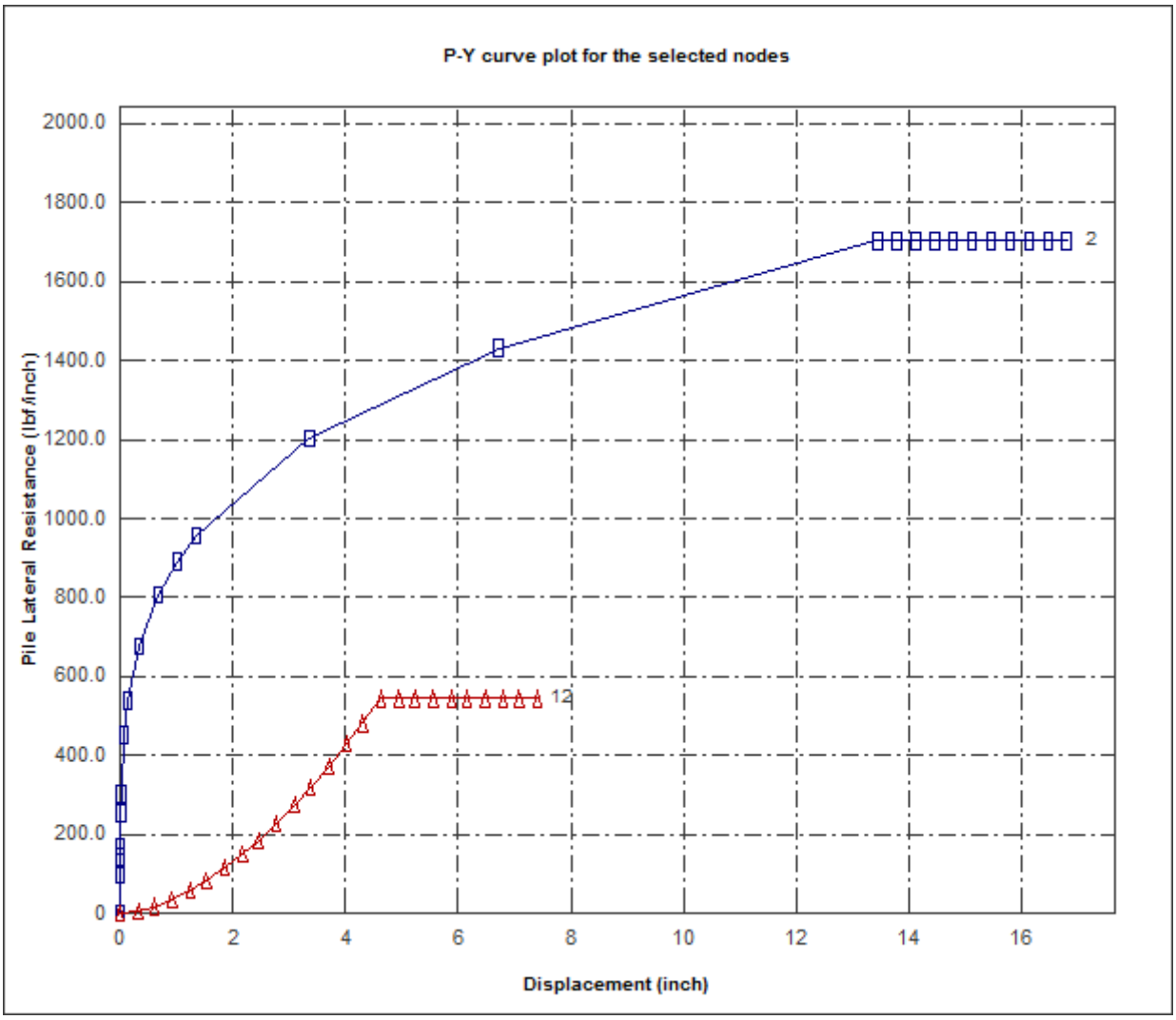


Figure C.5-4 Graphic plot of the p-y curves for Nodes 2 and 12

C.6 Example 6 – Pile under Lateral Loading in Soil Layer of Elastic Subgrade Model

This example mainly validates the solutions from PileLAT program by comparing with the lateral displacement results from the theoretical equations as given by Hetenyi (1946) as cited in Poulos and Davis (1980).

$$\delta = \frac{2P_H\lambda}{K_h b} \times \left[\frac{\sinh \lambda L \cos \lambda Z \cosh \lambda(L-z) - \sin \lambda L \cosh \lambda z \cos \lambda(L-z)}{(\sinh \lambda L)^2 - (\sin \lambda L)^2}\right]$$

Where

$$\lambda = \left(\frac{K_h b}{4E_p I_p}\right)^{1/4}$$

Note that L is the pile length, z is the depth below the pile head, b is the pile diameter, K_h is the subgrade modulus, $E_p I_p$ is the bending stiffness of pile and P_H is the lateral loading applied at the pile head.

This example involves a steel pipe pile with 12-inch external diameter and 11-inch internal diameter into the homogeneous soil layer modelled by the elastic subgrade model. The pile length is 50 ft and the soil layer is dry. The ground profile is shown in the table below.

Table C.6-1 Ground profile information for Example 6

Layer No	Layer Name	Layer Thickness (ft)	Elastic Subgrade Modulus (lbf/ft^2)	P-Y Model
1	Elastic soil layer	60	6000	Elastic subgrade

Static lateral load of 1000 kips is applied at the pile head. The boundary condition at the pile head is free pile head. Note the soil type is input as “cohesive soils” in this example and the unit weight of 121 lbf/ft^3 and undrained shear strength of 300 lbf/ft^2 are also entered as basic soil parameter information for completeness. Due to the adoption of elastic subgrade model for lateral force analysis, those input parameters will have no influence on the results related to lateral loading and are only relevant to the results such as pile settlement, shaft resistance and end bearing resistance which are caused by vertical loading.

Figure C.6-1 shows the analysis results of the pile under lateral loading as output from PileLAT program. Comparison results between PileLAT and Hetenyi’s closed-form equations are shown in Figure C.6-2. The results from two separate runs with different element numbers (30 elements and 100 elements over 50 ft long pile) based on PileLAT are plotted against the results from the closed-form equations. PileLAT program essentially predicts exactly the same results as Hetenyi’s closed-form equations and the results are not sensitive to the number of elements adopted in the analysis.

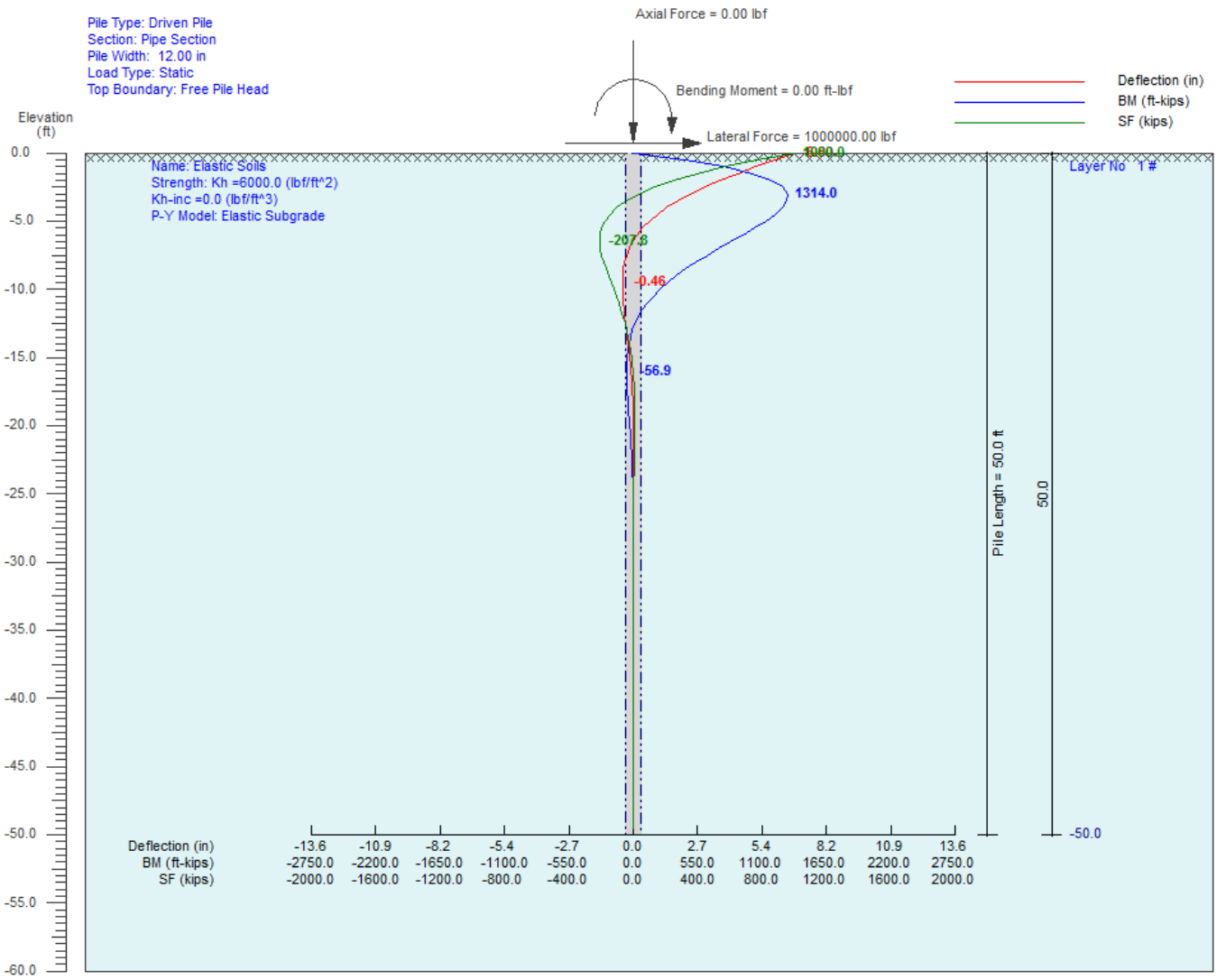


Figure C.6-1 Graphic plot of the analysis results

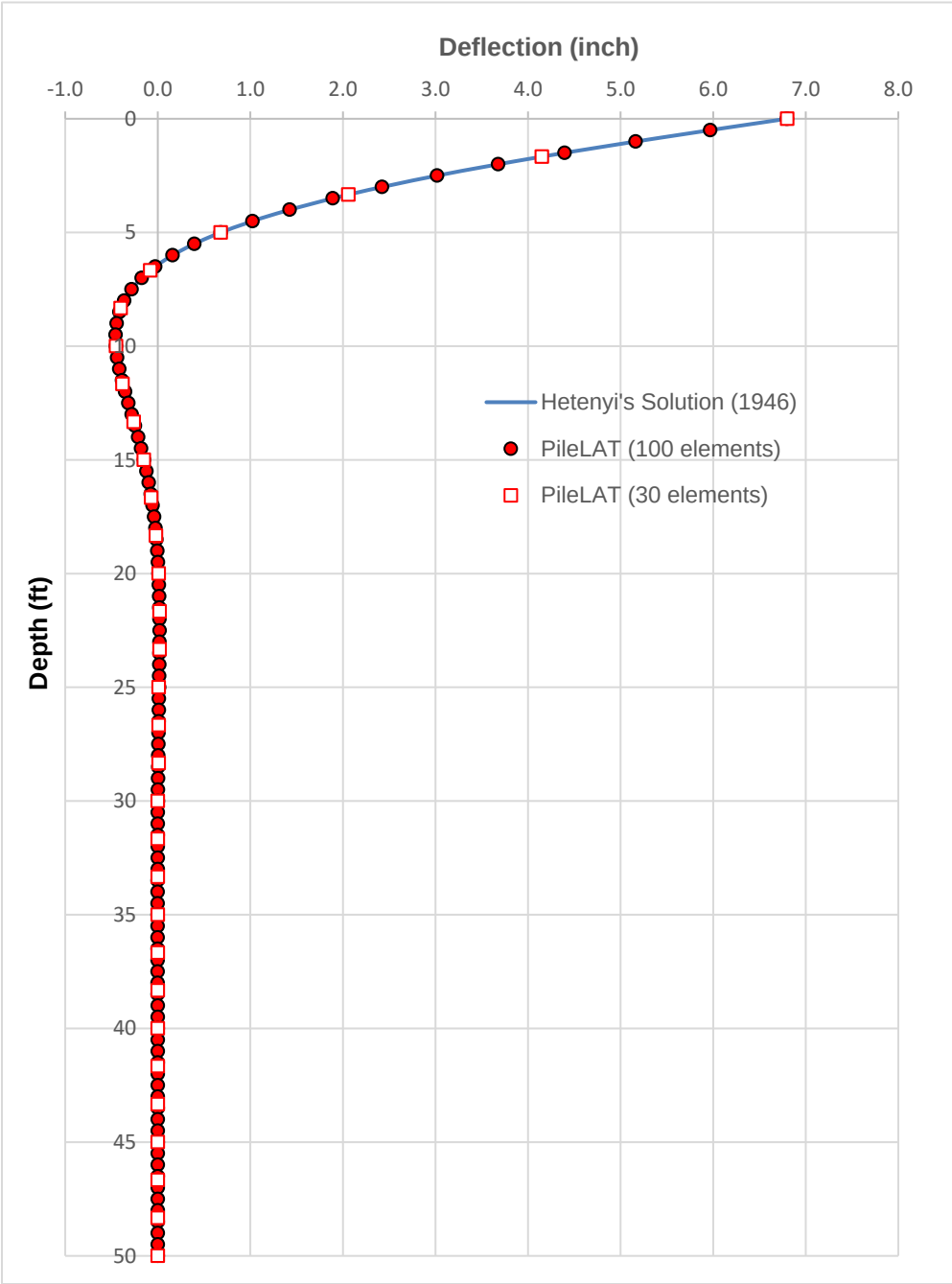


Figure C.6-2 Comparison results between Hetenyi's Solution and PileLAT

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