Innovative Geotechnics

# User Manual for PileGroup

## Three-dimensional Nonlinear Program for Pile Groups under General Loading

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# TABLE OF CONTENTS

# Chapter 1. Introduction

PileGroup is a finite-element based program which has been developed to calculate the deformations and loads of pile groups subject to general three-dimensional loadings such as axial and lateral forces and moments applied on the pile caps. The individual piles within the pile group can be vertical or on a batter with the connection between pile heads and pile cap to be fixed, pinned or elastically restrained by rotational springs. Some of the important features and benefits are summarised as follows:

- The pile cap behaves as a rigid body with displacement and rotation in any direction;
- Nonlinear response of soils and rocks such as p-y curves for lateral loading, t-z and q-w curves for axial loading and t-θ curves for torsional loading are automatically generated by the program. The behaviour of each pile under six components of loadings (forces and moments) is solved with an improved iterative approach to satisfy the equations of equilibrium, which results in the compatibility of geometry and equilibrium of forces between the applied external loads and the reactions of each pile head;
- The external loadings (vertical loads Fy, horizontal loads Fx and Fz, rotational moment My, bending moments Mx and Mz) can be applied at any position on the pile cap and multiple sets of loadings can be specified by the users. The program will automatically calculate the equivalent loading at the origin in the analysis;
- P-y curves can be internally generated for a wide range of soils and rocks such as API soft clay, stiff clay with free water, stiff clay without free water, modified stiff clay with initial stiffness, Reese Sand, API sand, liquefied sand, strong rock, Reese weak rock, massive rock, elastic-plastic model and elastic subgrade model;
- Various section types are available in PileGroup program and these include circular section, rectangular section, octagonal section, H-section, pipe section and user-defined section. The program considers the pile installation type as either driven or bored in the analysis to account for different approaches to estimate pile settlement under axial loading;
- Nonlinear p-y curves generated internally by the program can be displayed and printed at any node point for any one pile within the pile group along the pile length for reviews or references;
- Reduction factors for p-y curves are automatically determined by the program to account for pile-soil-pile interaction for closely-spaced piles based on the pile cap movement and individual pile positions within the group. In addition, PileGroup also provides other options of (1) ignore group effects (widely spaced piles, for example) and (2) user-specified group reduction factors for each pile;
- The graphical interface has been designed to enable the users to view complicated geometry in three-dimensional space. Users can display various input details of pile group analysis for any selected pile within the displayed 3-D geometry;
- The program displays the amplified deformed shape of pile group under applied loads and this feature is very useful for the user to understand and interpret the analysis results;
- The well-designed graphical interface allows users to easily view pile-head reactions and displacements at the pile cap;

- An interactive graphical input interface allows the users to easily define the soil layer geometry and pile details. Any change in the input data such as pile length, pile batter, pile head restraint types, soil layer numbers, soil layer name, soil layer thickness, soil layer colour, p-y curve model type, water table position, certain soil parameters and applied external loadings will be automatically updated in the main graphical output area. This helps the users to visually view the input change, especially for the battered piles within the pile group;
- A simple soil layer and properties input interface is provided to help the users to enter the input data more easily and smoothly. The user can add, delete, insert or modify the input parameters for each soil layer by soil type;
- The program provides a simple and easy approach to input pile layout for the pile group analysis. It is very straightforward for the users to enter the pile head coordinates, pile section types, pile lengths and pile batters. The users can click each pile position to display and review the relevant input properties. Three-dimensional display of the pile group on the main graphical area will be automatically updated once the input dialog is closed. This feature enables the users to review and check their inputs and therefore minimise the uncertainties in the input data;
- Detailed analysis results for each pile with the group such as deflection, shear force, bending moment and mobilised soil reaction are plotted against the pile length and presented in the result output dialog graphically together with the soil layer geometry. The users can view, copy and print the results for the selected pile/piles; and
- Axial load settlement curves and rotational moment rotation curves are displayed in the graphical dialog and can be viewed by the users for any pile within the group.

# Chapter 2. Start the new file

When PileGroup 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.

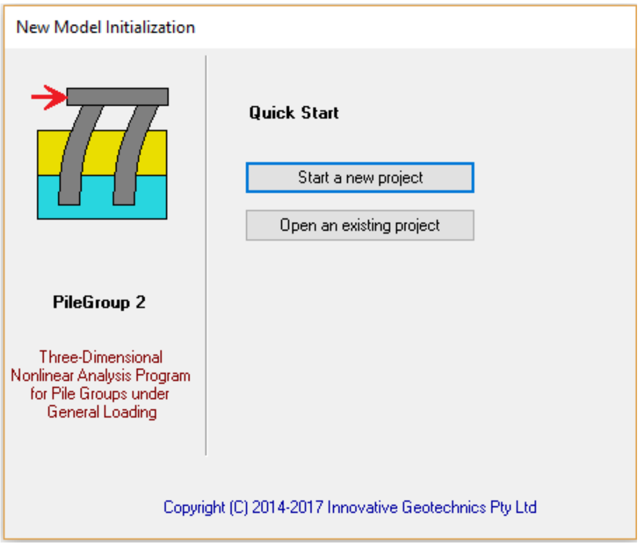



**Figure 2-1** Project start dialog in PileGroup

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.GRP". 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.

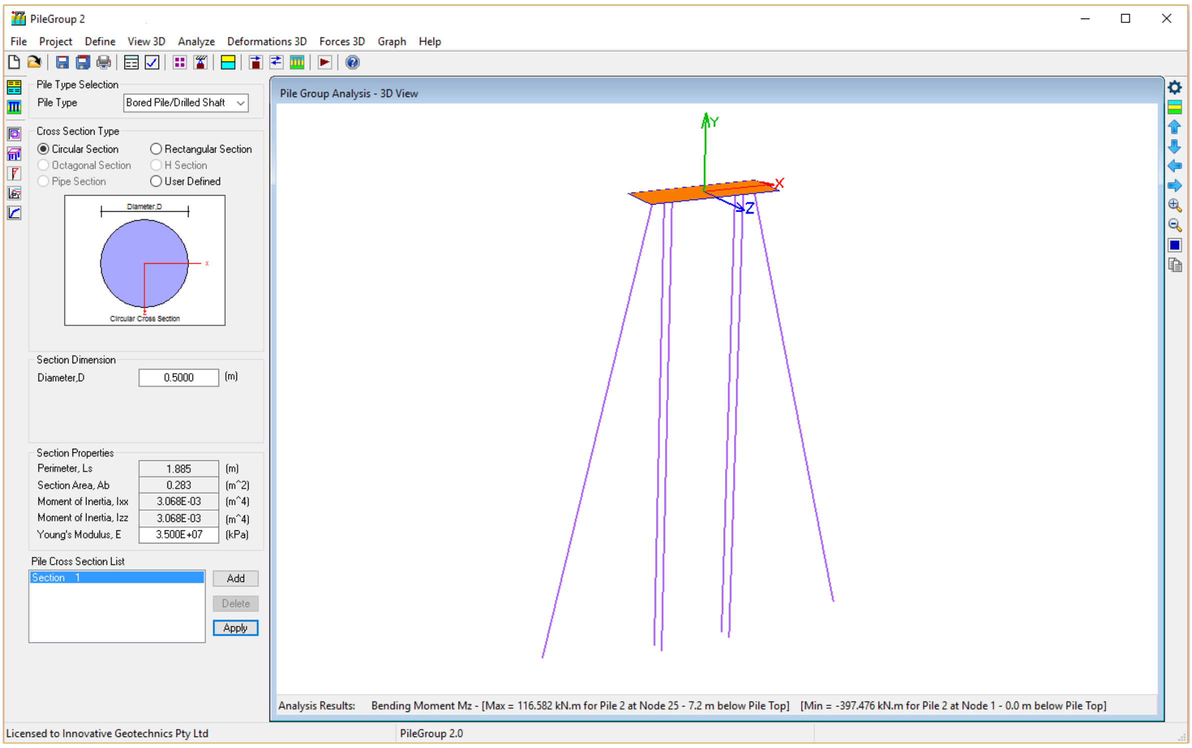



**Figure 2-2** General layout of the program interface for PileGroup

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 PileGroup analysis file with the file type of GRP.

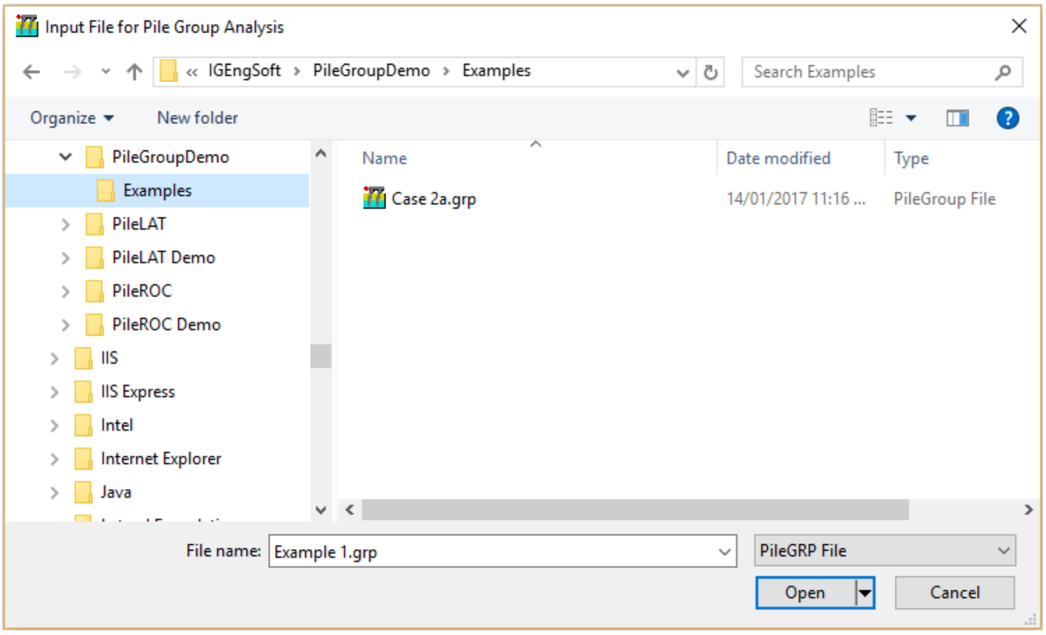



**Figure 2-3** Analysis file selection dialog for PileGroup

# 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.

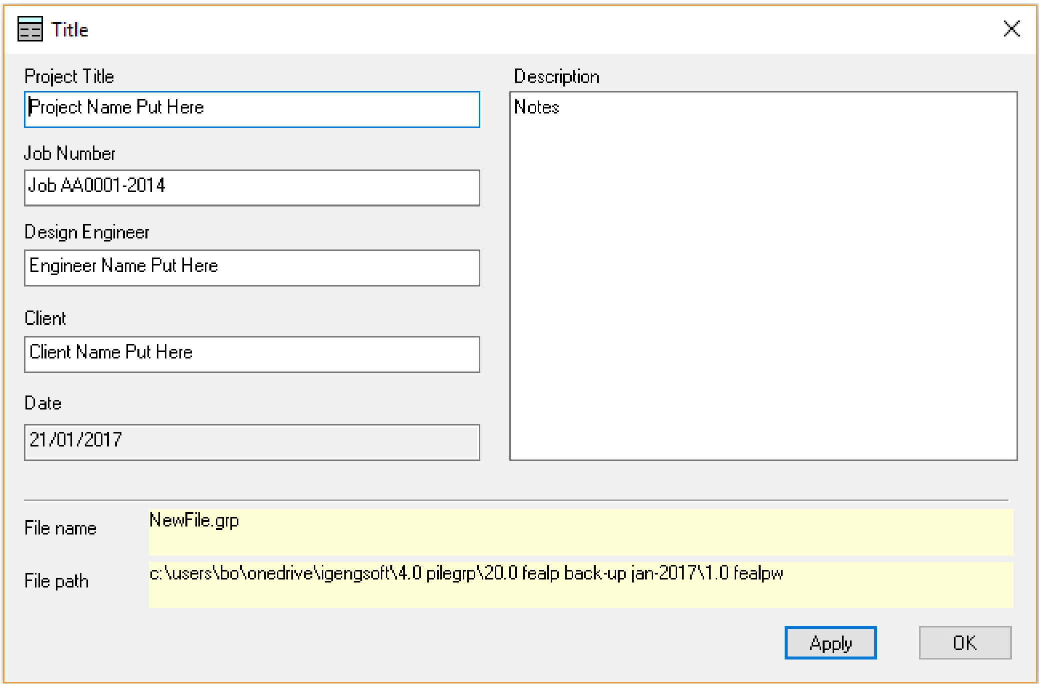



**Figure 3-1** General layout of “Project Title” Dialog

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.

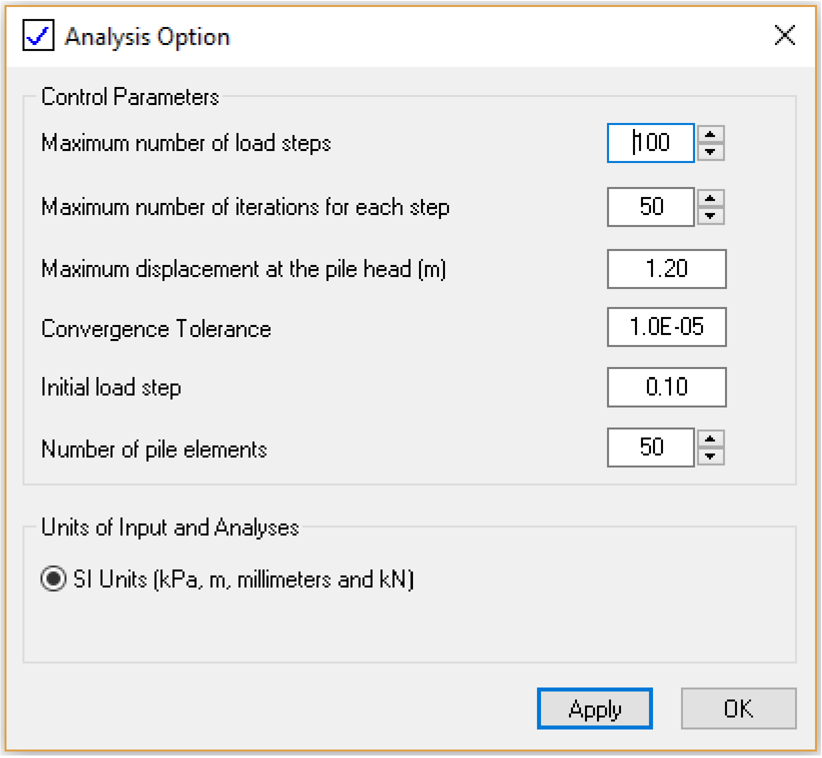



**Figure 4-1** General Layout of Analysis Option Dialog for PileGroup

"Control Parameters" group lists six main control parameters for the pile group 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 50 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 cap (m): This is the maximum lateral displacement allowed by the program at the pile cap. 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 group 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 an unnecessary small value in numerical analysis.
- Initial load step: This is the initial load step used in the lateral force analysis of the individual piles to form the stiffness matrix for the pile group and the default value is 0.1.
- Number of pile elements: This is the number of pile elements for the individual piles used in the analysis. The pile length will be equally divided into elements with the specified number. The minimum value is 30 and the maximum value is 100. The default value in PileGroup is 50 and this generally satisfies the needs of the pile group analysis.

"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. This option is currently not available.

# Chapter 5. Pile Section Properties Input

PileGroup allows the user to adopt different installation and section types for each individual pile within the same pile group. 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.

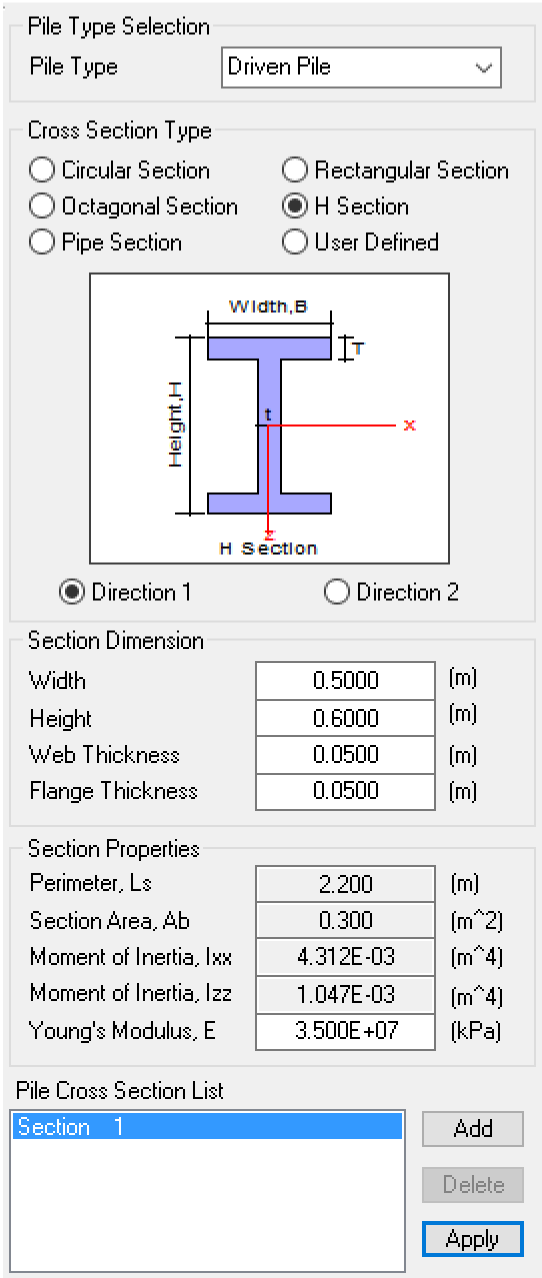



**Figure 5-1** General Layout of Pile Type and Cross Section Dialog

More than one section types can be specified for the piles within the pile group. The users can add additional section types through "Add" button or delete the wanted section types through "Delete" button. For each section type, either "Driven Pile" or "Bored Pile" option can be selected for the piles. The following cross section types as shown in Figure 5-2 can be used in the pile group analysis:

**Driven Piles:**

- Circular Section
  i) Section diameter, D;
  ii) Young's modulus of pile material, E
- Rectangular Section
  i) Section width, W;
  ii) Section height, H; and
  iii) Young's modulus of pile material, E
- Octagonal Section
  i) Section diameter, D;
  ii) Young's modulus of pile material, E
- H Section;
  i) Section width, W;
  ii) Section height, H;
  iii) Web thickness, T;
  iv) Flange thickness, t;
  v) Young's modulus of pile material, E
- Pipe Section
  i) Outside diameter, D1;
  ii) Inside diameter, D2
  iii) Young's modulus of pile material, E
- User-defined Section
  i) Section diameter/width, D;
  ii) Perimeter, Ls;
  iii) Section area, Ab;
  iv) Moment of inertia, Ixx;
  v) Moment of inertia, Izz;
  vi) Young's modulus of pile material, E

**Bored Piles or Drilled Shaft:**

- Circular Section;
  - i) Section diameter, D;
  - ii) Young's modulus of pile material, E
- Rectangular Section
  - i) Section width, W;
  - ii) Section height, H; and
  - iii) Young's modulus of pile material, E
- User-defined Section
  - i) Section diameter/width, D;
  - ii) Perimeter, Ls;
  - iii) Section area, Ab;
  - iv) Moment of inertia, Ixx;
  - v) Moment of inertia, Izz;
  - vi) Young's modulus of pile material, E

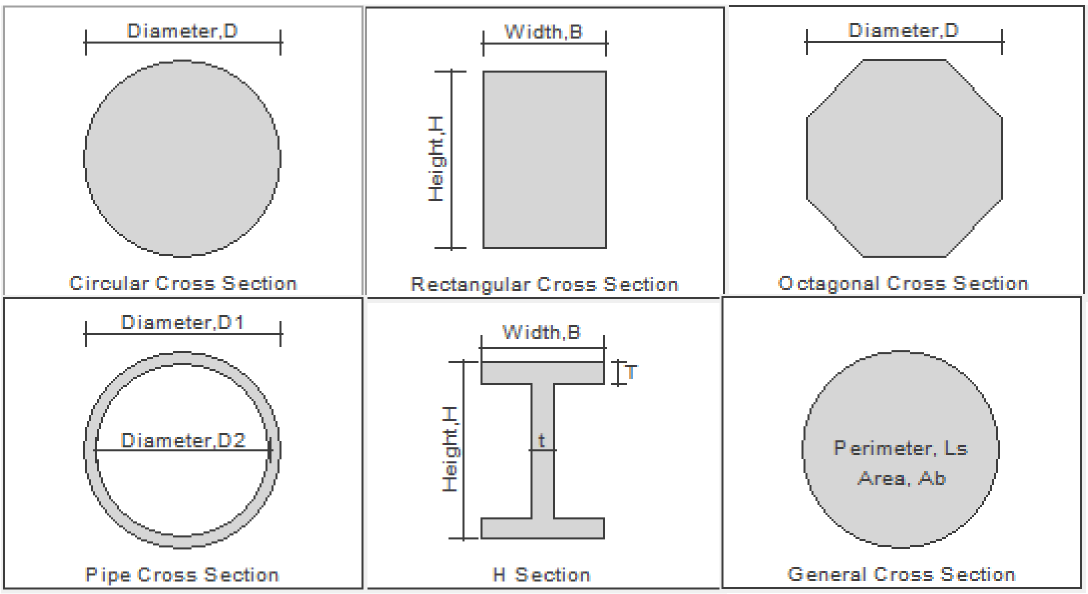



**Figure 5-2** Cross Section Types in PileGroup

The input pile section properties will be saved into the internal memory once the users press "Enter" key from the key board or press "Apply" button near the bottom of the dialog. All section properties except for user-defined section will be automatically updated in this process, for example, Perimeter Ls, Section area Ab, Moment of inertia Ixx and Izz.

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.

The local x and z axes are shown on the section input dialog to help the users to input the section dimension in the right direction. For rectangular and H sections, two directions are available: Direction 1 and Direction 2. The users are able to switch between two different local directions by clicking the radio buttons as shown in Figures 5-1.

The cross-section type created on this dialog and shown under “Pile Cross Section List” will be available for selection in pile layout input where the pile length, X and Z coordinates, batters will be defined for each pile within the group. The maximum number of cross section types available in PileGroup program is currently set to 10.

# Chapter 6. Pile layout input with length and batter information

The individual pile position and length for each pile within the pile group can be entered with clicking "Pile Length and Layout" item under "Define" main menu or clicking "Pile Length and Layout" icon on the toolbar.

The Pile Length and Layout Dialog as shown in Figure 6-1 enables the users to specify various pile length and layout parameters for the pile group analysis in a simple and efficient way.

The parameters include pile length, pile section type, pile position (X and Z Coordinates), pile batters in XY and ZY planes. Pile top level also can be input in the dialog however it is only used for geometry and results display.

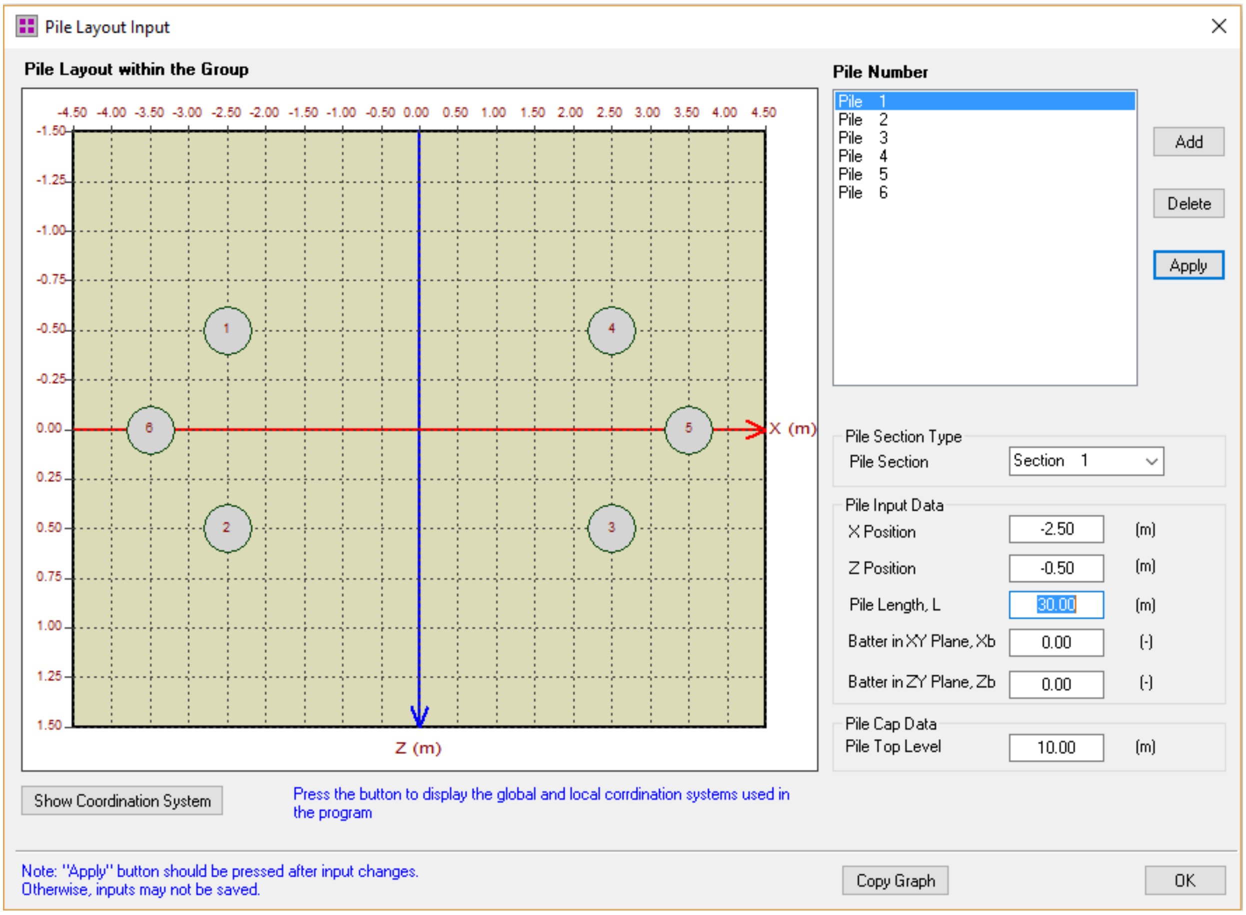



**Figure 6-1** Pile layout input dialog

The users can specify the following inputs related to the pile position, pile type and pile length for the pile group analysis:

- Number of the piles within the pile group. The minimum number is 2 and the maximum number is 50 in the current version. The user can add or delete the pile by clicking "Add" and "Delete" buttons just below the pile number list box;
- X and Z position of each pile on the pile cap plane (XZ Plane);

- Pile length for each individual pile;
- Pile section type for each individual pile. Note that PileGroup allows the users to adopt different pile section types within the same pile group;
- Pile batter in XY plane, Xb – the maximum batter is 1;
- Pile batter in ZY plane, Zb – the maximum batter is 1; and
- Pile top level. Note that this property will not affect the analysis results and is just used for displaying purpose.

The pile group layout can be copied into the clipboard by clicking “copy graph” button and the figure can be inserted into word or excel file for reporting purpose. Figure 6-2 shows the positions of the piles within the pile group.

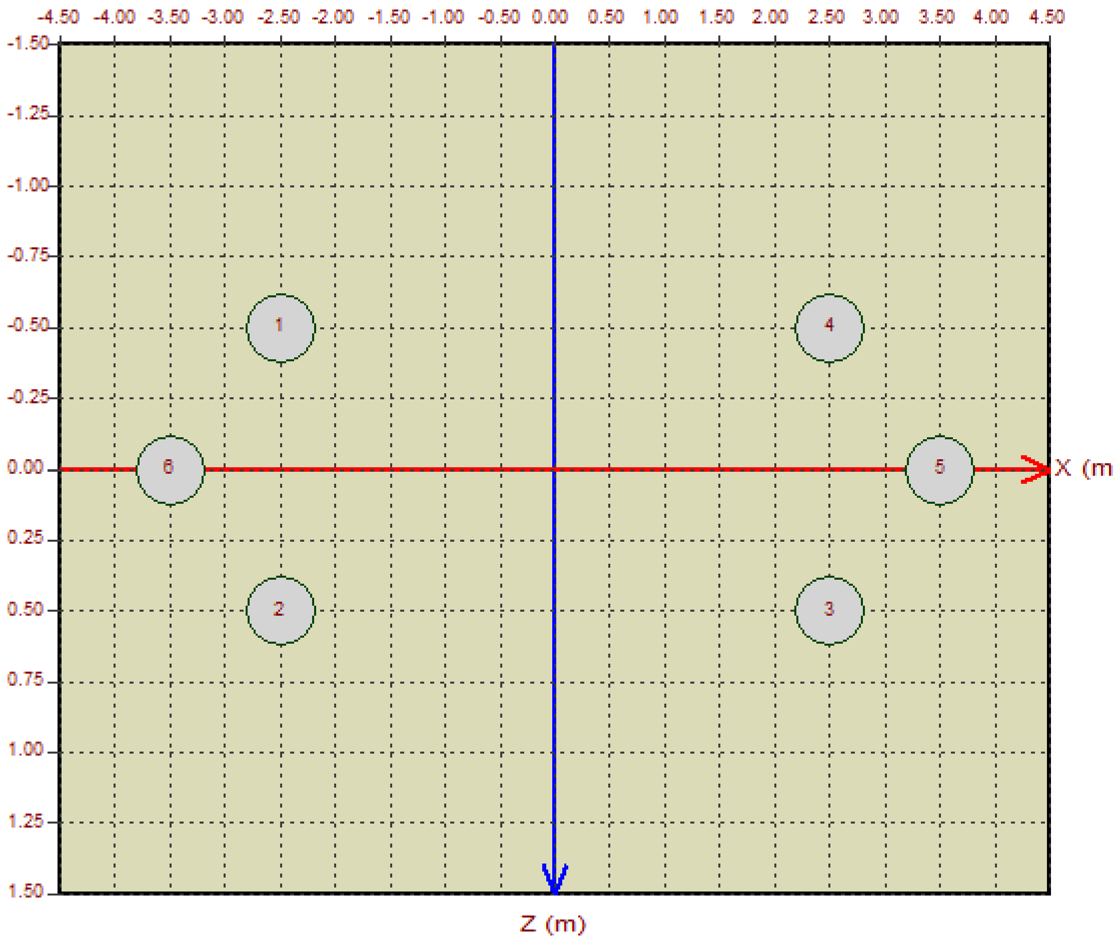



**Figure 6-2** Pile layout input dialog

The coordinate system used by the program can be viewed by the users through clocking “show coordinate system” button just below the pile position and length input area. Figure 6-2 shows the coordinate system used in the program for pile groups. The global X and Z directions are on the horizontal pile cap plane and the global Y direction is vertical to the pile cap plane.

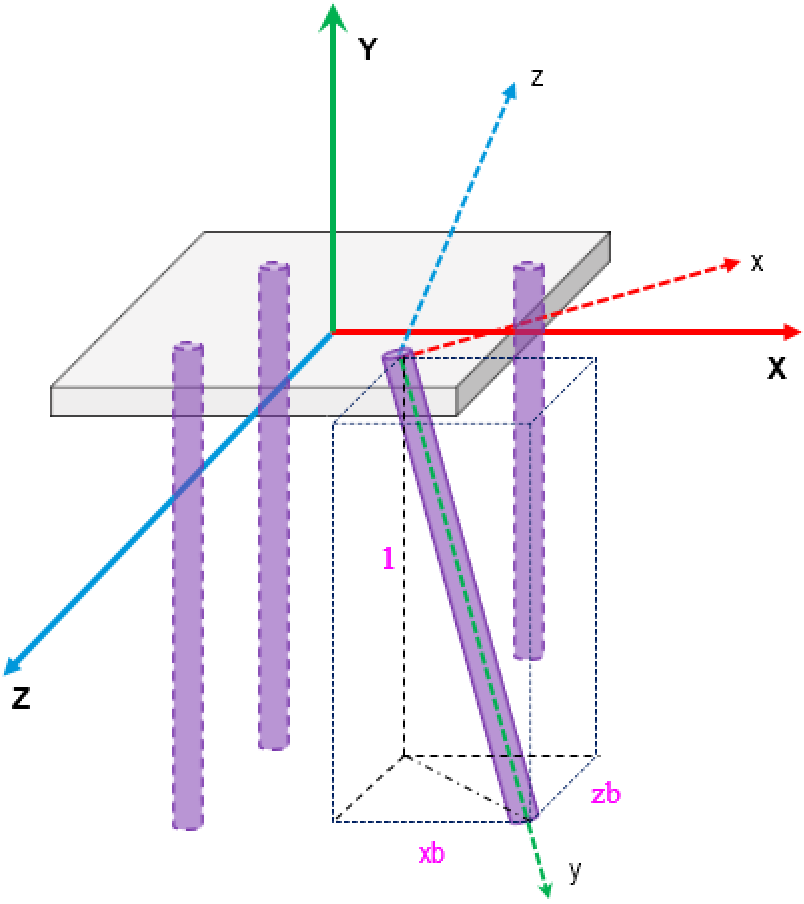



**Figure 6-2** Pile group global and local coordinate systems

Three-dimensional view of the pile group will be automatically updated during the input of the pile layout, length and batter degree input parameters. The users can freely rotate and zoom 3D displaying of the pile group through the mouse. Figure 6-3 shows the three-dimensional view of the pile group.

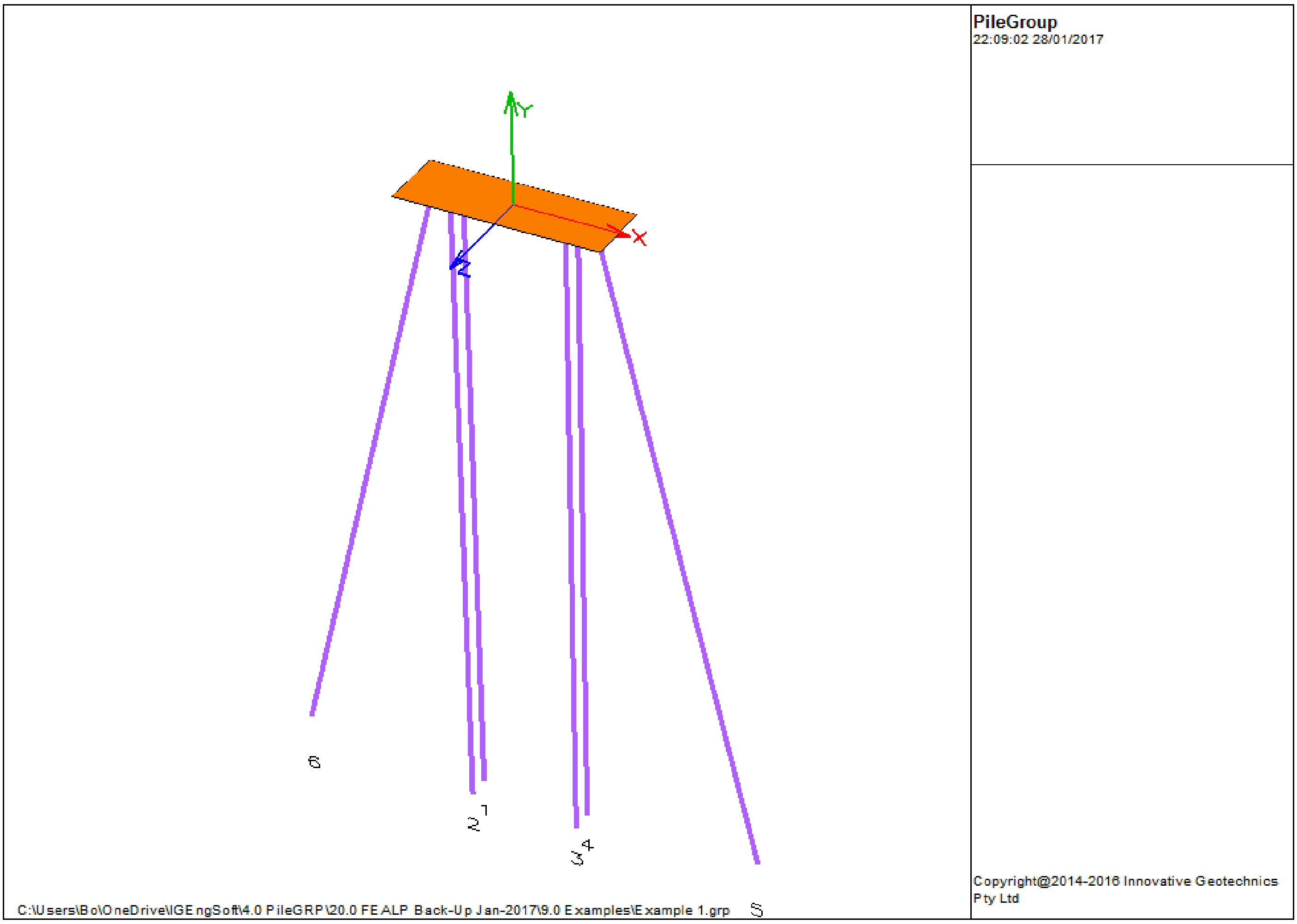



**Figure 6-3** Example of 3D geometry of pile group

# Chapter 7. Pile to Cap Connection Conditions

It is easy to specify the connection conditions between the pile head and pile cap in PileGroup program. The dialog of "Pile To Cap Connection" as shown in Figure 7-1 can be invoked by either clicking "Pile To Cap Connection" item under the "Define" menu or "Pile To Cap Connection" icon from the toolbar.

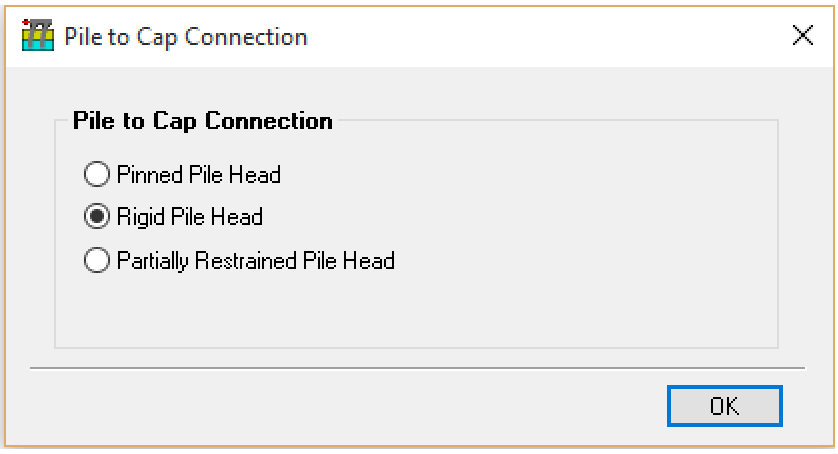



**Figure 7-1** Pile to cap connection input dialog

The following three different options can be used to define the connections between pile head and pile cap:

- Option 1: Pinned Pile Head. Pile head is free to rotate;
- Option 2: Rigid Pile Head. Pile head can move laterally but cannot rotate. Moment will be generated at the pile head; and
- Option 3: Partially Restrained Pile Head. Rotational spring value needs to be provided in the unit of moment per unit slope.

# Chapter 8. Soil Layers and Properties Input

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

In PileGroup, 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.

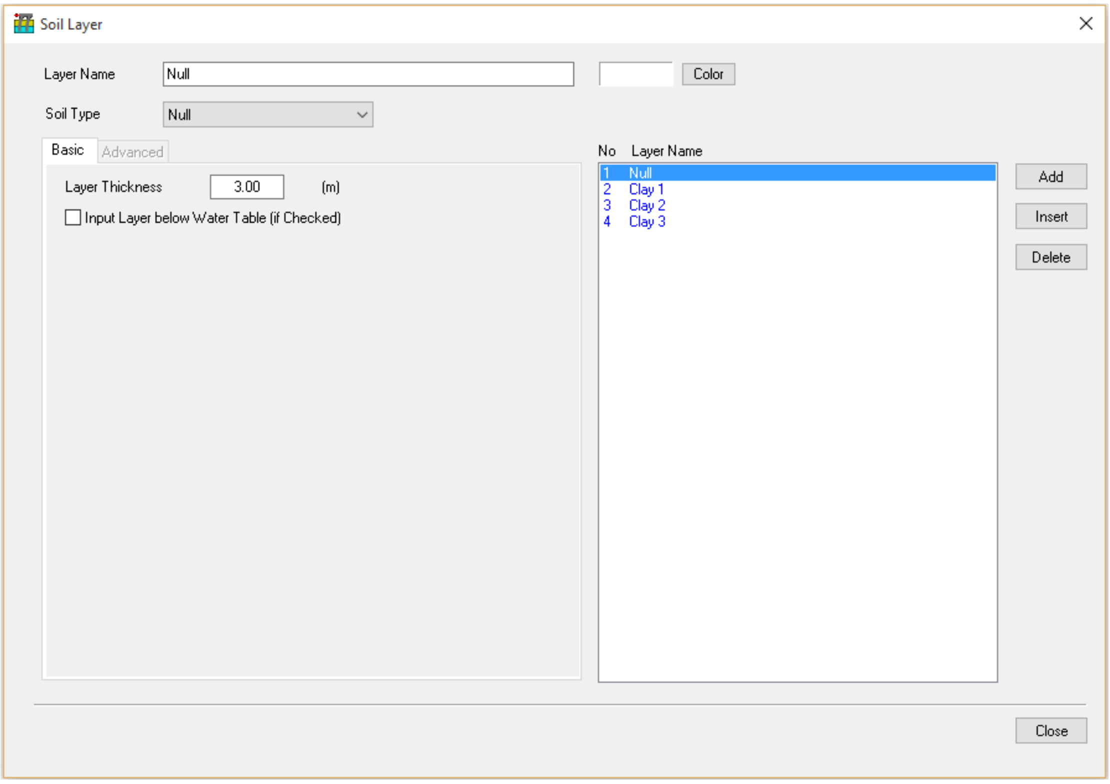



**Figure 8-1** Soil layers and properties input for “Null” type soil layer

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 PileGroup are presented in Appendix A.

Figure 8-1 shows the soil layer and property input for the layer with “Null” property. Since it is a layer with “Null” material type, the “Advanced” tab is disabled with grey colour and cannot be clicked. Noted that, if the check box of “Input Layer below Water Table” is ticked, this means that the first layer is under the water table. Figure 8-2 shows the example of soil layers and properties input of a clay layer for the basic parameters.

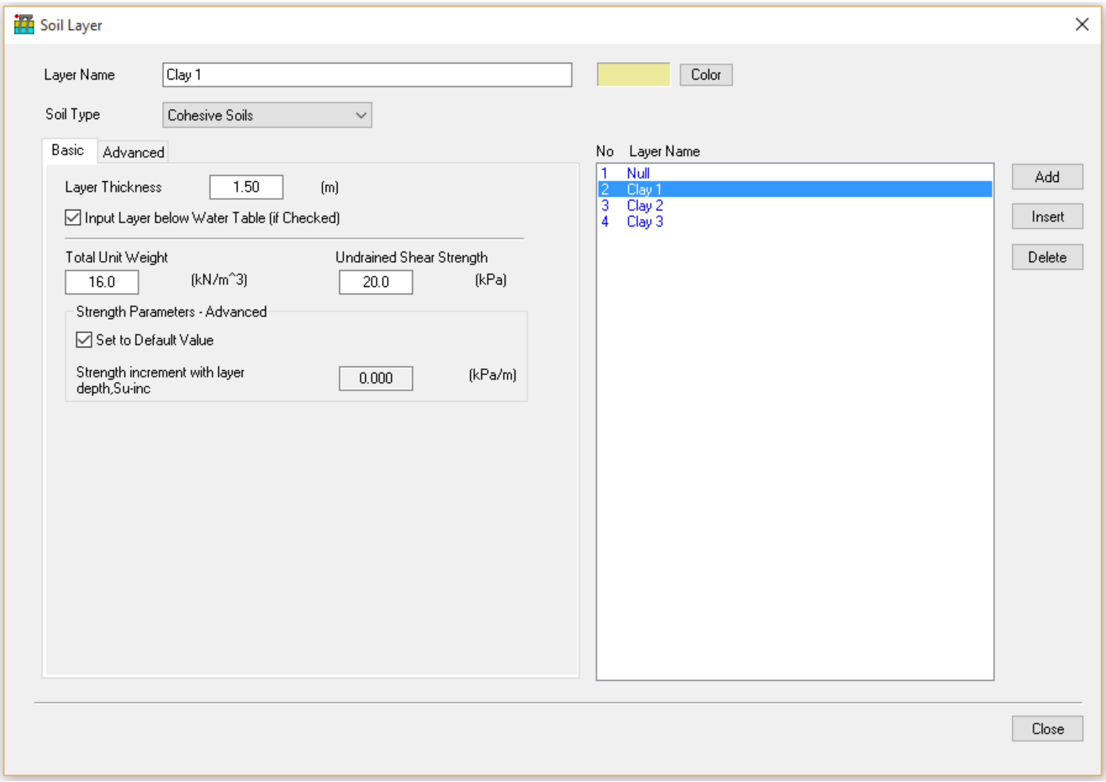



**Figure 8-2** Soil layers and properties input for a clay soil layer

Figure 8-3 shows the advanced parameters input for this layer. In this example, soft clay (Matlock) model is adopted as P-Y model with the default P-Y parameters.

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 “Close” button at the bottom or “X” button at the top right corner is pressed. The ground profile as shown in Figure 8-4 will be created and updated after any layer input is made. The ground profile also can be copied into the clipboard which can be later inserted into the word or excel document for reporting purpose.

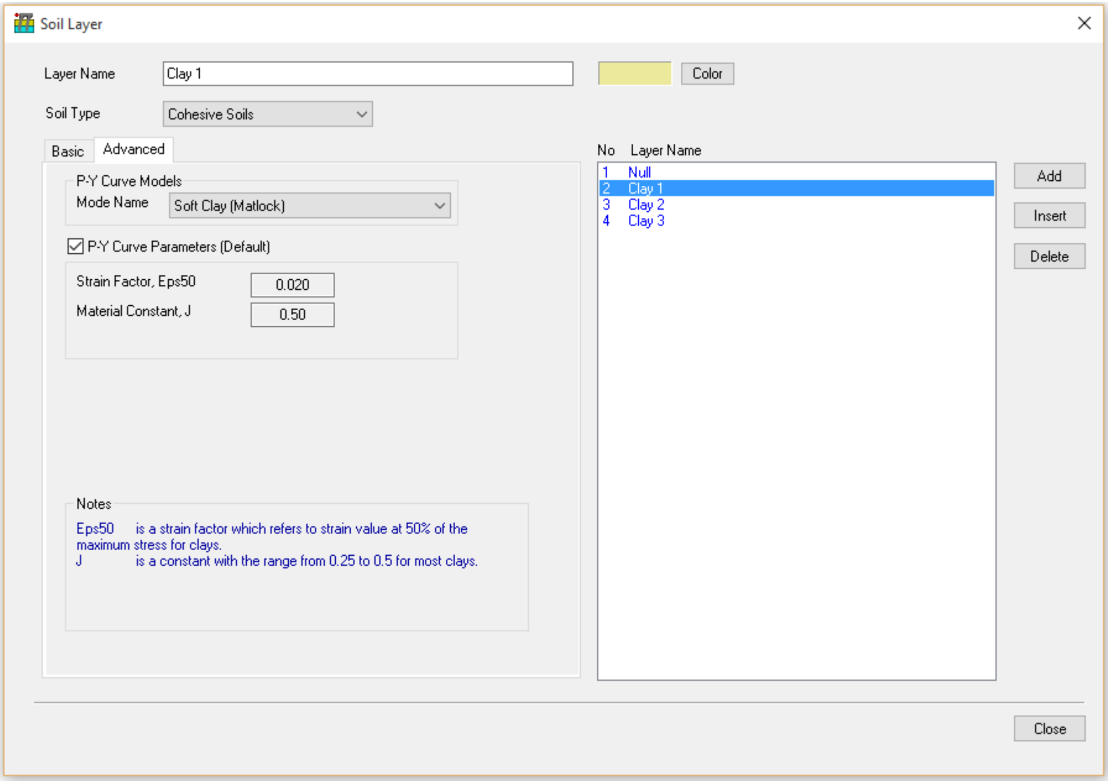



**Figure 8-3** Soil layers and properties input for a clay soil layer – advanced parameters

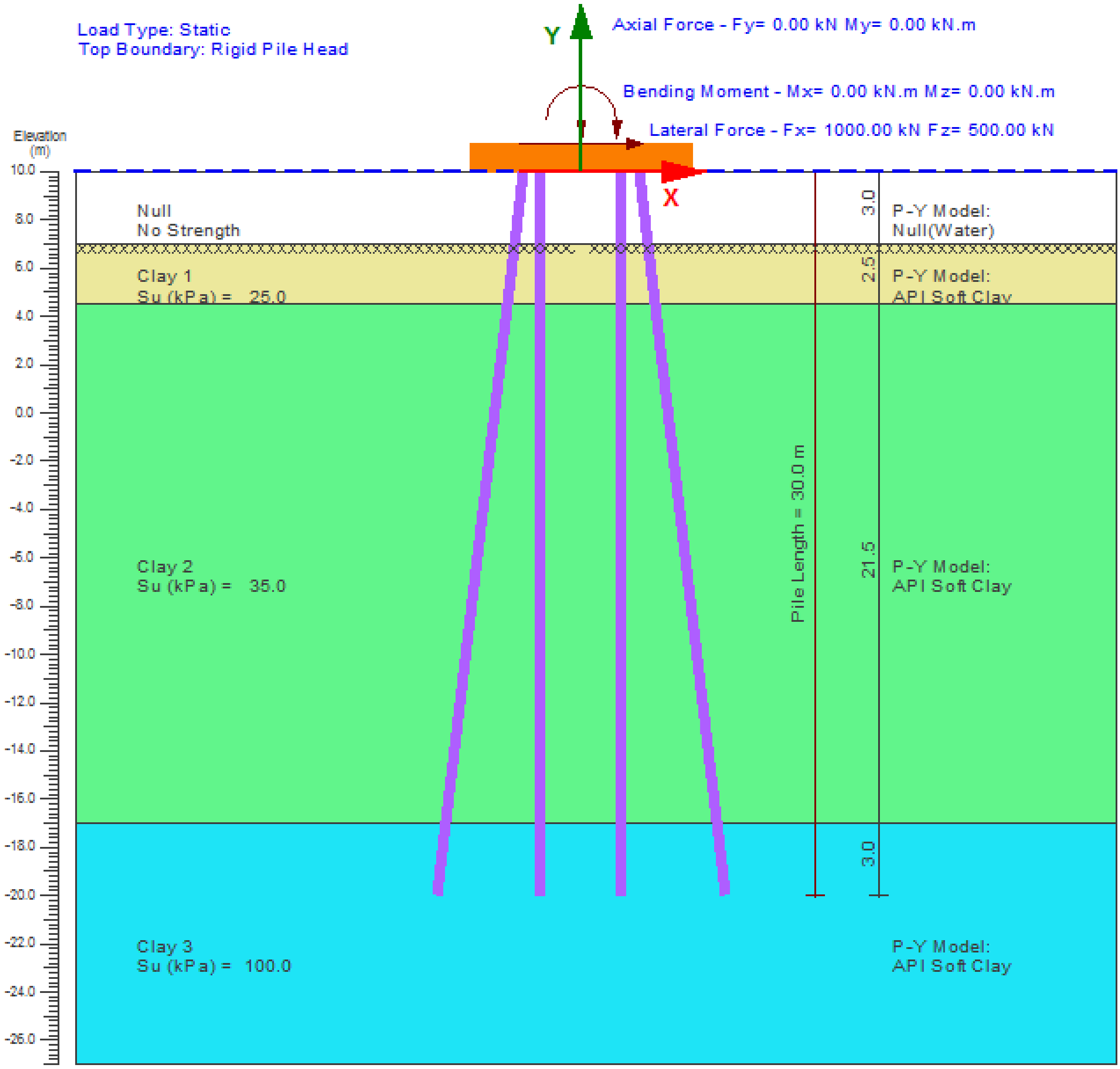



**Figure 8-4** Ground profile with the pile group geometry on the plane of XY

# Chapter 9. Pile Cap Load Input

The dialog box for the load input on the top of the pile cap for the pile group can be opened by clicking "Loading on Pile Cap" option under "Define" menu or "Pile Cap Load Input" icon from the toolbar. Axial force Fy, horizontal shear forces (Fx and Fz), bending moments (Mx and Mz) and rotational moment (My) on the pile cap can be input by the user through this dialog.

Figure 9-1 shows the “Pile Cap Load Input” dialog. The user can input different combinations of axial forces, horizontal shear forces, bending moments and torsions at different location of the pile cap. The program will automatically calculates the equivalent loads at the origin which can be used by the program in the analysis. The calculated loads at the origin will be displayed just below the load input box. Right-hand rule is adopted for the bending moment and rotational moment input.

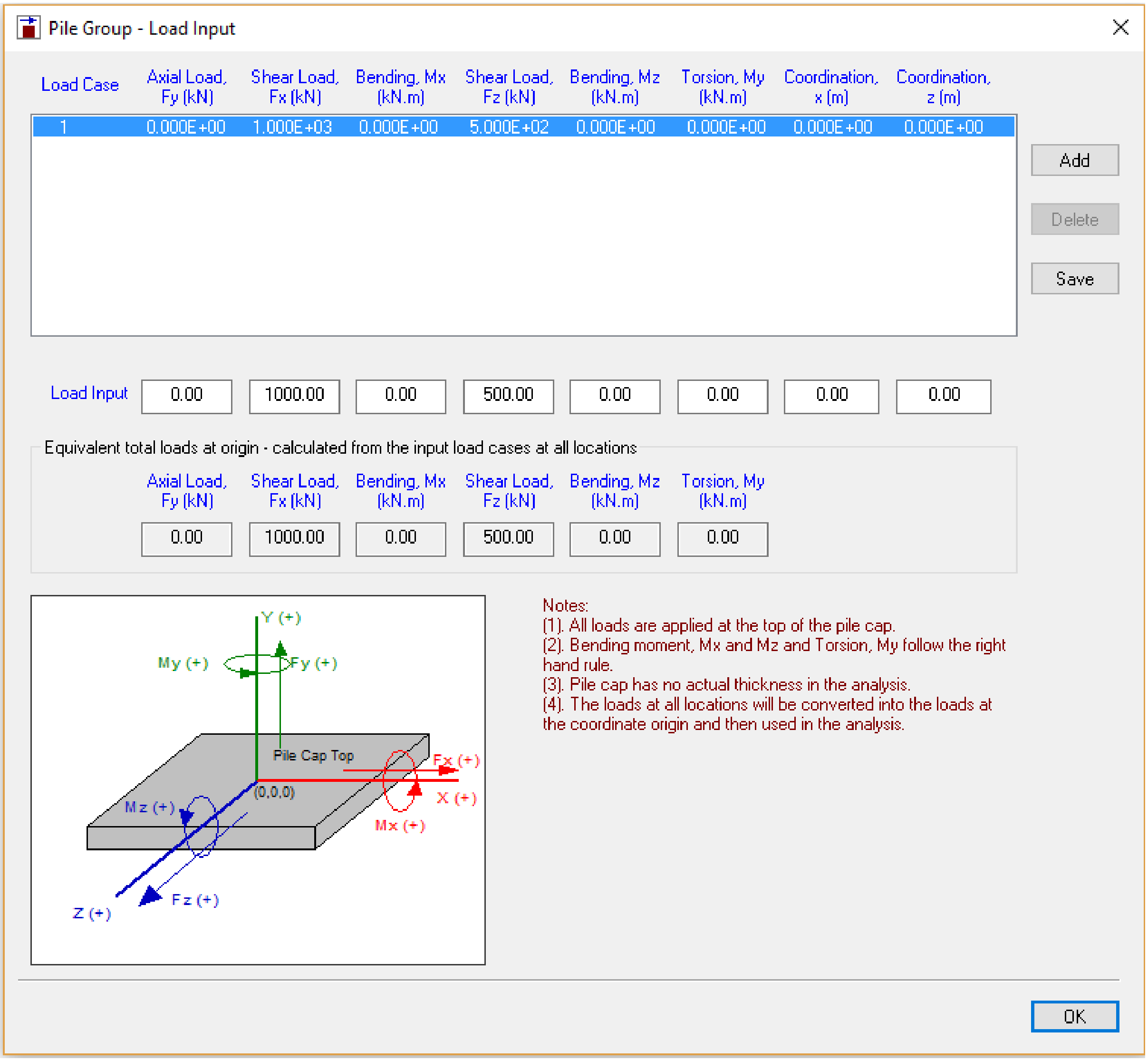



**Figure 9-1** Loads at the top of the pile cap

The following loads can be applied at the top of the pile cap:

- Axial load acting on the top of the pile cap, Fy, which is positive upwards (tension) and negative downwards (compression);
- Horizontal shear force acting on the pile cap along the global X direction, Fx;
- Horizontal shear force acting on the pile cap along the global Z direction, Fz;
- Bending moment acting on the pile cap about the global X direction, Mx;
- Bending moment acting on the pile cap about the global Z direction, Mz; and
- Rotational moment acting on the pile cap about the global Y direction, My.

The global X and Z coordinates of the loads can be input by the user for different load cases and the program will automatically calculate the equivalent loads at origin which will be used by the main calculation subroutines for the pile group analysis.

# Chapter 10. Pile Group Effect

PileGroup program offers comprehensive ways to deal with the pile group effects for both lateral and vertical loads applied at the pile cap. When a group of piles are subject to vertical or lateral loads, the pile group resistance is generally less than the sum of the individual pile resistance, depending on the pile spacing and locations within the group.

Three flexible options are available in PileGroup program for considering group capacity reduction due to group effects. The user can choose to (1) ignore group effects (widely spaced piles, for example.); (2) specify group reduction factors for each pile and (3) use the program-generated group reduction factors in the analysis. For the option 3, PileGroup program will automatically determine the group reduction factors for lateral loading based on the pile cap movement direction and individual pile positions and spacing within the group based on the recommendations by Reese and Van (2001).

The dialog for the group effect input option can be invoked by clicking "Pile Group Effect" option under "Define" menu or clicking “Pile Group Effect” icon from the toolbar.

Figure 10-1 shows the input dialog for the group factors for axial and lateral loading. For the group of “Reduction Factors for Lateral Loading”, the columns of “Pile No”, “X Coord (m)” and “Z Coord (m)” are for the pile number, X and Z coordinates for each individual piles within the group and are read only. PM-X and PM-Z are the P-Multipliers for each pile along the X direction and the Z direction, respectively on the pile cap plane (X-Z plane).

There are three different ways for the application of P-Multipliers in the program for pile group analysis:

- For the option of “Ignore Group Effects for Lateral Loading”, all P-Multipliers will be automatically set to 1 and cannot be changed by the users. Pile group effects will be ignored if this option is selected;
- For the option of “User-Specified Group Factors for Lateral Loading’’, the columns of “PM-X” and “PM-Z” become editable and the user can specify the values for P-Multipliers along X and Z directions. For this option, it is assumed that the P-Multipliers are the same for both positive and negative directions of X and Z axes on the X-Z plane;
- For the option of “Program-Generated Group Factors for Lateral Loading”, both columns of “PM-X” and “PM-Z” will become read-only and the program will automatically determine the P-Multiplier values based on the pile position, spacing and pile cap movement directions. This is the most advanced option to consider the pile group effects with using P-Y curve approach and is recommended for general pile group analysis. Noted that only P-Multipliers along the positive direction of X and Z axes are shown in the table on the input dialog and the actual values used by the program could vary between the negative and positive directions of X and Z axes on the X-Z plane, especially when the pile layout is not symmetric along the movement direction of the pile cap.

For the last option, PileGroup will carry out the analysis with ignoring pile group effects for lateral loading first, then update the values of PM-X and PM-Z based on the pile cap movement directions and re-carry out the group analysis with the updated P-Multipliers.

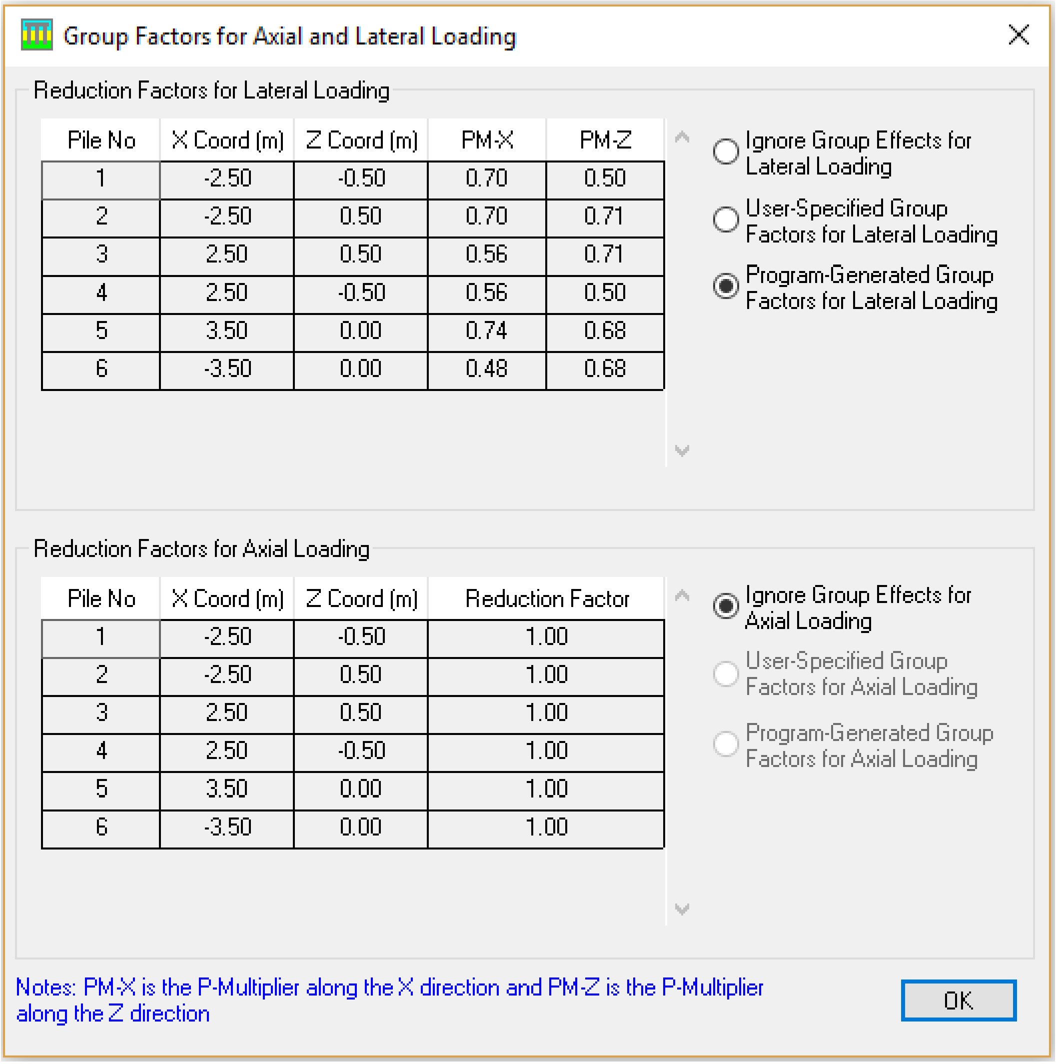



**Figure 10-1** Group Effects Input Options

PileGroup also allows the users to input the reduction factor for each individual pile to consider the effects of pile groups on the axial capacity of the piles. Similar to the group for the lateral loading, three different options are available in the program for the axial loading:

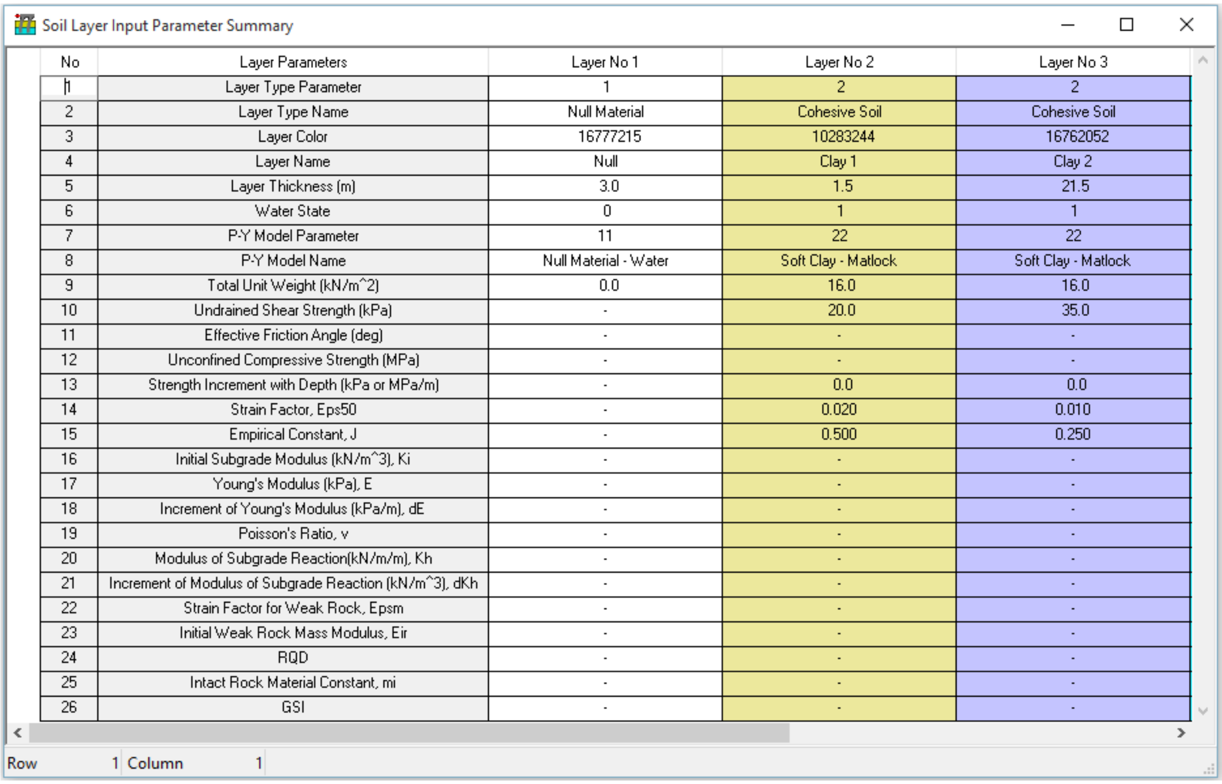
1. For the option of "Ignore Group Effects for Axial Loading", the column of "Reduction Factor" will be automatically set to 1 and cannot be changed by the user;
2. For the option of "User-Specified Group Factors for Axial Loading", the users are able to enter a value between 0.0 and 1.0 for the reduction factor in the column of "Reduction Factor"; and
3. For the option of "Program-Generated Group Factors for Axial Loading", the program will automatically generate the reduction factors for each pile within the group based on the pile diameter and spacing.

In the current version of PileGroup, both options 2 and 3 are not available.

# Chapter 11. Reviewing Soil Layer Input Parameters

PileGoup program 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 "Project" menu or "Soil Layer Input Summary" icon from the left toolbar.

The summary table is shown in Figure 11-1 which enables the user to review the detailed soil layer parameter inputs into the analysis and identify the input errors if any.



Soil Layer Input Parameter Summary

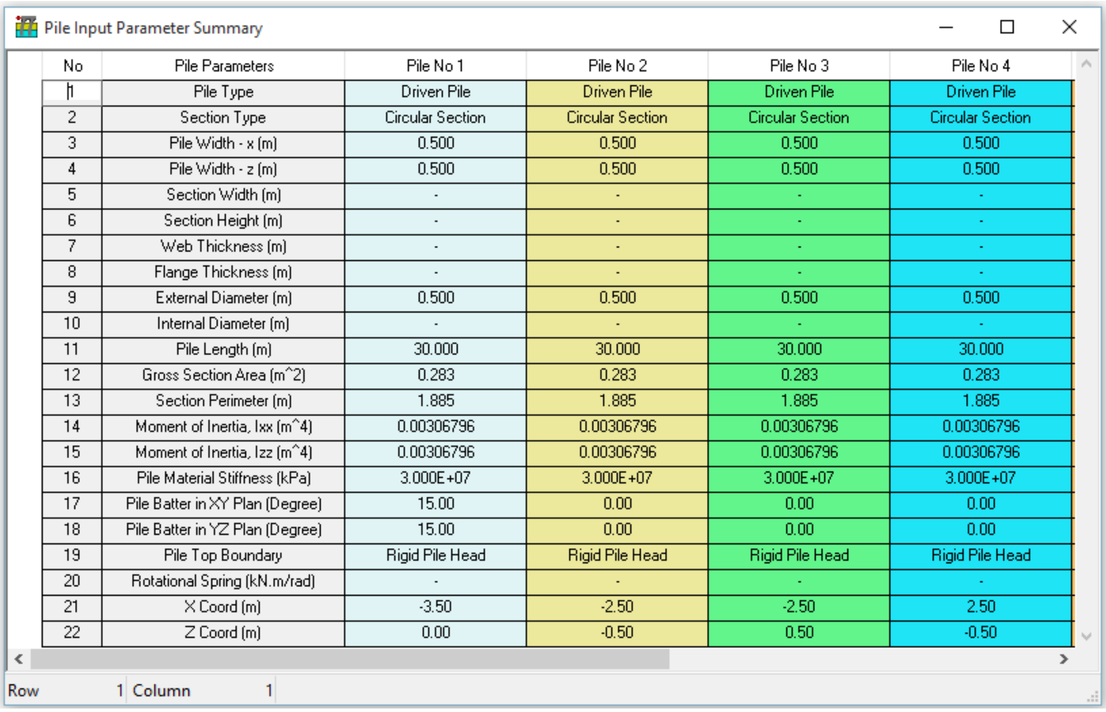
| No | Layer Parameters | Layer No 1 | Layer No 2 | Layer No 3 |
|---|---|---|---|---|
| 1 | Layer Type Parameter | 1 | 2 | 2 |
| 2 | Layer Type Name | Null Material | Cohesive Soil | Cohesive Soil |
| 3 | Layer Color | 16777215 | 10283244 | 16762052 |
| 4 | Layer Name | Null | Clay 1 | Clay 2 |
| 5 | Layer Thickness (m) | 3.0 | 1.5 | 21.5 |
| 6 | Water State | 0 | 1 | 1 |
| 7 | P-Y Model Parameter | 11 | 22 | 22 |
| 8 | P-Y Model Name | Null Material - Water | Soft Clay - Matlock | Soft Clay - Matlock |
| 9 | Total Unit Weight (kN/m^2) | 0.0 | 16.0 | 16.0 |
| 10 | Undrained Shear Strength (kPa) | - | 20.0 | 35.0 |
| 11 | Effective Friction Angle (deg) | - | - | - |
| 12 | Unconfined Compressive Strength (MPa) | - | - | - |
| 13 | Strength Increment with Depth (kPa or MPa/m) | - | 0.0 | 0.0 |
| 14 | Strain Factor, Eps50 | - | 0.020 | 0.010 |
| 15 | Empirical Constant, J | - | 0.500 | 0.250 |
| 16 | Initial Subgrade Modulus (kN/m^3), Ki | - | - | - |
| 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 | - | - | - |
| 24 | RQD | - | - | - |
| 25 | Intact Rock Material Constant, mi | - | - | - |
| 26 | GSI | - | - | - |

Row 1 Column 1

**Figure 11-1** Soil layer input summary table for an example

# Chapter 12. Reviewing Pile Input Parameters

Similar to soil layer input parameters, pile input summary table can be opened through clicking "Pile Input Summary" option under "Project" menu or pressing "Pile Input Summary" from the left toolbar. It summaries the values of pile input parameters from the user. The dialog as shown in Figure 12-1 enables the user to review the input parameters related to the pile type, section type, section dimension, material stiffness, top connection conditions, pile positions and pile batters.

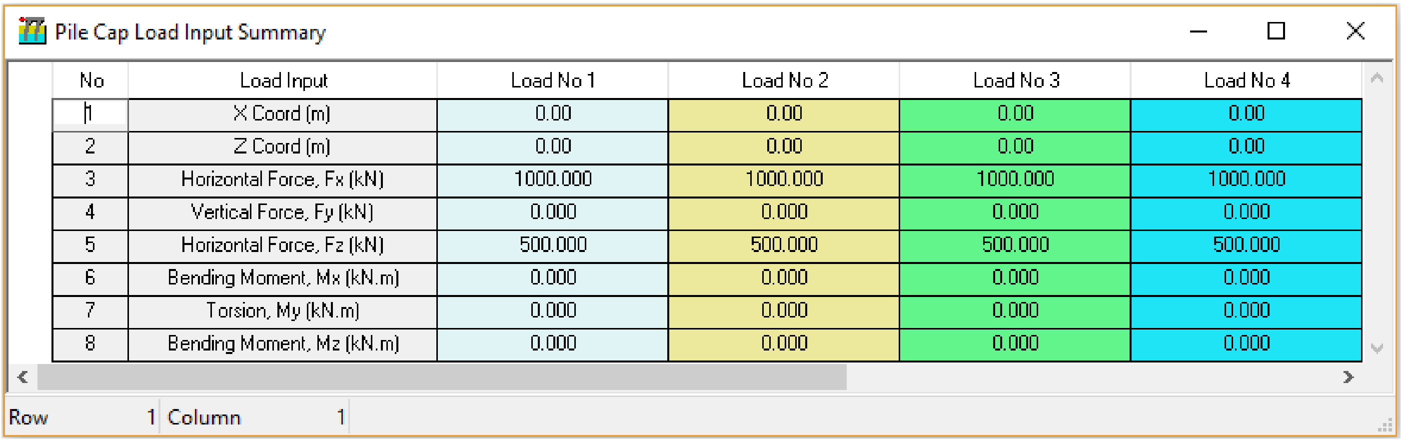


| No | Pile Parameters | Pile No 1 | Pile No 2 | Pile No 3 | Pile No 4 |
|---|---|---|---|---|---|
| 1 | Pile Type | Driven Pile | Driven Pile | Driven Pile | Driven Pile |
| 2 | Section Type | Circular Section | Circular Section | Circular Section | Circular Section |
| 3 | Pile Width - x (m) | 0.500 | 0.500 | 0.500 | 0.500 |
| 4 | Pile Width - z (m) | 0.500 | 0.500 | 0.500 | 0.500 |
| 5 | Section Width (m) | - | - | - | - |
| 6 | Section Height (m) | - | - | - | - |
| 7 | Web Thickness (m) | - | - | - | - |
| 8 | Flange Thickness (m) | - | - | - | - |
| 9 | External Diameter (m) | 0.500 | 0.500 | 0.500 | 0.500 |
| 10 | Internal Diameter (m) | - | - | - | - |
| 11 | Pile Length (m) | 30.000 | 30.000 | 30.000 | 30.000 |
| 12 | Gross Section Area (m^2) | 0.283 | 0.283 | 0.283 | 0.283 |
| 13 | Section Perimeter (m) | 1.885 | 1.885 | 1.885 | 1.885 |
| 14 | Moment of Inertia, Ixx (m^4) | 0.00306796 | 0.00306796 | 0.00306796 | 0.00306796 |
| 15 | Moment of Inertia, Izz (m^4) | 0.00306796 | 0.00306796 | 0.00306796 | 0.00306796 |
| 16 | Pile Material Stiffness (kPa) | 3.000E+07 | 3.000E+07 | 3.000E+07 | 3.000E+07 |
| 17 | Pile Batter in XY Plan (Degree) | 15.00 | 0.00 | 0.00 | 0.00 |
| 18 | Pile Batter in YZ Plan (Degree) | 15.00 | 0.00 | 0.00 | 0.00 |
| 19 | Pile Top Boundary | Rigid Pile Head | Rigid Pile Head | Rigid Pile Head | Rigid Pile Head |
| 20 | Rotational Spring (kN.m/rad) | - | - | - | - |
| 21 | X Coord (m) | -3.50 | -2.50 | -2.50 | 2.50 |
| 22 | Z Coord (m) | 0.00 | -0.50 | 0.50 | -0.50 |

**Figure 12-1** Pile group analysis input summary table

# Chapter 13. Reviewing Pile Cap Load Input

Pile cap load input summary table can be viewed through clicking "Pile Input Summary" option under "Define" menu. It summaries the pile cap loadings input from the user. The dialog as shown in Figure 13-1 enables the users to review the detailed information of various loadings input by the users.




| No | Load Input | Load No 1 | Load No 2 | Load No 3 | Load No 4 |
|---|---|---|---|---|---|
| 1 | X Coord (m) | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | Z Coord (m) | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | Horizontal Force, Fx (kN) | 1000.000 | 1000.000 | 1000.000 | 1000.000 |
| 4 | Vertical Force, Fy (kN) | 0.000 | 0.000 | 0.000 | 0.000 |
| 5 | Horizontal Force, Fz (kN) | 500.000 | 500.000 | 500.000 | 500.000 |
| 6 | Bending Moment, Mx (kN.m) | 0.000 | 0.000 | 0.000 | 0.000 |
| 7 | Torsion, My (kN.m) | 0.000 | 0.000 | 0.000 | 0.000 |
| 8 | Bending Moment, Mz (kN.m) | 0.000 | 0.000 | 0.000 | 0.000 |

**Figure 13-1** Pile input summary table for an example

# Chapter 14. Run Analysis

Pile group analysis can be started by clicking "Run Analysis" option under "Analyze" menu or clicking “Run Analysis” icon from the top toolbar. The message dialog box as shown in Figure 14-1 details the load step information during the analysis, which includes maximum displacement, force error, analysis status and warning messages.

The analysis is considered to be successful when 100% of applied loads are solved within the specified error tolerance. Otherwise, warning messages 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.

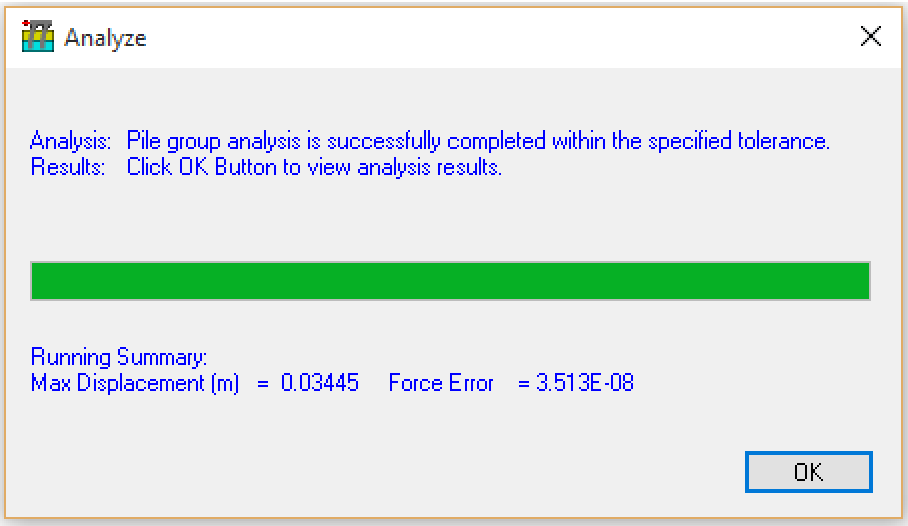



**Figure 14-1** Run Analysis Message Box during Pile Group Analysis

# Chapter 15. Viewing Analysis Results for Pile Cap and Pile Top

PileGroup provides an easy way to access various analysis results such as pile top results and detailed analysis results along the pile lengths. In general, the results which are available to the users once the analysis is completed successfully include (1) analysis result summary at the pile cap and pile top and (2) detailed analysis results along the pile length for each individual pile within the group.

The analysis result summary at the pile top includes the following results:

1. Pile cap deformations and rotations along X, Y and Z axes under the applied loads – Displacements X, Y, and Z, Rotation X, Y and Z;
2. Pile top deformations and rotations along X, Y and Z axes for each individual pile within the group – Displacements X, Y and Z, Rotation X, Y and Z; and
3. Pile top reactions such as axial force Fy, shear forces Fx and Fz, bending moments Mx and Mz and rotational moment My for each individual pile within the group.

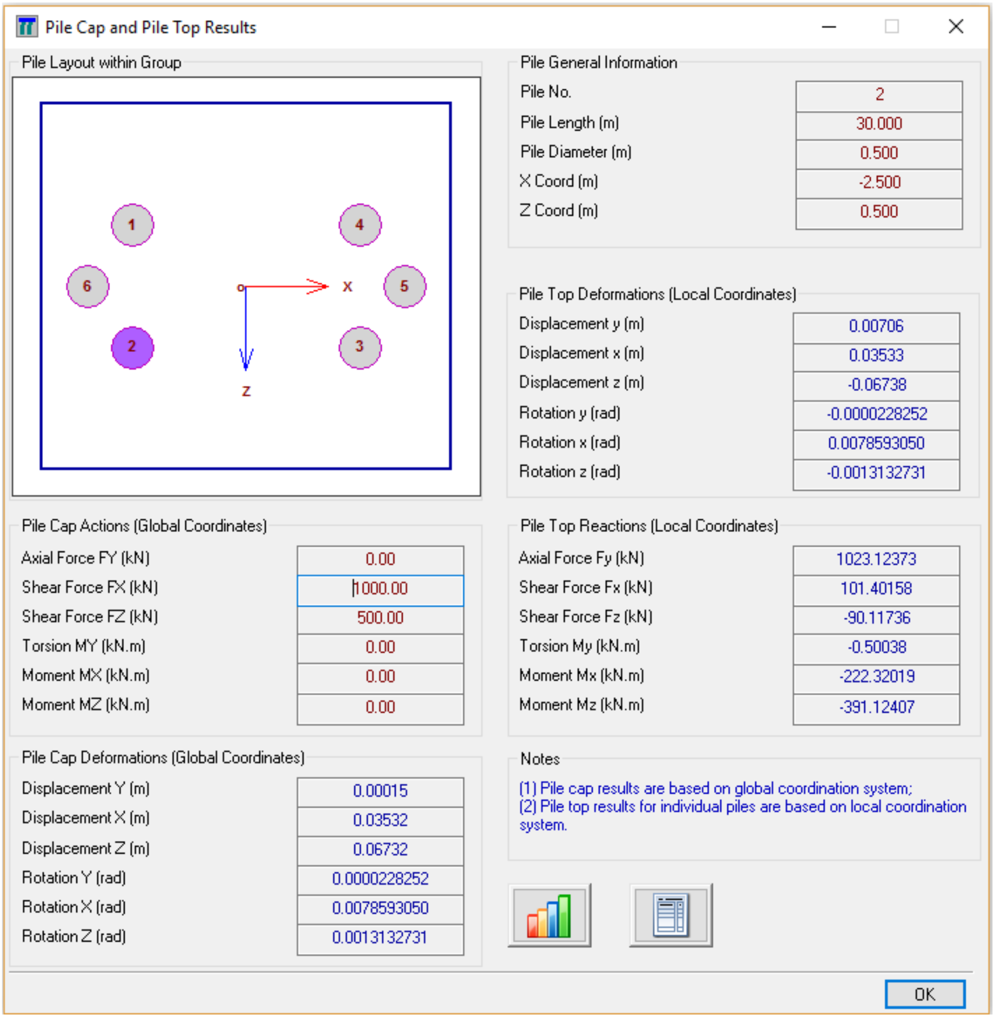



**Figure 15-1** Analysis results for pile cap and pile top

The dialog box for the pile cap and pile top results can be opened by clicking "Pile Top Results" option under "Graph" menu or clicking “Pile Top Results” icon from the top toolbar. Figure 15-1 shows the dialog of the pile cap and pile top results which comprise of two parts: (1) Pile Cap Deformations under global coordinate and (2) Pile Top Deformations and Reactions under local coordinates.

The users can select any pile within the group to view the results at the pile top by clicking the pile position shown on the graphical pile layout.

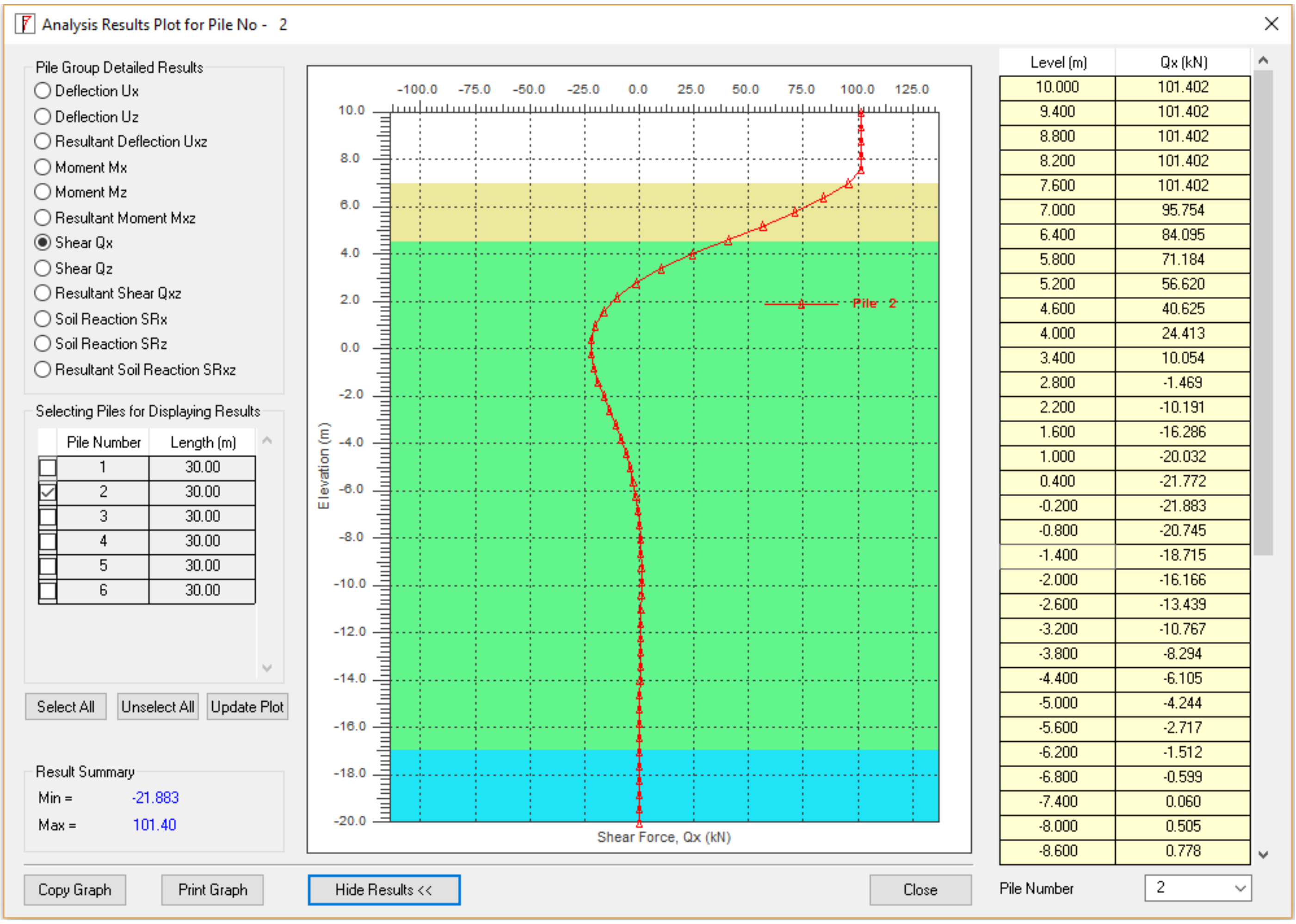



**Figure 15-2** Pile group analysis result plot

Once a pile is selected for results displaying, the detailed analysis results along the pile length can be viewed by the users by pressing “Graph” button closed to the bottom of the dialog. A new dialog will be invoked and the following analysis results are available for viewing:

1. Distribution of the lateral deflection of each pile with the elevation or depth – Ux, Uz and Uxz;
2. Distribution of the pile bending moment with the elevation or depth – Mx, Mz and Mxz;
3. Distribution of the pile shear force with the elevation or depth – Qx, Qz and Qxz;
4. Distribution of the mobilised soil reaction with the elevation or depth – SRx, SRz and SRXz;

Clicking the corresponding radio button at the left side under the group of “Pile Group Results” enables the users 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.

The program 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 the “Analysis Results” Dialog. The copied graph can be easily pasted into the third-party application for reporting purpose.

# Chapter 16. Pile Cap Deformation Results

PileGroup presents the contour shading plot of horizontal displacements (Ux and Uz) and vertical displacement (Uy) for any point on the pile cap as shown in Figure 16-1. The dialog box for the pile cap deformation result shading ploy can be opened by clicking "Pile Cap Deformation" icon from the left toolbar.

The dimension of the pile cap for deformation results plot is automatically set as follows:

- X coordinate for left bottom corner is minimum X coordinate of all pile positions minus one pile diameter;
- Z coordinate for left bottom corner is maximum Z coordinate of all pile positions plus one pile diameter;
- X coordinate for right top corner is maximum X coordinate of all pile positions plus one pile diameter; and
- Z coordinate for left bottom corner is minimum Z coordinate of all pile positions minus one pile diameter;

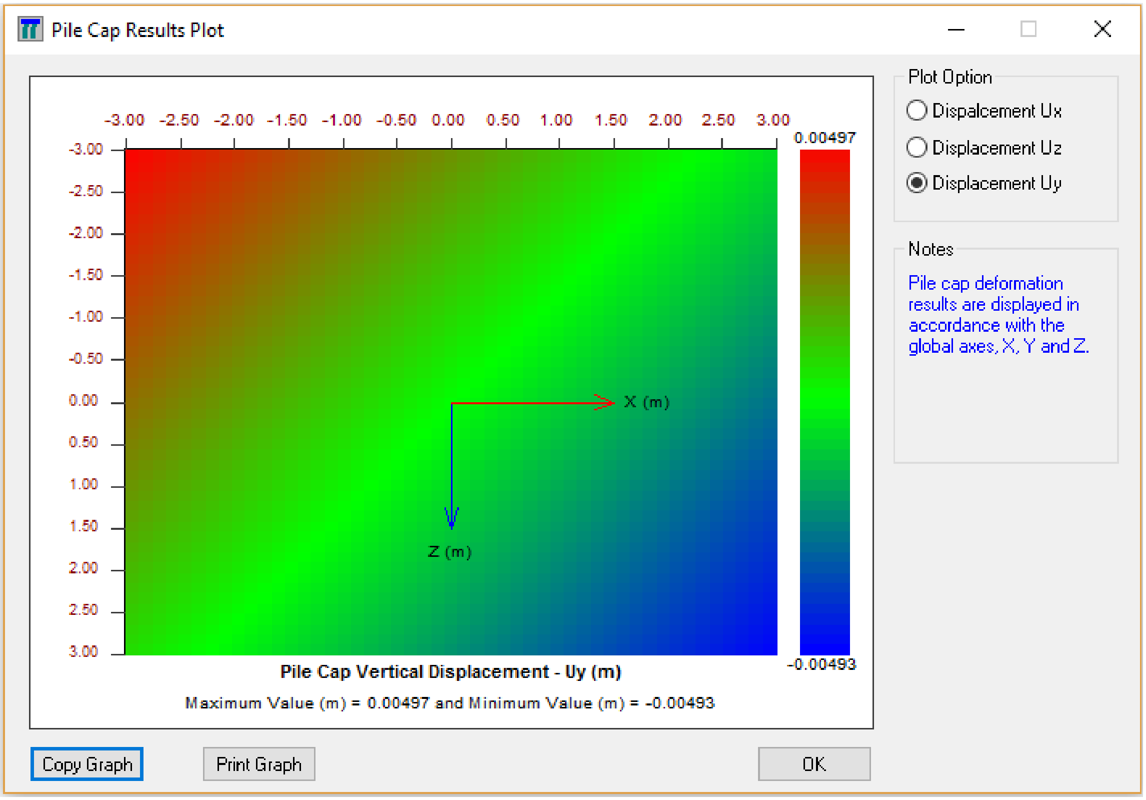



**Figure 16-1** Pile cap deformation result shading plot

# Chapter 17. Viewing P-Y Curves

In PileGroup, 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.

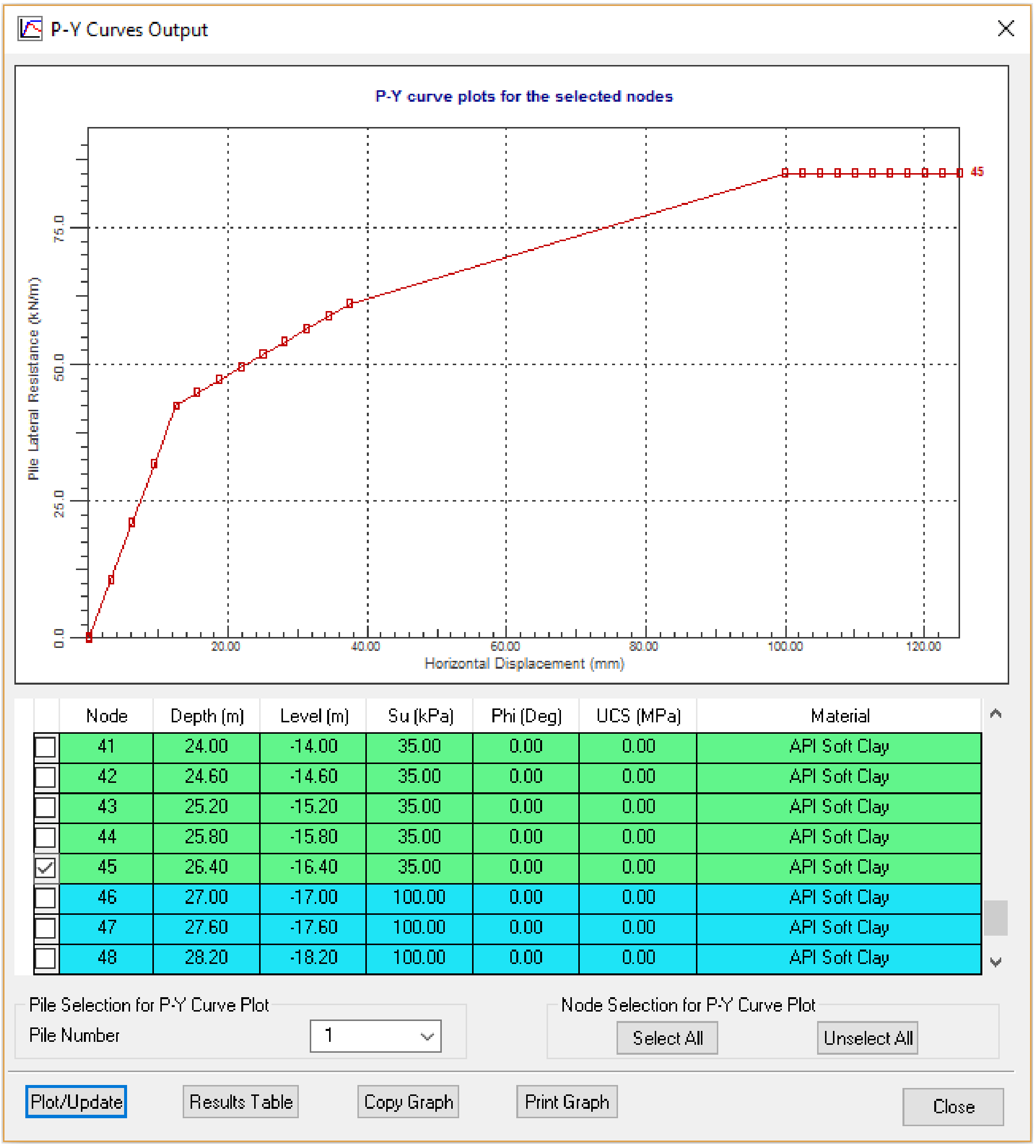



**Figure 17-1** Soil p-y curve plot dialog

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:

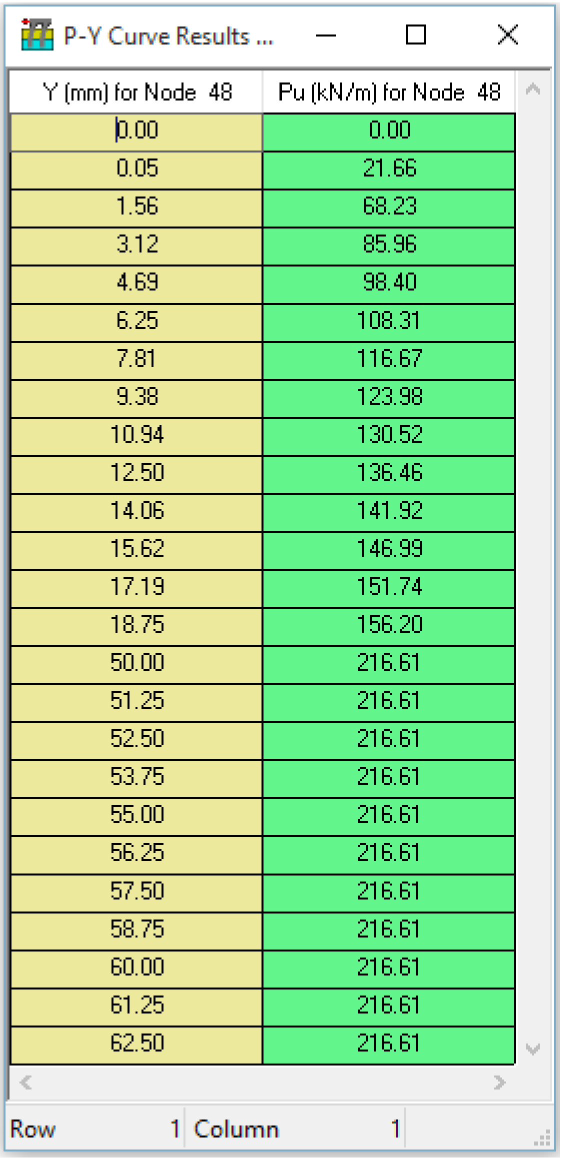
Step 1: Tick the check box for the pile node number where you want to view the results. Note that multiple node points can be selected;

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, Undrained shear strength (Su) at the layer top, Effective angle of friction (Phi), Unconfined compressive strength (UCS) at the layer top 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.

Under the group of "Pile Selection for P-Y Curve Plot", the users can select the Pile Number for which P-Y curves will be displayed for the selected nodes. The users can select or unselect all nodes for P-Y Curve Plot through the group of "Node Selection for P-Y Curve Plot". This helps the users to re-select the nodes for display without the needs to update the selection for each previously selected node.

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" displacement (mm) and "P" mobilised lateral pile force (kN/m) for the selected node points.




| Y (mm) for Node 48 | Pu (kN/m) for Node 48 |
|---|---|
| 0.00 | 0.00 |
| 0.05 | 21.66 |
| 1.56 | 68.23 |
| 3.12 | 85.96 |
| 4.69 | 98.40 |
| 6.25 | 108.31 |
| 7.81 | 116.67 |
| 9.38 | 123.98 |
| 10.94 | 130.52 |
| 12.50 | 136.46 |
| 14.06 | 141.92 |
| 15.62 | 146.99 |
| 17.19 | 151.74 |
| 18.75 | 156.20 |
| 50.00 | 216.61 |
| 51.25 | 216.61 |
| 52.50 | 216.61 |
| 53.75 | 216.61 |
| 55.00 | 216.61 |
| 56.25 | 216.61 |
| 57.50 | 216.61 |
| 58.75 | 216.61 |
| 60.00 | 216.61 |
| 61.25 | 216.61 |
| 62.50 | 216.61 |

**Figure 17-2** Tabulated p-y curve results

The program 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 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 17-3 for this example.

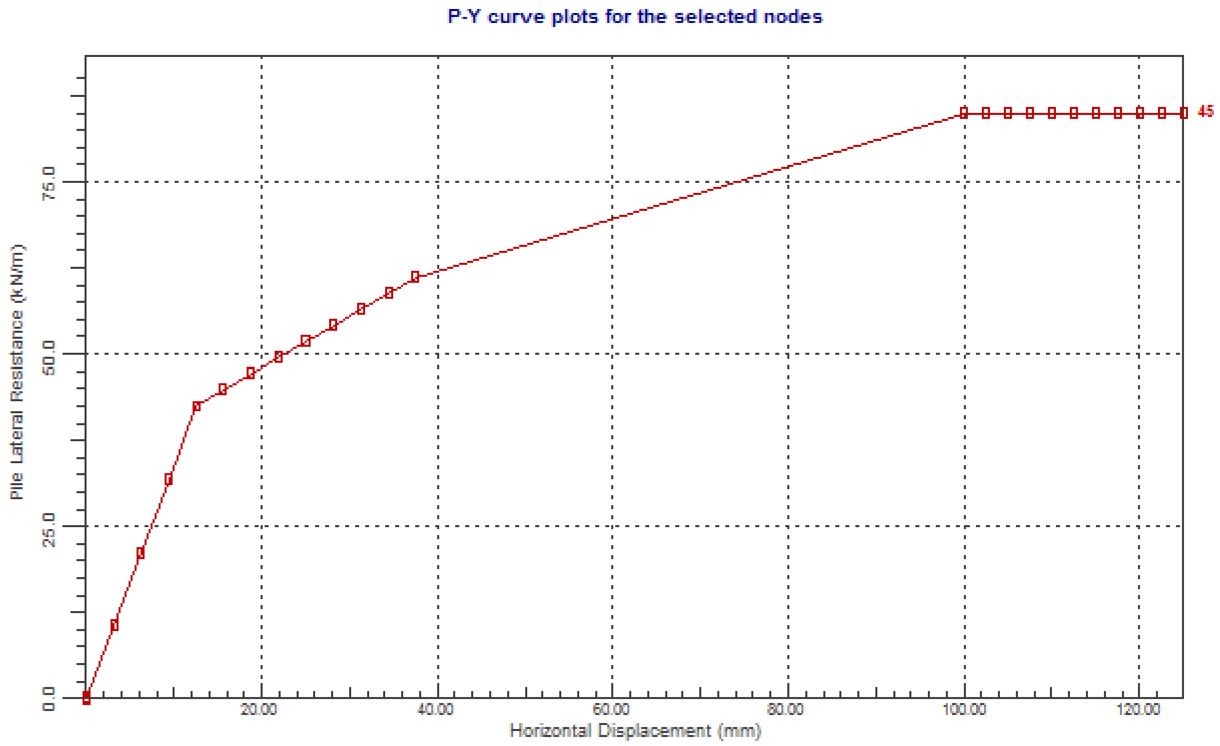



**Figure 17-3** Copied p-y curve graph

# Chapter 18. Pile Axial Load Settlement and Torque Rotation Curve

For settlement calculation of the piles within the group, 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.

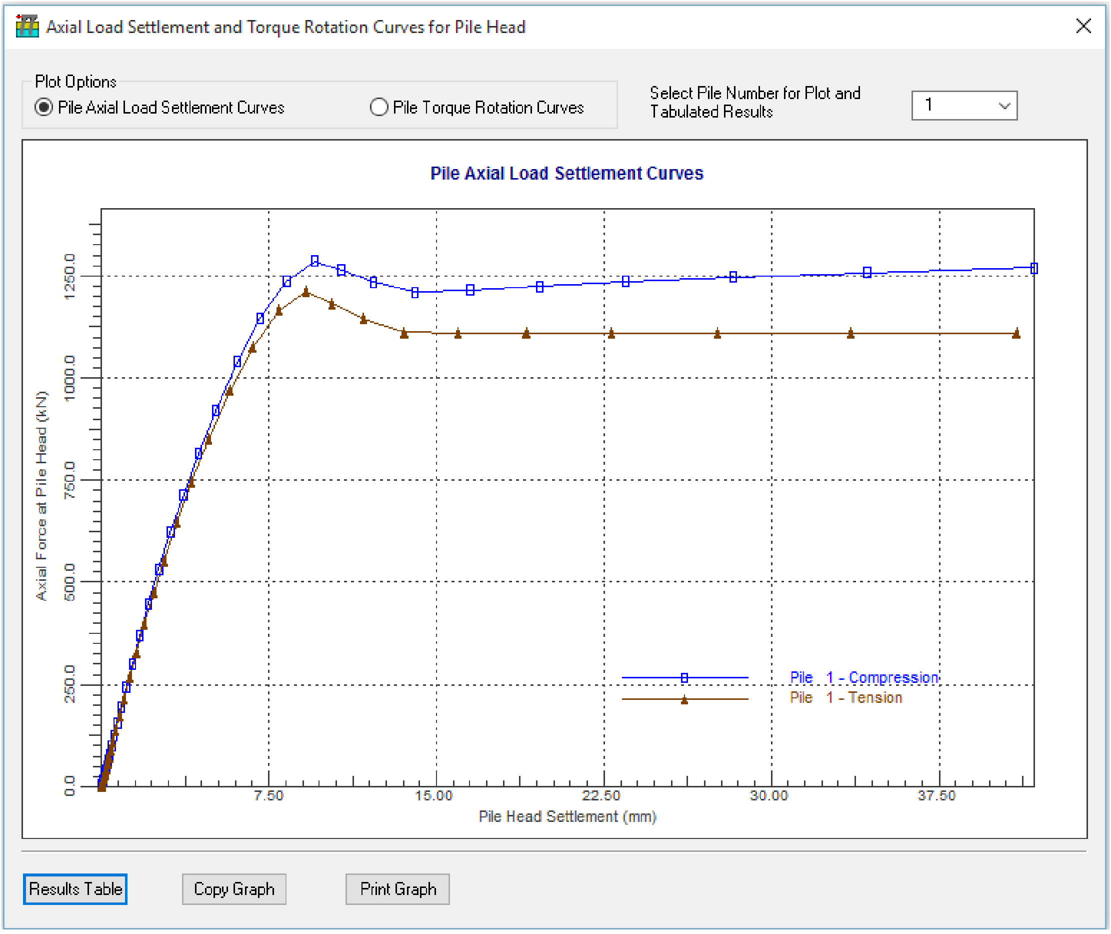



**Figure 18-1** "Axial Load Settlement Curve and Torque Rotation Plot" dialog

In additions to the lateral and axial loading on the top of each pile within the group, torsion will be also applied to the pile heads through the connections between the pile heads and pile cap under the general loading conditions. In PileGroup, a hyperbolic relationship is assumed for the torsional spring (T-θ Spring) at the pile head, where T is the torque at the pile head and θ is the angle of twist in radians.

Detailed approaches to calculate the ultimate shaft resistance, ultimate end bearing resistance for different types of soils or rocks together with t-z, q-w and T-θ nonlinear curves are briefly reviewed and summarised in the Appendix B and Appendix C.

The dialog for pile settlement and torque rotation curve plot can be invoked by clicking the "Axial Load Settlement and Torque Rotation Plot" option under "Display" menu or "Axial Load Settlement and Torque

Rotation Plot" icon from the toolbar.

Figure 18-1 shows the "Axial Load Settlement and Torque Rotation Plot" dialog. Two different plot options are available to the users: (1) Pile Axial Load Settlement Curve and (2) Pile Torque Rotation Curve. Load-settlement curve is generated by the program for the specified axial loading at the pile head for the selected pile. The calculation of ultimate shaft resistance, ultimate end bearing resistance and ultimate axial pile capacity both in compression and tension are carried out by the program. For the torque and rotation curve, the torque at the pile head is calculated and plotted against the rotation in radian. Under the group of "Select Pile Number for Plot and Tabulated Results", the users can select the pile number for which the results will be plotted.

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

Pile Head Load Settlement and Torque Torsion Curves for Pile Number 4

| Pile Settlement (mm) | Pile Compression (kN) | Pile Uplift (mm) | Pile Tension (kN.m) | Pile Head Rotatior |
|---|---|---|---|---|
| 0.0000 | 0.00 | 0.0000 | 0.00 | 0.00000 |
| 0.0005 | 0.12 | 0.0005 | 0.10 | 0.00408 |
| 0.0012 | 0.27 | 0.0011 | 0.24 | 0.00816 |
| 0.0021 | 0.45 | 0.0018 | 0.40 | 0.01224 |
| 0.0031 | 0.68 | 0.0028 | 0.60 | 0.01633 |
| 0.0044 | 0.97 | 0.0040 | 0.86 | 0.02041 |
| 0.0061 | 1.33 | 0.0055 | 1.18 | 0.02449 |
| 0.0081 | 1.79 | 0.0073 | 1.58 | 0.02857 |
| 0.0107 | 2.35 | 0.0096 | 2.07 | 0.03265 |
| 0.0139 | 3.06 | 0.0125 | 2.70 | 0.03673 |
| 0.0179 | 3.94 | 0.0161 | 3.48 | 0.04082 |
| 0.0229 | 5.04 | 0.0207 | 4.45 | 0.04490 |
| 0.0292 | 6.42 | 0.0263 | 5.66 | 0.04898 |
| 0.0370 | 8.14 | 0.0334 | 7.19 | 0.05306 |
| 0.0468 | 10.30 | 0.0422 | 9.09 | 0.05714 |
| 0.0590 | 12.99 | 0.0532 | 11.46 | 0.06122 |
| 0.0743 | 16.36 | 0.0670 | 14.43 | 0.06531 |
| 0.0934 | 20.56 | 0.0842 | 18.15 | 0.06939 |
| 0.1173 | 25.82 | 0.1058 | 22.79 | 0.07347 |
| 0.1472 | 32.40 | 0.1327 | 28.59 | 0.07755 |
| 0.1846 | 40.61 | 0.1664 | 35.84 | 0.08163 |
| 0.2312 | 50.89 | 0.2085 | 44.90 | 0.08571 |
| 0.2896 | 63.73 | 0.2611 | 56.23 | 0.08980 |
| 0.3625 | 79.78 | 0.3268 | 70.40 | 0.09388 |
| 0.4537 | 99.84 | 0.4090 | 88.10 | 0.09796 |
| 0.5677 | 124.92 | 0.5117 | 110.23 | 0.10204 |
| 0.7101 | 156.26 | 0.6402 | 137.89 | 0.10612 |
| 0.8882 | 195.45 | 0.8007 | 172.47 | 0.11020 |
| 1.1102 | 243.66 | 1.0012 | 215.52 | 0.11429 |

Row 24 Column 4

**Figure 18-2** Tabulated axial load settlement and torque rotation curve results

PileGroup program 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 18-3.

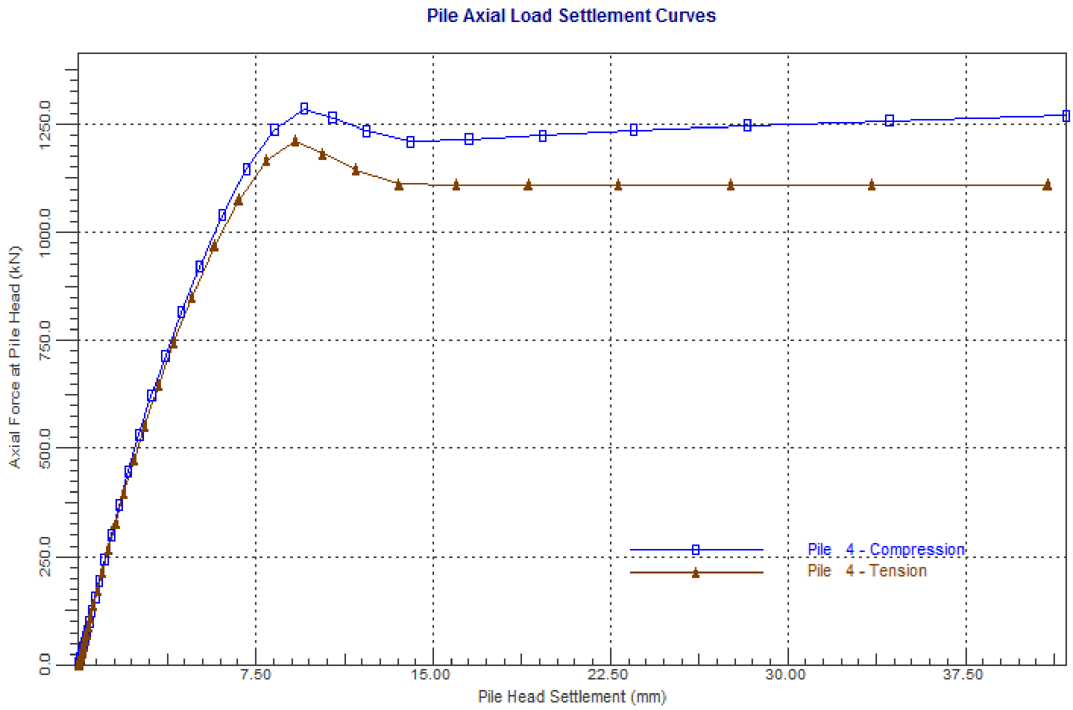



**Figure 18-3** Copied axial load pile settlement curve

# Chapter 19. Three-Dimensional Visualization of Analysis Results

PileGroup presents three-dimensional visualization of analysis results after pile group analysis is successfully completed. This unique feature offers the users the opportunities of viewing various deformation and force plots within 3D space. Advanced 3D display options as shown in Figure 19-1 are available to the users for various 3D displaying details.

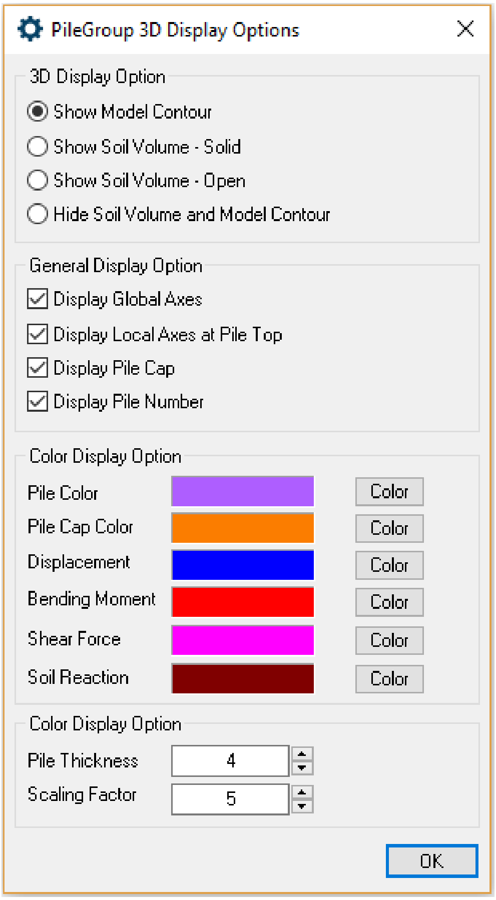



**Figure 19-1** PileGroup 3D display options

The following results are available for 3D viewing in PileGroup:

1. Deformed shape of pile group;
2. Total pile group displacements Uxz;
3. Pile group displacement Ux;
4. Pile group displacement Uz;
5. Bending moment distribution along length for all piles – Mx (about global axis X);
6. Bending moment distribution along length for all piles – Mz (about global axis Z);

7. Bending moment distribution along length for all piles – Qx (along global axis X);
8. Bending moment distribution along length for all piles – Qz (along global axis Z);
9. Soil reaction distribution along length for all piles – SRx (along global axis X);
10. Soil reaction distribution along length for all piles – SRz (along global axis Z);

Note that the items from 2 to 10 are presented together with undeformed shape of pile group. Displaying items for displacements can be opened by clicking “Deformations” menu. Displaying items for bending moments, shear forces and soil reactions can be opened by clicking “Forces 3D” menu. All the results can be copied into clipboard and pasted into word or excel files for reporting purposes.

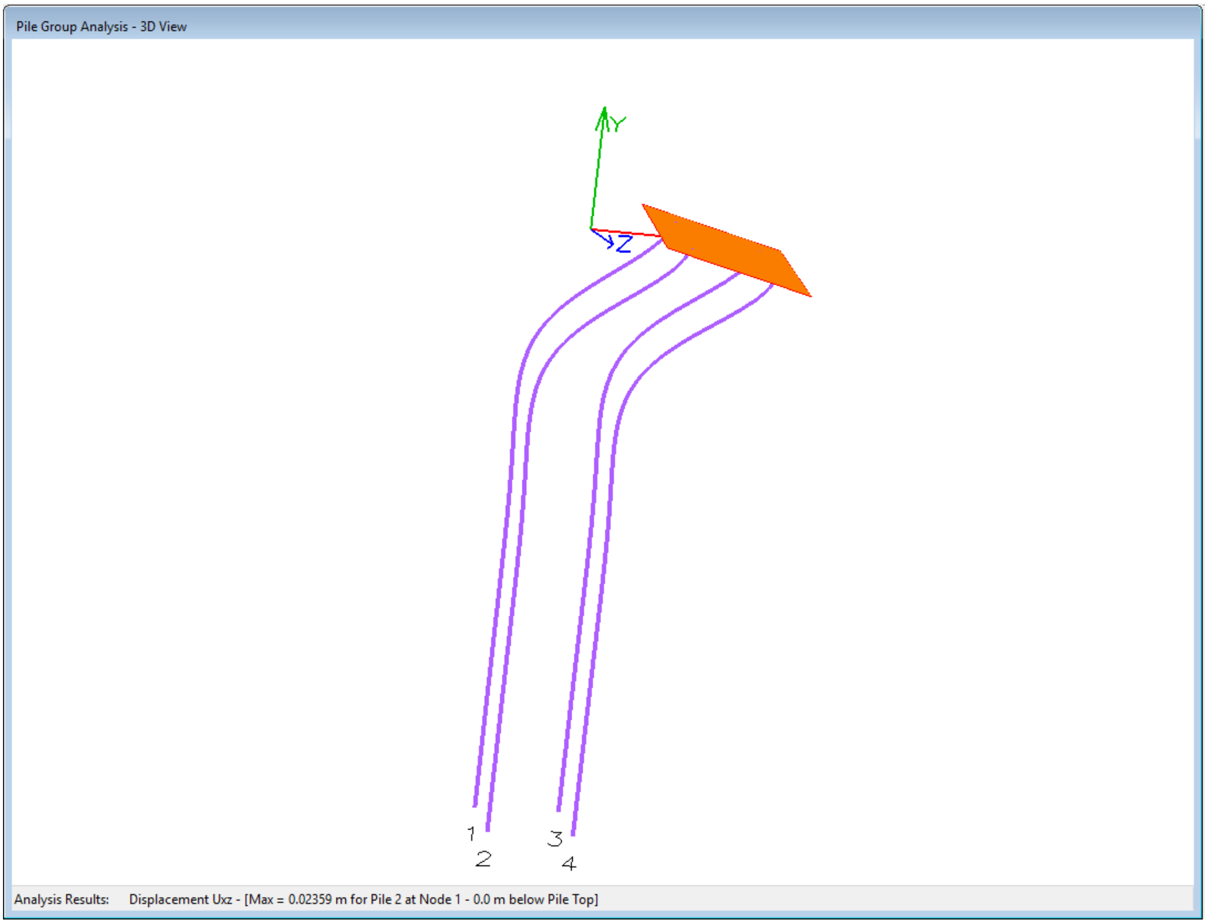



**Figure 19-2** Deformed shape of pile groups

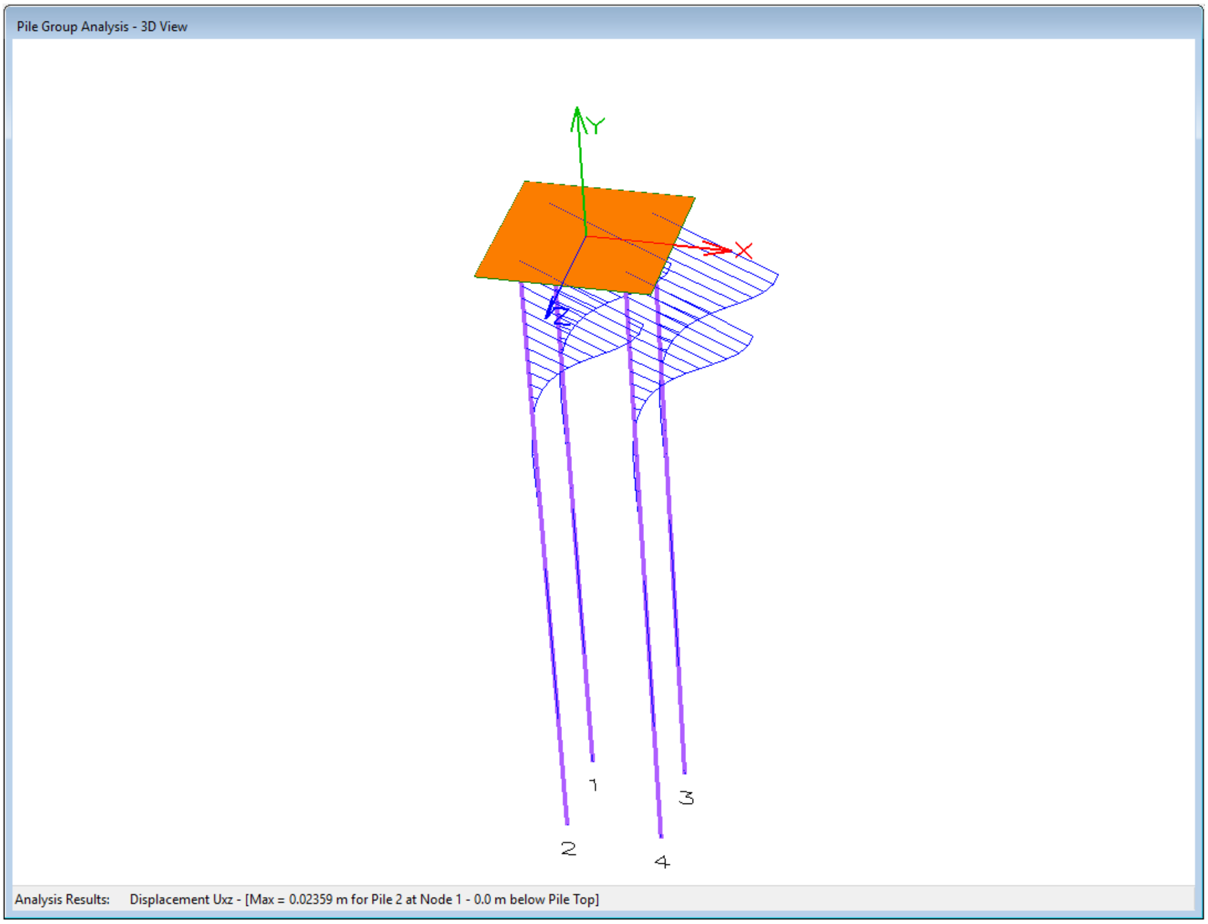



**Figure 19-3** Total pile group displacement Uxz

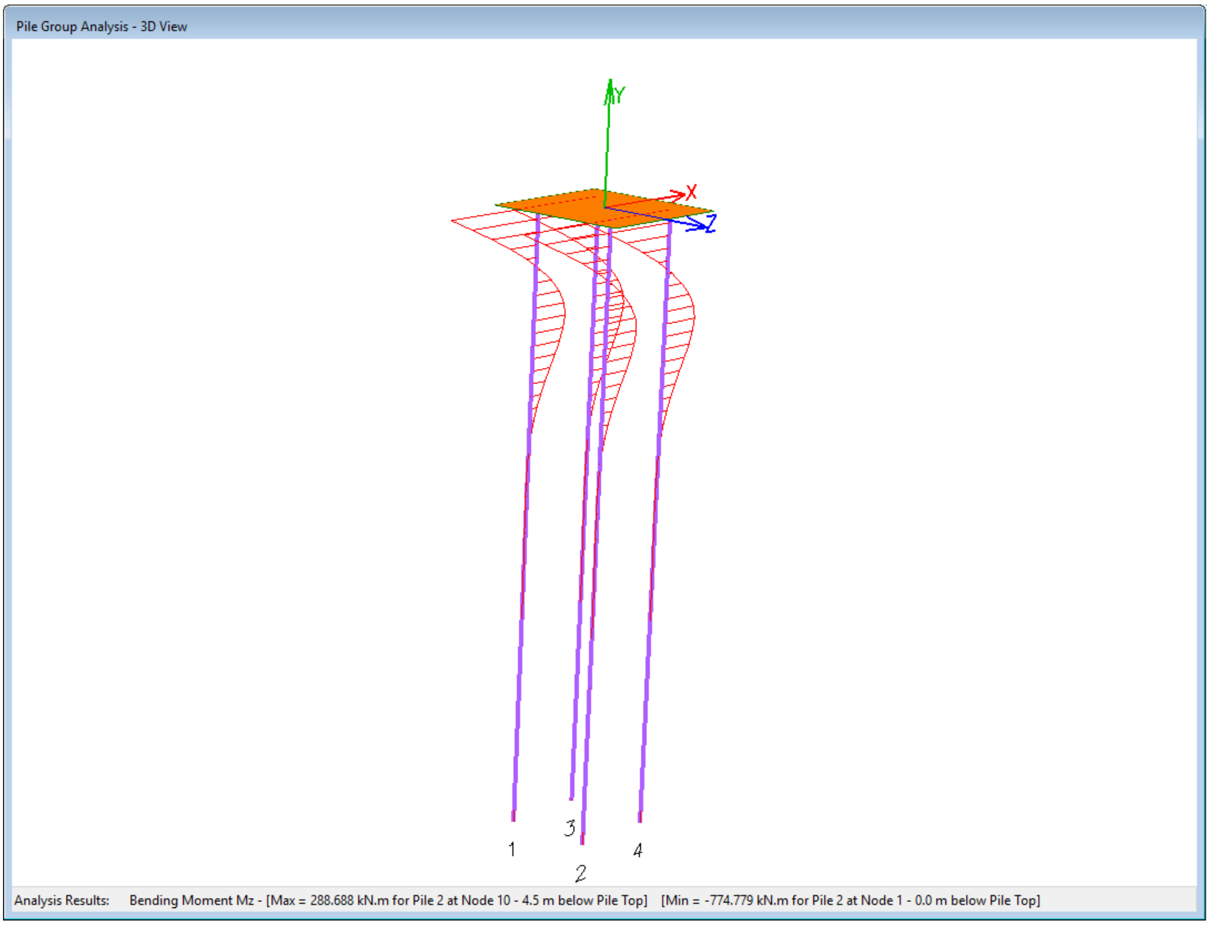



**Figure 19-4** Bending moment Mz of all piles within pile group

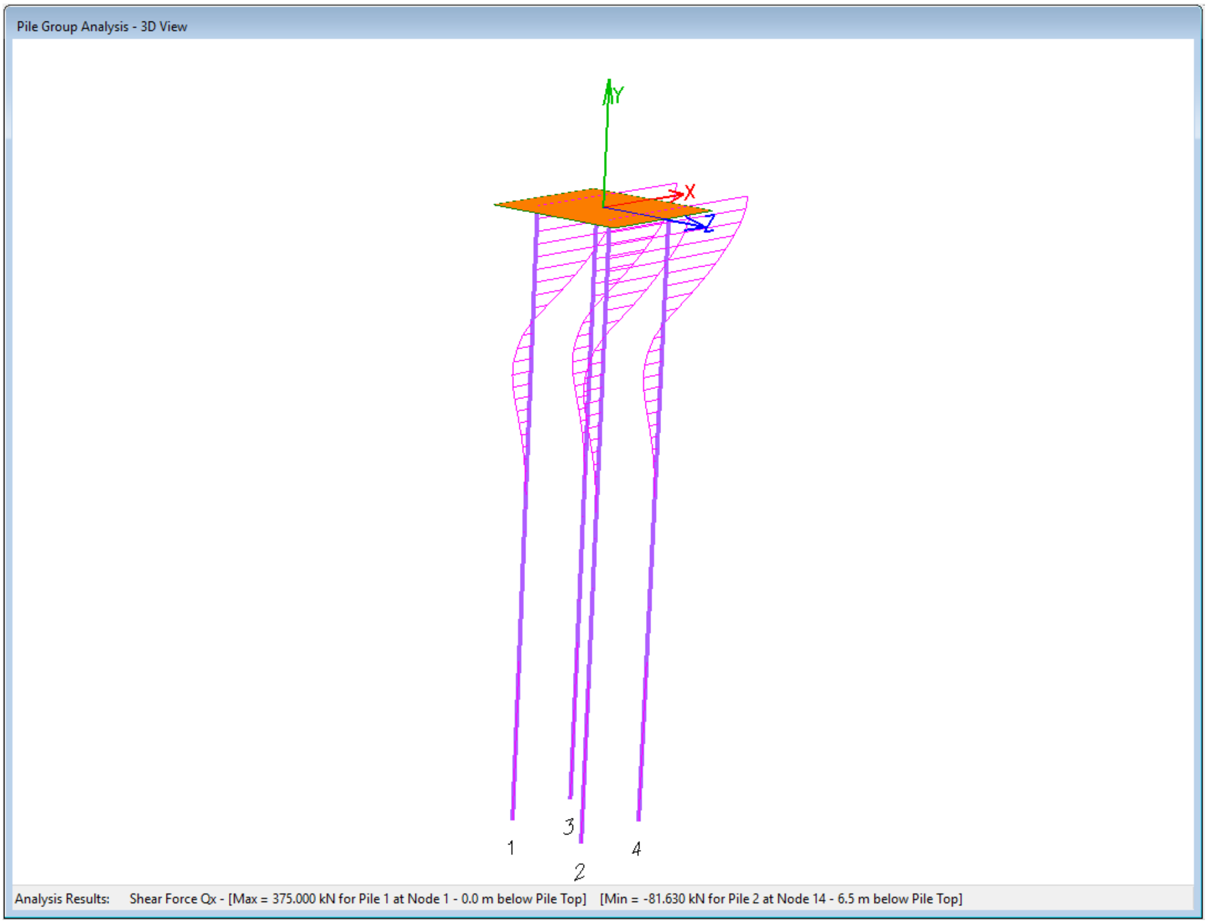



**Figure 19-5** Shear force Qx of all piles within pile group

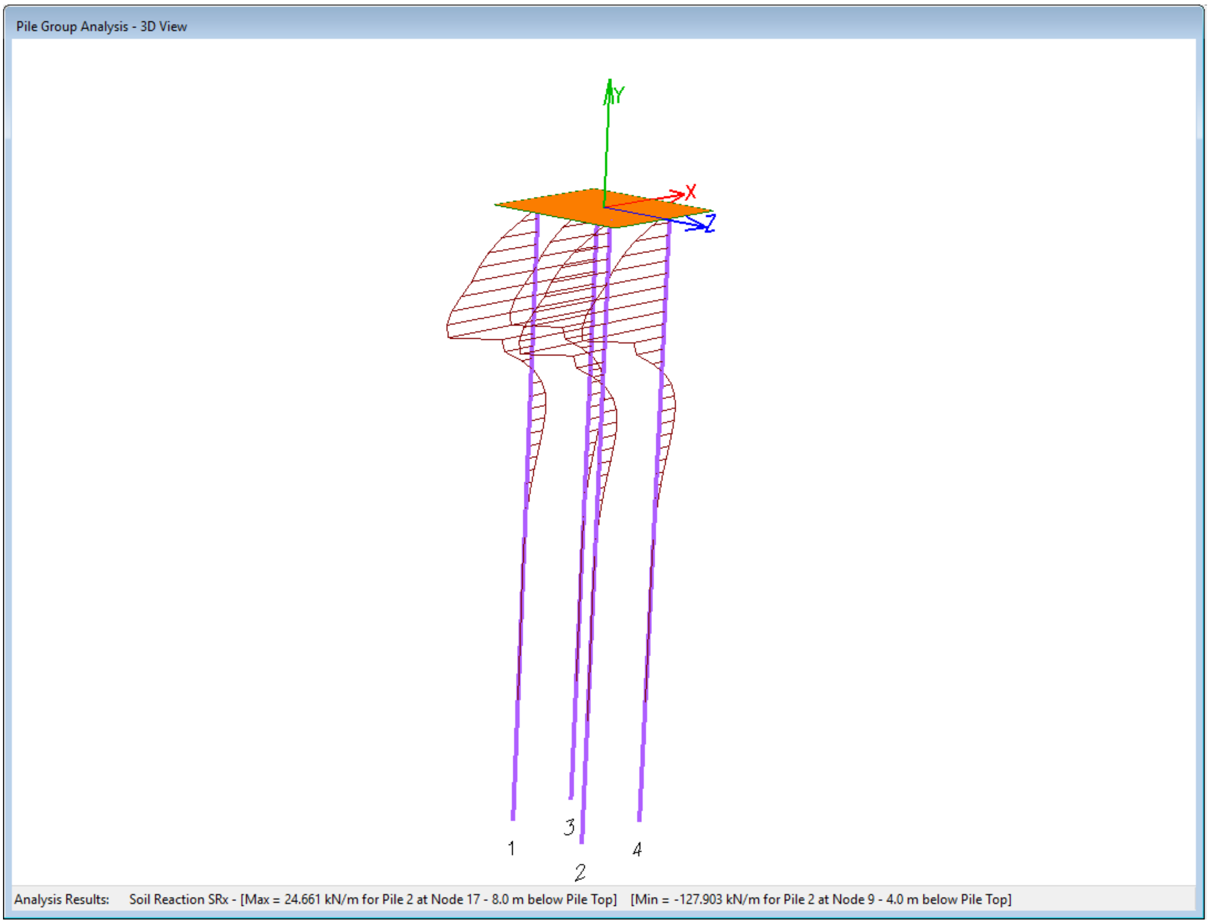



**Figure 19-6** Soil reaction SRx of all piles within pile group

# 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.

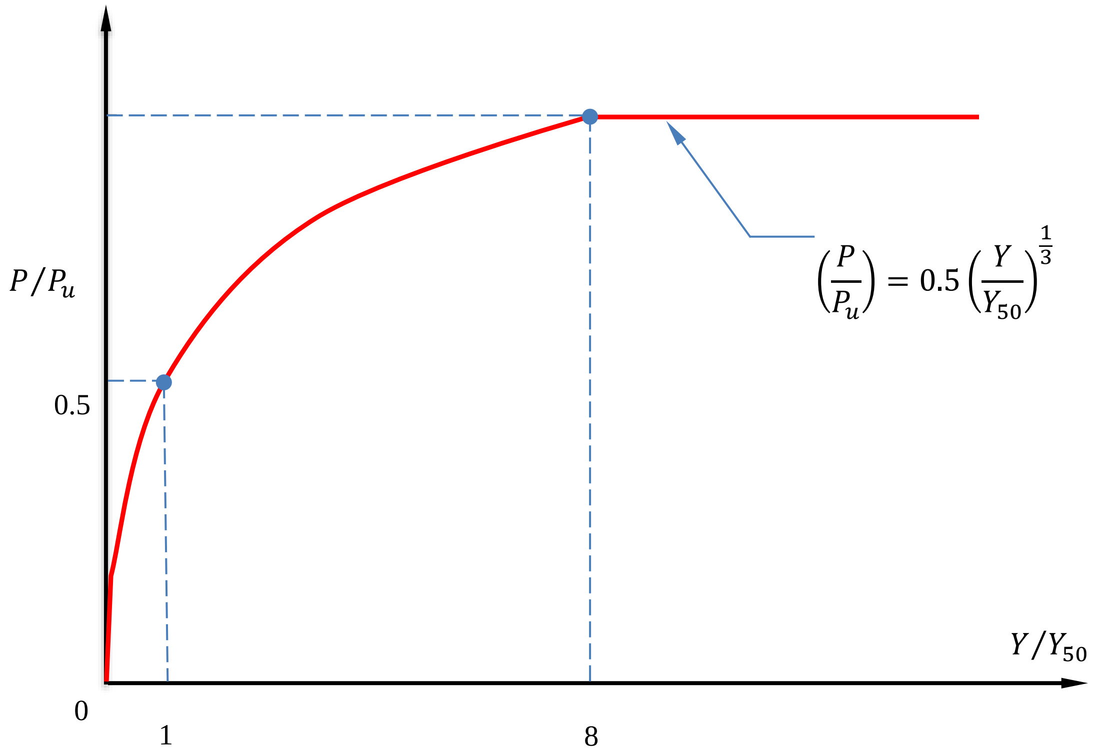



**Figure A.1-1** P-Y curve for soft clay (Matlock) model under static loading condition

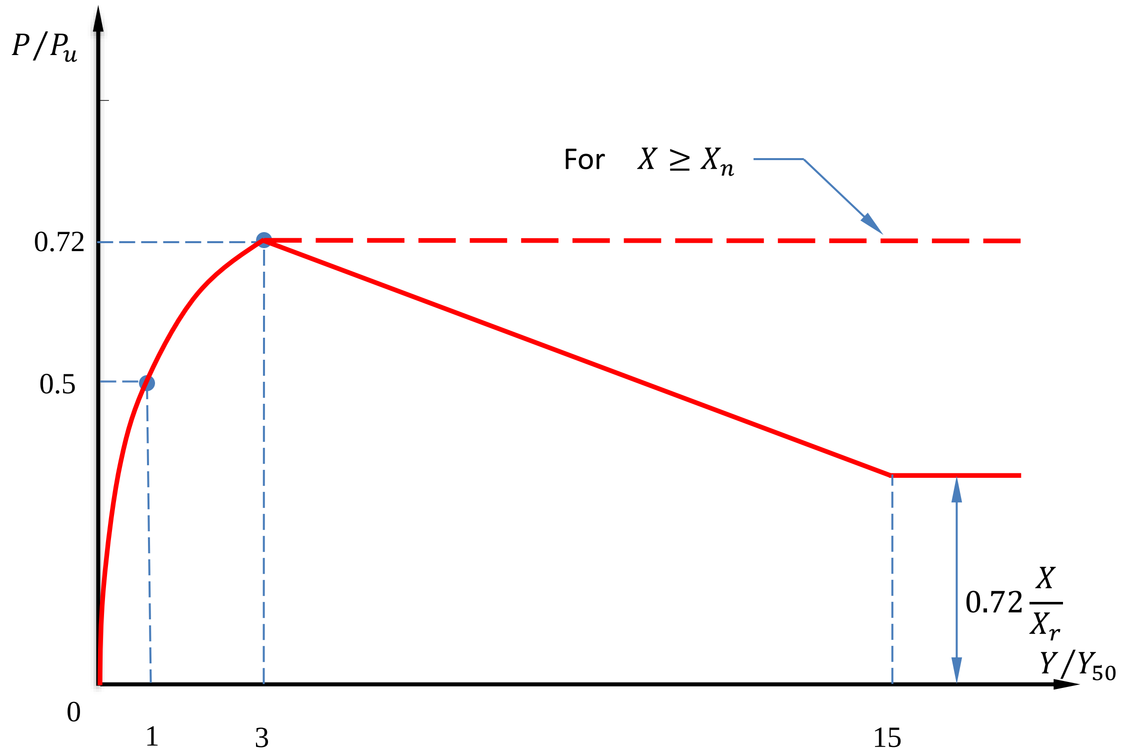



**Figure A.1-2** P-Y curve for soft clay (Matlock) model under cyclic loading condition

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

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

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

Where:

$P_u$ = ultimate soil resistance per unit length

$c_u$ = undrained shear strength

$\sigma'_n$ = 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 $\varepsilon_{50}$ 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 $\varepsilon_{50}$ are adopted in PileLAT for clays:

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

| Undrained Shear Strength (kPa) | Strain Factor, $\varepsilon_{50}$ |
|---|---|
| ≤ 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.

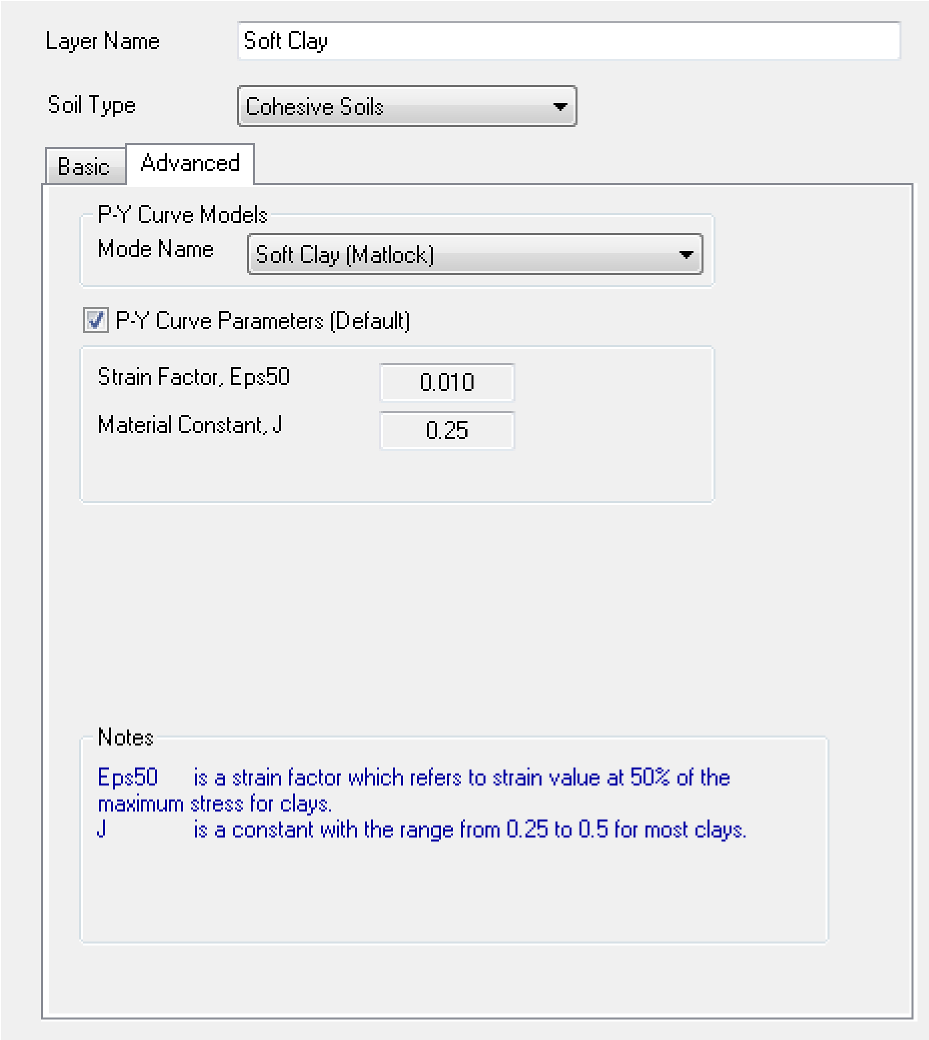



**Figure A.1-3** P-Y parameter input dialog for soft clay (Matlock) model in PileLAT

## 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.

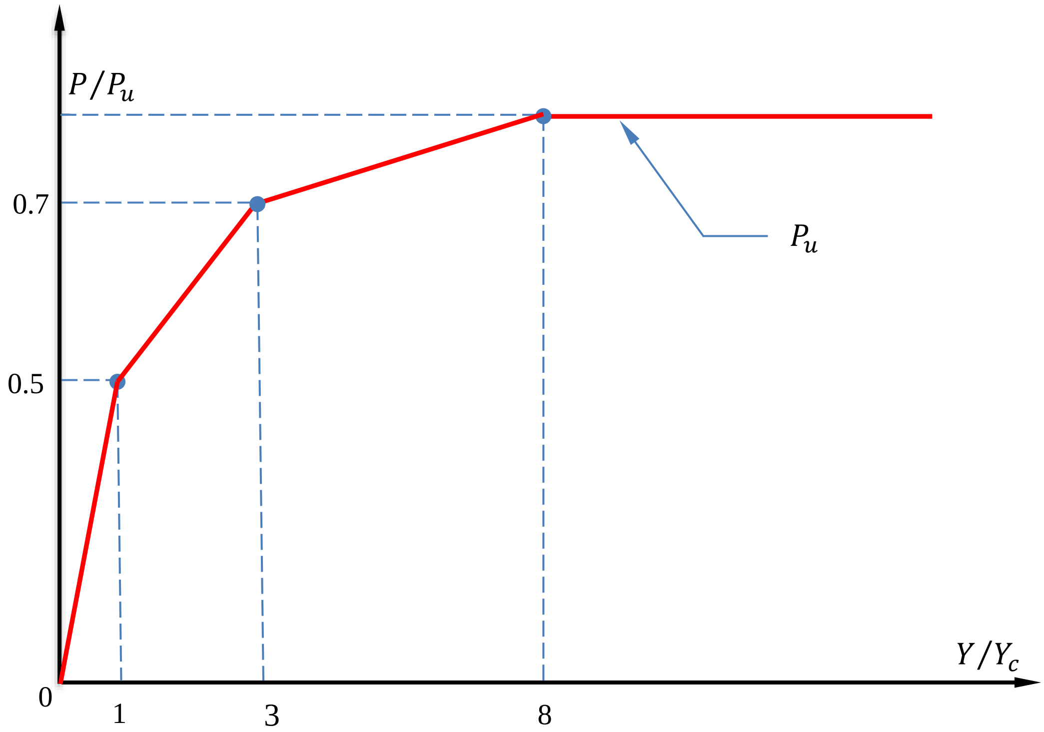



**Figure A.2-1** P-Y curve for soft clay (API) model under static loading condition

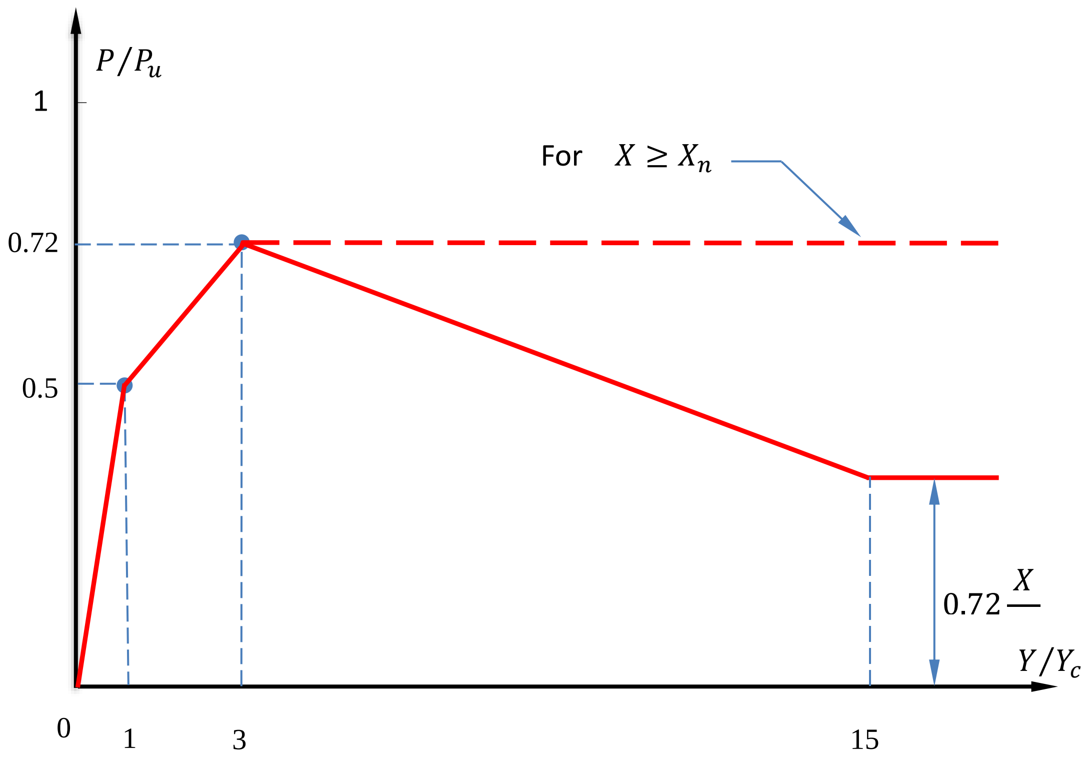



**Figure A.2-2** P-Y curve for soft clay (API) model under cyclic loading condition

The reference displacement $Y_c$ is calculated by the equation below:

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

where $\varepsilon_{50}$ 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.

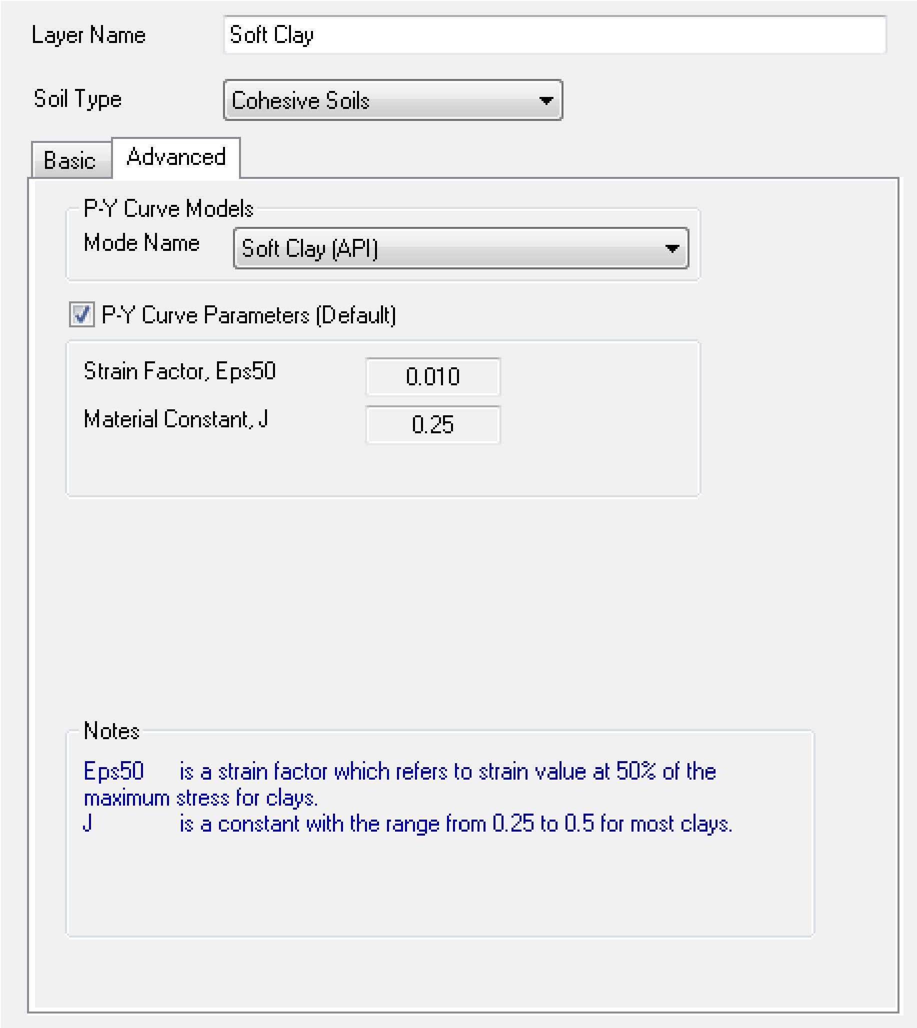



**Figure A.2-3** P-Y parameter input dialog for soft clay (API) model in PileLAT

## 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).

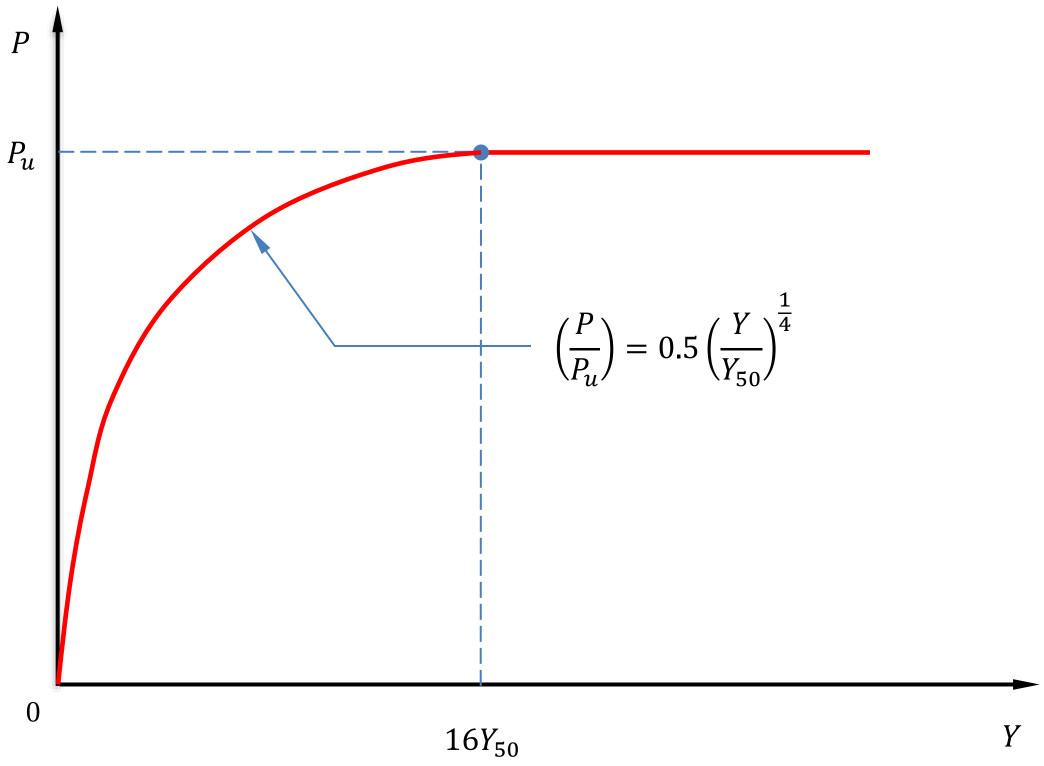



**Figure A.3-1** P-Y curve for stiff clay without water model under static loading condition

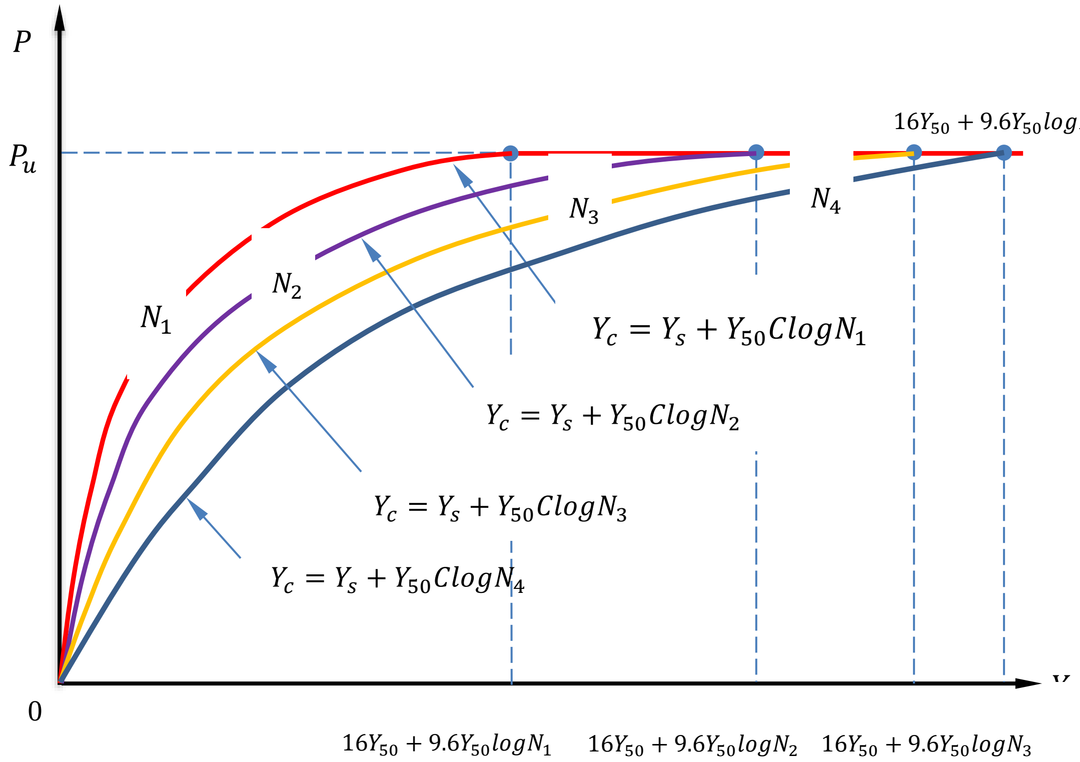



**Figure A.3-2** P-Y curve for stiff clay without water model under cyclic loading condition

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.

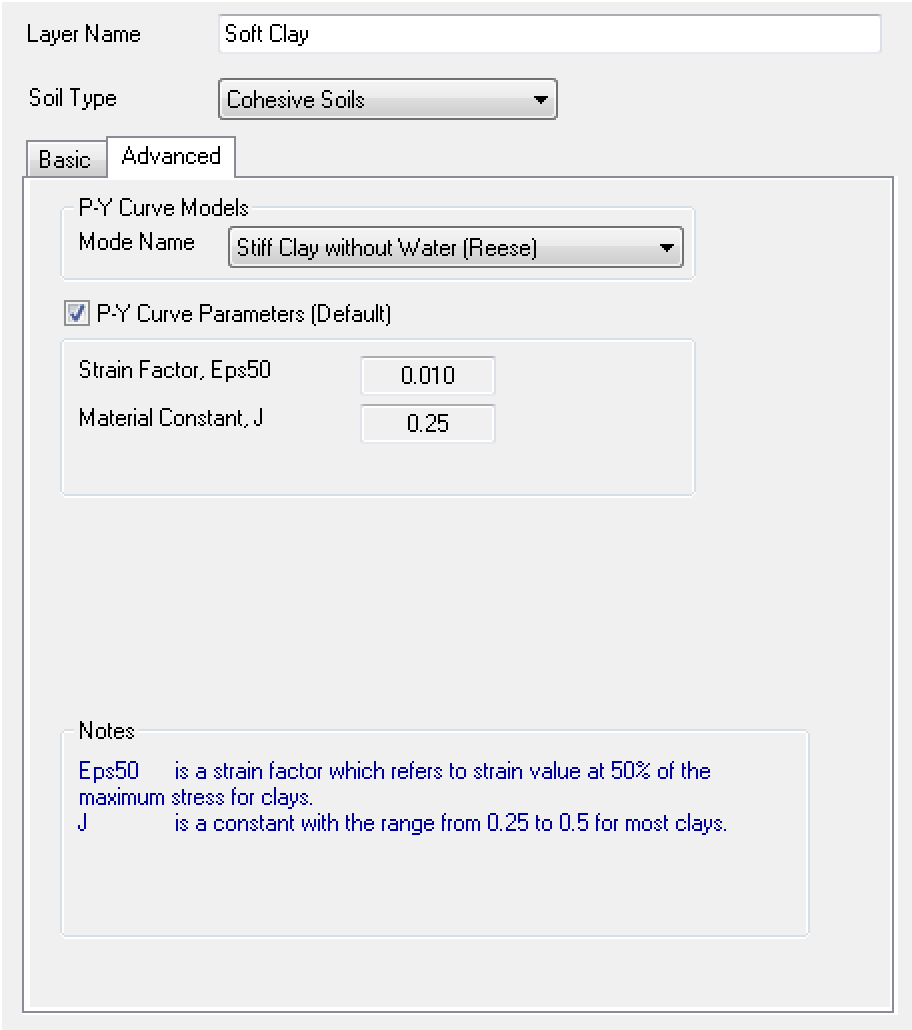



**Figure A.3-3** P-Y parameter input dialog for stiff clay without water model in PileLAT

## 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).

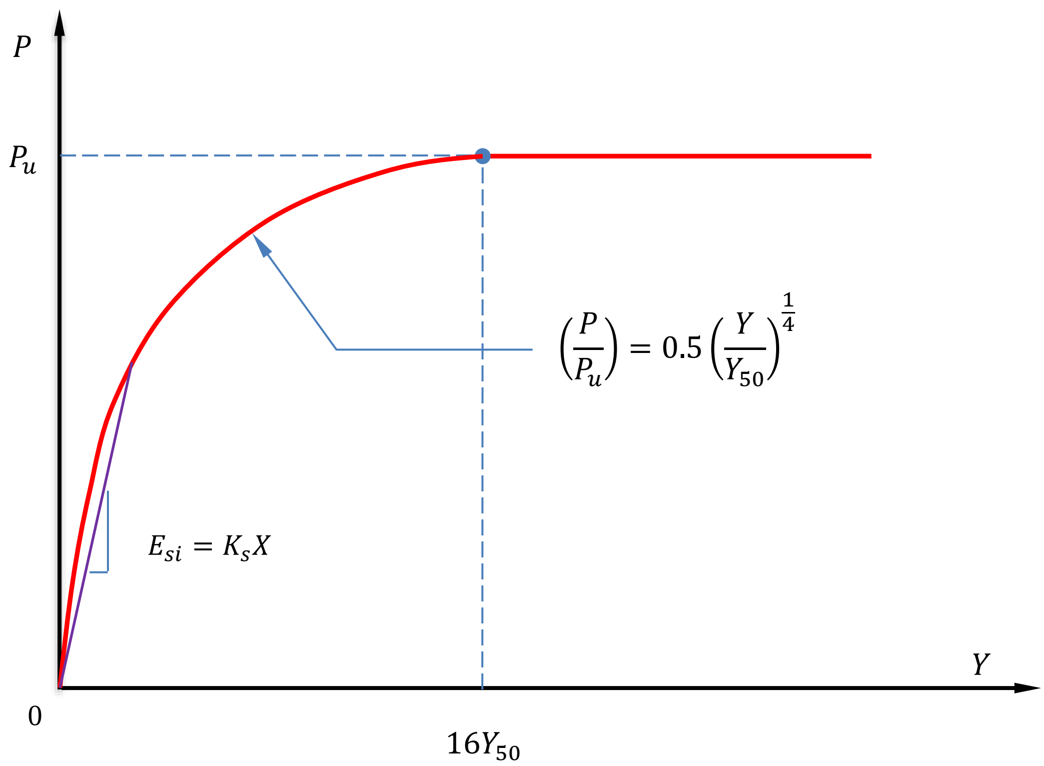



**Figure A.4-1** P-Y curve for the stiff clay with initial modulus model under static loading condition

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

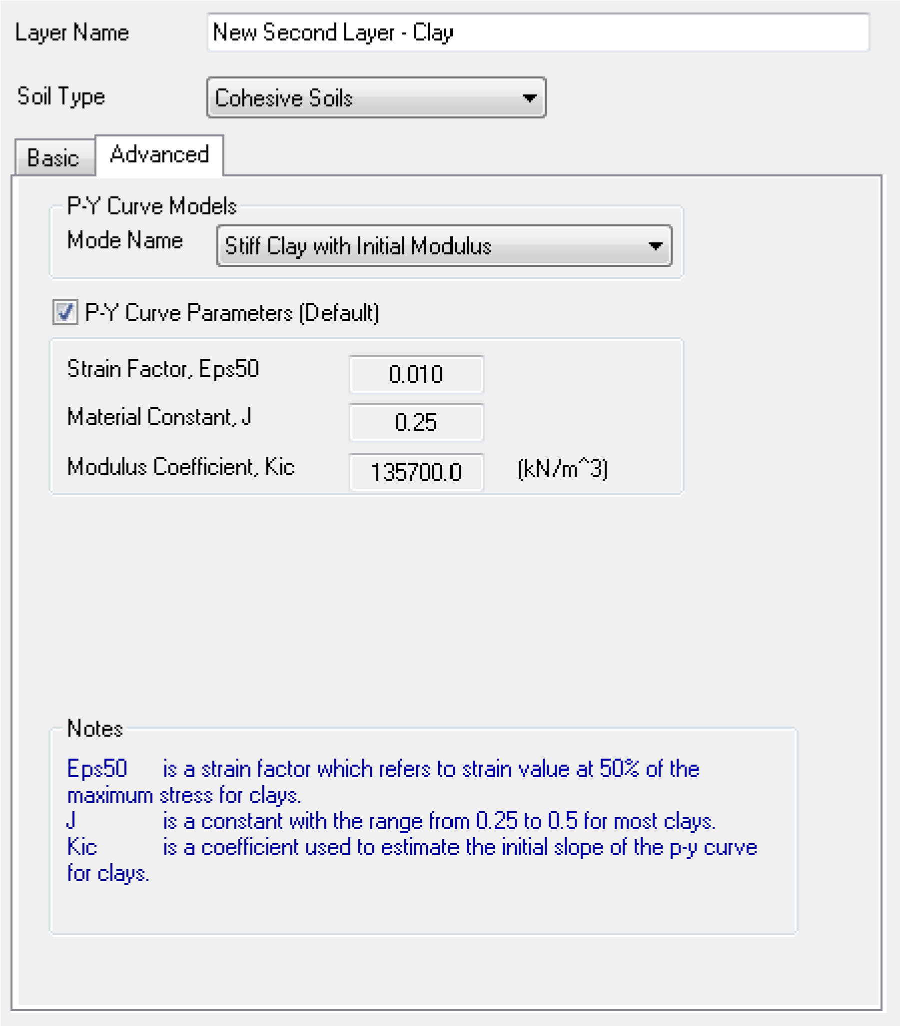



**Figure A.4-2** P-Y parameter input dialog for the stiff clay with initial modulus model in PileLAT

## 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

$\gamma'$ = 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.

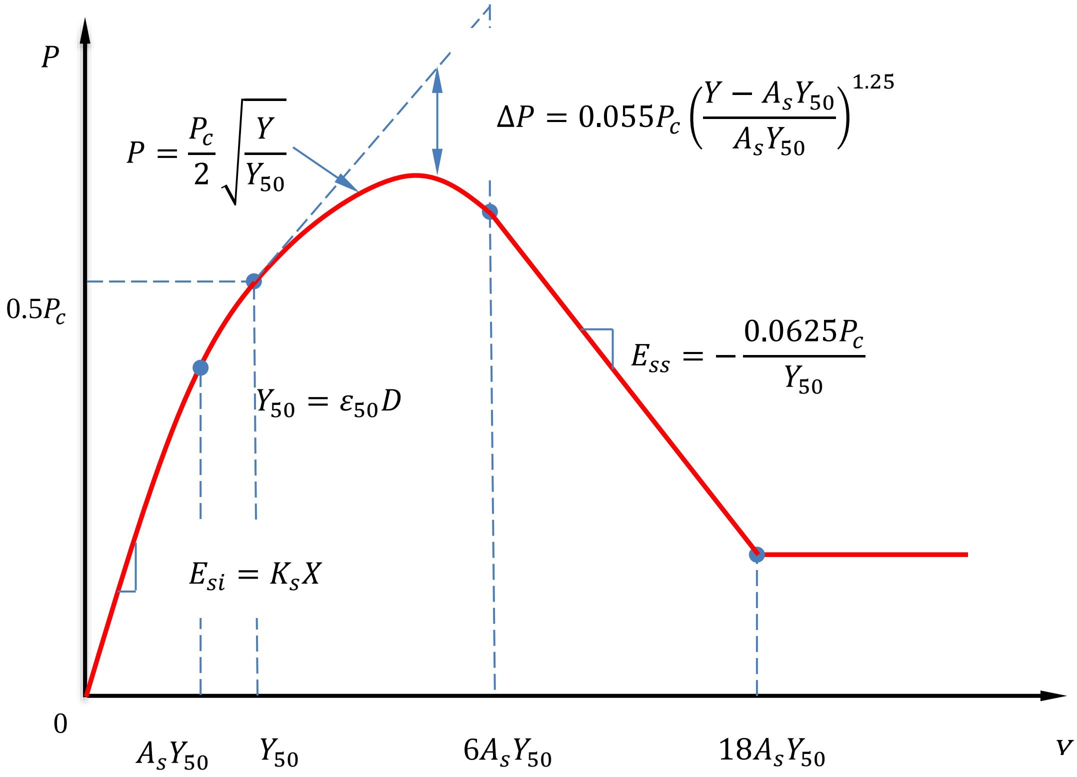



**Figure A.5-1** P-Y curve for the stiff clay with water model under static loading condition

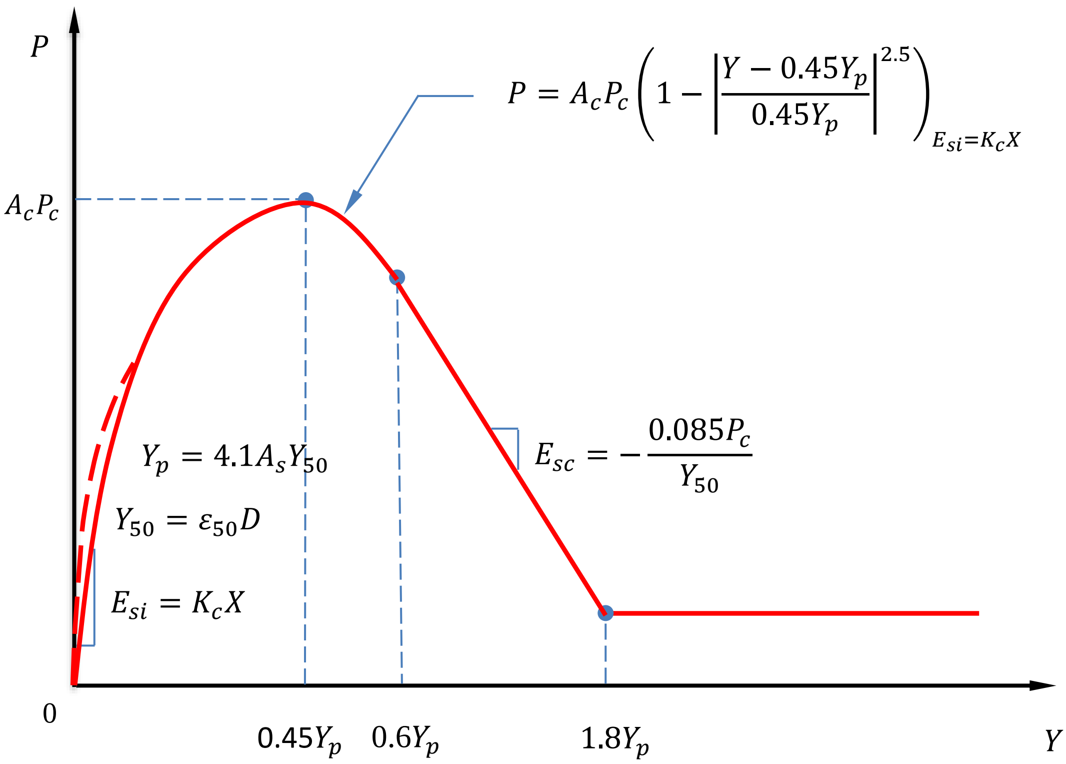



**Figure A.5-2** P-Y curve for the stiff clay with water model under cyclic loading condition

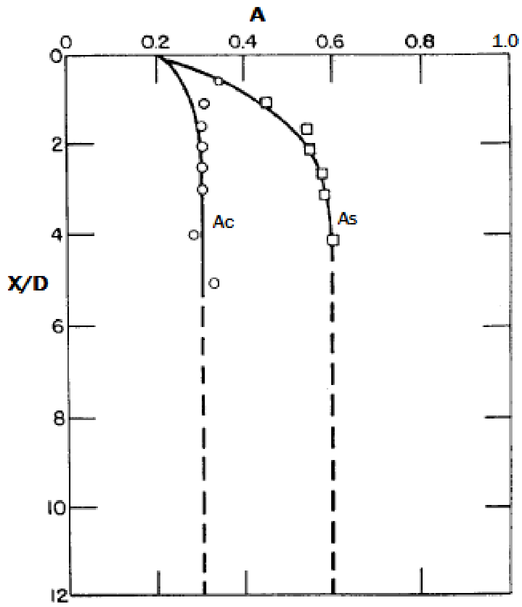



**Figure A.5-3** Variation of As and Ac parameters with the depth for the stiff clay with water model

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 $\varepsilon_{50}$ 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.

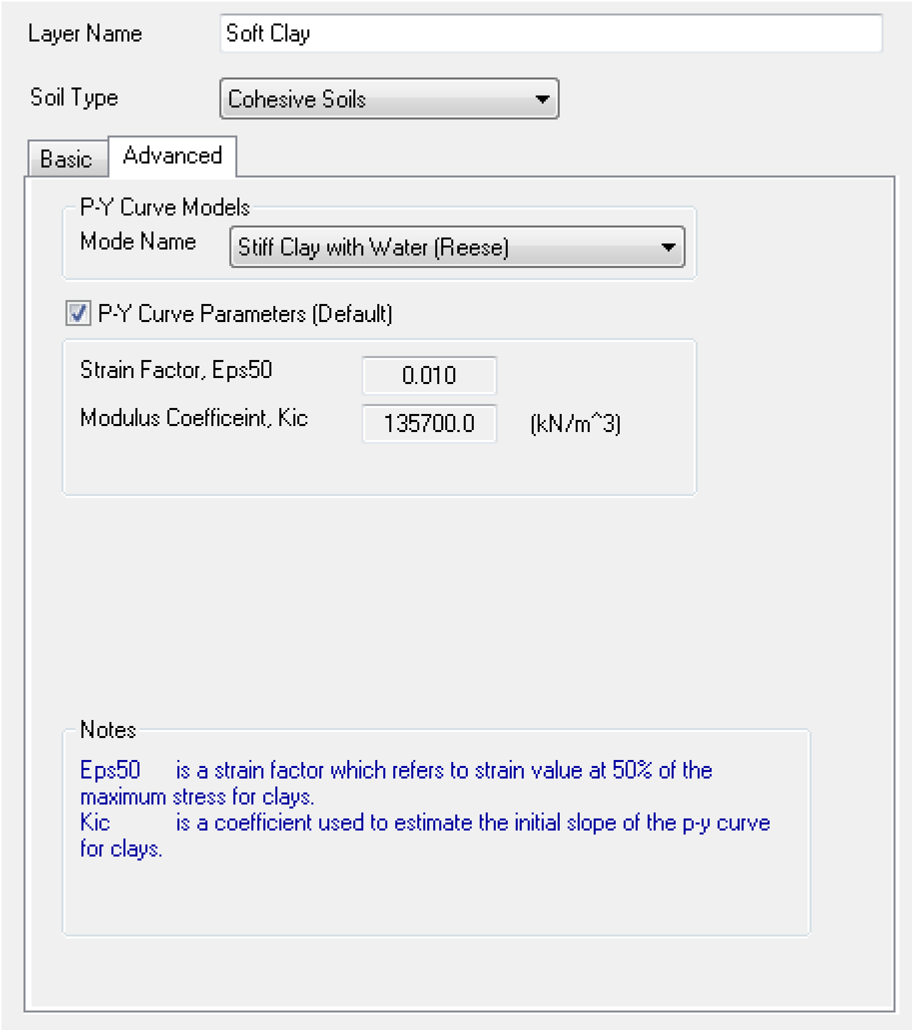



**Figure A.5-4** P-Y parameter input dialog for the stiff clay with water model in PileLAT

## 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;

$\gamma'$ = 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.

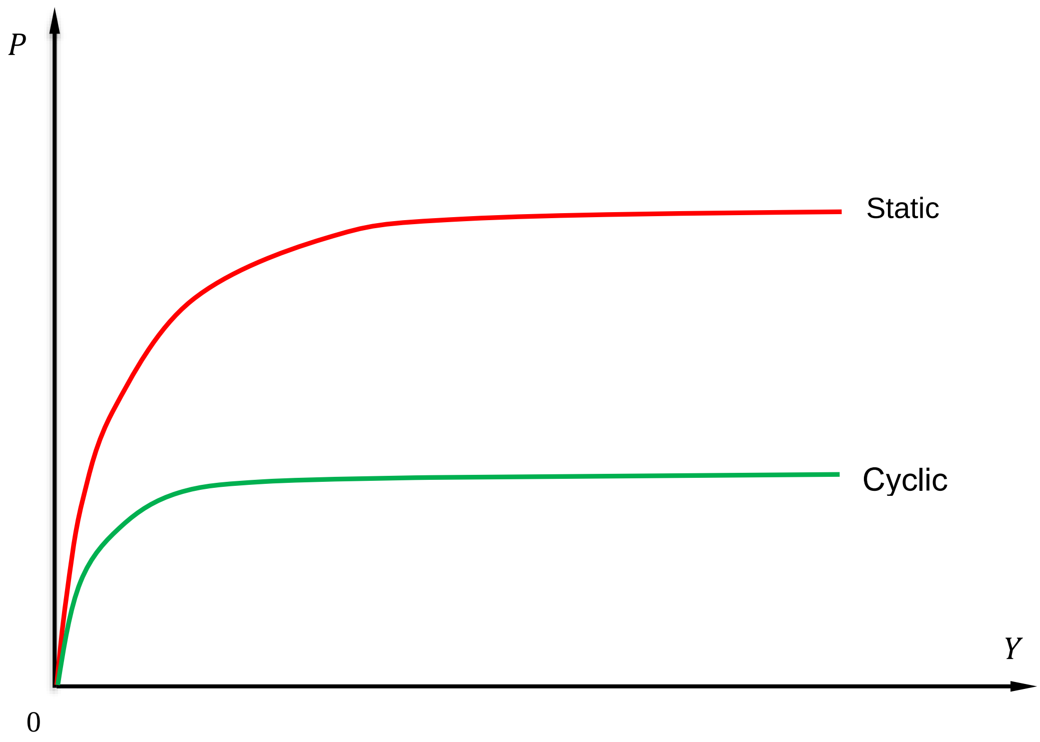



**Figure A.6-1** P-Y curve for API Sand model under both static and cyclic loading condition

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, $\max(3.0 - 0.8\text{H}/\text{D}\,, 0.9)$ 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

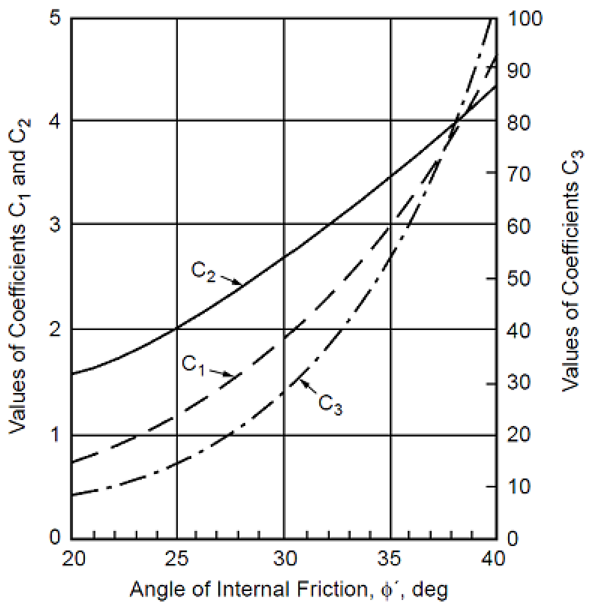



**Figure A.6-2** Variation of C1, C2 and C3 with the friction angle for API sand model (after API 2000)

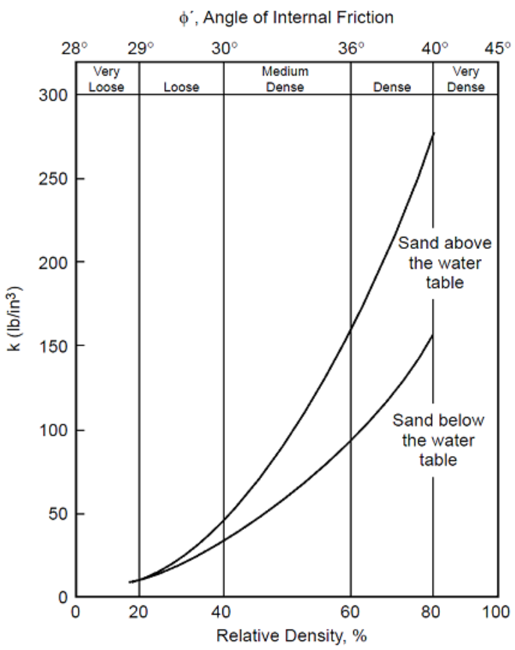



**Figure A.6-3** Variation of initial modulus of subgrade with the friction angle for API sand model (after API 2000)

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.

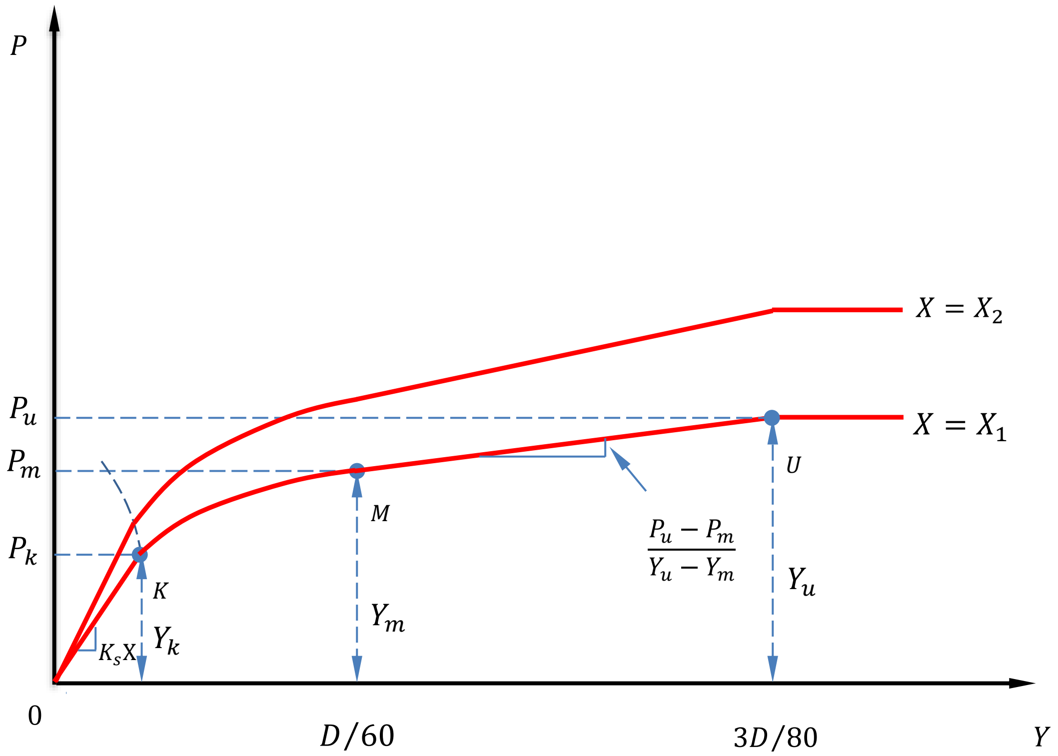



**Figure A.7-1** P-Y curve for Reese Sand model under both static and cyclic loading condition

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

$\varphi'$ = 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.

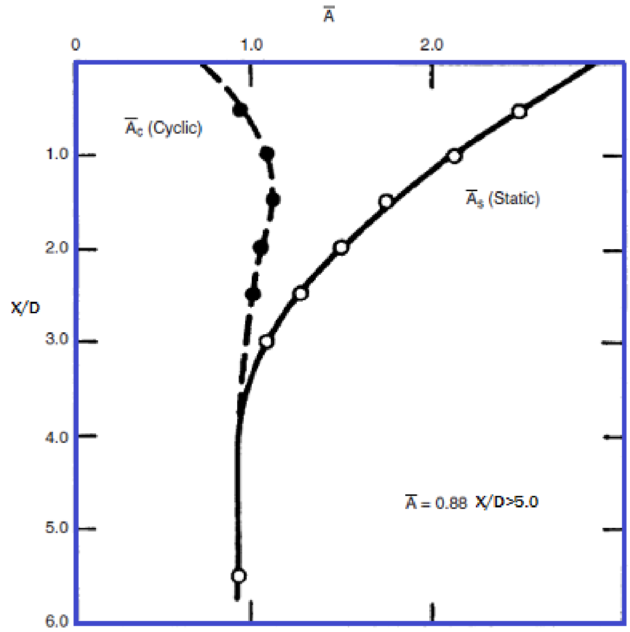



**Figure A.7-2** Variation of As and Ac with the depth for Reese sand model (After Reese at al. 1974)

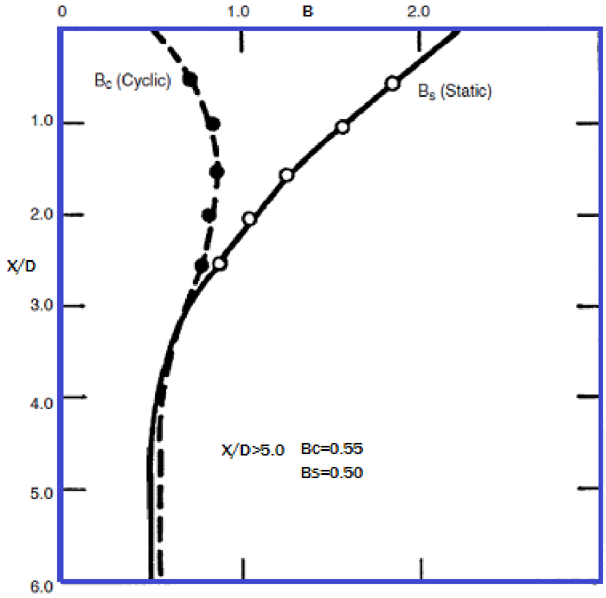



**Figure A.7-3** Variation of Bs and Bc with the depth for Reese sand model (After Reese et al. 1974)

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

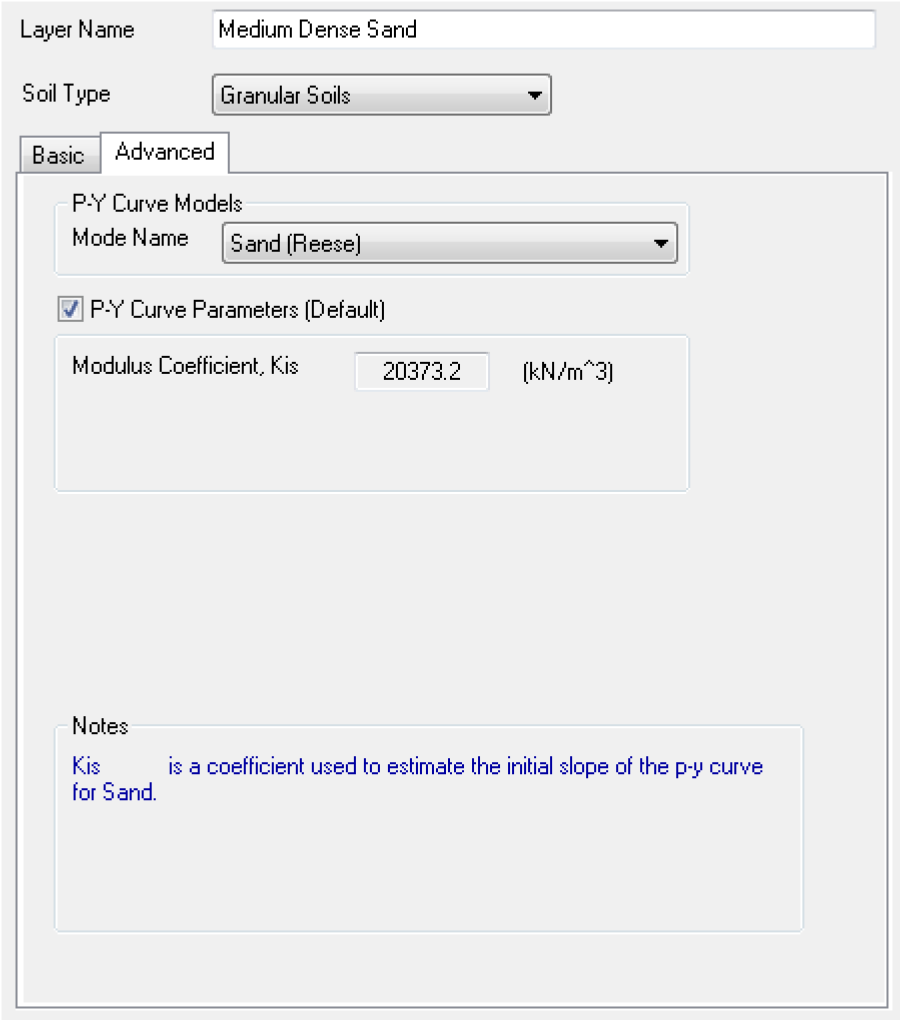



**Figure A.7-4** P-Y parameter input dialog for the Reese Sand in PileLAT

## 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.

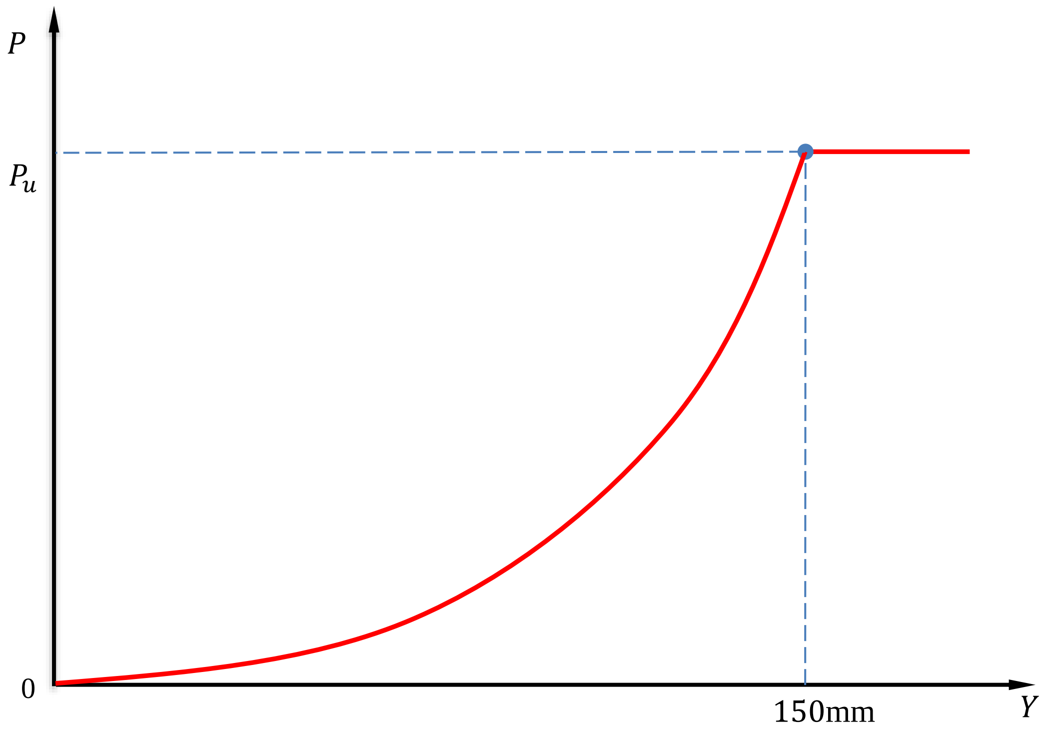



**Figure A.8-1** P-Y curve for Liquefied Sand

The following equations are used to produce the curve:

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

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

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

$$A = 3{\times}10^{-7}(X+1)^{6.05} \qquad \text{(A.8-4)}$$

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

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

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.

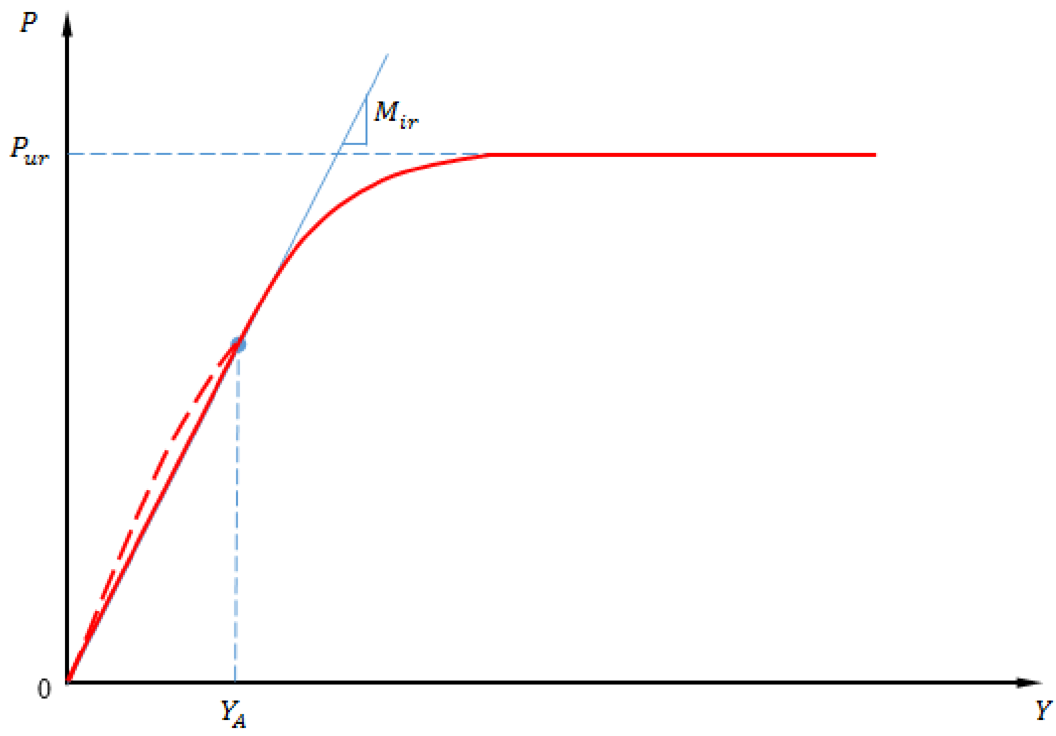



**Figure A.9-1** P-Y curve for Weak Rock – Reese (1997)

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

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

(For $0 \le X_r \le 3D$)

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

(For $X_r \ge 3D$)

where $P_{ur}$ is ultimate soil resistance per unit length; $\alpha_r$ 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:

$$P = M_{ir}Y \qquad \text{For} \quad Y \le Y_A \tag{A.9-3}$$

$$P = \frac{P_{ur}}{2}\left(\frac{Y}{Y_m}\right)^{0.25} \tag{A.9-4}$$

For $Y \ge Y_A$ and $P \le P_{ur}$

$$P = P_{ur} \qquad \text{For} \quad Y \ge 16Y_m \tag{A.9-5}$$

$Y_A$ can be found by solving the following equation:

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

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

$$M_{ir} = k_{ir}E_m \tag{A.9-7}$$

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

$$k_{ir} = 100 + \frac{400Xr}{3D} \qquad (\text{For} \quad 0 \le X_r \le 3D) \tag{A.9-8}$$

$$k_{ir} = 500 \qquad (\text{For } X_r \ge 3D) \tag{A.9-9}$$

The parameter $Y_m$ can be determined by:

$$Y_m = \varepsilon_{rm}D \tag{A.9-10}$$

where $\varepsilon_{rm}$ 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 $\varepsilon_{rm}$- 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 $\sigma_c$ 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.

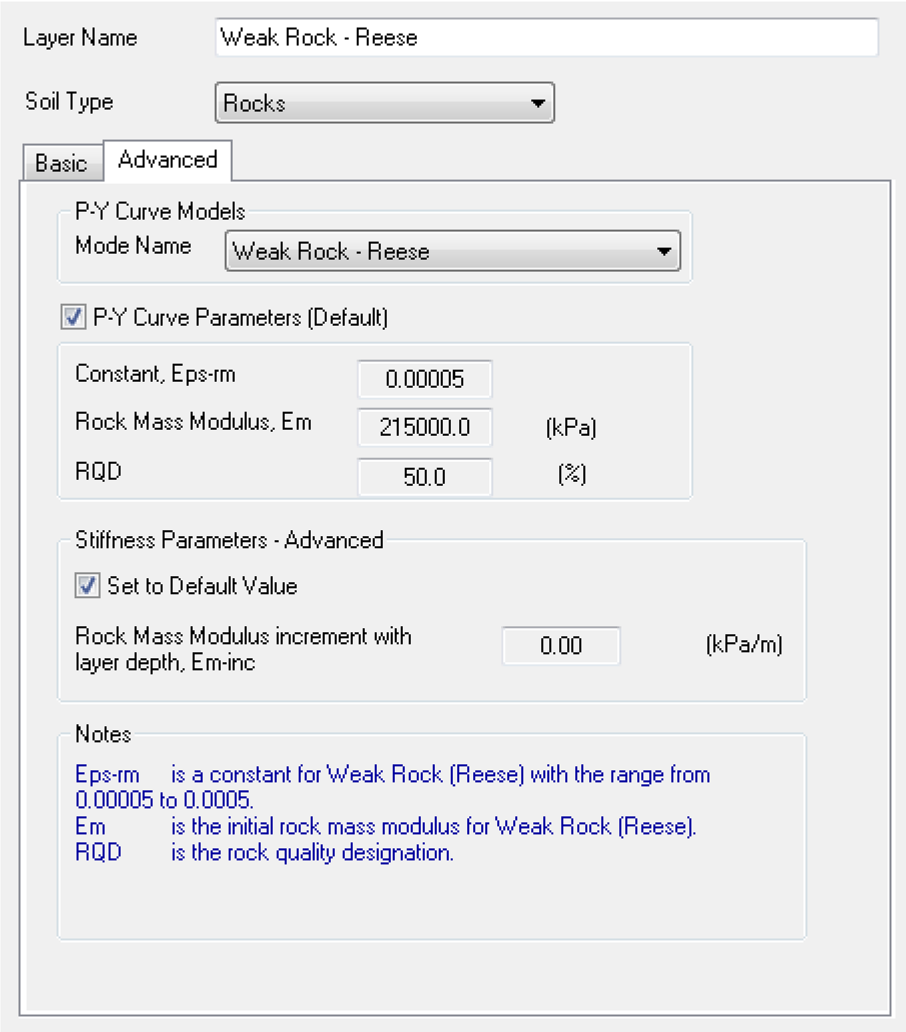



**Figure A.9-2** P-Y parameter input dialog for the Weak Rock in PileLAT

## 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.

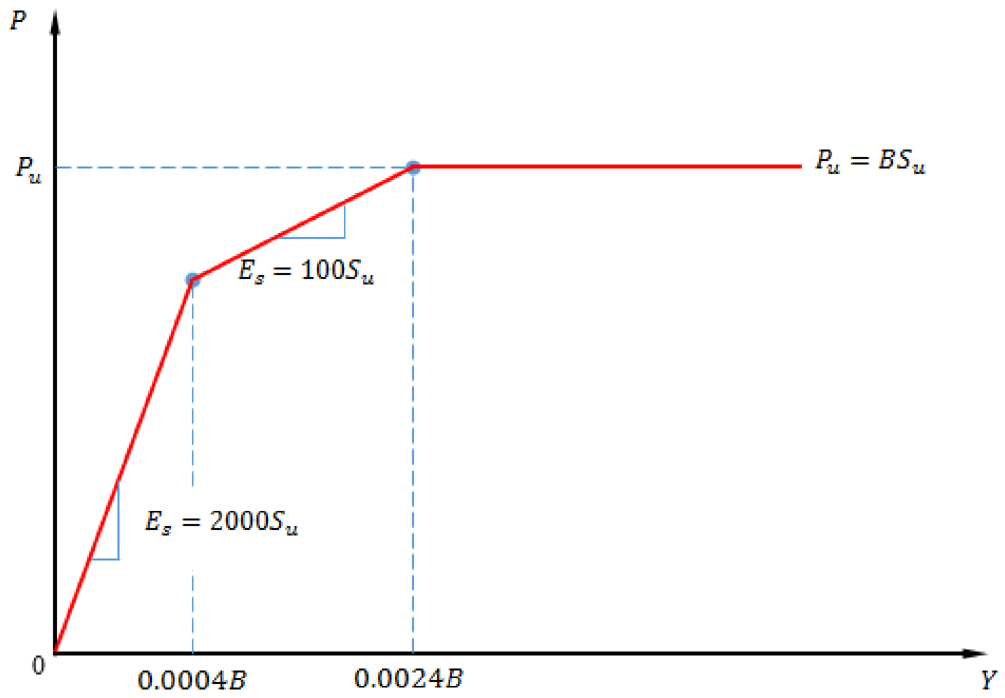



**Figure A.10-1** P-Y curve for Strong Rock

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

$$P_u = BS_u$$

where $B$ is the pile diameter and $S_u$ 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.

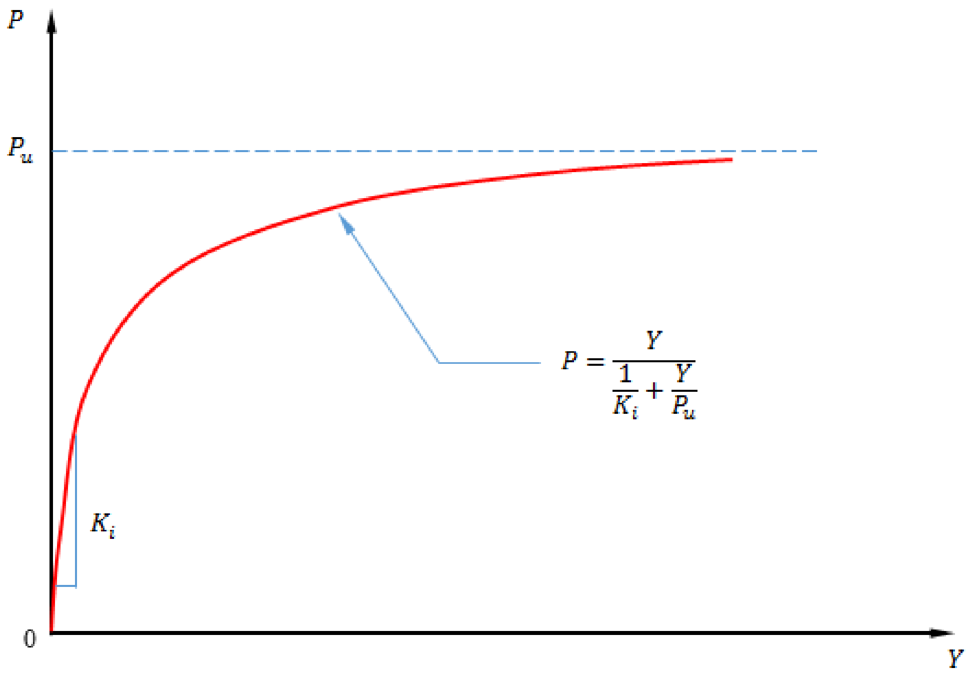



**Figure A.11-1** P-Y curve for Massive Rock

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

$$P_{us} = 2C_1 \cos\theta \sin\beta + C_2 \sin\beta - 2C_4 \sin\theta - \mathrm{C}_5$$

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

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

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

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

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

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

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

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

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

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

where $c'$ is the effective cohesion, $\emptyset'$ is the effective friction angle, $\gamma'$ 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 $\sigma'_v$ is the effective overburden pressure at the deep depth and $\sigma_c$ 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:

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

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 $v$ is Poisson's ratio of the pile.

The effective strength parameters of massive rock, $c'$ and $\phi'$ 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 $\sigma_c$ 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.

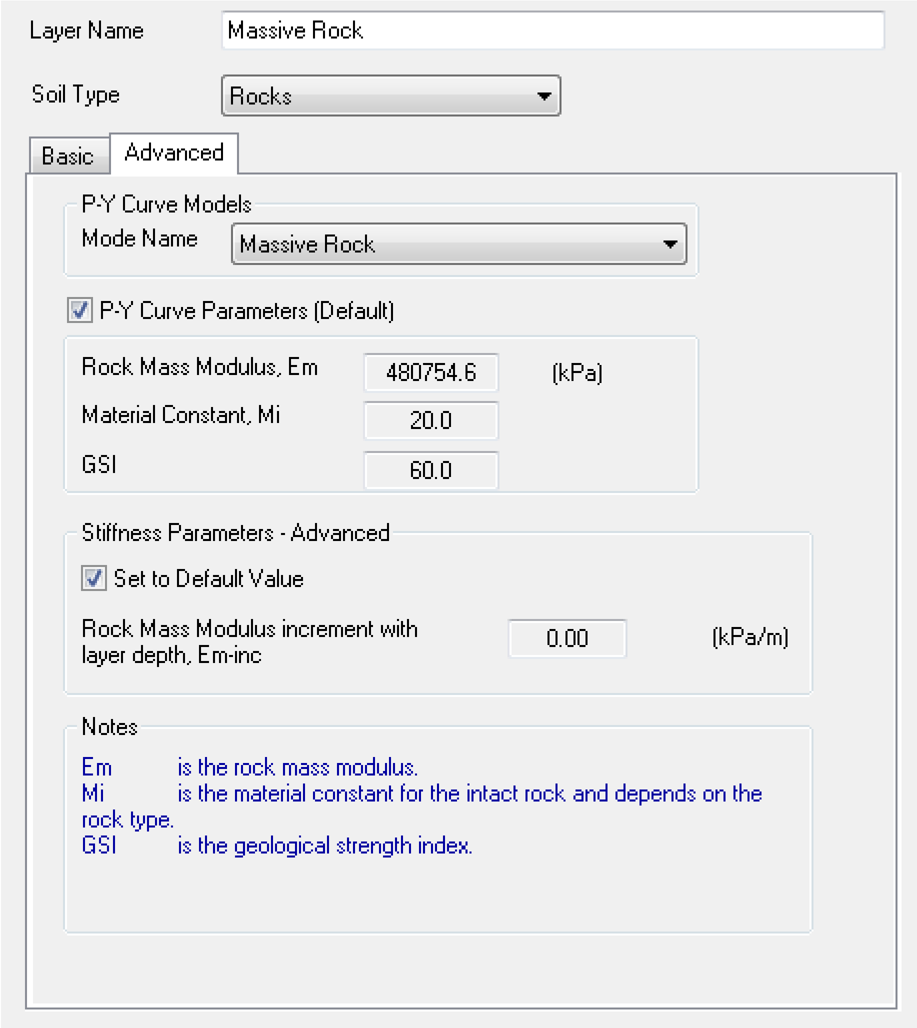



**Figure A.11-2** P-Y parameter input dialog for the Massive Rock in PileLAT

## 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.

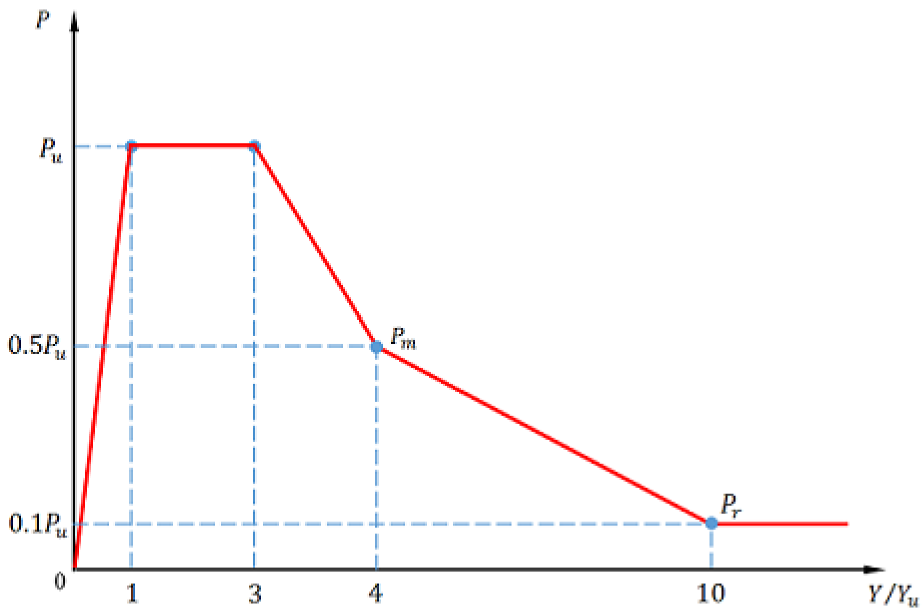



**Figure A.12-1** P-Y curve for calcareous rock near the ground surface

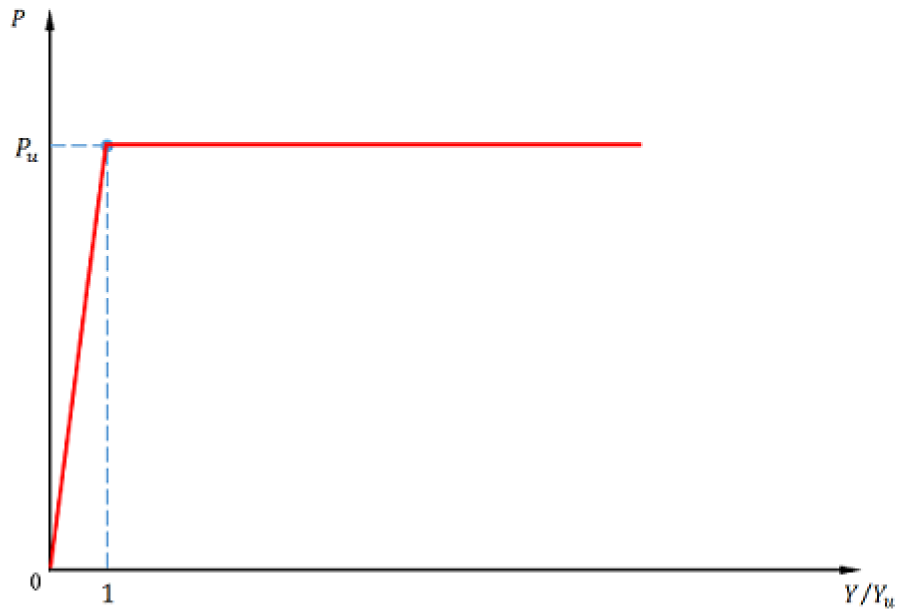



**Figure A.12-2** P-Y curve for calcareous rock below the transition depth

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 $\sigma_s$ 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.

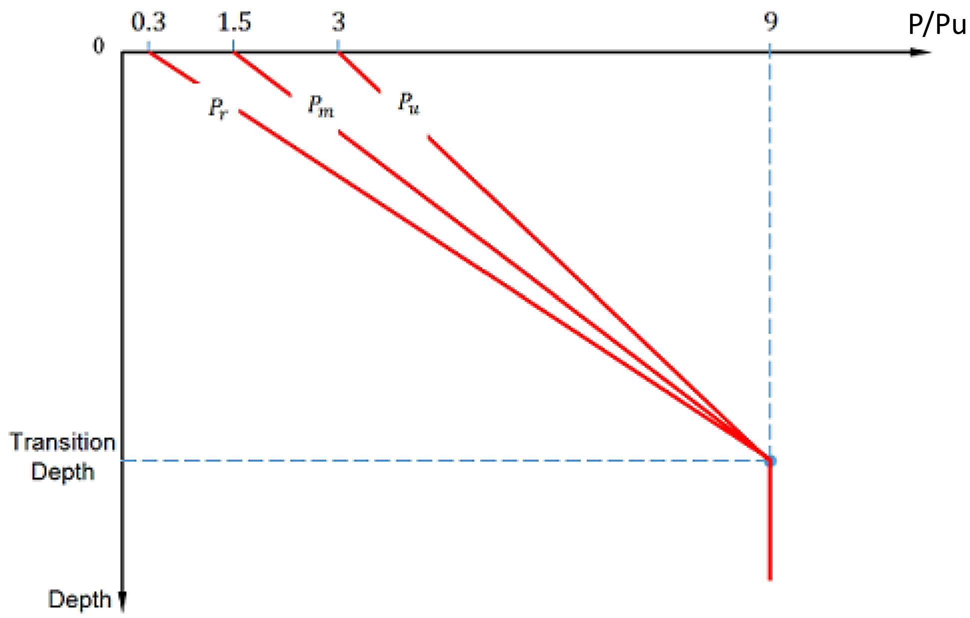



**Figure A.12-3** Variation of the lateral resistance with the depth

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, $\upsilon$ is soil's Poisson's ratio and $E_pI_p$ 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 $\sigma_c$ 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.

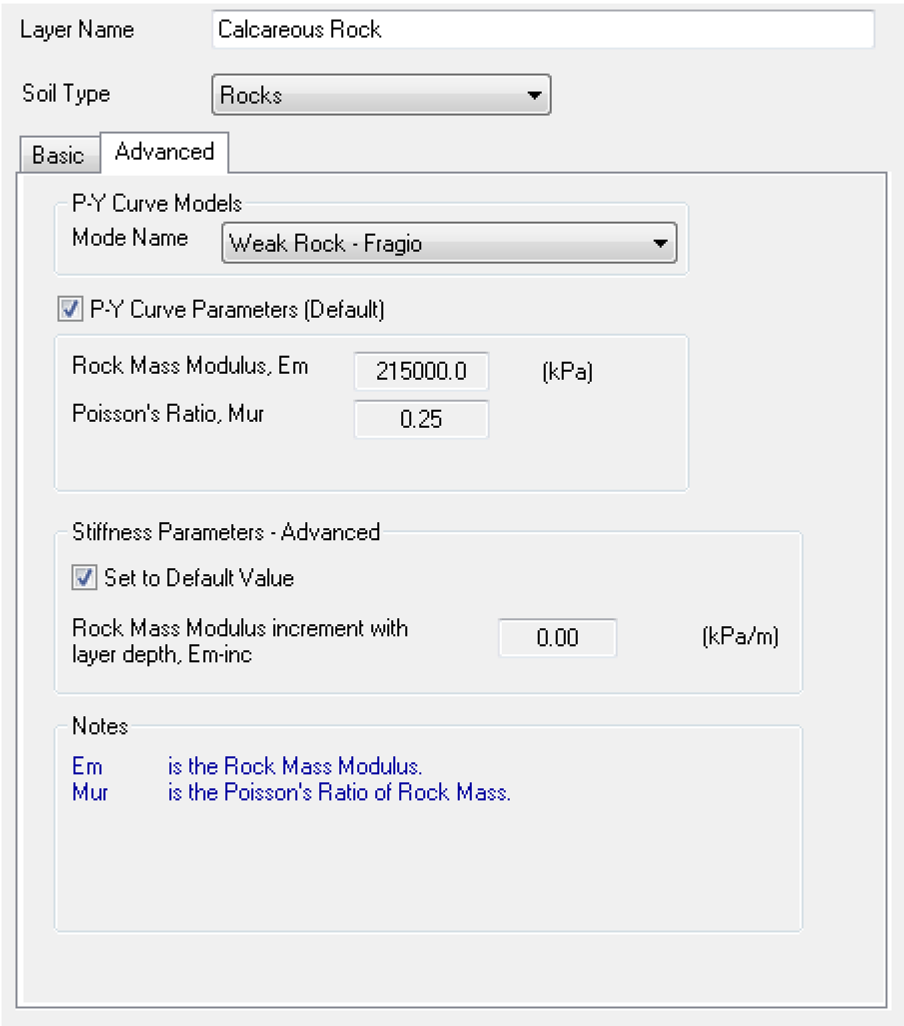



**Figure A.12-4** P-Y parameter input dialog for the Weak Rock – Fragio in PileLAT

## 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:

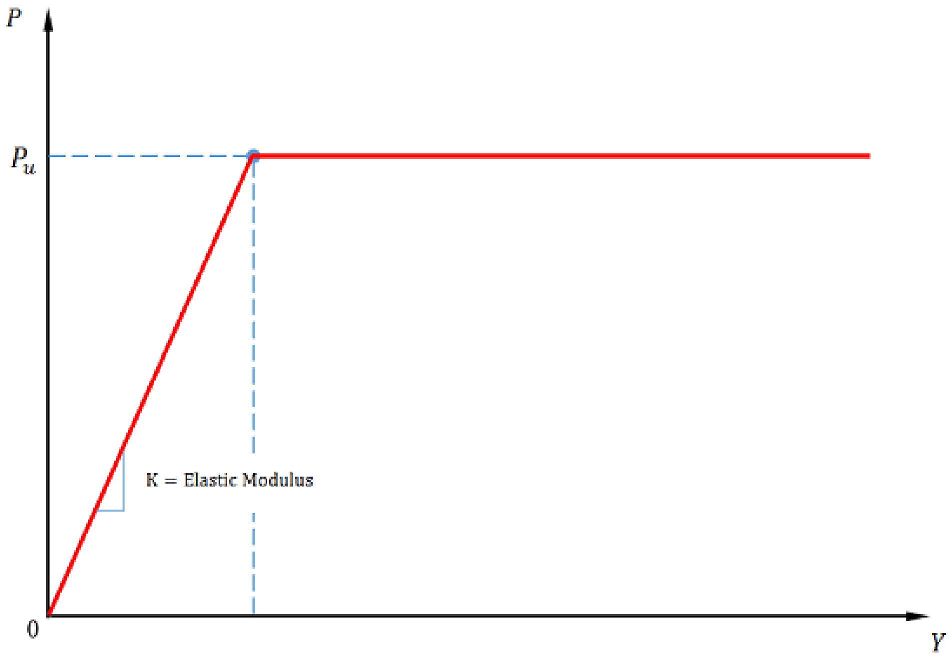



**Figure A.13-1** P-Y parameter input dialog for the Elastic-Plastic Model

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, $\upsilon$ 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.

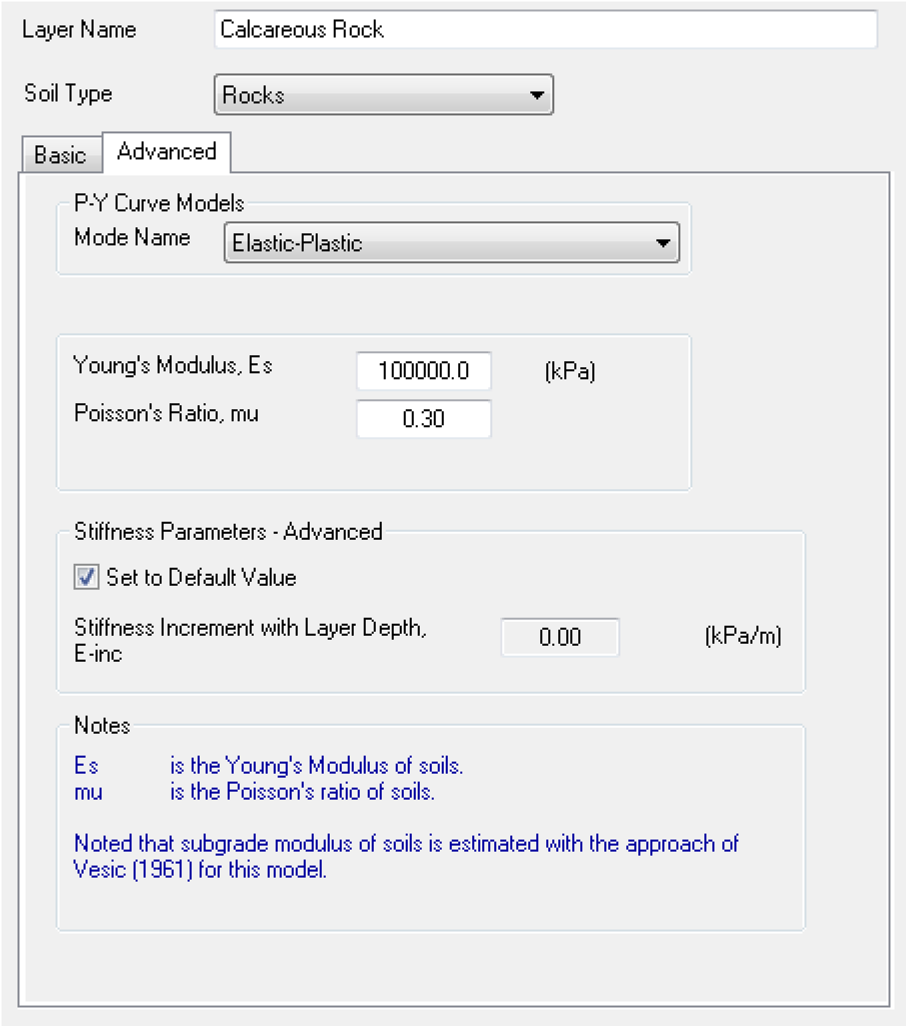



**Figure A.13-2** P-Y parameter input dialog for the Elastic-Plastic Model in PileLAT

## 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.

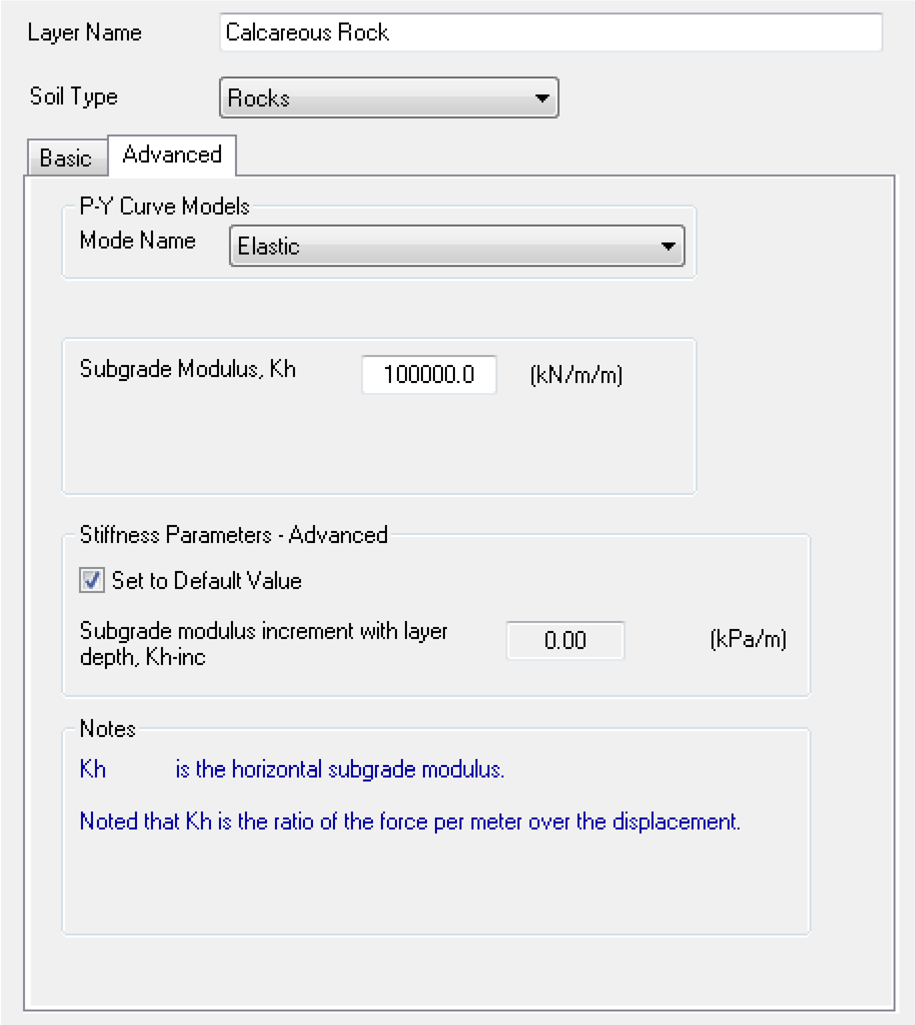



**Figure A.14-1** P-Y parameter input dialog for the Elastic Model in PileLAT

# 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.

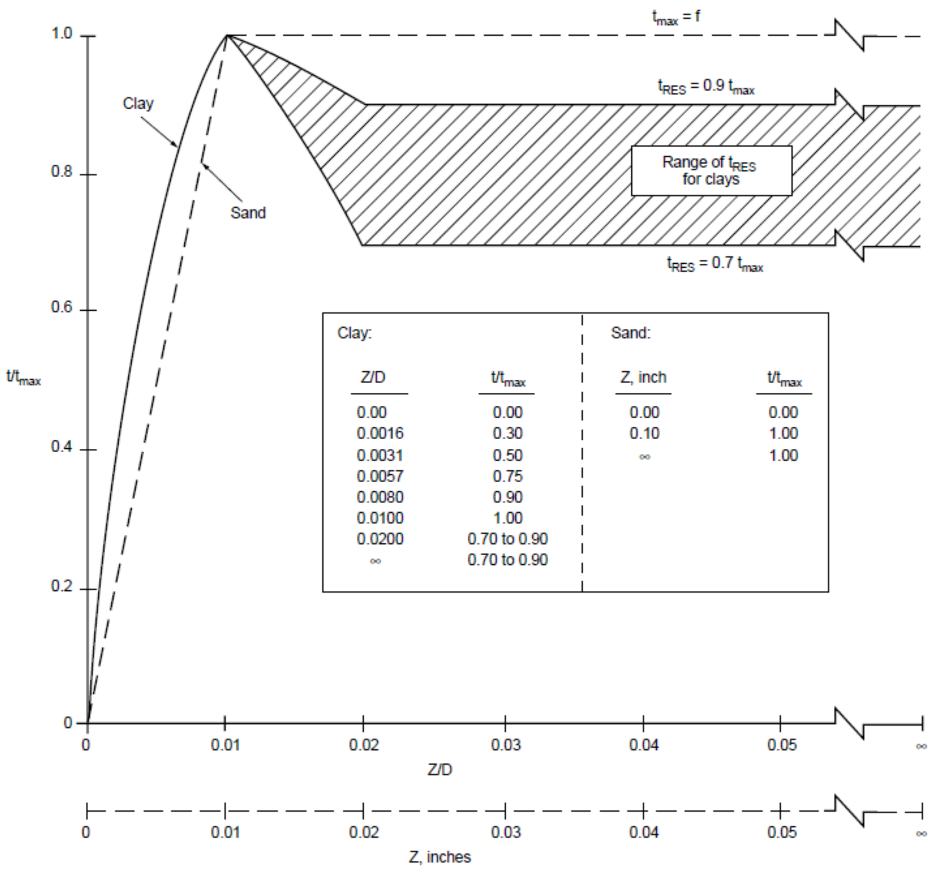



**Figure B.1-1** t-z curve adopted for the cohesive soils – driven piles (after API 2000)

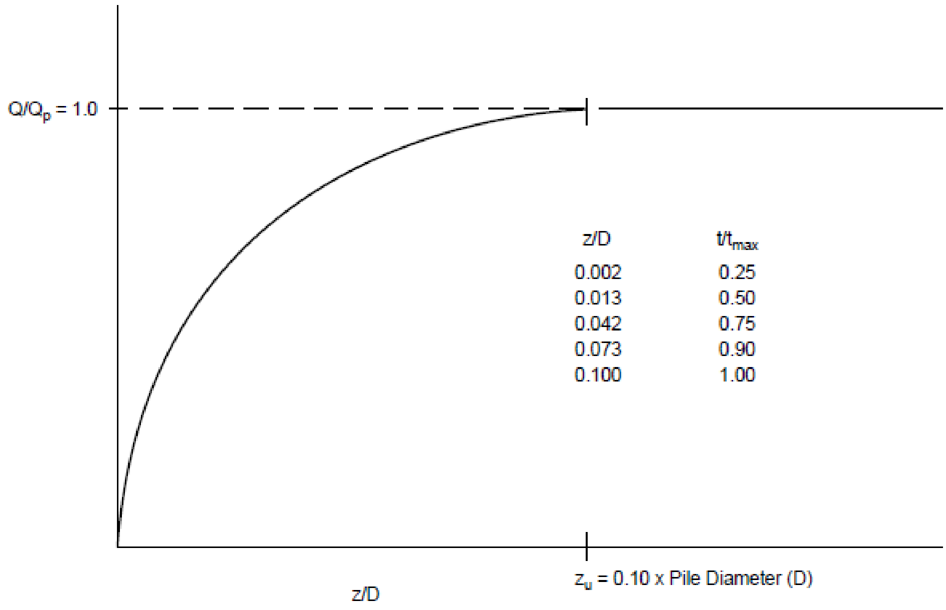



**Figure B.1-2** q-w curve adopted for the cohesive soils – driven piles (after API 2000)

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.

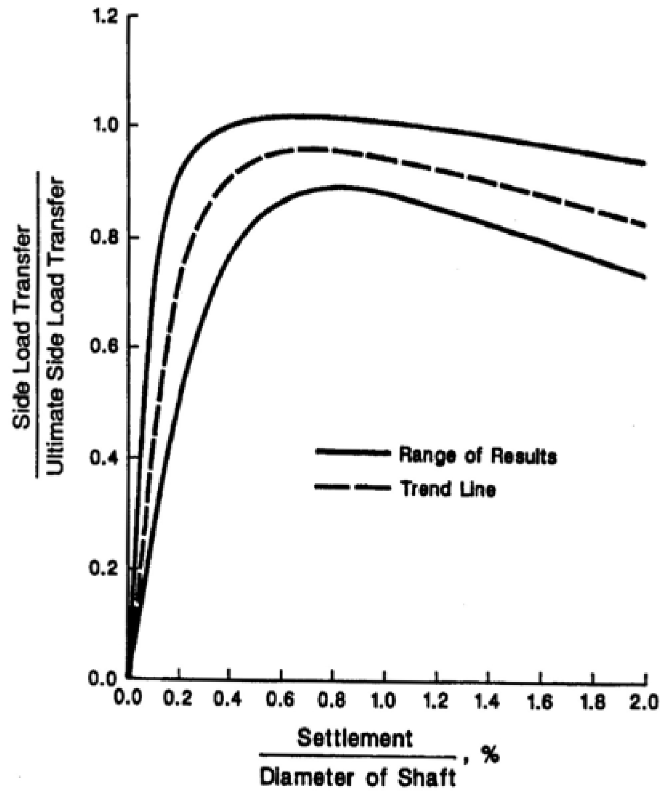



**Figure B.1-3** t-z curve adopted for the cohesive soils – bored piles (O'Neill and Reese 1999)

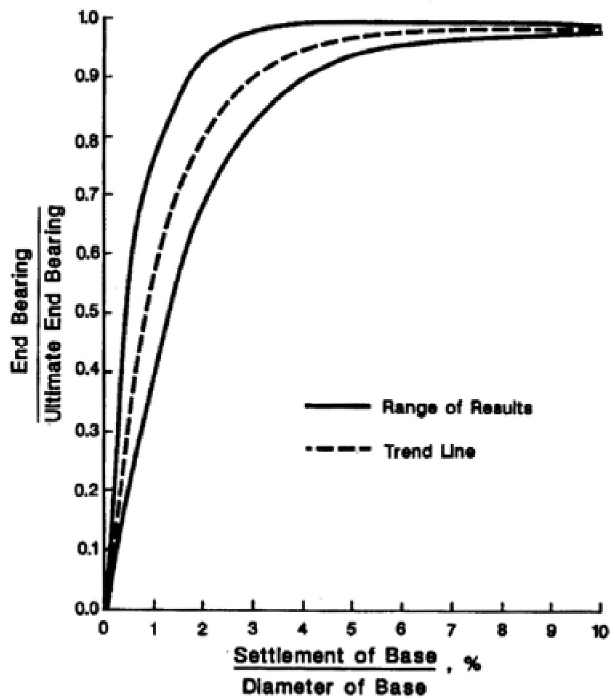



**Figure B.1-4** q-w curve adopted for the cohesive soils – bored piles (O'Neill and Reese 1999)

## 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, $\delta$ 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, $\delta$ 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, $\delta$ 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, $f_b$:

$$f_s = \beta\sigma_z'$$

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

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

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

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

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

where z is the depth below the ground surface, $\sigma_v'$ is the effective overburden pressure and $\phi$ is the effective friction angle of the sand.

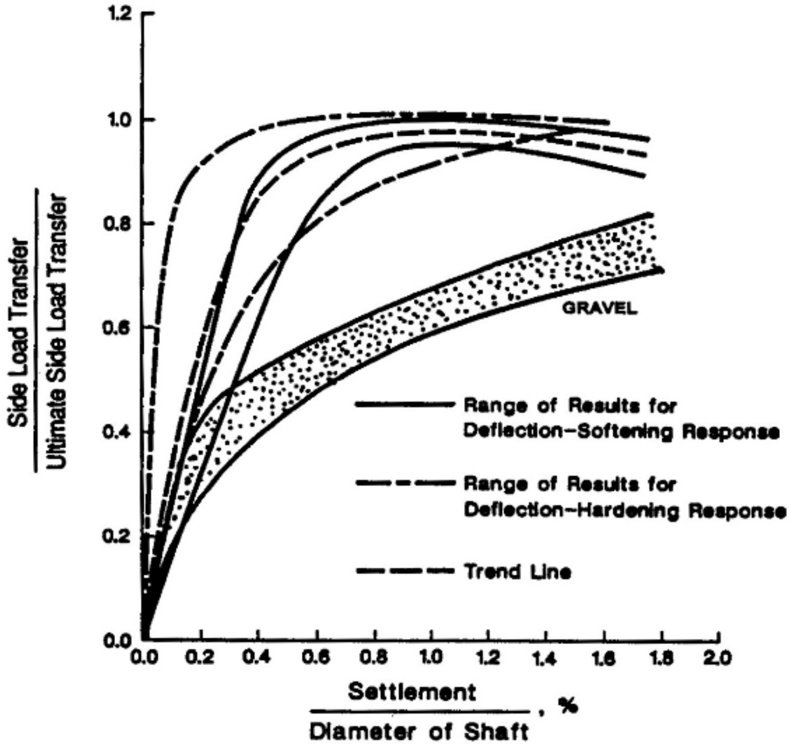



**Figure B.2-1** t-z curve adopted for the granular soils – bored piles (O'Neill and Reese 1999)

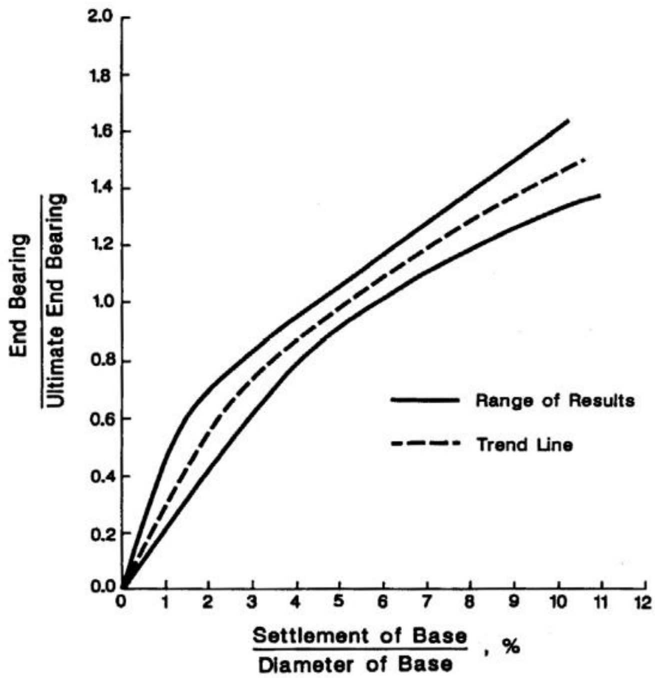



**Figure B.2-2** q-w curve adopted for the granular soils – bored piles (O’Neill and Reese 1999)

## 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 $\alpha$ and $\beta$ are empirical factors determined from the various load tests, $\sigma_c$ 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 $\beta$ can be adopted as 0.5 for all practical purposes. As for the empirical factor, $\alpha$, 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; $\upsilon_b$ is Poisson's ratio (0.25 is adopted in the program); D is the pile diameter and $\sigma_b$ is the mobilised end bearing pressure at the pile toe. This elastic-plastic relationship is adopted in PileLAT.

# Appendix C. T-θ curve for torque and rotation relationship

## C.1 Introduction

PileGroup uses T- θ nonlinear spring to model the torsional stiffness of the individual piles within the pile group. The torsional springs are applied at the nodes along the pile length. The following simple hyperbolic curve is used by PileGroup for the nonlinear T- θ springs:

$$\Delta T = \frac{\theta}{a + b\theta}$$

Where $\Delta T$ is torque for the pile segment with length of $\Delta L$ and $\theta$ is the rotation of the long rigid pile which is assume to be constant along the pile length. The coefficient $a$ and $b$ are defined in the relationships as follows:

$$a = \frac{1}{4\pi {r_0}^2 G \Delta L}$$

$$b = \frac{1}{2\pi {r_0}^2 f_s \Delta L}$$

where G is the shear modulus of the soil, $r_0$ is the radius of the pile and $f_s$ is the ultimate shaft resistance as determined with the procedures described in Appendix B.2.

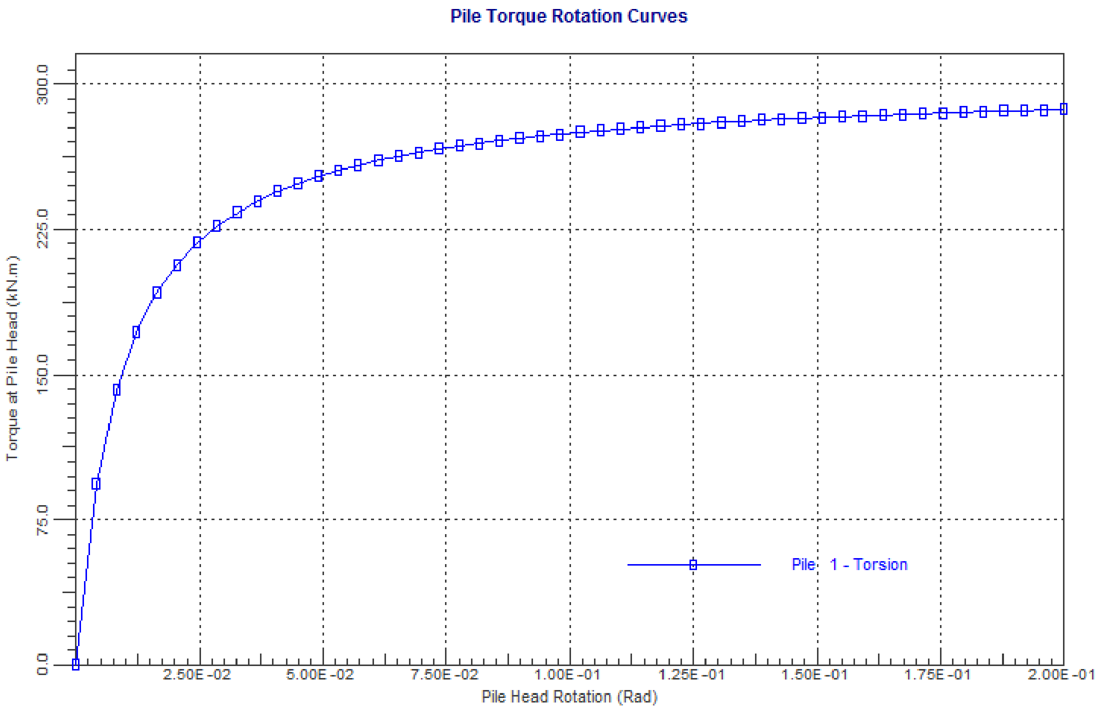



**Figure C.1-1** Torque and rotation nonlinear curve at the pile head

The total torque at the pile head is the sum of the torque for each pile segment as determined based on the equations above for a specified rotation, $\theta$. Based on this simple approach, PileGroup will develop a nonlinear relationship between the pile head torque and rotation and use this nonlinear torsional spring in the analysis. The contribution from the pile tip is ignored and the stiffness is not considered. A typical torque and rotation curve at the pile head is shown in the figure below.

# Appendix D. Examples

## D.1 Example 1 – Pile group in clay with battered piles

This example involves a pile group consisting of six numbers of 500 mm diameter driven reinforced concrete piles of 30 m long. Two piles (Pile No 1 and pile No 6) are installed with the batter angle of 10 degrees – pile batter of 1V: 0.18H. The ground conditions at the site comprise 2.5 m thick soft clay, followed by 21.5 m thick firm clay which is underlain by stiff clay. The pile cap is 3 m above the ground surface level. The pile group is under the combination of 200 kN axial load and 1000 kN horizontal force in X direction and 500 kN horizontal force in Z direction.

Figure D.1-1 shows the pile layout for pile group analysis. The ground profile is shown in Table D.1-1 together with P-Y models and the detailed strength parameters for different soil layers are shown in Table D.1-2. Figure D.1-2 shows the ground profile with the pile length and loading conditions for this example.

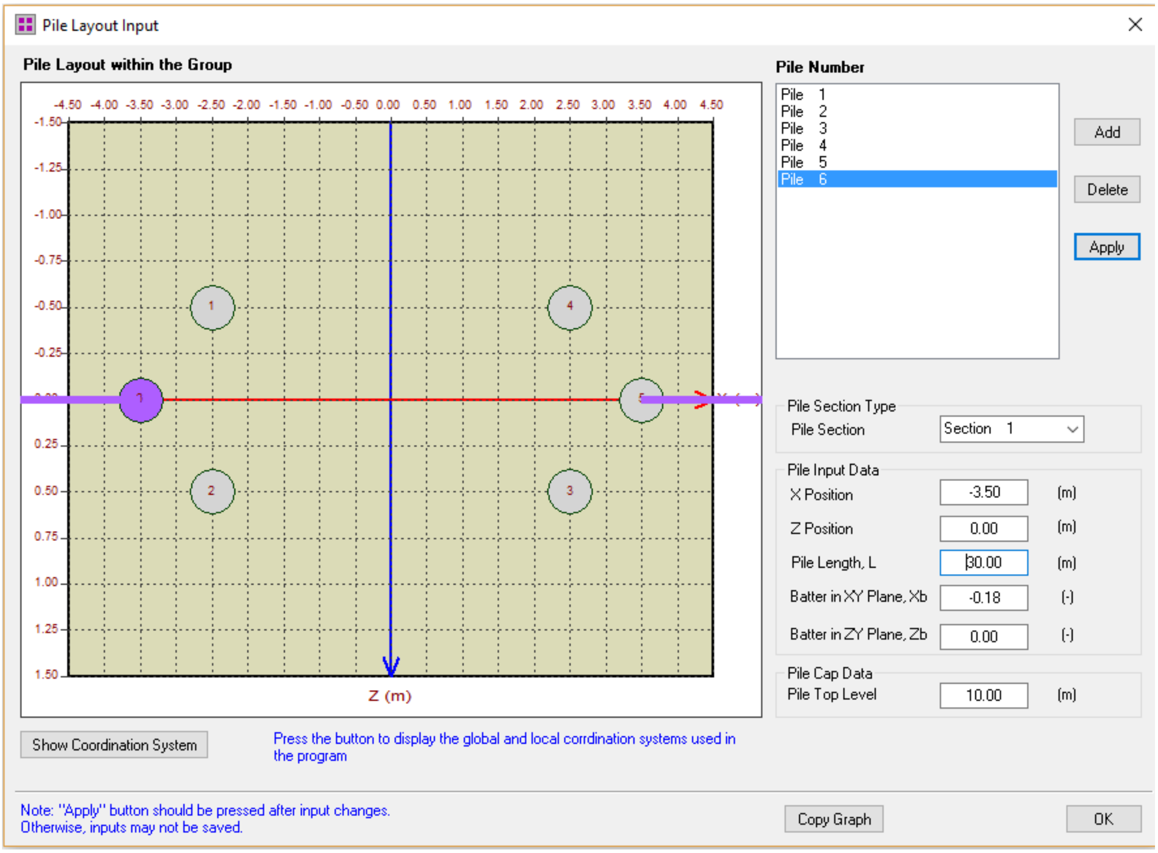



**Figure D.1-1** Pile layout for pile group analysis

Note that the cantilever portion of the pile group is modelled with using a layer with "Null" material type in PileGroup 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 D.1-2.

Table D.1-1 Ground profile information for Example

| Layer No | Layer Name | Layer Thickness (m) | P-Y Model |
|---|---|---|---|
| 1 | Clay 1 | 2.5 | Soft Clay |
| 2 | Clay 2 | 21.5 | Soft Clay |
| 3 | Clay 3 | 10.0 | Soft Clay |

Table D.1-2 Summarised soil strength parameters for Example

| Layer No | Strength Parameters | | | |
|---|---|---|---|---|
| | Undrained Shear Strength, $s_u$ (kPa) | Unit Weight, $\gamma$ (kN/m3) | Strain Factor, $\varepsilon_{50}$ | J |
| **1** | 20 | 16 | 0.01 | 0.5 |
| **2** | 35 | 16 | 0.005 | 0.25 |
| **3** | 100 | 16 | 0.005 | 0.25 |

Forces applied at the top of the pile cap are (1) compressive axial force of 200 kN, (2) horizontal force of 1000 kN along the global X direction and (3) horizontal force of 500 kN along the global Z direction on the pile cap plane. Figure D.1-3 shows the loading input for this example. Figure D.1-4 shows the 3D geometry of the pile group.

Pile group analysis results are shown in Figures D.1.5-D.1.13 for three-dimensional displaying of the results and in Figures D.1.14-D.1.17 for the detailed result plot along the length for all piles.

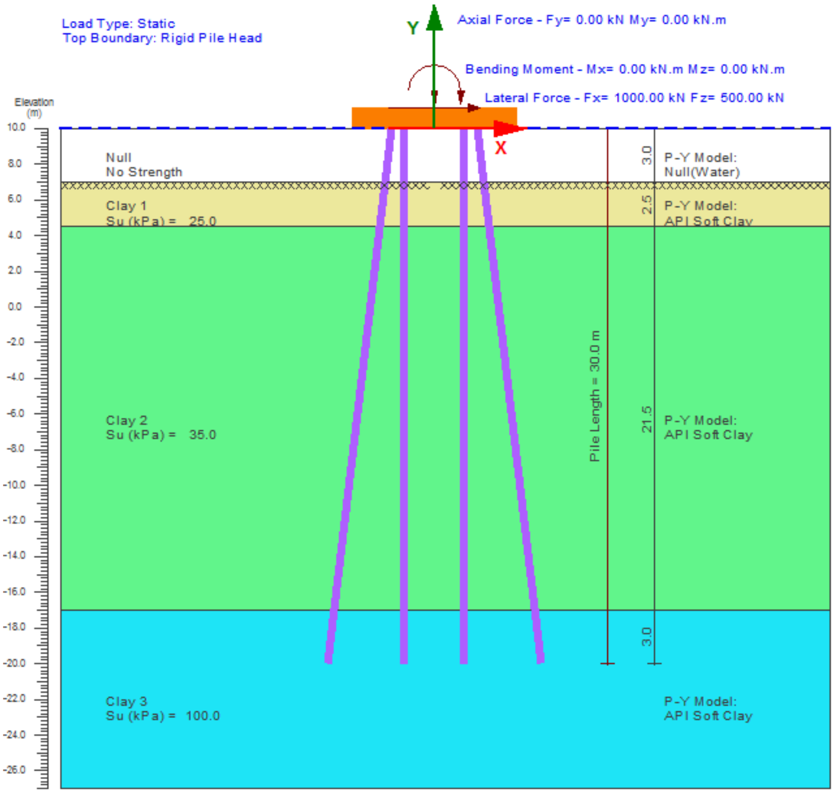



**Figure D.1-2** Ground profile with pile length and loading information on XY plane

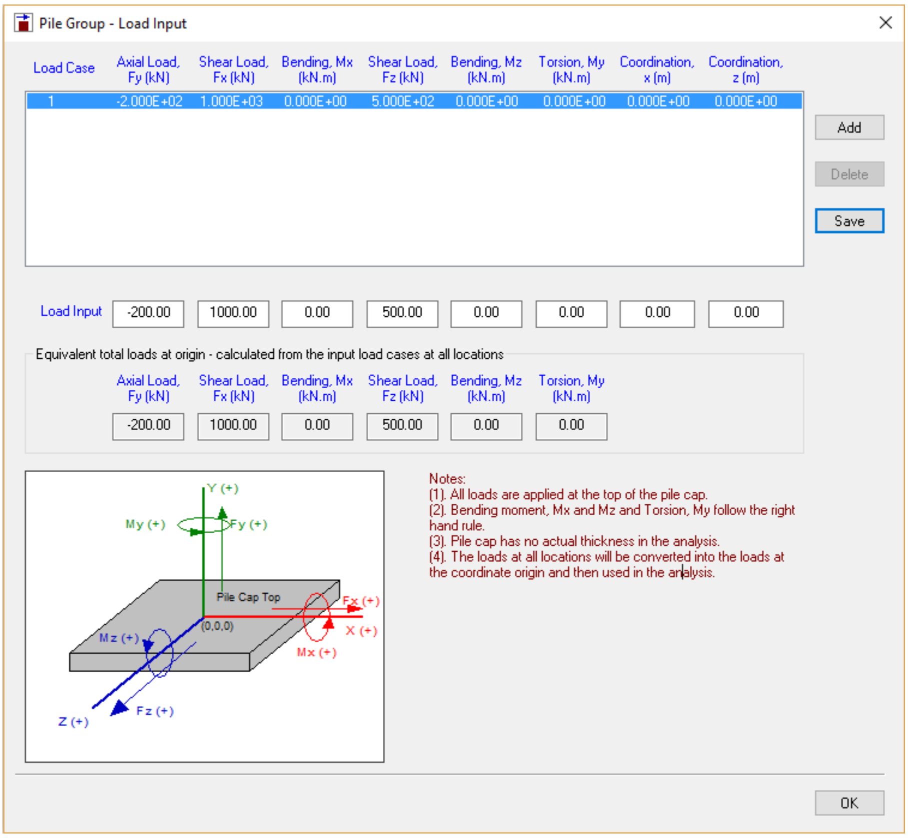



**Figure D.1-3** Applied loadings on the pile cap

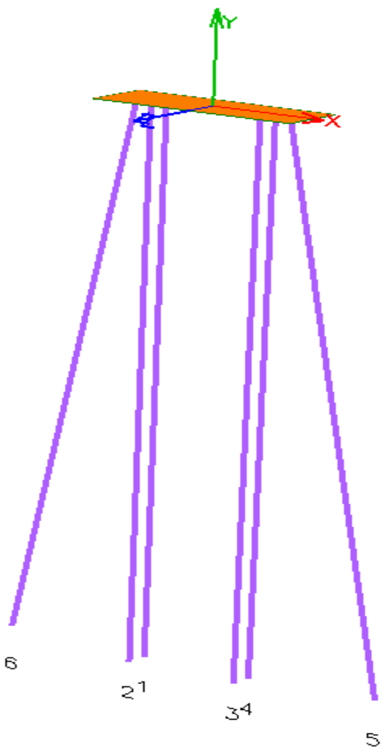



**Figure D.1-4** 3D display of pile group geometry

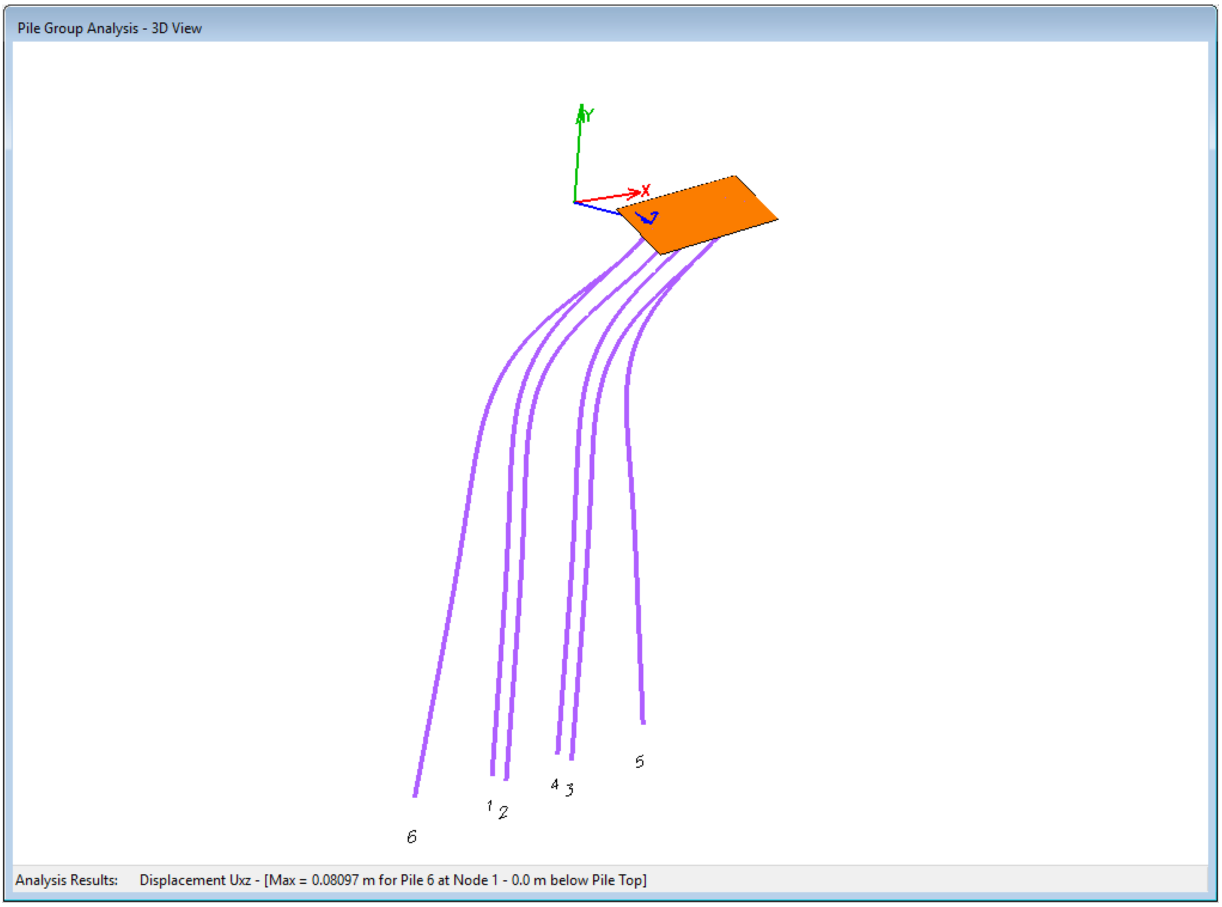



**Figure D.1-5** Deformed shape of pile group under the applied loading

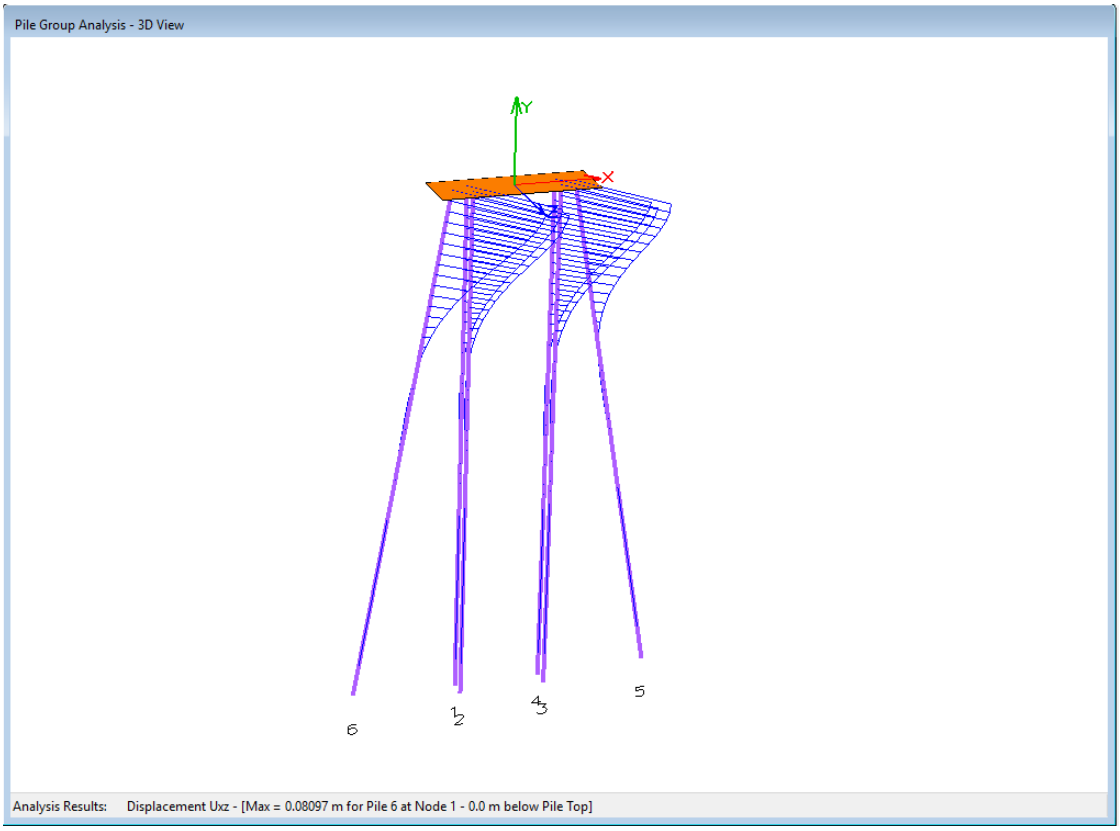



**Figure D.1-6** 3D view of displacement Uxz

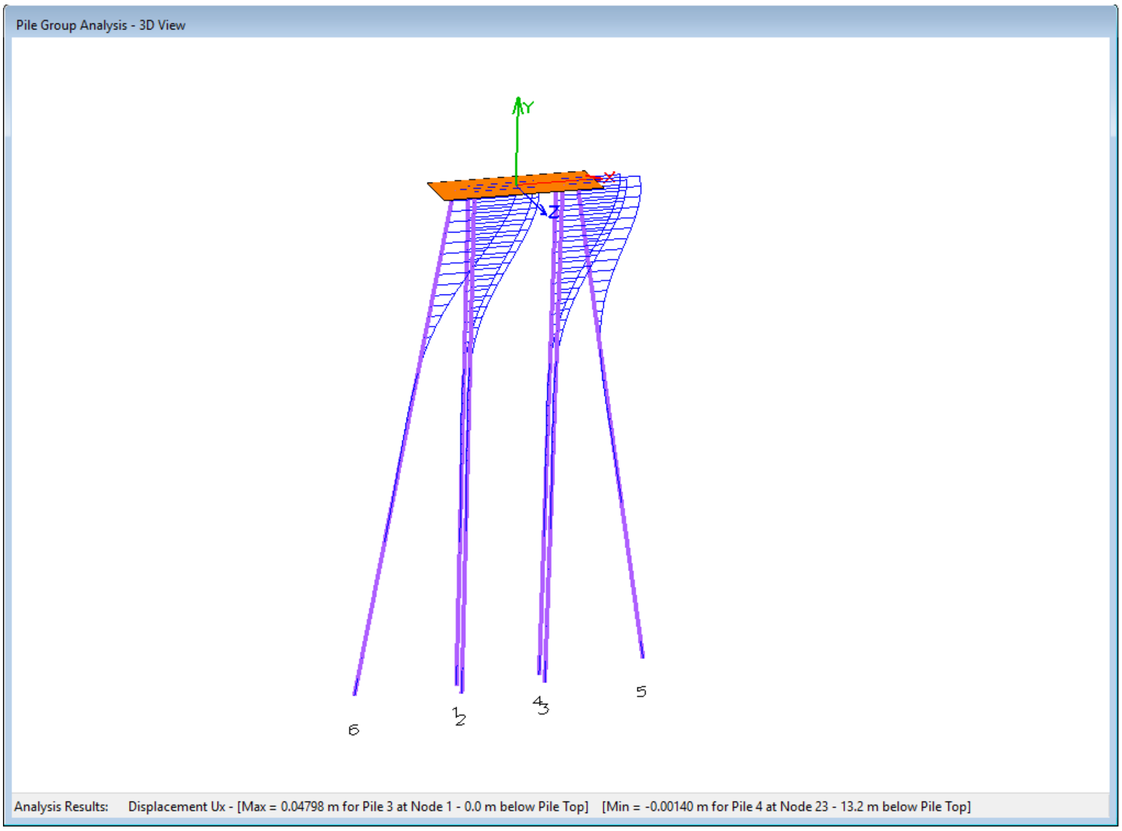



**Figure D.1-7** 3D view of displacement Ux

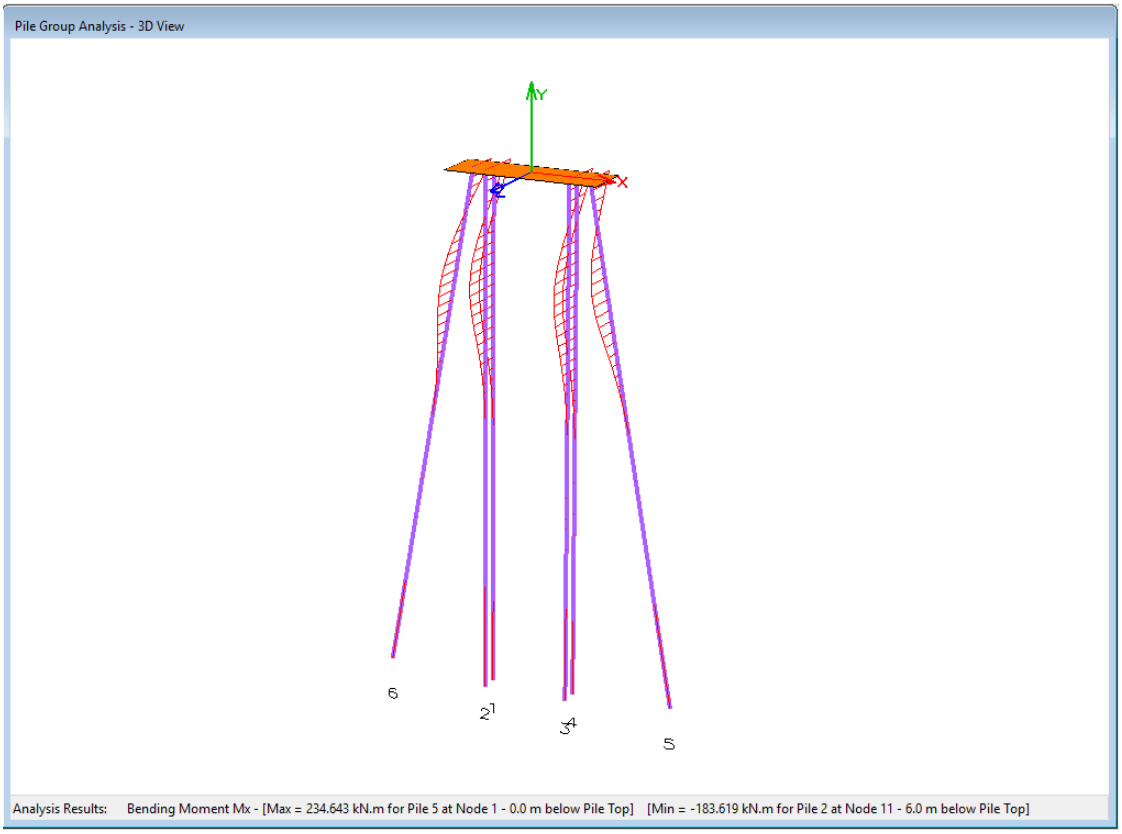



**Figure D.1-8** 3D view of bending moment Mx

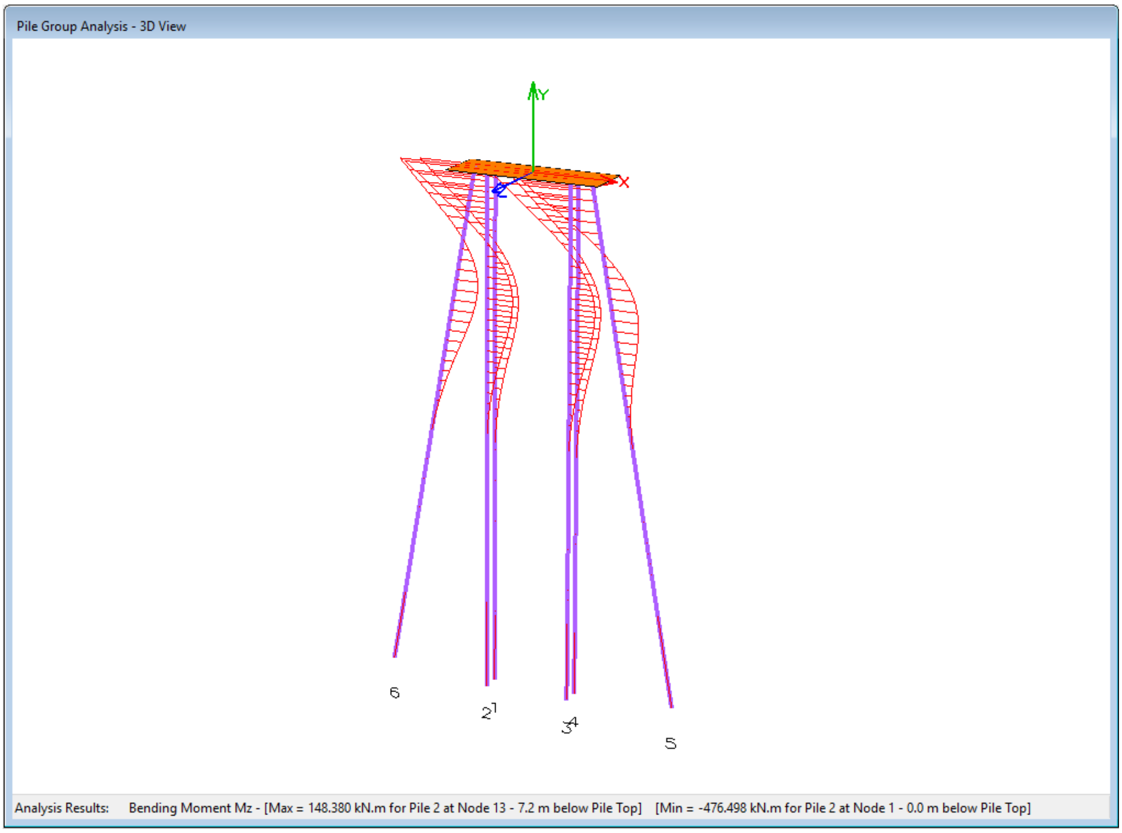



**Figure D.1-9** 3D view of bending moment Mz

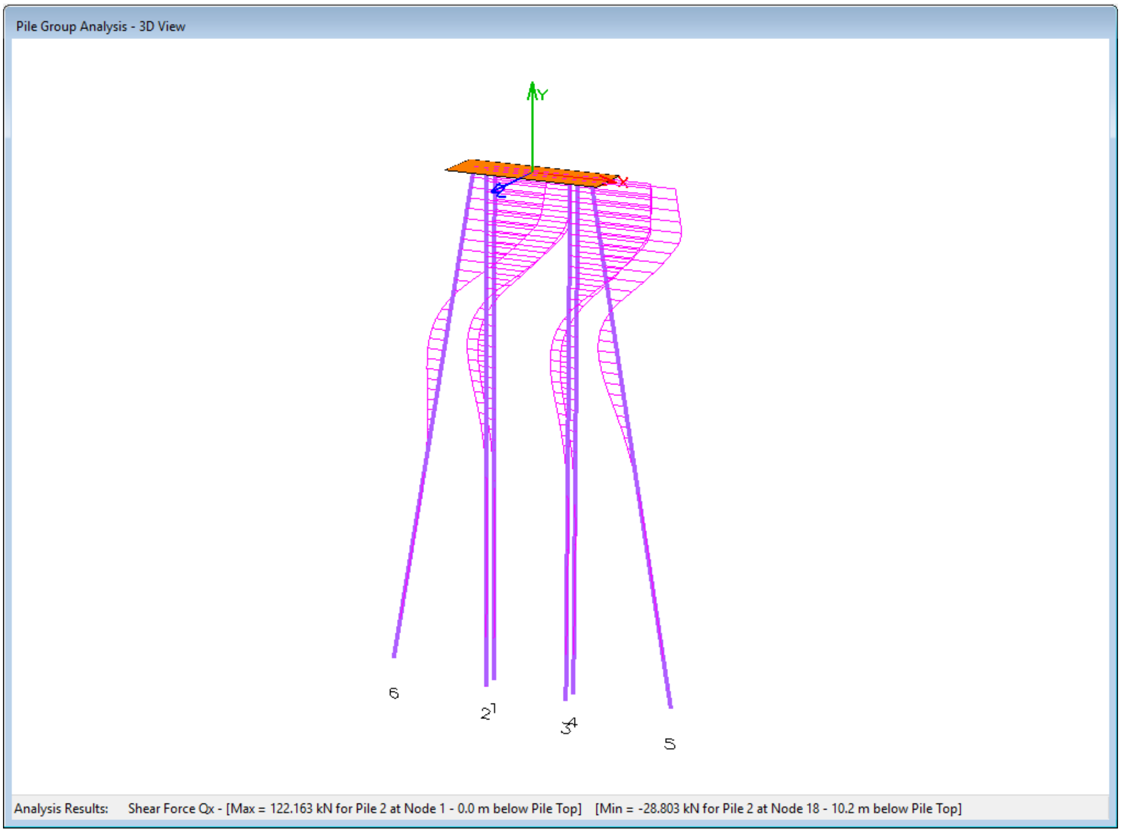



**Figure D.1-10** 3D view of shear force Qx

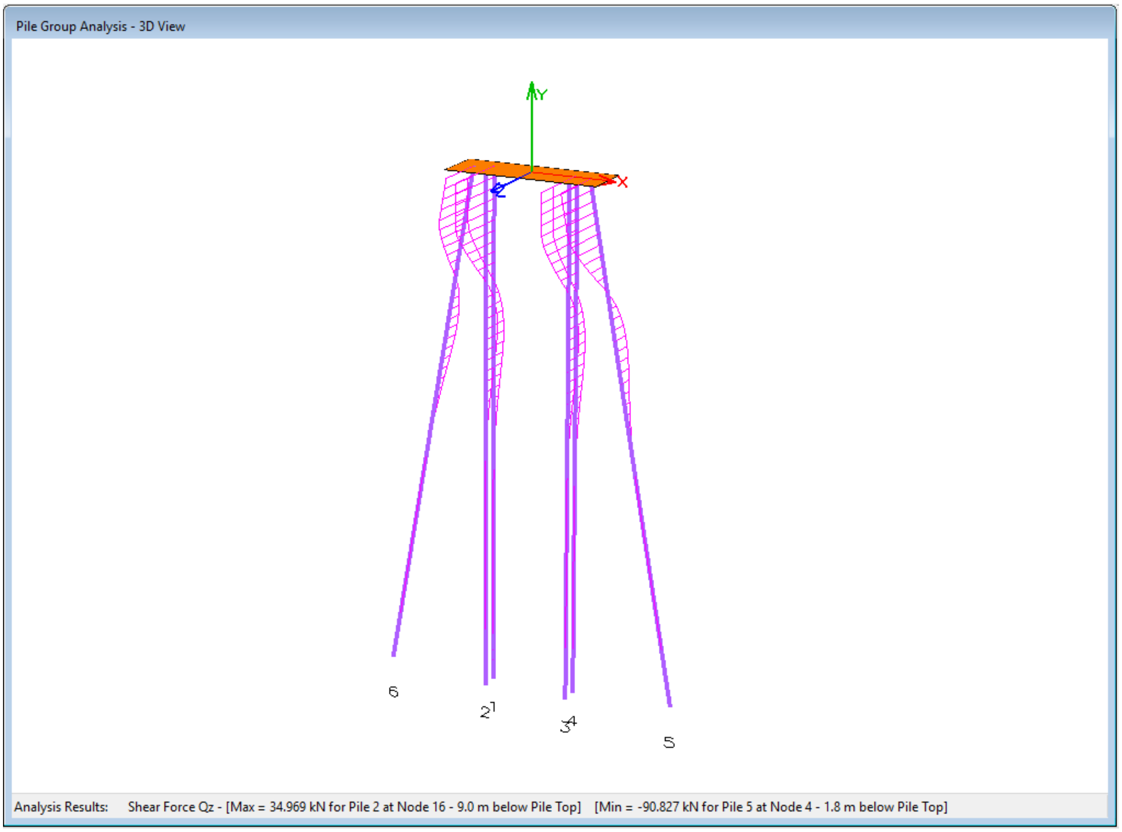



**Figure D.1-11** 3D view of shear force Qz

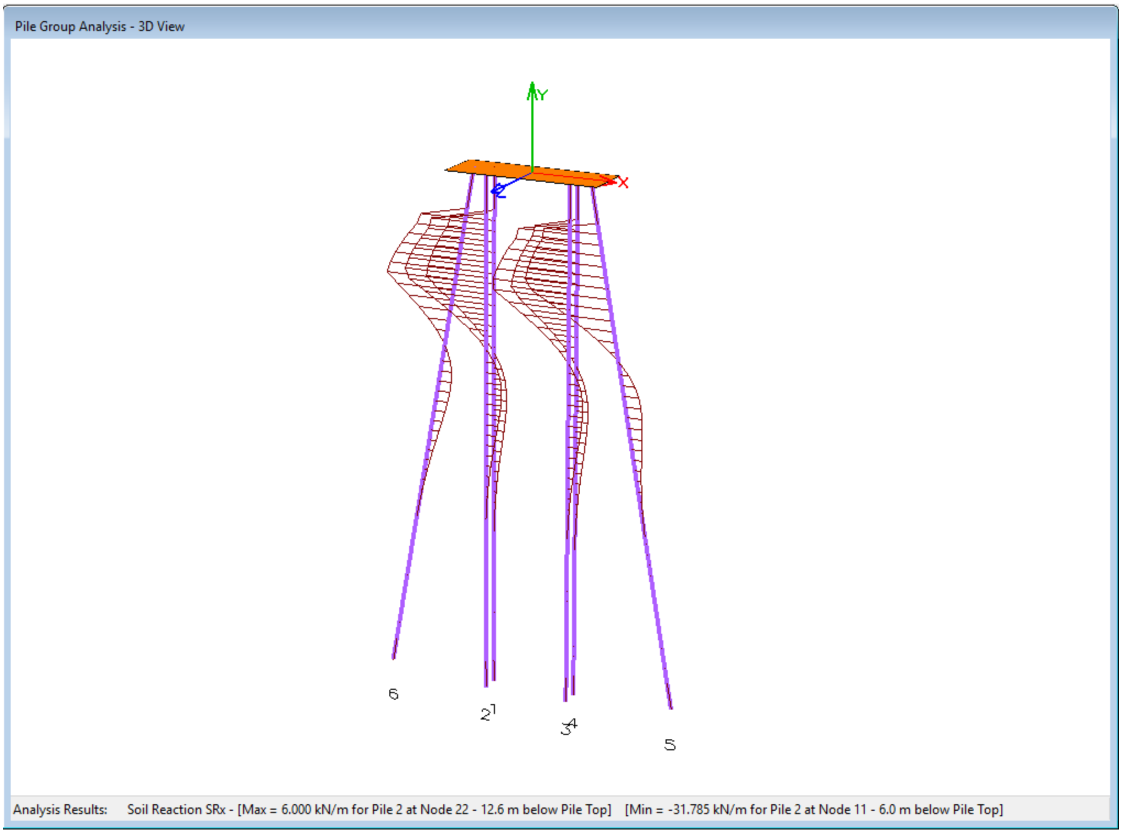



**Figure D.1-12** 3D view of soil reaction SRx

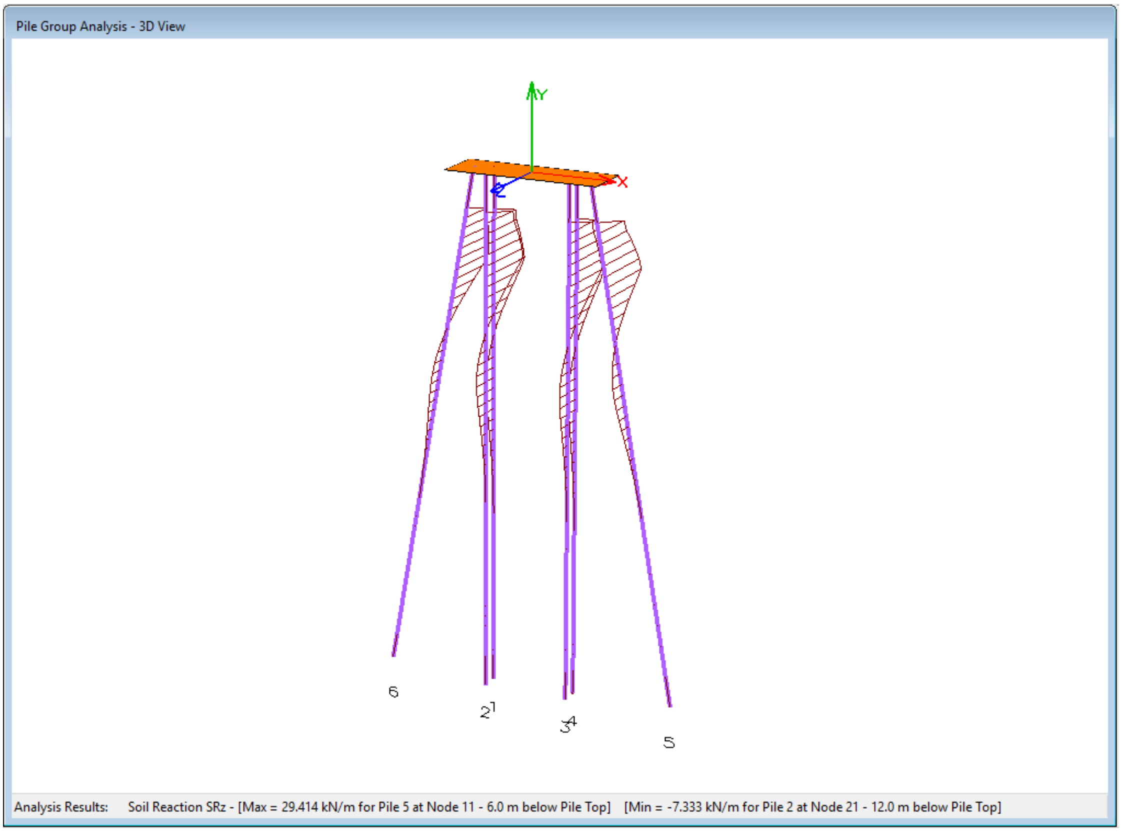



**Figure D.1-13** 3D view of soil reaction SRz

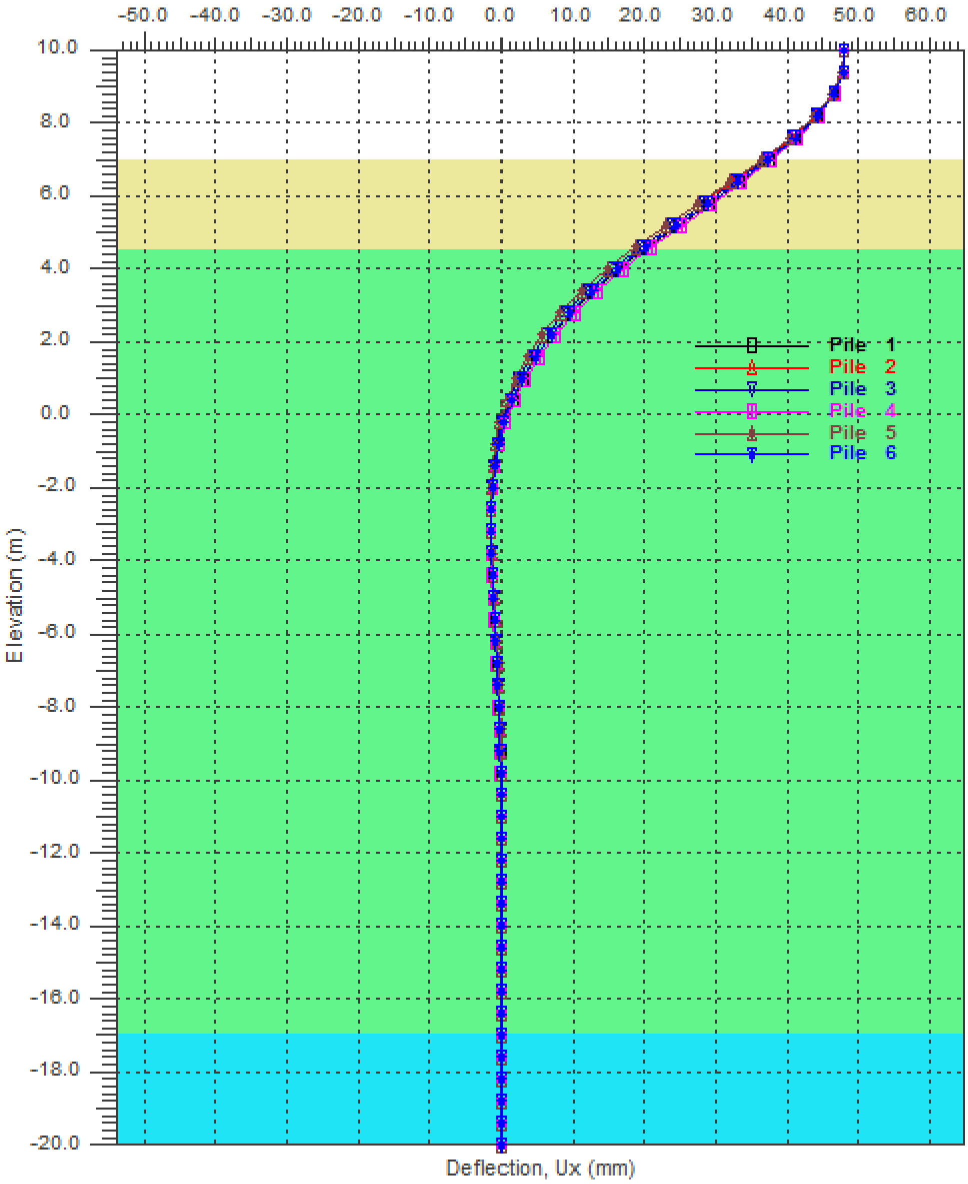



**Figure D.1-14** Distribution of displacement Ux

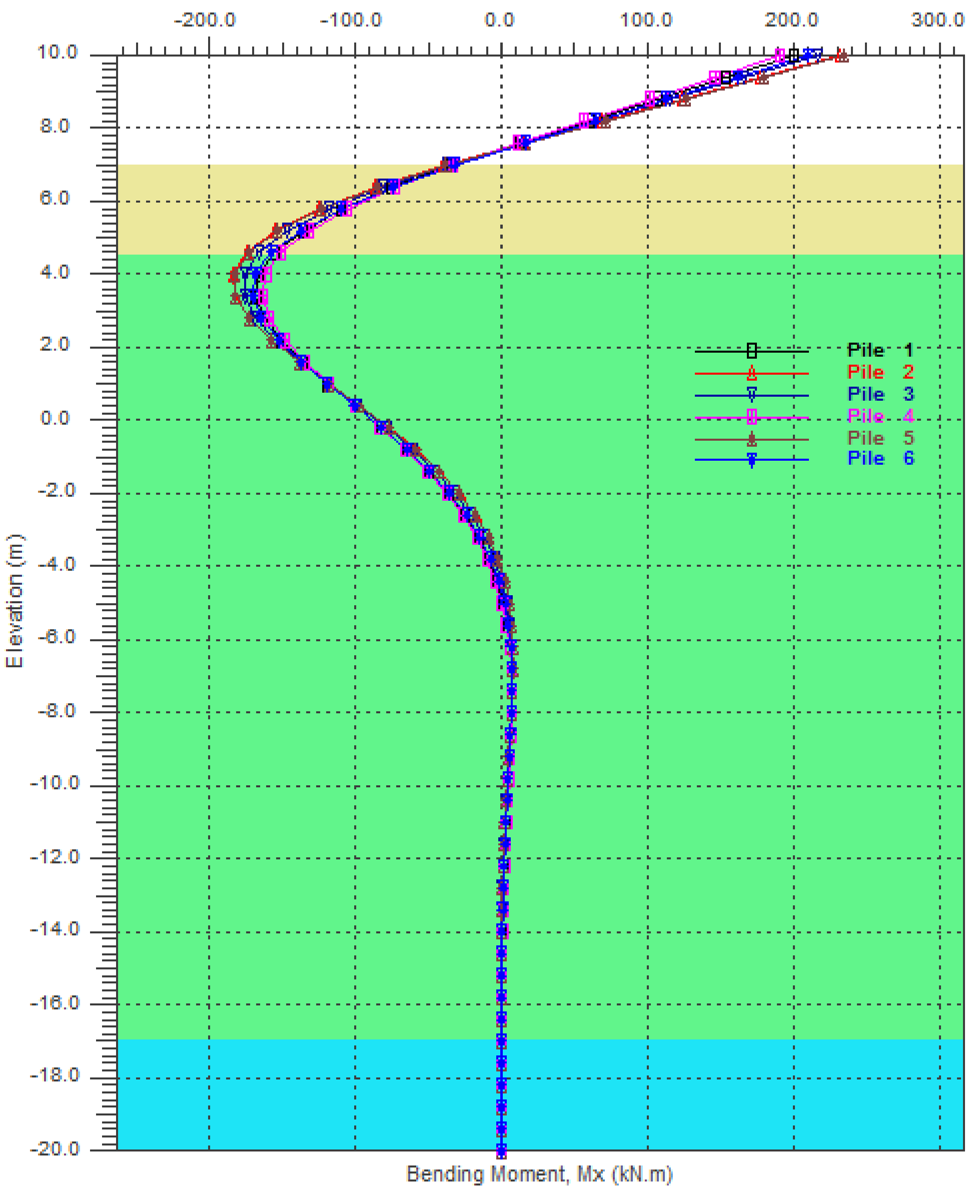



**Figure D.1-15** Distribution of bending moment Mx

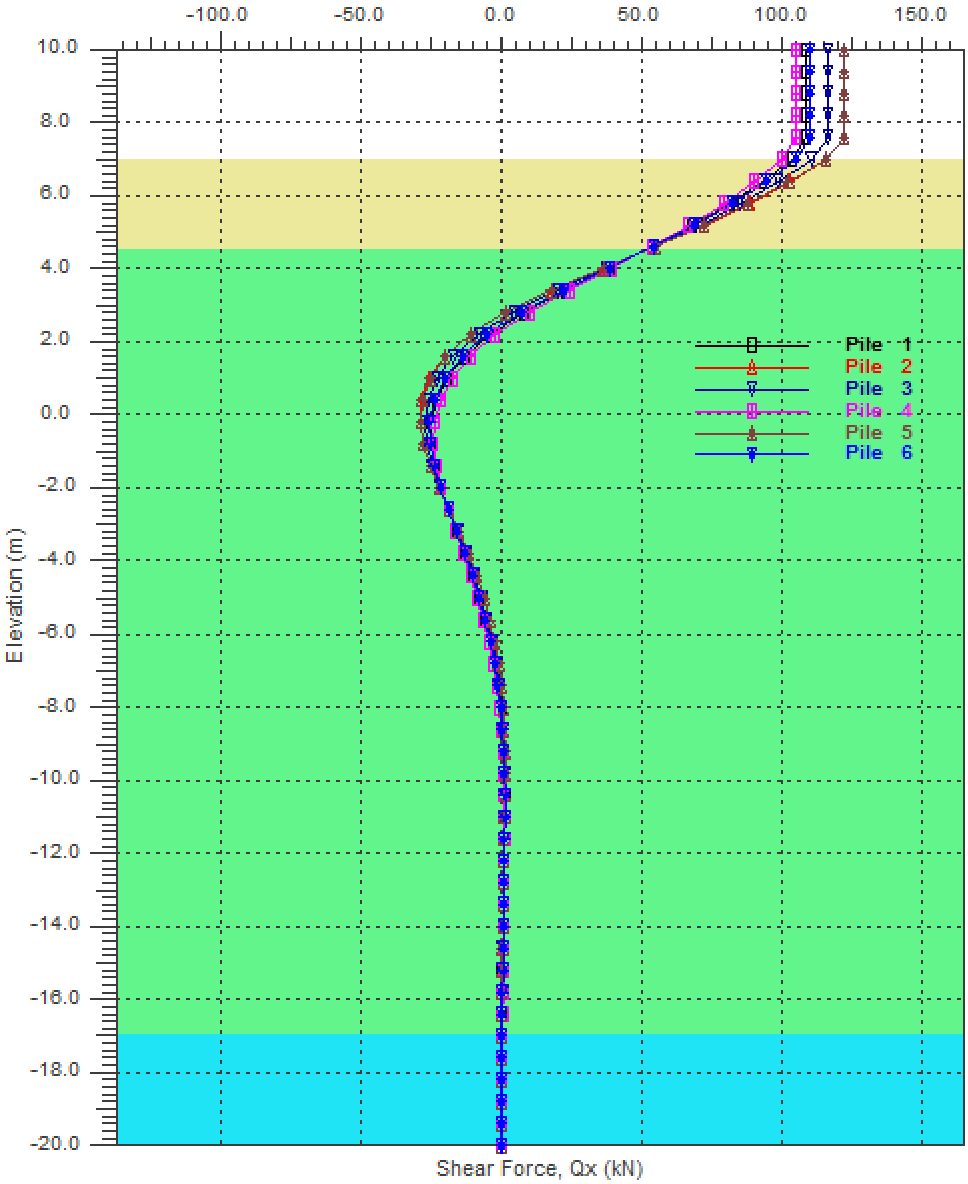



**Figure D.1-16** Distribution of shear force Qx

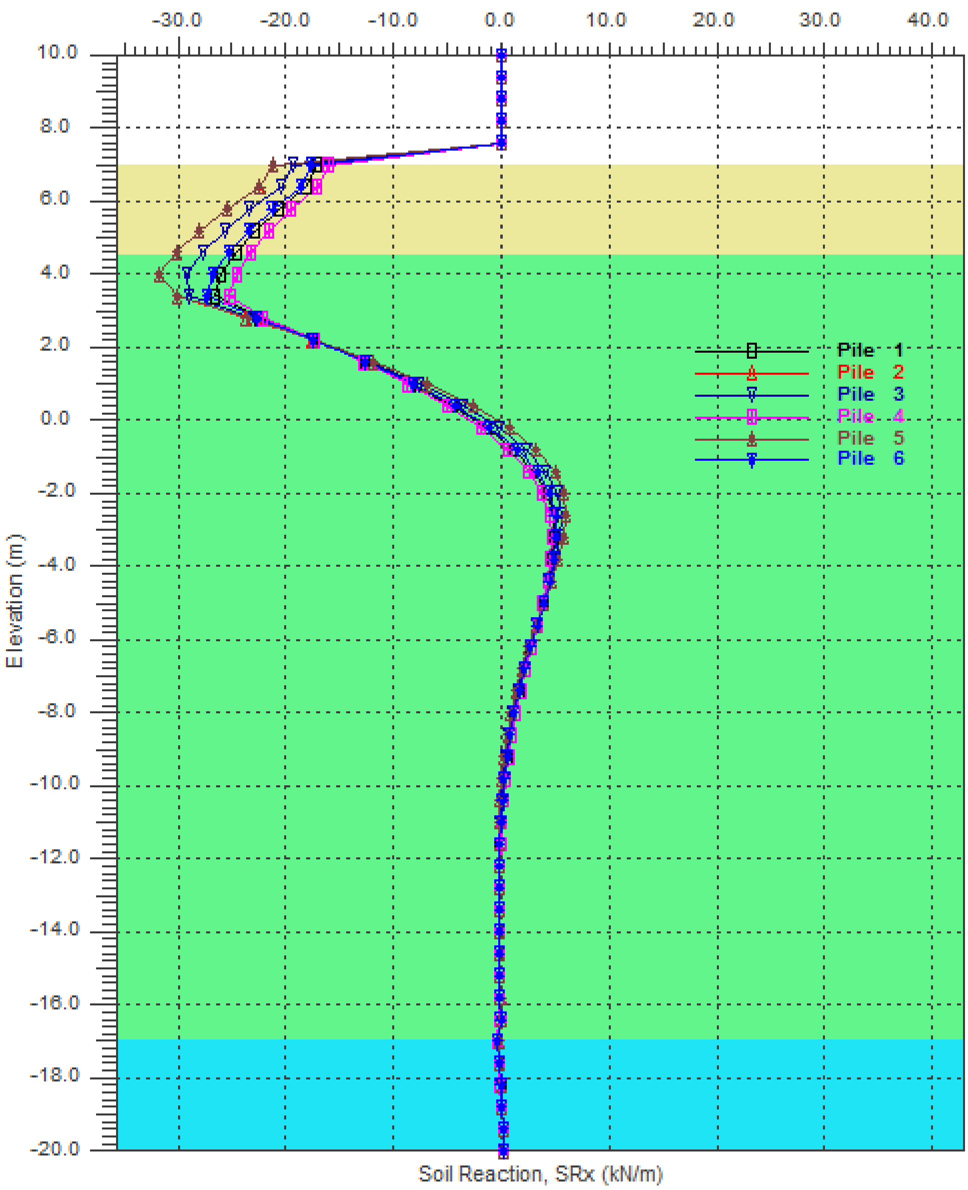



**Figure D.1-17** Distribution of soil reaction SRx

## D.2 Example 2 – Roosevelt bridge pile group analysis with using PileGroup program

This example involves a 4 x 4 pile group consisting of 16 numbers of 760 mm diameter driven prestressed concrete piles of 16.5 m long, which were spaced at three pile diameters. The lateral load behaviour of this pile group was studied by Ruesta and Townsend (1997) in Stuart, Florida. Figure 1 shows Roosevelt bridge where this pile group was tested during the construction. Figure 2 shows the pile group testing layout during the construction.

**Figure D.2-1** Roosevelt bridge after construction completion (from Anderson, 2015)

**Figure D.2-2** Pile layout for pile group testing (from Anderson, 2015)

The ground surface was 2 m below the water level and the soft profile consisted of two well-defined layers of cohesionless soils made up of 4 m of loose sand underlain by partially cemented sand. The pile layout input in the program is shown in Figure D.2-3.

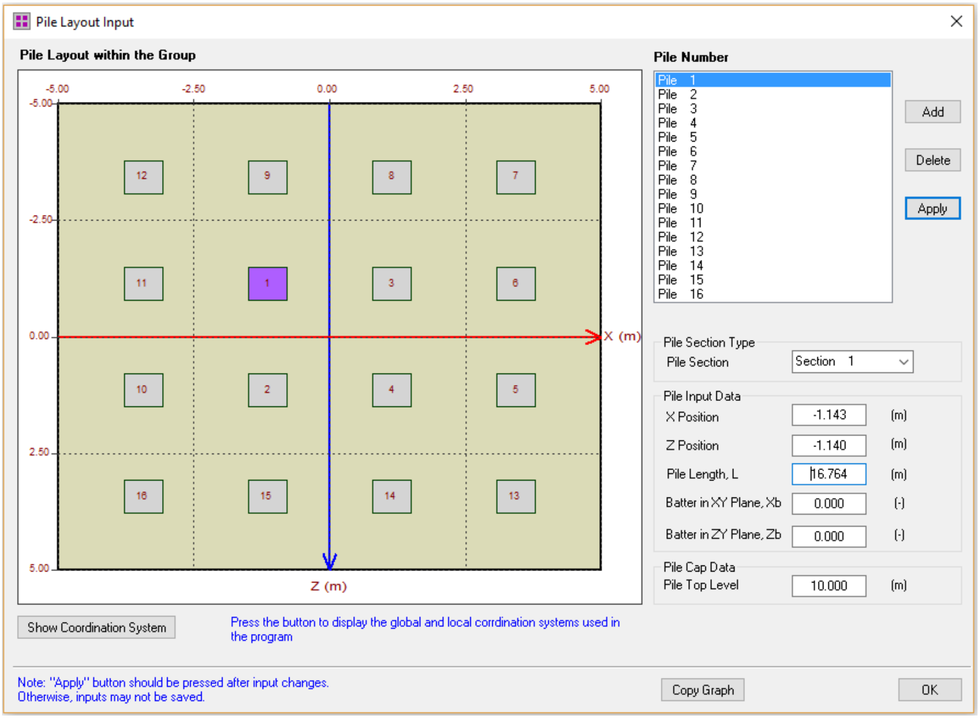



**Figure D.2-3** Pile layout input for the pile group analysis with using PileGroup

The ground profile adopted in PileGroup analysis of this case is shown in Figure D.2-4. The soil model of API Sand is used to model the lateral behaviour of the sand layer encountered on site and the effective friction angle is assumed to be 32 degree. The total unit weight of soil is 18.9 kN/m$^3$.

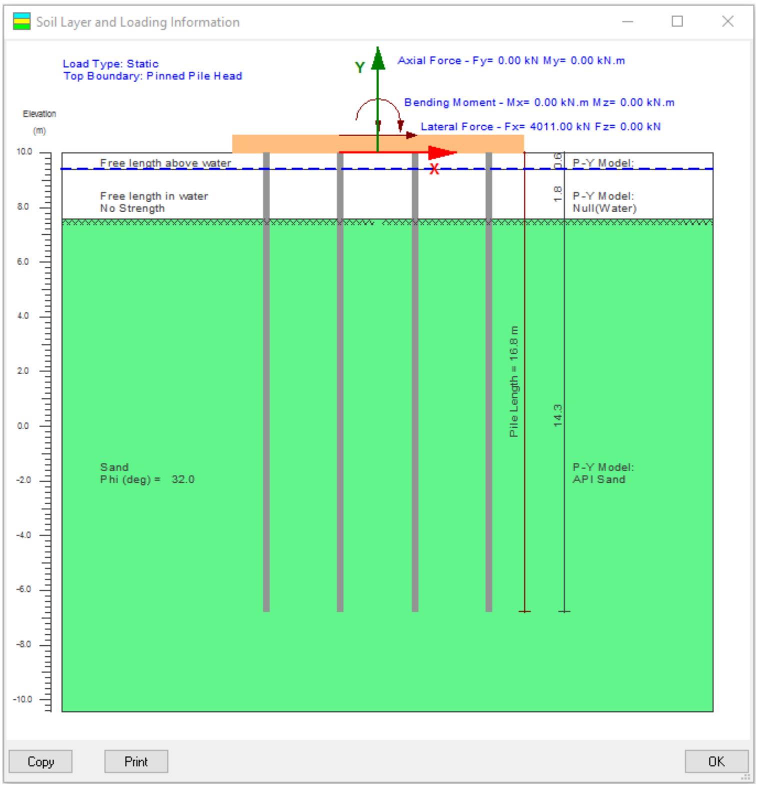



**Figure D.2-4** Ground profile adopted in PileGroup program for Roosevelt bridge pile group case

The pile group is under horizontal load applied at the middle of the pile cap edge in the global X direction. Figure D.2-5 shows the deformed shape of the pile group under the horizontal load.

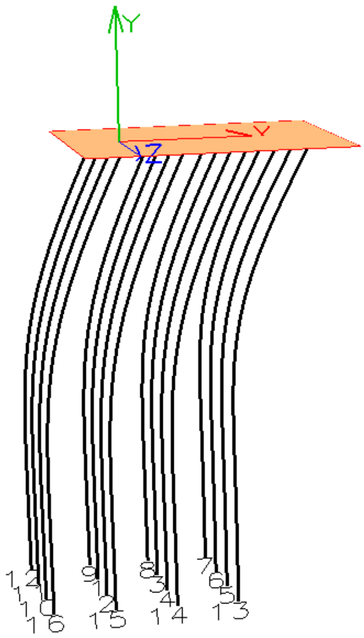


**Figure D.2-5** Deformed shape of pile group under horizontal load

Figure D.2-6 shows the three-dimensional graph of the horizontal displacement distribution along the pile length. The similar graphs such as bending moment, shear force and soil reactions are also available in PileGroup program.

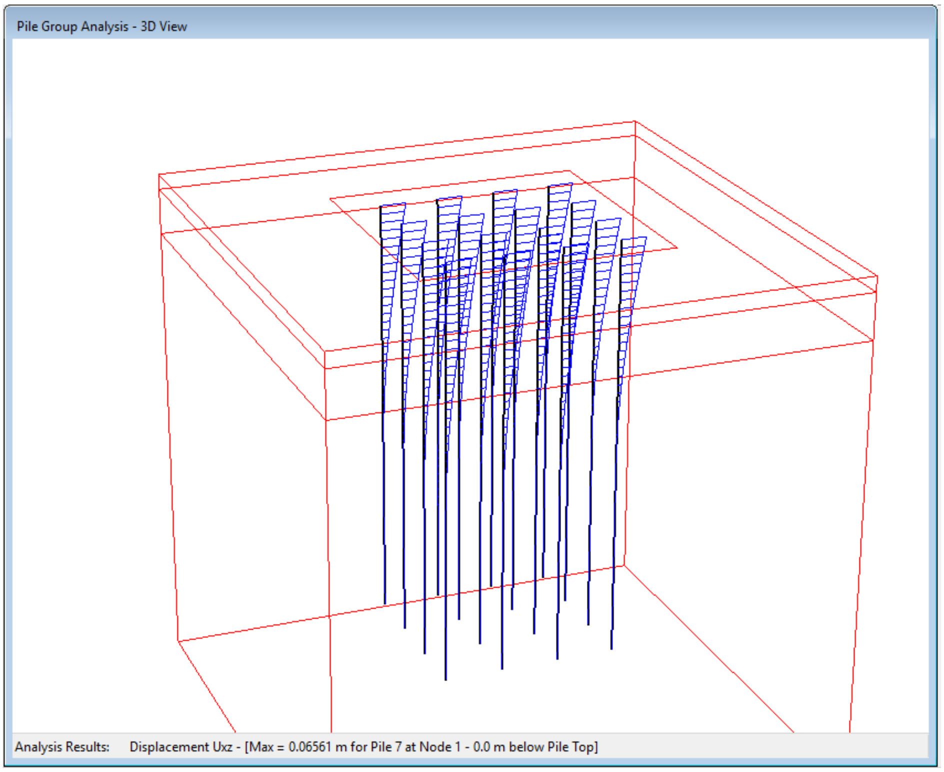



**Figure D.2-6** Deformed shape of pile group under horizontal load

The following figure compares different displacement results for this 4 x 4 pile group and it can be seen that the predictions from the analysis with using PileGroup program are very close to the measured values and also the predictions from FB-MultiPier program.

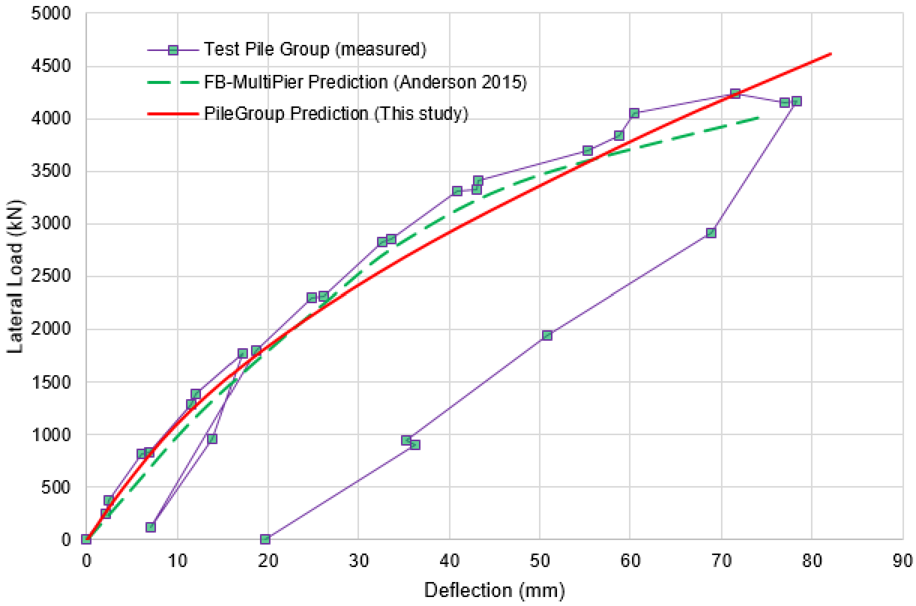



**Figure D.2-7** Comparison results of pile group analysis for Roosevelt bridge case

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