Pile

Version 19.6

Oasys

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Pile Oasys Geo Suite for Windows

This document has been created to provide a guide for the use of the software. It does not provide engineering advice, nor is it a substitute for the use of standard references. The user is deemed to be conversant with standard engineering terms and codes of practice. It is the users responsibility to validate the program for the proposed design use and to select suitable input data.

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1 About Pile

1.1 General Program Description

Oasys Pile Pile load capacity and Settlement

Oasys Pile calculates the vertical load carrying capacities and vertical settlements of a range of individual piles in a layered soil deposit. The theory is based on both conventional and new methods for drained (frictional) and undrained (cohesive) soils. Settlements are calculated for solid circular sections without under-ream.

1.2 Program Features

The main features of **Oasys Pile** are summarised below.

Capacity analysis, settlement analysis, or both can be performed for a range of pile lengths and cross-sections in different soil profiles.

Settlements are calculated for only solid circular cross-sections without under-ream.

The soil is specified in layers. Each layer is set to be drained (frictional) or undrained (cohesive) and appropriate strength parameters are specified. Maximum values can be set for ultimate soil/ shaft friction stress and end bearing stress within each layer.

Levels may be specified as
- depth below ground level; or
- elevation above ordnance datum (OD).

Porewater pressures within the soil deposit can be set to hydrostatic or piezometric.

Pile capacities may be calculated for a range of pile lengths and a range of cross-section types such as circular, square and H-section. The circular and square cross-sections may be hollow or solid, whereas the H-section is only solid. Under-reams or enlarged bases may be specified.

Pile settlements may be calculated for a range of pile lengths and a range of solid circular cross-sections without under-ream.

There are three approaches available to calculate the capacity of the pile -
- working load approach,
- limit-state approach, and
- code-based approach.

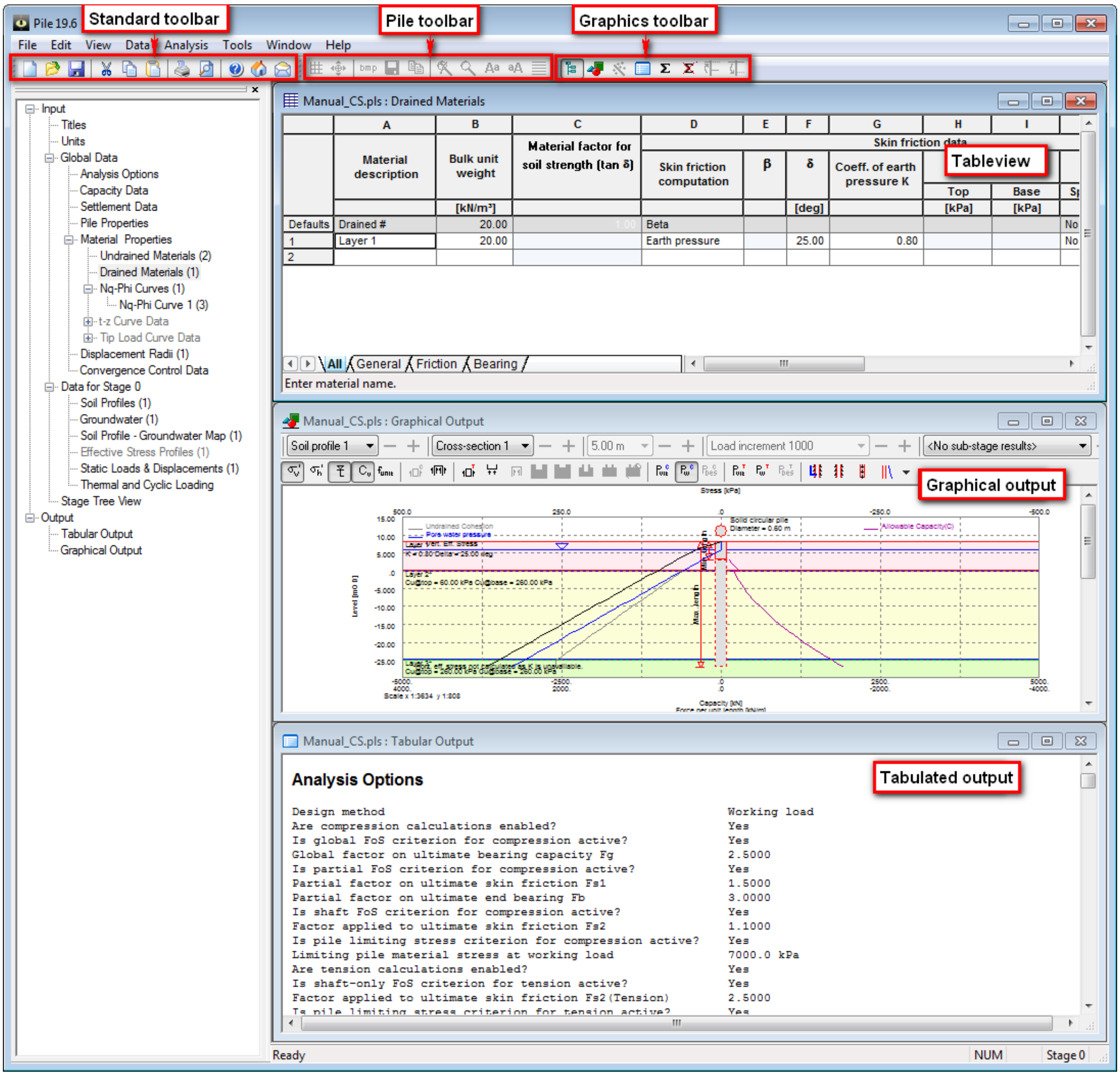
The graphical output depicts the variation of different pile capacities such as shaft resistance, end bearing, total bearing with pile depth and settlements of pile or soil. This may be exported in WMF format.

The text output contains the tabular representation of the input data and results. They may be exported to CSV format.

Legacy Pile and Pilset files may be read. Limiting shaft skin friction is now calculated from the material properties, so the reading of limiting shaft skin friction from legacy Pilset files is ignored.

1.3 Components of the User Interface

The principal components of Pile's user interface are the Gateway, Table Views, Graphical Output, Tabular Output, toolbars, menus and input dialogs. These are illustrated below.



1.3.1 Working with the Gateway

The Gateway gives access to all the data that is available for setting up a Pile model.

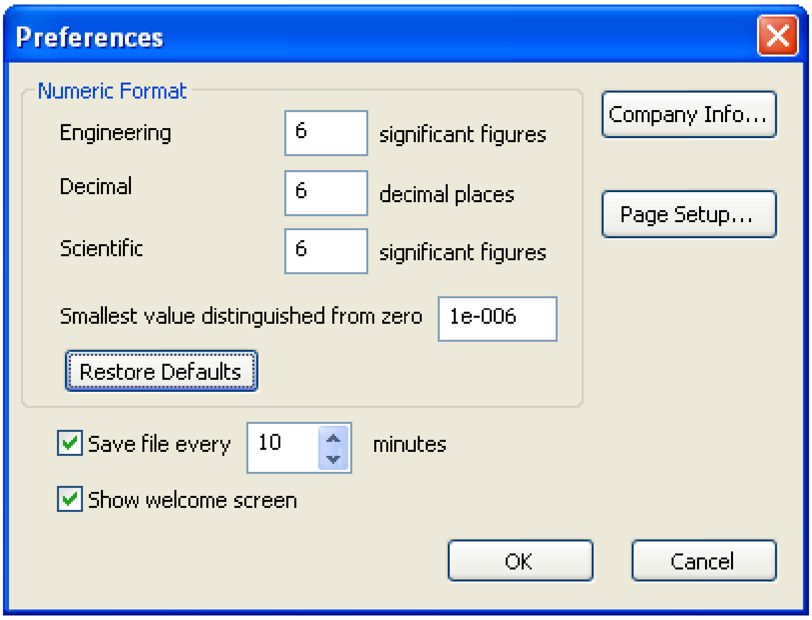
Top level categories can be expanded by clicking on the `+´ symbol beside the name or by double clicking on the name. Clicking on the `-´ symbol or double clicking on the name when expanded will close-up the item.

Double-clicking on an item will open the appropriate table view or dialog for data input. The greyed out items in the gateway are disabled.

1.3.2 Preferences

This dialog can be accessed by clicking Tools | Preferences. Preferences can be set whether a file is opened or not.

The Preferences dialog is accessible by choosing Tools | Preferences from the program's menu. It allows the modification of settings such as numeric format for output, show welcome screen, print parameters and company information. These choices are stored in the computer's registry and are therefore associated with the program rather than the data file. All data files will adopt the same choices.



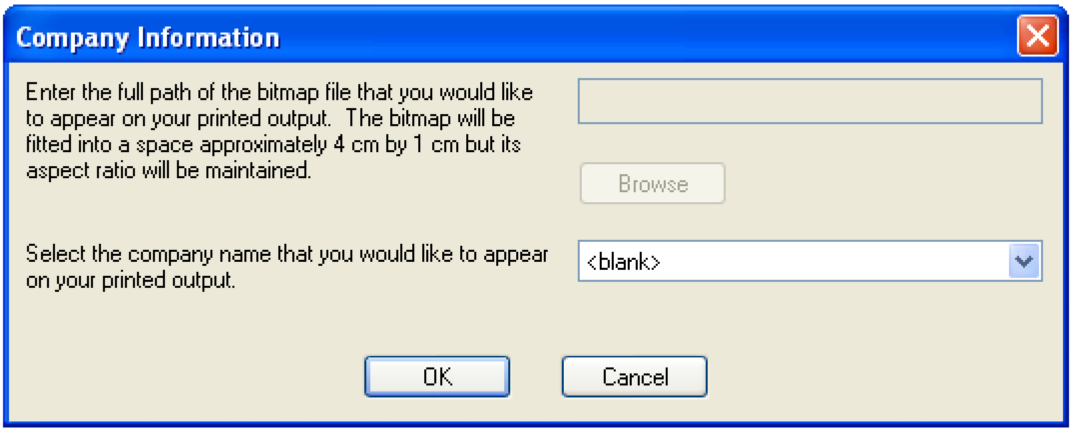
Numeric Format controls the output of numerical data in the Tabular Output. The Tabular Output presents input data and results in a variety of numeric formats, the format being selected to suit the data. Engineering, Decimal, and Scientific formats are supported. The numbers of significant figures or decimal places, and the smallest value distinguished from zero, may be set.

Restore Defaults resets the Numeric Format specifications to program defaults.

A time interval may be set to save data files automatically. Automatic saving can be disabled by clearing the "**Save file every ...**" check box.

Show welcome screen enables or disables the display of the Welcome Screen. The Welcome Screen will appear on program start-up, and gives the option to create a new file, to open an existing file by browsing, or to open a recently used file.

Company Info allows changes to the company name and logo on the top of each printed page. To add a bitmap enter the full path of the bitmap file. The bitmap will appear fitted into a space approximately 4cm by 1cm. The aspect ratio will be maintained. For Arup versions of the program the bitmap option is not available.



Page Setup opens the Page Setup dialog allowing the style of output for printed text and graphics to be selected.

If 'Calculation Sheet Layout´ is selected the page is formatted as a calculation sheet with details inserted in the page header.

If `Logo´ is selected the company logo is inserted in the top left corner of the page.

If `Border´ is selected this gives a border but no header information.

If `Clipped´ is selected the output is clipped leaving a space for the logo. This has no effect on text output.

1.4 Step by Step Guide

To perform capacity and settlement analysis of a pile follow the steps listed below. The data file should be saved at frequent intervals.

Item	Description
1	Begin a new data file by selecting "File | New" on the program menu.
2	Set the preferred units for data input and output in the Units dialog. The Units dialog is accessible by double-clicking "Units" in the Gateway, or via "Data | Units" on the program menu.
3	Choose the analysis type, via the Analysis Options dialog - whether capacity or settlement or both. Choose the effective stress profile, whether calculated or user-defined. Input for user-defined effective stresses profiles is explained in Item 8. Choose the datum type, whether levels are entered as depths or elevations. Choose the method for capacity analysis - whether working load or design resistance, and enter the factors for the selected method. The Analysis Options dialog is accessible by double-clicking "Analysis Options" in the

Gateway or via "Data | Analysis Options" on the program menu.

4 Specify the type of analysis i.e. Working Load / Design Resistance / Code-based, and also the relevant parameters using the Capacity Data property sheet.

5 Specify the method of settlement calculation i.e. Mindlin or t-z curves, and the relevant parameters such as Young's modulus of soil above and below pile base, rigid boundary level, number of load increments and number of pile elements. Data input for settlement analysis is available via the Settlement Data dialog.

If the t-z approach is selected, then input the relevant t-z curves and tip load curves to be used for the pile shaft and the pile base respectively.

A particular type of t-z or tip load curve can be input by double-clicking the appropriate type under the t-z Curve Data or Tip Load Curve Data gateway item, or under the "Data | t-z Curve Data or Tip Load Curve Data" item on the program menu.

6 Specify the type, length and diameter of pile via the Pile Geometry dialog. Follow the wizard to enter pile properties, pile lengths and pile cross-sections.

The Pile Geometry dialog is accessible by double-clicking "Pile Geometry" in the Gateway or via "Data | Pile Geometry" on the program menu.

7 Specify the input data for soil material, whether undrained or drained.

7.1 Specify any undrained material data in the Undrained Material table view.

The Undrained Material table view is accessible by double-clicking "Material Properties | Undrained Material" in the Gateway or via "Data | Material Properties | Undrained Material" on the program menu.

7.2 Specify any drained material data in the Drained Material table view.

The Drained Material table view is accessible by double-clicking "Material Properties | Drained Material" in the Gateway or via "Data | Material Properties | Drained Material" on the program menu.

8 Specify soil layers in the Soil Profiles table view. Multiple soil profiles can be defined.

The Soil Profiles table view is accessible by double-clicking "Soil Profiles" in the Gateway or via "Soil Profiles" on the program menu.

9 Specify any hydrostatic or piezometric pressure in the Groundwater table view. Multiple Groundwater tables can be defined.

The Groundwater table view is accessible by double-clicking "Groundwater" in the Gateway or via "Data | Groundwater" on the program menu.

Associate the groundwater data tables with soil profiles using the Soil Profile - Groundwater Table Map. This can also be accessed from the gateway.

10 If any custom stress profiles need to be used, specify such user-defined effective stress profiles in the Effective Stress Profiles table view. At least one soil layer should be defined in order to access this table view.

The Effective Stress Profiles table view is accessible by double-clicking "Effective Stress Profiles" in the Gateway or via "Effective Stress Profiles" on the program menu.

11 Specify user-defined Nq-Phi curves in the Nq-Phi curves tabbed table view. This table view is accessible when capacity analysis is selected in Analysis Options dialog

The Nq-Phi curves tabbed table view is accessible by double-clicking "Nq-Phi curves" in the Gateway or via "Data | Nq-Phi curves" on the program menu.

12 Specify applied loads and prescribed displacements in the Applied Loads & Displacements table view. This table view is accessible when settlement analysis is selected in the Analysis Options dialog.

The Applied Loads & Displacements table view is accessible by double-clicking "Applied Loads & Displacements" in the Gateway or via "Data | Applied Loads & Displacements" on the program menu.

13 Specify any thermal and/or cyclic loads in the Thermal and Cyclic Loading dialog. This is relevant to only settlement analysis.

This is accessible by double-clicking "Thermal and Cyclic Loading" in the Gateway or via "Data | Thermal & Cyclic Loads" on the program menu.

14 If the Mindlin option for calculating displacements is used, specify the radial distance from the pile at which soil displacements are to be calculated in the Displacement Radii table view. This table view is accessible when settlement analysis is selected in the Analysis Options dialog

The Displacement Radii table view is accessible by double-clicking "Displacement Radii" in the Gateway or via "Data | Displacement Radii" on the program menu.

15 Specify convergence control data in the Convergence Control Data dialog. This dialog is accessible when settlement analysis is selected in the Analysis Options dialog.

The Convergence Control Data dialog is accessible by double-clicking "Convergence Control
Data" in the Gateway or via "Data | Convergence Control Data" on the program menu.

16 If there are multiple stages of analysis, create new stages and enter stage-specific data as outlined in Stage tree view.

17 Perform an analysis by clicking the Analyse button on the Pile toolbar, or via "Analysis | Analyse" on the program menu.

18 Pile performs a check on data for consistency. Correct any errors that are shown in the subsequent report of warnings and errors.

19 Inspect the results in the Tabular Output view and/or the Graphical Output.

These are accessible by double-clicking the "Output | Tabular Output", "Output | Graphical Output" in the Gateway, via "View | Tabular Output", "View | Graphical Output" on the program menu, or via the appropriate buttons on the Pile toolbar.

20 Adjust the data and re-analyse as necessary.

2 Method of Analysis

2.1 Capacity

The soil is split up into a number of layers - each having necessary data to calculate end bearing and skin friction.

The program will calculate bearing capacity at discrete elevations, either to provide a single bearing capacity at a single elevation or to develop a bearing capacity versus depth profile over a specified range of elevations.

The calculation procedure will involve identifying a number of sub-layers within each specified soil layer corresponding to:

- depths at which capacity is to be assessed where these fall within a layer;
- depths at which capacity is to be assessed to allow a graph to be produced;
- changes in pile properties (i.e. under-reams);
- changes in groundwater/pore-pressure profile.

If there are n layers between the ground surface and the toe of the pile:

$$Q_{se} = \sum_{j=1}^{n} \Delta Q_{se}^{j}$$

where:

ΔQ_{se}^{j} = incremental external skin friction accumulated within a soil layer outside the pile

Within the layer:

$$\Delta Q_{se}^{j} = \Delta L_j P_e^j f_{se}^j$$

where:

ΔL_j = thickness of layer j

P_e^j = average external perimeter of outside the pile in contact with soil in layer j

f_{se}^j = average external skin friction in layer j outside the pile

Similarly:

$$\Delta Q_{si}^{j} = \Delta L_j P_i^j f_{si}^j$$

where:

ΔQ_{si}^{j} = incremental internal skin friction accumulated within a soil layer inside the pile

P_{i}^{j} = average internal perimeter of the pile in contact with soil in layer j

f_{si}^{j} = average internal skin friction in layer j inside the pile

2.1.1 Shaft Friction

Two basic methods are available, total stress and effective stress. The former is appropriate to clays and soft rocks and the latter to cohesionless soils and clays for long term loading where the stress conditions are likely to change.

2.1.1.1 Total Stress Approach

The friction per unit area, f_s is given by:

$f_s = \alpha\ c_u$

where:

α = an adhesion factor

c_u = the average undrained shear strength in the layer

α may be either user-specified or calculated by the specified API method.

API Method 1

The current API code recommends that for driven tubular steel piles:

$\alpha = 0.5\ \Psi^{-0.5}$, $\Psi < 1.0$

$\alpha = 0.5\ \Psi^{-0.25}$, $\Psi > 1.0$

$\Psi = c_u / \sigma_v'$

where:

σ_v' = vertical effective stress

Caution is required for cases where Ψ is greater than 3 or for long flexible piles (a program warning is generated).

API Method 2

Earlier editions of the API code advised that:

$\alpha = 1.0$, $c_u < 24$kPa

$\alpha = 0.5$, $c_u > 72kPa$

with linear interpolation between these values.

2.1.1.2 Effective Stress Approach

The friction per unit area, f_s is computed by the following two methods.

Beta Method

The Beta method relates friction directly to vertical effective stress, σ_v':

$f_s = \beta\sigma_v'$

Earth Pressure Method

More conventionally:

$f_s = \sigma_h'\tan(\delta)$

where:

σ_h' = average horizontal effective stress in layer
δ = soil/pile friction angle
σ_h' = either user-specified or calculated using:

$\sigma_h' = K\sigma_v'$

where:

K = earth pressure factor

2.1.1.3 Limiting Shaft Friction

Irrespective of the approach followed, the skin friction per unit area, f_s may be limited to a user-specified value.

If this value is set to zero, then the friction is assumed to increase indefinitely as one goes down the length of the pile.

2.1.1.4 Negative Skin Friction

Some layers may be defined as providing down-drag, in which case the cumulative capacity cannot contribute to the bearing capacity. The negative skin friction Q_{nsf} must be calculated separately to ensure that the factors of safety or partial load factors are applied correctly.

In bearing capacity calculations, negative skin friction is always calculated separately.

Cumulative skin friction is always exclusive of negative skin friction.

The negative skin friction is not taken into account when calculating the tension capacities, and and in "Design Resistance" option.

2.1.2 End Bearing

Two basic methods are available, **total stress** and **effective stress** based. The former is appropriate to clays and soft rocks and the latter to cohesionless soils and clays for long term loading where the stress conditions are likely to change.

2.1.2.1 Total Stress Approach

In this approach, end bearing stress, q_b is given by:

$q_b = N_c c_u$

where:

N_c - the bearing capacity factor for cohesion

For solid piles $N_c = 9$ for embedment of over about 2D.

where:

D - the diameter of the Pile

In the case of shallow embedment (< 2D), N_c is taken as zero and a warning to this effect is generated.

For hollow sections or H-piles, the pile wall acts more like a deep strip footing, therefore $N_c \approx 6$ is more appropriate.

2.1.2.2 Effective Stress Approach

In this approach, end bearing stress, q_b is given by:

$q_b = N_q \sigma_v'$

where:

σ_v' - the vertical effective stress at the base of the layer being considered

N_q - the bearing capacity factor for surcharge and friction.

The following methods may be used to calculate N_q:

i) N_q specified

The value of N_q can be user-specified.

ii) N_q calculated based on friction angle

The most commonly used method to assess N_q is that proposed by Berezantzev, as a function of drained friction angle ϕ'. The relationship can be defined explicitly or as a look-up table.

iii) N_q based on mean effective stress, relative density and friction angle

A more refined approach is given by Bolton (1984) taking into account dilatancy effects and the influence of stress level, particularly with heavily loaded piles.

This is an iterative approach based on the following expressions:

$I_R = I_D\ (10 - \ln p') - 1$

where:

I_R - corrected relative density (0 to 1)
I_D - original relative density (0 to 1)
p' - mean effective stress (kPa), calculated as:

$p' = (\sigma_v' + 2\sigma_h')/3$

$\phi' = \phi_{cv}' + 3I_R$ (degrees)

where:

ϕ_{cv}' = critical state angle of friction (degrees)

$p' \approx (\sqrt{N_q}) * \sigma_v'$

N_q is estimated using the Berezantzev method

To start the process it is suggested that N_q is first estimated using ϕ_{cv}'.

iv) N_q calculated based on friction angle, depth ratio (depth/width) and friction angle corresponding to the soil of overburden

This approach is based on the paper by Berezantzev et al (1961), wherein the bearing capacity is calculated from:

$q_b = A_k\, \gamma\, B \;+\; B_k\, \alpha_T\, \sigma_v'$

where:

A_k,B_k are coefficients depending upon ϕ, and are read from the ϕ - A_k and ϕ - B_k graphs respectively
γ is the unit weight of soil at the level of pile base. If the water table is above or at location of pile

base, buoyant unit weight is used. Otherwise, bulk unit weight is used.
α_T is a function of D/B, ϕ' and ϕ_D.
ϕ_D pertains to the soil of overburden.
σ_v' is the effective vertical stress at the level of pile toe.

The value of N_q is then calculated from the resulting bearing capacity.

2.1.2.3 Limiting End Bearing

Irrespective of the approach followed, the end bearing stress q_b may be limited to a user-specified value.

If this value is set to zero, then the end bearing stress is assumed to increase indefinitely with increasing toe depth.

2.1.3 Bearing Capacity

The following capacities are calculated by the program.

Solid piles:
- Ultimate Capacity
- Allowable Capacity
- Design Capacity

Hollow piles:
- Plugged Capacity
- Unplugged Capacity (fixed and changing internal soil level)
- Ultimate capacity
- Allowable capacity
- Design Capacity

Solid piles

The total bearing capacity of solid piles is:

$Q = Q_{se} + Q_b$

where:

Q_{se} = cumulative skin (or shaft) friction
Q_b = end bearing

For piles in tension $Q_b = 0$

Hollow piles

The total bearing capacity of hollow piles is the lesser of:

$Q_{plugged} = Q_{bp} + Q_{bw} + Q_{se}$ and

$Q_{unplugged} = Q_{bw} + Q_{se} + Q_{si}$

where:

Q_{si} = cumulative internal skin friction (kN)
Q_{se} = cumulative external skin friction (kN)
Q_{bp} = end bearing acting over the soil plug area (kN)
Q_{bw} = end bearing acting over the pile wall area (kN)

For piles in tension $Q_{bw} = Q_{bp} = Q_{si} = 0$

2.1.3.1 Ultimate Capacity

Solid Piles

The ultimate bearing capacity, Q of solid piles is:

$Q = Q_{se} + Q_b - Q_{nsf}$

where:

Q_{se} = cumulative skin (or shaft) friction
Q_b = end bearing
Q_{nsf} = negative skin friction

For piles in tension $Q_b = Q_{nsf} = 0$

Hollow piles

The ultimate bearing capacity, Q of hollow piles is given by:

$Q = \text{Minimum}(Q_{plugged}, Q_{unplugged,case1}, Q_{unplugged,case2})$

where:

$Q_{plugged}$ is the plugged capacity of the hollow pile
$Q_{unplugged,case1}$ is the unplugged capacity for case 1
$Q_{unplugged,case2}$ is the unplugged capacity for case 2

The above quantities are described below.

2.1.3.2 Plugged Capacity

The plugged capacity of hollow piles is given by:

$Q_{plugged} = Q_{bp} + Q_{bw} + Q_{se} - Q_{nsf,Ext}$

where:

Q_{se} = cumulative external skin friction exclusive of negative skin friction (kN)
Q_{bp} = end bearing acting over the soil plug area (kN)
Q_{bw} = end bearing acting over the pile wall area (kN)
$Q_{nsf,Ext}$ = external negative skin friction

For piles in tension, $Q_{bp} = Q_{bw} = Q_{nsf,Ext} = 0$

2.1.3.3 Unplugged Capacity

The unplugged capacity of hollow piles is given by:

$$Q_{unplugged} = Q_{bw} + Q_{se} + Q_{si} - Q_{nsf,Ext} - Q_{nsf,Int}$$

where:

Q_{si} = cumulative internal skin friction exclusive of negative skin friction (kN)
Q_{se} = The cumulative external skin friction exclusive of negative skin friction (kN)
Q_{bw} = end bearing acting over the pile wall area (kN)
$Q_{nsf,Ext}$ = external negative skin friction
$Q_{nsf,Int}$ = internal negative skin friction

When driving hollow piles it may not be possible to mobilise the full theoretical internal friction; this may be too great to allow the plug end bearing force to push the soil up inside the pile (typically in clay soils). In this situation the pile becomes plugged and the level of soil inside is lower than that outside. If the end bearing later increases within a deeper layer, the accumulated internal friction will be fully mobilised again and more material will be pushed up inside the pile. However the internal capacity will be less than if the plug level is at the ground surface.

Thus, there are two cases for calculation of unplugged capacity as described below.

- Case 1: Internal soil level is the same as external soil level, wherein the internal skin friction is calculated assuming an internal soil profile similar to the external soil profile. Thus, the external and internal friction will be in the ratio of external perimeter to internal perimeter of the pile.

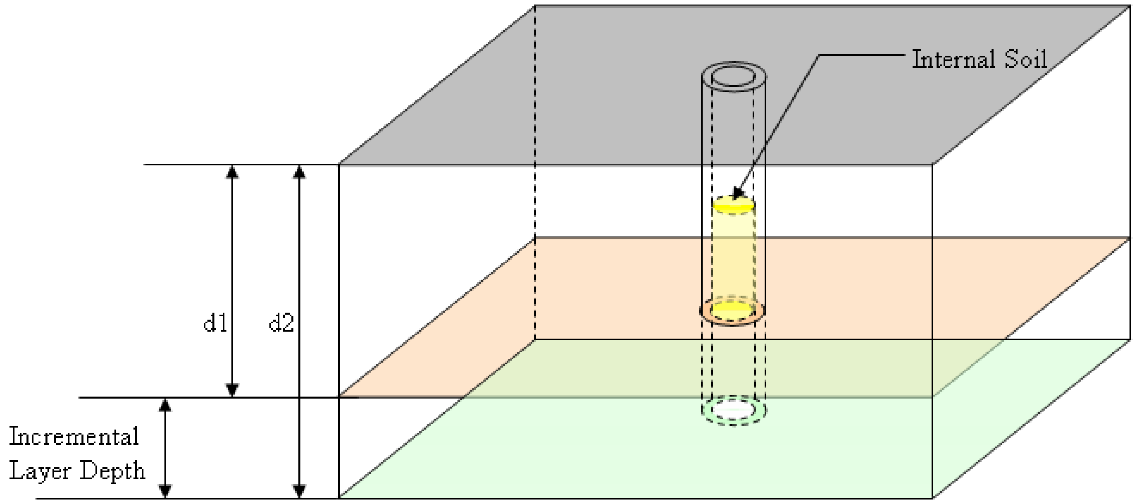
- Case 2: Internal soil level changes with the driven pile depth. In this case, calculations are made at each depth increment to ensure that soil is pushed inside the pile only if the entire skin friction has been mobilised as follows.

During driving, the layers marked as contributing to negative skin friction will also act in the same way as the layers that do not contribute to negative skin friction.

However, the skin friction accumulated from the layers contributing to skin friction is stored separately from the skin friction from layers that do not contribute to negative skin friction.

Thus, it is assumed that the layers contributing to negative skin friction contribute to negative skin friction ONLY in the longer term, and not during the driving.

Consider two pile embedment depths d1 and d2 such that d1 < d2.



If the **incremental layer does not contribute to negative skin friction**

If

$Q_{si,d1} + Q_{nsf,Int,d1} + Q_{si,inc} < Q_{bp,d2}$

then

$Q_{si,d2} = Q_{si,d1} + Q_{si,inc}$

else

$Q_{si,d2} = Q_{si,d1}$

where:

$Q_{si,d1}$ = internal skin friction at a pile embedment depth d1
$Q_{si,d2}$ = internal skin friction at a pile embedment depth d2
$Q_{nsf,Int,d1}$ = cumulative internal negative skin friction accumulated over depth d1
$Q_{si,inc}$ = incremental internal skin friction between depths d1 and d2
$Q_{bp,d2}$ = bearing capacity at depth d2 over the plug area alone - excluding the wall area

However, if the incremental layer contributes to negative skin friction

If

$Q_{si,d1} + Q_{nsf,Int,d1} + Q_{si,inc} < Q_{bp,d2}$

then

$Q_{nsf,Int,d2} = Q_{nsf,Int,d1} + Q_{si,inc}$

else

$Q_{nsf,Int,d2} = Q_{nsf,Int,d1}$

where:

$Q_{si,d1}$ = internal skin friction at a pile embedment depth d1
$Q_{si,d2}$ = internal skin friction at a pile embedment depth d2
$Q_{nsf,Int,d1}$ = cumulative internal negative skin friction accumulated over depth d1
$Q_{nsf,Int,d2}$ = cumulative internal negative skin friction accumulated over depth d2
$Q_{si,inc}$ = incremental internal skin friction between depths d1 and d2
$Q_{bp,d2}$ = bearing capacity at depth d2 over the plug area alone - excluding the wall area

Note:

- The reported unplugged capacity from case 2 will be the minimum of the capacities from case 1 and case 2;
- For piles in tension, $Q_{bw} = Q_{nsf,Ext} = Q_{nsf,Int} = 0$.
- The program first divides the soil profiles into sub-layers with a minimum thickness of at least 1 cm or one-hundredth of the layer thickness - whichever is minimum. Then it uses bisection approach to find the transitions between plugged and unplugged phases.

2.1.3.4 Allowable Capacity - Working Load Approach

Traditionally, global factors of safety are applied to the ultimate end bearing capacity and the skin friction to take into account uncertainties in soil properties, loads, installation method and the calculation method and also to limit settlement.

Solid Piles

The factored load is termed the allowable or working load. For solid piles, this is defined as the lesser of:

$P_d = (Q_s + Q_b)/F_g - Q_{nsf}$

$P_d = Q_s / F_{s1} + Q_b / F_b - Q_{nsf}$

$P_d = Q_s / F_{s2}$

$P_d = (f_{allowable})*(A_p)$

where:

Q_s = skin friction (cumulative positive skin friction)

Q_{nsf} = negative skin friction
Q_b = end bearing capacity of the solid pile
A_p = cross-sectional area of pile
$f_{allowable}$ = allowable stress in pile at working load (compression)
F_g = global factor applied to the calculated ultimate bearing capacity
F_{s1} = partial factor applied to the ultimate skin friction component
F_b = partial factor applied to the ultimate end bearing component
F_{s2} = factor applied to the ultimate skin friction component

Note: It is not mandatory to select all combinations. The same applies for the tension case and for hollow piles.

In tension, Q_b and Q_{nsf} are both zero, and the criteria are:

$$P_d = Q_s / F_{s2}$$

$$P_d = (f_{allowable})*(A_p)$$

Note: The corresponding parameters(F_{s2} and $f_{allowable}$) for the tension case have to be explicitly specified.

Hollow piles

For hollow piles however, we have the following criteria to consider, owing to the plugged condition of the pile:

$$P_d = (Q_{se} + Q_{si} + Q_b)/F_g - Q_{nsf,e} - Q_{nsf,i}$$

$$P_d = (Q_{se} + Q_{si} + Q_b)/F_g - Q_{nsf,e} - Q_{nsf,i,autoplugging}$$

$$P_d = (Q_{se} + Q_b + Q_{plug})/F_g - Q_{nsf,e}$$

$$P_d = (Q_{se} + Q_{si}) / F_{s1} + Q_b / F_b - Q_{nsf,e} - Q_{nsf,i}$$

$$P_d = (Q_{se} + Q_{si}) / F_{s1} + Q_b / F_b - Q_{nsf,e} - Q_{nsf,i,autoplugging}$$

$$P_d = (Q_{se}) / F_{s1} + (Q_b + Q_{plug})/F_b - Q_{nsf,e}$$

$$P_d = (Q_{se}) / F_{s2}$$

$$P_d = (f_{allowable})*(A_p)$$

where:

Q_{se} = external skin friction (excluding negative skin friction)
Q_{si} = internal skin friction (excluding negative skin friction)

$Q_{nsf,e}$ = external negative skin friction
$Q_{nsf,i}$ = internal negative skin friction - in this case, the top of the internal soil at the same level as ground level
$Q_{nsf,i,autoplugging}$= internal negative skin friction - in this case, internal soil level changes with driven pile depth
Q_b = end bearing capacity of the hollow pile (over the wall area)
Q_{plug} = bearing capacity of the plugged portion of the hollow pile (excluding wall area)
A_p = cross-sectional area of pile
$f_{allowable}$ = allowable stress in pile at working load
F_g = global factor applied to the calculated ultimate bearing capacity
F_{s1} = partial factor applied to the ultimate skin friction component
F_b = partial factor applied to the ultimate end bearing component
F_{s2} = factor applied to the ultimate skin friction component

In tension, Q_b, Q_{plug}, $Q_{nsf,e}$ and $Q_{nsf,i}$ are all zero, and there are just the following criteria:

$$P_d = Q_{se} / F_{s2}$$

$$P_d = (f_{allowable})*(A_p)$$

Note: The corresponding parameters (F_{s2} and $f_{allowable}$) for the tension case have to be explicitly specified.

2.1.3.5 Design Resistance - Limit State Approach

In limit state codes it is usual to assess the ultimate limit state (ULS) for one or more combinations of factored applied loads and material properties. Additional factors may be applied relating to the pile type and calculation method.

In EC7 terms the design action, based on factored loads, is compared with the design bearing resistance calculated using factored soil parameters and other related factors. Different factors are used, appropriate to one or more load cases. Other codes use a similar approach.The design bearing resistance **in compression** is the minimum of :

$$R_d = (R_{bk}/ \gamma_b + R_{sk}/ \gamma_s)/\gamma_{Rd}$$

$$R_d = (R_{bk} + R_{sk})/(\gamma_{t*}\gamma_{Rd})$$

where:

R_{bk} = characteristic base resistance
R_{sk} = characteristic shaft resistance
γ_b and γ_s = base and shaft resistance factors respectively
γ_t = total resistance factor
γ_{Rd} = model factor (compression)

Only one of the above two combinations can be used depending on the code. For example, for EC7 calculations where shaft and base resistances are evaluated separately, only the first equation is applicable.

For solid piles the above definitions are straightforward. However, for hollow piles in compression, there are three conditions to be considered:

Unplugged condition - (internal soil level remains at ground level)

- R_{bk} is obtained by calculating bearing capacity only over the wall area.
- R_{sk} is obtained by adding the contributions of external skin friction and internal skin friction, assuming the internal soil level remains at ground level.

Unplugged condition - (internal soil level changes with driven pile depth)

- R_{bk} is obtained by calculating bearing capacity only over the wall area.
- R_{sk} is obtained by adding the contributions of external skin friction and internal skin friction, with the internal soil level not necessarily at ground level.

Plugged condition

- R_{bk} is obtained by calculating bearing capacity only over the wall area, and the plug area.
- R_{sk} is obtained by considering only the external skin friction.

For both hollow and solid piles in tension

$R_d = (R_{sk})/(\gamma_{st*}\gamma_{Rd})$

where,

R_{sk} = characteristic shaft resistance (The internal skin friction is ignored for hollow piles in tension)
γ_{st} = shaft resistance factor in tension
γ_{Rd} = model factor (tension)

Depending on the load case under consideration, the characteristic resistances may or may not be determined using partial material factors. However, presently**, partial material factors are always applied when "Design Resistance" option is chosen**.

When calculating pile capacity it is important to note that the calculated bearing resistance is neither an allowable working load or an ultimate capacity, and must be compared with the appropriately factored combination of applied loads, dependent on the design case being assessed.

The **negative skin friction** is treated as an "action" and is **not included** in the calculation of design resistance i.e. it is not subtracted from cumulative positive skin friction.

2.1.3.6 Code-Based

If the code-based option is chosen then one of the following design codes may be selected:

- EC7 (No National Annex)
- EC7 (United Kingdom)
- IS 2911

In EC7 (No National Annex) any of the three Design Approaches may be chosen, as may the Model Pile Procedure or Alternative Procedure. However, in EC7 (United Kingdom), only DA1 and the Alternative Procedure are allowed.

2.1.4 Solution Algorithm

1. divide the soil into required number of layers, based on:

   - soil profile;
   - effective stress profiles/groundwater profiles;
   - depth of the pile (single or range);
   - changes in the pile properties (eg. under-ream);

2. calculate the vertical stress profile and vertical effective stress profile (if not specified);

3. compute the skin friction and end bearing (if necessary) of each layer (as described below);

4. compute the cumulative positive skin friction and negative skin friction taking into account layers which contribute to negative skin friction;

5. compute the end bearing capacity of the pile;

6. compute the working load or the design resistance of the pile;

7. store the values obtained in steps 5 and 6, in order to plot the variation of the above quantities with depth.

2.1.4.1 Skin Friction Computation

If total stress:

1. Get the profile of c_u across the layer;

2. Get the profile of α across the layer (user-specified value or from API methods 1 or 2);

3. Get the profile of f_{se} and f_{si} (if necessary) across the layer, taking into account the limiting skin friction in the layer;

4. Get the average value of f_{se} and f_{si} for the layer;

5. Get the perimeter of the pile in the layer (both external and internal);

6. Compute external and internal skin friction provided by the layer;

Else if effective stress:

1. Get the profile of f_s based on the method selected:

If β method:

a. Get the user-specified value β;

b. Get the profile of f_s from σ_v' profile using $f_s = \beta * \sigma_v'$

Else if earth pressure method

a. Get the profile of σ_h' (user-specified or using the value of earth pressure coefficient K, viz. $\sigma_h' = K\sigma_v'$);

b. Get the profile of f_s using the relation $f_s = \sigma_h' \tan\delta$, where δ is the friction angle between the pile and soil;

2. Get the average value of f_{se} and f_{si} for the layer;

3. Get the perimeter P of the pile layer (both external and internal);

4. Compute external and internal skin friction provided by the layer.

2.1.4.2 End Bearing Computation

1. Get the profile of bearing pressure, q_b:

If total stress:

a. Get the profile of undrained cohesion, c_u, across the layer;

b. Get value of N_c (user-specified or calculated) based on embedment depth;

c. Get the profile of bearing pressure from $q_b = N_c c_u$;

Else if effective stress:

a. Get the profile of σ_v' across the layer(either calculated or user-specified);

b. Get the value of N_q – either user-specified, or Berezantzev Method or Bolton method;

c. Get the bearing pressure, q_b from $q_b = N_q \sigma_v'$;

2. Get the cross sectional area of the pile base, pile wall, and soil plug as appropriate;

3. compute end bearing capacity of the pile.

2.1.4.2.1 Berezantzev Method

The following steps are implemented in the Nq calculation algorithm when "Berezantzev method" is selected in the Effective stress table view.

i) Berezantzev A_k B_k Curves

These curves are based on the paper by Berezantzev et al (1961).

This calculation algorithm is performed when the standard "Berezantzev Ak Bk Curves" option is selected in the N_q-Phi curve field of the Effective stress table view.

1. Get the user-specified value of drained friction angle ϕ' for the layer at the location of pile toe depth;

2. Get the user-specified value of friction angle ϕ_D corresponding to the soil of overburden;

Note: When there are multiple soil layers around the shaft, the program uses the user-specified ϕ_D of the layer at the location of pile toe depth as the equivalent ϕ_D of the whole overburden soil around the pile shaft.

3. From the given ϕ' value interpolate/extrapolate the value of coefficients A_k and B_k from the ϕ' - A_k and ϕ' - B_k graphs respectively;

4. The values of A_k and B_k in the program are calculated by the polynomial equations generated for the data points that are read from the graph;

Note: In digitising the curve, the lower bound values have been read.

the generated polynomial equations for A_k and B_k are given below:

$$A_k = 0.00261719\times\left(\phi'\right)^4 - 0.300278\times\left(\phi'\right)^3 + 13.0706\times\left(\phi'\right)^2 - 253.216\times(\phi') + 1837.45$$

$$B_k = 0.0033242\times\left(\phi'\right)^4 - 0.363837\times\left(\phi'\right)^3 + 15.1495\times\left(\phi'\right)^2 - 280.875\times(\phi') + 1955.20$$

Note: For the above two equations, the units of ϕ' are in degrees.

5. From the given ϕ', ϕ_D and depth ratio (depth/width), calculate the value of α_T which is given by the following equation:

$$\alpha_T = 1 - \frac{2\times f\left(\phi_D\right)}{s\left(\phi'\right)} \times \left[1 + \frac{H\left(\frac{D}{B}\right)}{g\left(\phi_D\right)}\left(1 - P\left(\phi_D\right)\right)\right]$$

where:

$$\lambda = 2 \times \tan \phi_D \times \tan\left(\frac{\pi}{4} + \frac{\phi_D}{2}\right)$$

$$f(\phi_D) = \frac{\tan(\phi_D) \times \tan\left(\frac{\pi}{4} - \frac{\phi_D}{2}\right)}{\lambda - 1}$$

$$s(\phi') = \left[1 - \left(\frac{\ell_0}{R}\right)^{-2}\right]$$

$$g(\phi_D) = (2 - \lambda) \times \tan\left(\frac{\pi}{4} - \frac{\phi_D}{2}\right)$$

$$\ell_0 = R \times \left[1 + \frac{\left(\sqrt{2} \times e^{\left(\frac{\pi}{2} - \frac{\phi}{2}\right) \times \tan\frac{\phi}{2}}\right)}{\sin\left(\frac{\pi}{4} - \frac{\phi'}{2}\right)}\right]$$

$$H\left(\frac{D}{B}, \phi'\right) = \frac{1}{2 \times \left(\frac{D}{B}\right)} \times \left[1 + \frac{\left(\sqrt{2} \times e^{\left(\frac{\pi}{2} - \frac{\phi}{2}\right) \times \tan\frac{\phi}{2}}\right)}{\sin\left(\frac{\pi}{4} - \frac{\phi'}{2}\right)}\right]$$

$$P\left(\phi_D,\phi',\frac{D}{B}\right)=\left\{1+\left(\frac{1}{H\left(\frac{D}{B}\right)}\times\tan\left(\frac{\pi}{4}-\frac{\phi_D}{2}\right)\right)\right\}^{2-\lambda}$$

where:

R = radius of the pile
D = depth of the pile toe
B = diameter of the pile
ϕ' = angle of friction of the soil layer at the pile base
ϕ_D = angle of friction of the soil layer around the pile shaft

Note: For all the equations related to the calculation of α_T above, the units of ϕ' and ϕ_D are in radians. Also, in the Berezantzev (1961) paper, the value of α_T is given in a table as a function of D/B and ϕ_D alone. The ϕ' term does not seem to be considered when evaluating α_T. But, in the equation above, which has been derived based on the theory in the Berezantzev (1961) paper, the effect of both ϕ' and ϕ_D is considered.

6. Finally calculate the value of end bearing pressure q_b.

$$q_b = A_k\gamma B + B_k\alpha_T\sigma'_v$$

where:

σ'_v = effective vertical stress at the level of pile base
γ = unit weight of soil at the level of pile base. If the water table is above or at the location of the pile base, buoyant unit weight is used. Otherwise, bulk unit weight is used.
B = diameter of the pile

ii) User-defined Nq-Phi curve

This calculation algorithm is performed when any user-defined Nq-Phi curve is selected in the Nq-Phi curve field of the Effective stress table view.

1. Get the user-specified value of drained friction angle ϕ';

2. Get the value of Nq based on user-specified equation or user-specified look-up table.

2.1.4.2.2 Bolton Method

This is a more refined approach is given by Bolton (1984), taking into account dilatancy effects and the influence of stress level, particularly with heavily loaded piles.

It involves the following steps:

1. Get the user-specified values of ϕ_{cv}' and I_R;
   where:

   I_R = corrected relative density (0 to 1).

2. Get the value of $\phi' = \phi_{cv'} + 3I_R$;

3. Get the value of N_q using the Berezantzev method;

4. Get the value of mean effective stress p', using the relation $p' \approx \sqrt{(N_q \sigma_v')}$;

5. Get the value of I_R using the relation $I_R = I_D$ (10 - ln p') -1,

   where:

   I_R = Corrected relative density (0 to 1),

   I_D = Original relative density (0 to 1).

6. Get the value of $\phi' = \phi_{cv}' + 3I_R$;

7. Get the value of N_q using the Berezantzev method;

8. If difference between the new value of N_q and value of N_q from step 3 is within tolerance, stop the iteration, else repeat steps 4 to 8.

2.2 Settlement

Settlement analysis calculates the settlement of a range of piles with different lengths and cross-section dimensions and of the surrounding soil. Pile soil slip is modelled, together with the effects of soil heave inducing tension, or settlement causing compression and negative skin friction. Currently, only solid circular piles can be analysed for settlements. The solid square pile is modelled by an equivalent circular pile whose area is the same as the original square pile.

There are two methods provided by the program for the settlement analysis: a) Mindlin (based on finite difference method)

b) t-z Curves (based on finite element method)

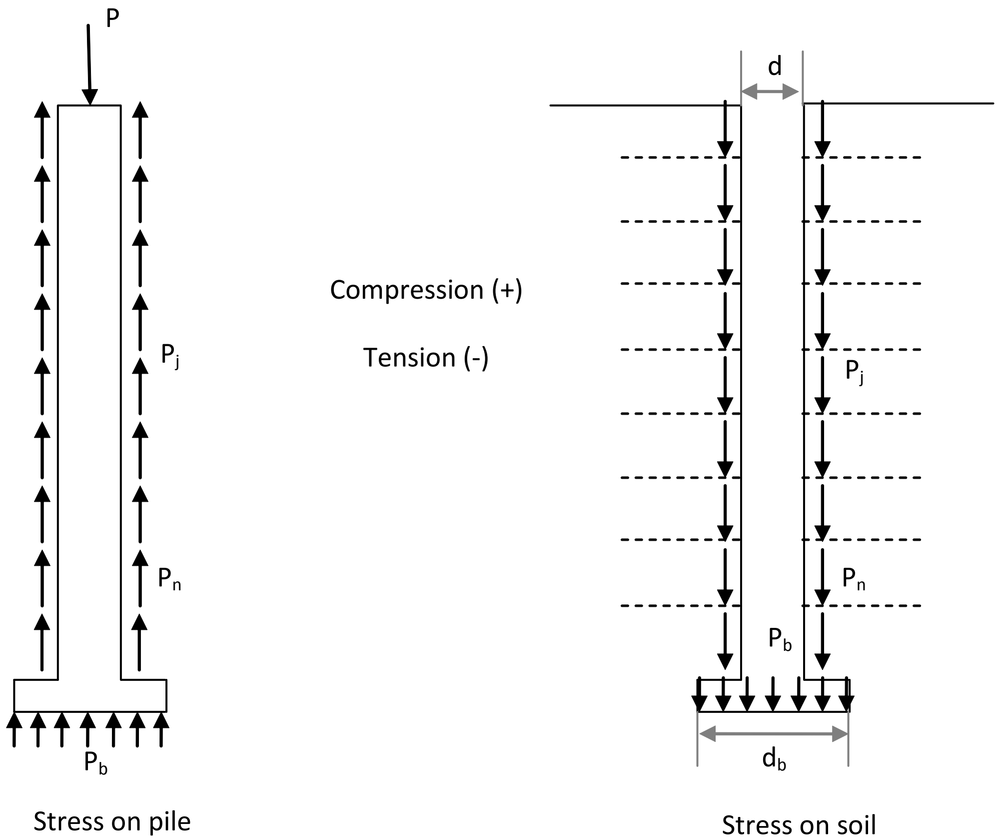
2.2.1 Mindlin Approach

2.2.1.1 Theory of Analysis

Settlement calculation is based on theoretical analyses of the settlement of single compressible piles using linear elastic theory. The analysis uses the integral method adopted by Mattes and Poulos, and is explained briefly below.

Limiting shaft skin friction is calculated from the material properties.

Soil Displacements



Stresses acting on Pile and Adjacent Soil

The soil displacements adjacent to the pile can be expressed by:

$$\{\rho^s\} = \frac{d}{E^s}[I^s]\{p\}$$

where:

$\{\rho^S\}$ = soil displacement vector

$$\{\rho^s\} = \begin{Bmatrix} \rho_1^s \\ \rho_2^s \\ \rho_3^s \\ \vdots \\ \vdots \\ \rho_n^s \\ \rho_b^s \end{Bmatrix}$$

$\{p^S\}$ = shaft skin friction vector

$$\{p^s\} = \begin{Bmatrix} p_1 \\ p_2 \\ p_3 \\ \vdots \\ \vdots \\ p_n \\ p_b \end{Bmatrix}$$

E^S = soil Young's modulus

n = number of nodes on pile shaft

$[l^S]$ = soil displacement factor matrix

$$[l^s] = \begin{bmatrix} l_{11} & l_{12} & \cdots & \cdots & l_{1n} & l_{1b}\dfrac{d_b}{d} \\ l_{21} & l_{22} & \cdots & \cdots & l_{2n} & l_{2b}\dfrac{d_b}{d} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ l_{n1} & l_{n2} & \cdots & \cdots & l_{nn} & l_{nb}\dfrac{d_b}{d} \\ l_{b1} & l_{b2} & \cdots & \cdots & l_{bn} & l_{bb}\dfrac{d_b}{d} \end{bmatrix}$$

in which d = diameter of pile shaft
d_b = diameter of pile base

where superscript s and subscript b denote soil and pile base respectively.

The elements in $[l^S]$ are derived from integrations of Mindlin's equations.

The equation can be rewritten in the form of soil stiffness:

$$\{p\} = \frac{E^s}{d}[l^s]^{-1}\{\rho^s\}$$

Pile Displacements

The pile shaft stresses at nodes can be expressed by:

$$\{p\} = \frac{d}{4\delta^2} E^p R_A [l^p]\{\rho^p\} + \{Y\}$$

where:

superscript p denotes pile

$\{\rho^p\}$ = pile displacement vector

$$\{\rho^p\} = \begin{Bmatrix} \rho_1^p \\ \rho_2^p \\ \rho_3^p \\ \vdots \\ \vdots \\ \rho_n^p \\ \rho_b^p \end{Bmatrix}$$

δ = length of pile element

E^p = pile Young's Modulus

$$R_A = \frac{A}{{}^1/_4\,\pi d^2}$$

A = pile cross-sectional area

$[l^p]$ = pile action matrix

$$[l^p] = \begin{bmatrix} -1 & 1 & 0 & 0 & \dots & \dots & \dots & 0 \\ 1 & -2 & 1 & 0 & \dots & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 0 & -0.2 & 2 & -5 & 3.2 \\ 0 & 0 & 0 & 0 & 0 & -1.33f & 12f & -10.67f \end{bmatrix}$$

in which:

$$f = \frac{\delta}{dR_A}$$

$\{Y\}$ = applied stress vector

$$\{Y\} = \frac{1}{\pi d\delta}\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ \vdots \\ \vdots \\ F_n \\ F_b \end{Bmatrix}$$

in which:

F = applied force at node down the pile

The elements in $[l^{p}]$ are obtained using the finite difference method.

Displacement Compatibility

When elastic conditions at the pile-soil interface are maintained, the displacements of adjacent points along the interface are equal.

$$\{\rho^{s}\} = \{\rho^{p}\} = \{\rho\}$$

$$\left[\frac{E^{s}}{d}[l^{s}]^{-1} - \frac{d}{4\delta^{2}}E^{p}R_{A}[l^{p}]\right]\{\rho\} = \{Y\}$$

The pile displacements are then calculated and shaft skin frictions are calculated from those pile displacements.

Effect of Rigid Boundary

The elements of $[l^{s}]$ apply only for the soil having an infinite depth, i.e. a floating pile. To allow for the effect of a rigid boundary on the pile displacement the mirror-image approximation suggested by D'Appolonia and Romulaldi was introduced. The elements in $[l^{S}]$ are then corrected to $(l_{ij} - l'_{ij})$

where:

l_{ij} = vertical displacement factor for i due to shear stress on element j

l'_{ij} = vertical displacement factor for i due to shear stress on imaginary element j'

Pile-Soil Slip

Displacement compatibility requires that no slip occurs at the pile-soil interface. However, real soils have a finite shear strength. Slip or local yield will occur when the shaft skin friction reaches the limiting value so the elastic analysis as previously described is modified to take account of the possible slip.

For any loading stage, first the displacements are solved on the assumption that all elements are elastic. From these displacements the shear stresses are calculated and are then compared with the specified limiting stresses. At an element, say element i, if the computed skin friction p_i exceeds the limiting value T_i the extra displacement caused by the out-of-balance force is calculated and is added to the previous elastic solution. The shear stresses are then calculated again based on the modified displacements. The procedure is repeated until all the computed shear stresses do not exceed the appropriate limiting shear stresses.

Downward drag (or gap between pile base and soil) correction

If there is a gap between the pile base and the soil beneath then Pile ignores the force due to end-bearing and iterates until force equilibrium and displacement compatibility are achieved.

Correction of Soil Stiffness

To allow for the two different soil stiffnesses above and below the pile toe an approximate treatment is included in the program.

The elements of the flexibility matrix $\{\delta\}$ consist of two components:

$$\delta_{ii} = \delta_{bi}(E_b) + (\delta_{ii} - \delta_{bi})(E_s)$$

where:

$\delta_{bi}(E_b)$ = displacement at the pile toe in the soil with E_b due to a unit load at element i

$(\delta_{ii} - \delta_{bi})(E_s)$ = relative displacement between i and b in the soil with E_s due to a unit load at element i;

$$\delta_{ij} = \delta_{ji}(E_s) \times F_{ij} = \delta_{ij}$$

where F_{ij} is the smaller of:

$$\frac{\delta_{ii}}{\delta_{ii}(E_s)} \; and \; \frac{\delta_{jj}}{\delta_{jj}(E_s)}$$

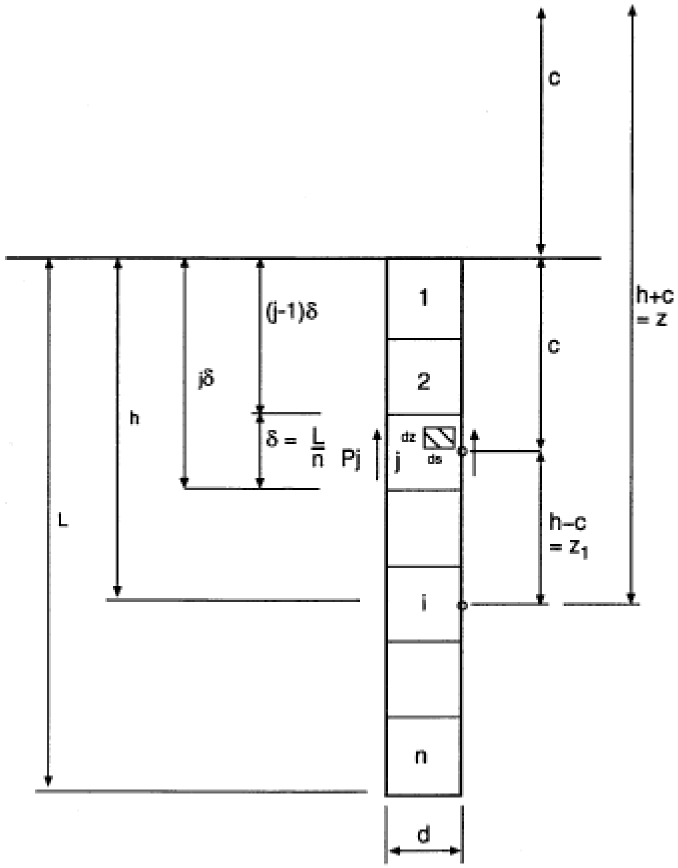
in which:

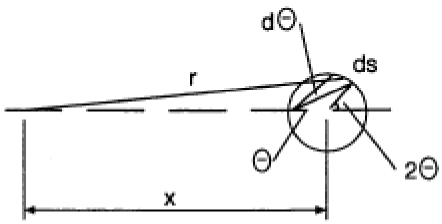
$\delta_{ii}(E_s)$ = displacement at element i in a soil with E_s due to a unit load at element i

$\delta_{jj}(E_s)$ = displacement at element j in a soil with E_s due to a unit load at element j

2.2.1.2 Integration of Mindlin's equations

Displacement of Point i due to Stress on Element j





Geometry of Single Pile

For a general point i, the value of l_{ij} is

$$l_{ij} = 2 \int_{(j-1)\delta}^{j\delta} \int_{0}^{\pi/2} l^{\rho} \, d\theta \, dc$$

where:

I^p = influence factor for vertical displacement due to a vertical point load

From Mindlin's equation, I^p is given by:

$$I^\rho = \frac{(1+\vartheta)}{8\pi(1-\vartheta)}\{\frac{z_1}{R_1^3} + \frac{(3-4\vartheta)}{R_1} + \frac{(5-12\vartheta+8\vartheta^2)}{R_2} + \frac{[(3-4\vartheta)z^2 - 2cz + 2c^2]}{R_2^3} + \frac{[6cz^2(z-c)]}{R_2^5}\}$$

where:

$z = h + c$

$z_1 = h - c$

$$R_1^2 = \frac{d^2}{4} + x^2 + dx\,cos2\theta + z_1^2$$

$$R_2^2 = \frac{d^2}{4} + x^2 + dx\,cos2\theta + z^2$$

The integral with respect to c is given by:

$$I^\rho dc = \frac{(1+\vartheta)}{8\pi(1-\vartheta)}\{\frac{z_1}{D_1} - 4(1-\vartheta)\ln(z_1 + D_1) + 8(1 - 2\vartheta + \vartheta^2)\ln(z + D) + \frac{[2h^2 z/r^2 - 4h - (3-4\vartheta)z]}{D} + \frac{2(hr^2 - h^2 z^3/r^2)}{D}\}$$

where:

$$D_1 = \sqrt{(r^2 + z_1^2)}$$

$$D = \sqrt{(r^2 + z^2)}$$

and the limits of integration are:

z_1 from $h - (j - 1)d$ to $h - jd$

z from $h + (j - 1)d$ to $h + jd$

The integration with respect to θ is evaluated by numerical means.

Displacement of Base Centre due to Stress on Element j

$$l_{bj} = \pi \int_{(j-1)\delta}^{j\delta} l^p \, dc$$

the integral with respect to c is

$$l^p dc = \frac{(1+\vartheta)}{8\pi(1-\vartheta)} \{ \frac{z_1}{D_1} - 4(1-\vartheta)\ln(z_1 + D_1) + 8(1 - 2\vartheta + \vartheta^2)\ln(z + D) + \frac{[2h^2 z/r^2 - 4h - (3 - 4\vartheta)z]}{D} + \frac{2(hr^2 - h^2 z^3/r^2)}{D} \}$$

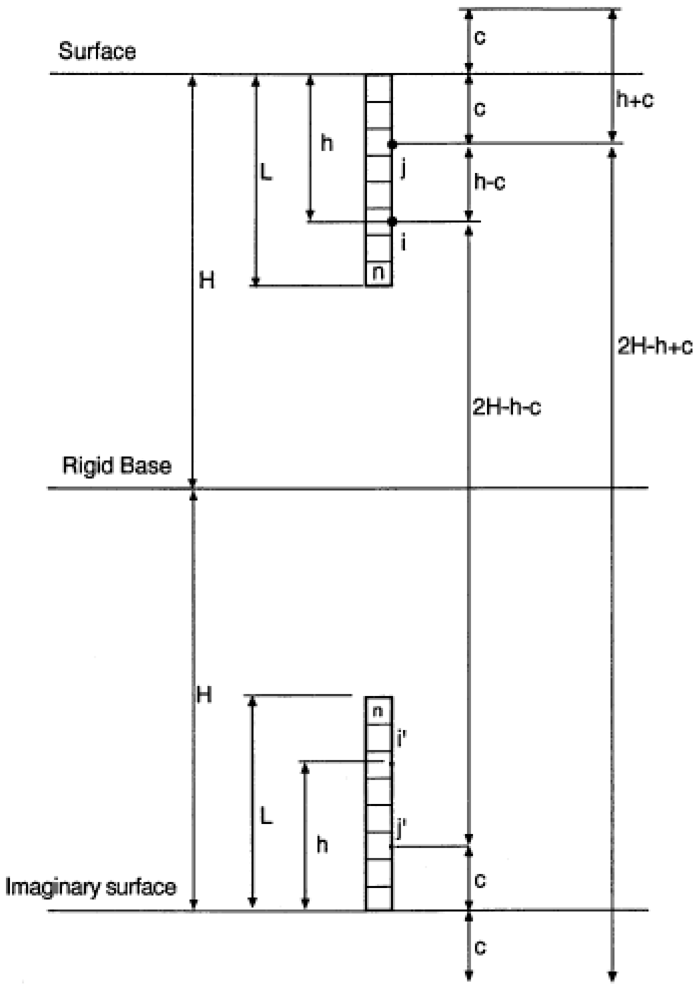
where:

$h = L$

$$D^2 = z^2 + \frac{d^2}{4}$$

$$D_1^2 = z_1^2 + \frac{d^2}{4}$$

Displacement of Base due to the Base itself



Geometry of Integration Over Pile Base Area

$$l_{bb} = \frac{\pi^2}{2d}\int_0^{d_b/2} l^p \, r dr$$

with:

$c \quad = L$

$R_1 \quad = r$

$R_2^2 = 4c^2 + r^2$

$z_1 = 0$

therefore:

$$l_{bb} = \frac{\pi(1+\vartheta)}{16(1-\vartheta)d}\{(3-4\vartheta)\frac{d_b}{2} + (5-12\vartheta+8\vartheta^2)(R-z) + \frac{(5-8\vartheta)}{2}z^2\left(\frac{1}{z}-\frac{1}{R}\right) + \frac{z}{2} - \frac{z^4}{2R^3}\}$$

where:

$$R = \sqrt{\left(z^2 + \frac{d_b^2}{4}\right)}$$

$$z = 2L$$

Displacement of Point i due to the Base

$$l_{jb} = \frac{1}{d}\int_0^{2\pi}\int_0^{d_b/2} l^\rho \, r dr \, d\theta$$

with:

$$c = L$$

$$R_1^2 = z_1^2 + x^2 + r^2 - 2rx\cos\theta$$

$$R_2^2 = z^2 + x^2 + r^2 - 2rx\cos\theta$$

$$z = z_1 + 2c$$

the integration with respect to *r* is:

$$\begin{aligned} l^\rho r\, dr = \frac{(1+\vartheta)}{8\pi(1-\vartheta)}\Bigg\{ & \frac{z_1^2(rA-R_0^2)}{(R_0^2-A^2)\sqrt{x_0}} + (3+4\vartheta)\left[\sqrt{x_0} + A\ln\left(r-A+\sqrt{x_0}\right)\right] \\ & + (5-12\vartheta+8\vartheta^2)\left[\sqrt{x_1} + A\ln\left(r-A+\sqrt{x_1}\right)\right] \\ & + [(3-4z^2)-2cz+2c^2]\frac{(rA-R_1^2)}{(R_1^2-A^2)\sqrt{x_1}} \\ & + 2cz^2(z-c)\left[\frac{(rA-R_1^2)}{(R_1^2-A^2)\sqrt[3]{x_1}} + \frac{2A(r-A)}{(R_1^2-A^2)^2\sqrt{x_1}}\right]\Bigg\} \end{aligned}$$

where:

$$R_0^2 = z_1^2 + x^2$$

$$A = x\cos\theta$$

$$x_0 = r^2 - 2Ar + R_0^2$$

$$R_1^2 = z^2 + x^2$$

$$x_1 = r^2 - 2Ar + R_1^2$$

$$z = z_1 + 2c$$

$$c = L$$

The limit of integration is from 0 to $d_b/2$. The integration with respect to θ is evaluated by numerical means.

It is assumed that the influence of the pile base on the displacement of i is negligible, hence

$$I_{ib} = 0$$

Mirror-Image Method

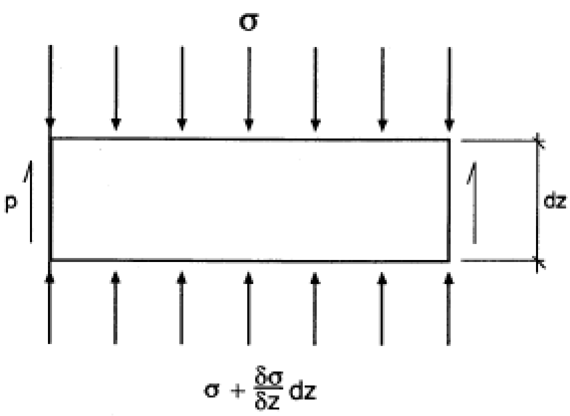
The element l_{ij}' is similar to l_{ij}, but with

$z \ = 2H - h + c$ and

$z_1 = 2H - h - c$

2.2.1.3 Pile Stiffness Matrix

In calculating the displacement of the pile itself, only axial compression of the pile is considered.



Consider the vertical equilibrium of a small element of the pile.

An equilibrium equation can be derived as:

$$\frac{\delta\sigma}{\delta z} = -\frac{p\pi d}{A} = -\frac{4p}{R_A d}$$

The axial strain of the element is approximately:

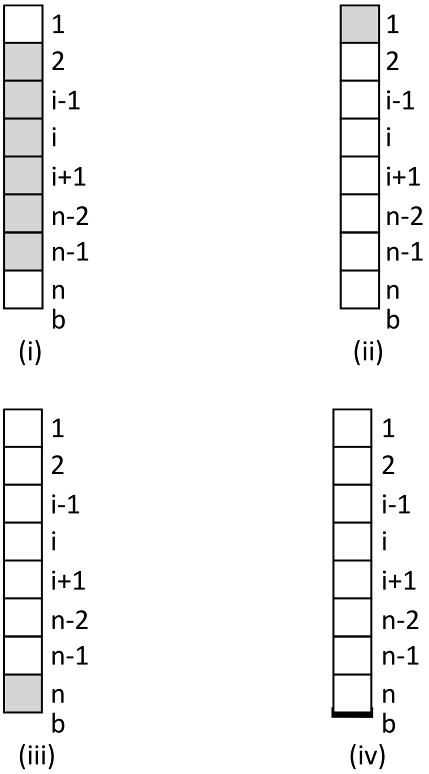
$$\frac{\delta \rho}{\delta z} = -\frac{\sigma}{E^p}$$

therefore:

$$\frac{\delta^2 \rho}{\delta z^2} = \frac{4p}{d}\frac{1}{E^p R_A}$$

This is solved by using finite difference method which may be approximately expressed by the Taylor Expansion.

Difference Formulations



(i) For 2 ≤ i ≤ n-1

$$\rho_{i-1} = \rho_i - \delta\rho_i' + {}^1/_2\,\delta^2 \rho_i''$$

$$\rho_{i+1} = \rho_i + \delta\rho_i' + {}^1/_2\,\delta^2 \rho_i''$$

$$\rho_i'' = \frac{\rho_{i-1} - 2\rho_i + \rho_{i+1}}{\delta^2}$$

therefore:

$$p_i = \frac{d}{4} E^p R_A \frac{(\rho_{i-1} - 2\rho_i + \rho_{i+1})}{\delta^2}$$

(ii) For i = 1

$$\sigma = \frac{F_1}{A}$$

$$\frac{\delta\rho}{\delta z} = -\frac{\delta}{E^p} = -\frac{F_1}{AE^p}$$

$$\rho_1' = \rho_1 - \delta\rho_i'$$

$$\rho_1' = \frac{\rho_1 - \rho_1'}{\delta} = -\frac{F_1}{AE^p}$$

$$\rho_1' = \rho_1 + \frac{F_1\delta}{AE^p}$$

$$p_1 = \frac{d}{4} E^p R_A \frac{(-\rho_1 + \rho_2)}{\delta^2} + \frac{F_1}{\pi d\delta}$$

(iii) For i = n

$$\rho_b = \rho_n + {}^1/_2\, \delta\rho_n' + \frac{\delta^2}{8}\rho_n''$$

$$\rho_{n-2} = \rho_n + 2\delta\rho_n' + 4\delta^2\rho_n''$$

so:

$$16\rho_b - \rho_{n-2} - 15\rho_n = 10\delta\rho_n'$$

$$\rho_{n-1} = \rho_n - \delta\rho_n' + {}^1/_2\, \delta^2\rho_n''$$

or:

$$\rho_n' = \frac{1}{\delta}(\rho_n - \rho_{n-1} + {}^1/_2\, \delta^2\rho_n'')$$

so:

$$16\rho_b - \rho_{n-2} - 15\rho_n = 10(\rho_n - \rho_{n-1} + {}^1/_2\, \delta^2\rho_n'')$$

$$\rho_n'' = \frac{1}{\delta^2}(-0.2\rho_{n-2} + 2\rho_{n-1} - 5\rho_n + 3.2\rho_b)$$

therefore:

$$\rho_n = \frac{d}{4}\frac{E^p R_A}{\delta^2}(-0.2\rho_{n-2} + 2\rho_{n-1} - 5\rho_n + 3.2\rho_b)$$

(iv) For pile base:

$$\rho_n = \rho_b - {}^1\!/_2\,\delta\rho_b' + \frac{\delta^2}{8}\rho_b''$$

$$\rho_{n-1} = \rho_b - \frac{3}{2}\delta\rho_b' + \frac{9}{8}\delta^2\rho_b''$$

so:

$$\rho_b' = \frac{\rho_{n-1} - 9\rho_n + 8\rho_b}{3\delta} = \frac{-p_b}{E^p}$$

therefore:

$$p_b = \frac{d}{4}\frac{E^p R_A}{\delta^2}\frac{\delta}{dR_A}(-\frac{4}{3}\rho_{n-1} + 12\rho_n - \frac{32}{3}\rho_b)$$

$$p_b = \frac{d}{4}\frac{E^p R_A}{\delta^2}(-\frac{4}{3}f\rho_{n-1} + 12f\rho_n - \frac{32}{3}f\rho_b)$$

where:

$$R_A = \frac{A}{{}^1\!/_4\,\pi d^2}$$

$$f = \frac{\delta}{dR_A}$$

Pile Stiffness

The pile stiffness matrix is given by:

$$\frac{d}{4}\frac{E^p R_A}{\delta^2}\begin{bmatrix} -1 & 1 & 0 & 0 & \dots & \dots & \dots & 0 \\ 1 & -2 & 1 & 0 & \dots & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -2 & 1 \\ 0 & 0 & 0 & 0 & -0.2 & 2 & -5 & 3.2 \\ 0 & 0 & 0 & 0 & 0 & -1.33f & 12f & -10.67f \end{bmatrix}$$

2.2.2 t-z Curves

2.2.2.1 Soil Stiffness Matrix

The soil stiffness matrix is given by:

$$\begin{bmatrix} k_{11} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & k_{22} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \ldots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \ldots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & k_{ii} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & k_{nn} \end{bmatrix}$$

where k_{ii} is the stiffness at node i, obtained from the t-z curve associated with the soil material in which the node lies. For the last node, i.e. for the base, the stiffness is sum of the stiffness obtained from t-z curve and the stiffness obtained from the tip load curve associated with the soil material in which the last node lies.

$$k_{shaft-node} = (k_{t-z})_{\text{shaft-node}}$$

$$k_{base-node} = (k_{t-z})_{\text{base-node}} + (k_{tip\ load})_{\text{base-node}}$$

If the node lies at the junction of two layers, then the top layer's curve is used.

The stiffness terms are for the shaft and base springs are dependent on the type of t-z curves.

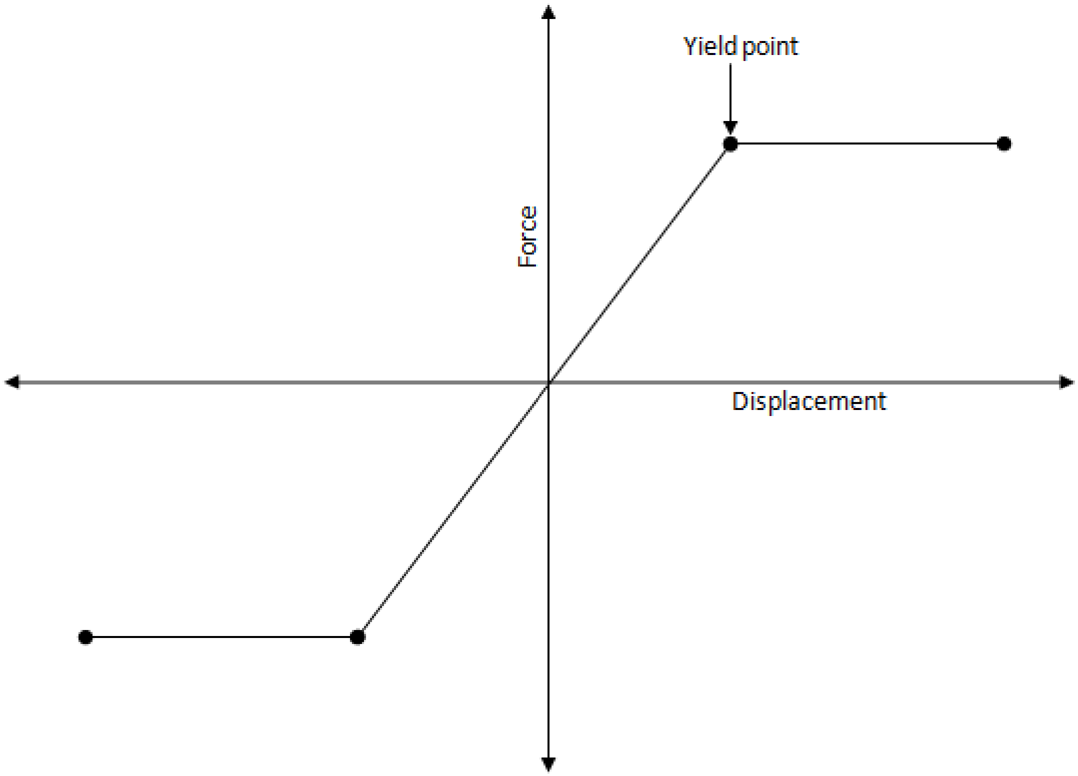
The types of t-z curves and tip load supported by the program are:

- Elastic-Plastic (Randolph and Wroth);
- Hyperbolic (Chin & Poulos)
- Logarithmic
- API
- Empirical (Vijayvergiya); and
- User specified, in which stiffness values are calculated directly from stress-displacement curves given by the user.

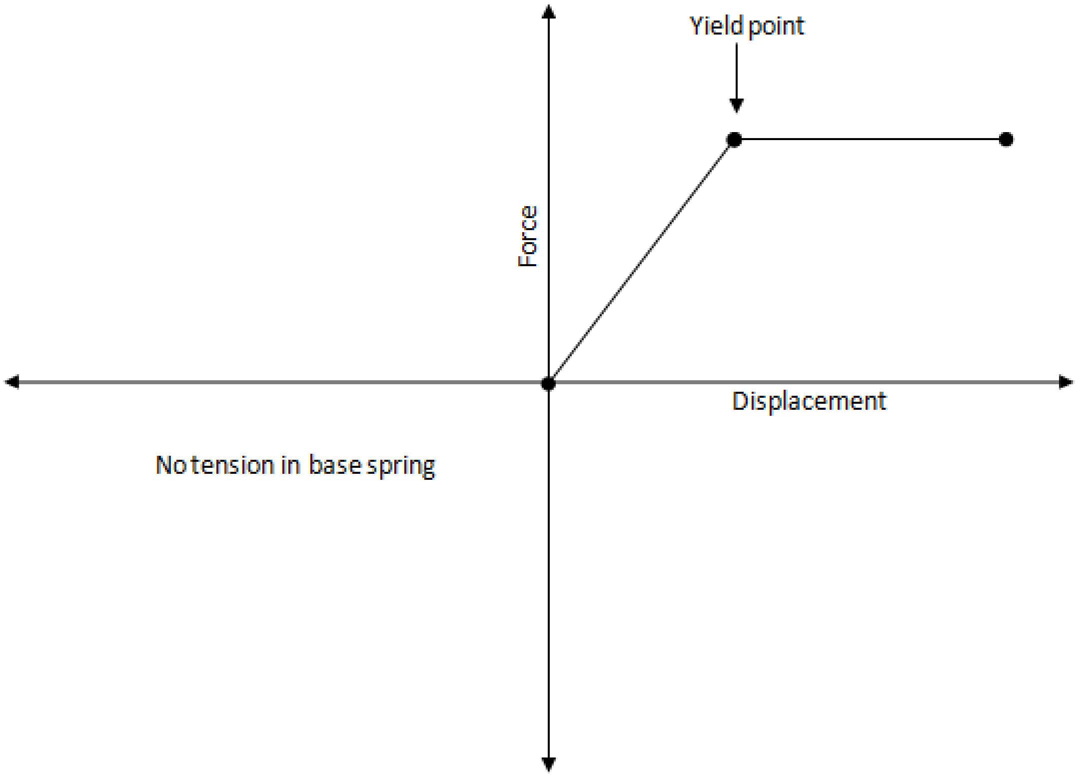
2.2.2.1.1 Elastic-Plastic Curves

These curves are characterized by a constant stiffness till yield. After yield, the stiffness is zero. This is common to both the shaft and base curves. It is also important to note that the base curves are limited to compression only. They do not carry tension.

Typical elastic-plastic t-z curve is shown below:



Typical elastic-plastic tip load load curve is shown below:



2.2.2.1.2 Hyperbolic Curves

These are based on Chin & Poulos (1991). These show a continuous degradation of stiffness with increasing load.

The equation for the initial loading curve for the shaft is given by:

$$z = \frac{\tau_0 r_0}{G_{max}} ln \left[\frac{\frac{r_m}{r_0} - \frac{\tau_o}{\tau_f} R_f}{1 - \frac{\tau_o}{\tau_f} R_f} \right]$$

where :

r_0 is the radius of the pile

τ_0 is the pile-soil interface shear stress

τ_f is the limiting shear stress

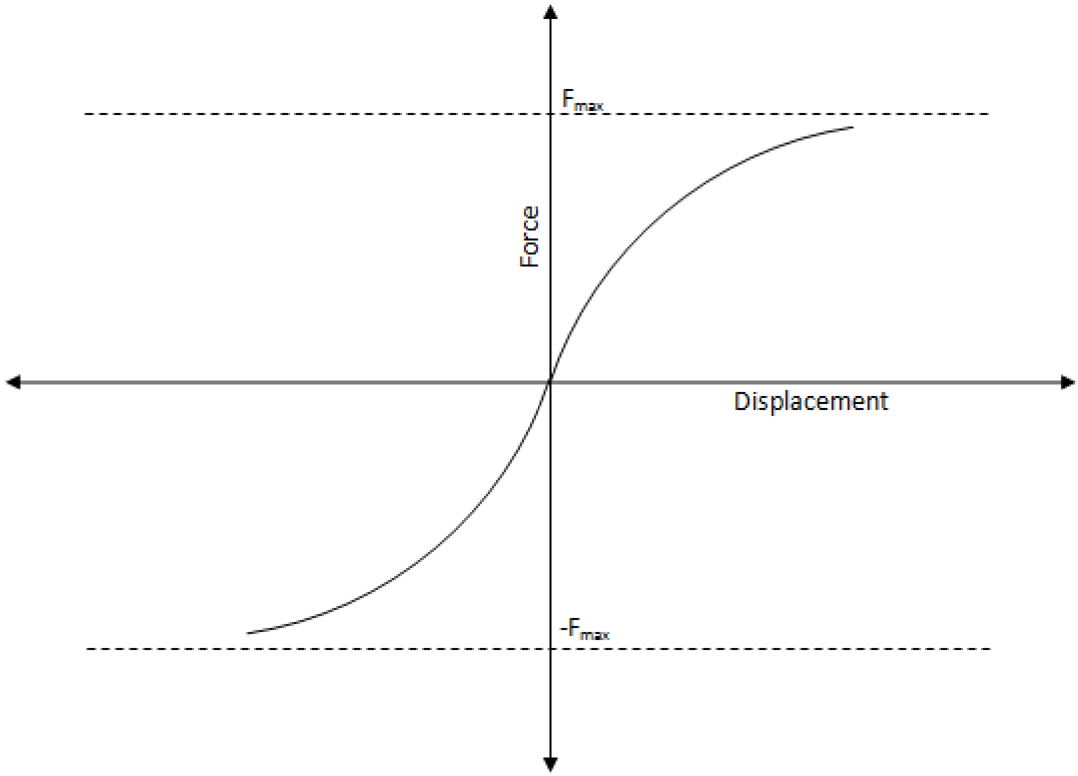
r_m is the empirical distance at which the shear stress in the soil becomes negligible

R_f is a hyperbolic constant which controls the shape of the Force-displacement curve.

Gmax is the initial shear modulus.

The displacement at maximum force is controlled by a hyperbolic constant R_f. For R_f = 1, the pile displacement is infinite at maximum force. The program generates 10 (t,z) pairs between τ_0 = 0 and $\tau_0 = \tau_f$.

Typical t-z curve of this type is shown below:



The equation for the initial loading curve for the base is given by:

$$z = \frac{p_b}{k_i * \left(1 - \frac{p_b * R_{fb}}{p_f}\right)}$$

where:

p_b is the mobilised shear load

R_{fb} is the hyperbolic curve fitting constant for the base

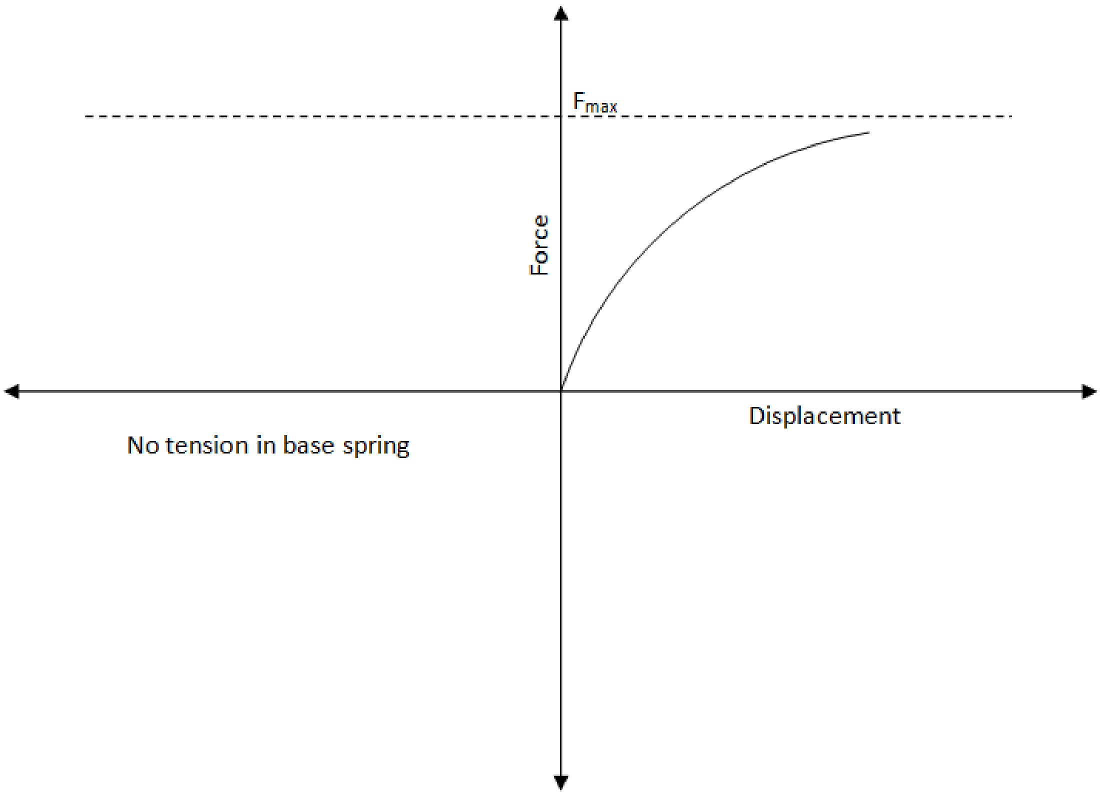
p_f is the limiting base load

k_i is the initial stiffness at the base and is given by

$$k_i = \frac{4G_i r_0}{(1-\vartheta)} = \frac{2E_i r_0}{(1-\vartheta^2)}$$

In the above expression, E_i and G_i are the initial Young's modulus and shear modulus of the soil respectively, and ν is the Poisson's ratio of the soil.

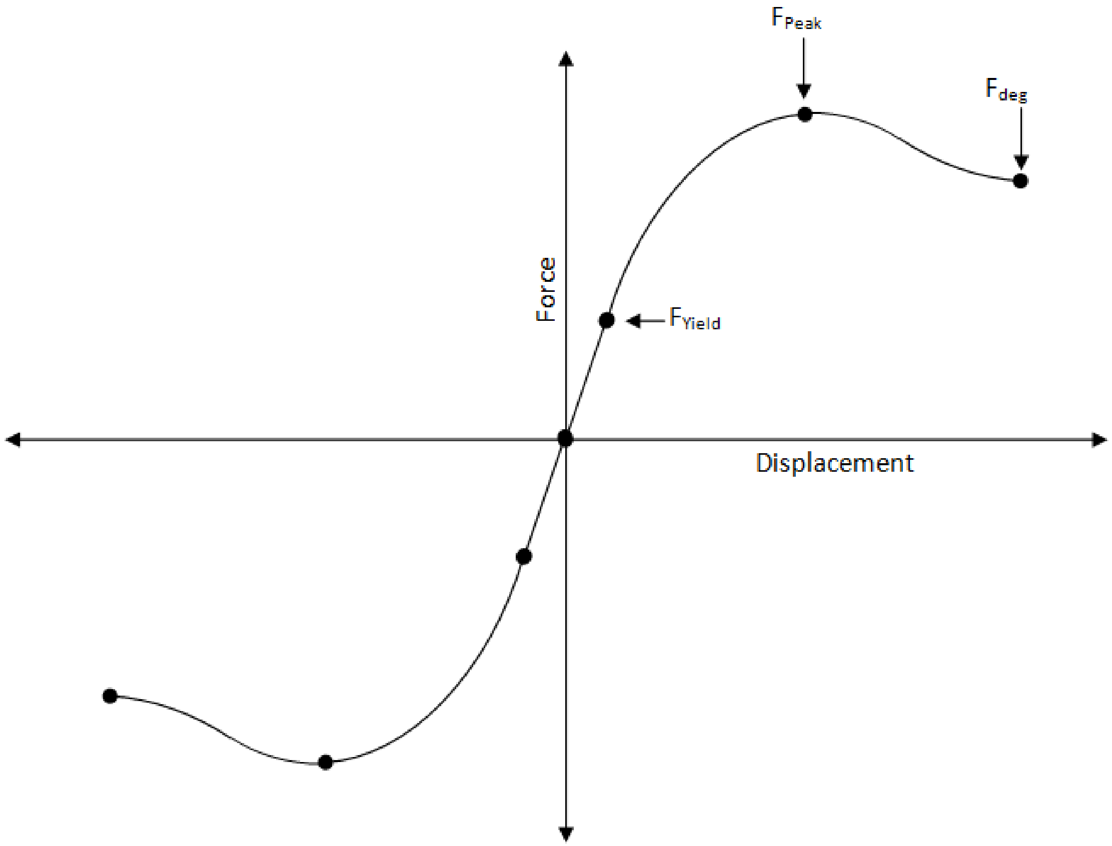
Typical tip load curve of this type is given below:



2.2.2.1.3 Logarithmic

For logarithmic shaft curves, the initial curve is consists of three distinct zones:

- Linear elastic zone till yield;
- Logarithmic yielding zone;
- Exponential degrading zone.



For the linear elastic zone the stiffness of the soil spring is given by:

$$k_{el} = \frac{E * (\Delta l)}{2 * (1 + \vartheta) * r_0 * \ln\left({}^{r_m}/_{r_0}\right)}$$

where:

E = Young's modulus of soil layer at the location of soil spring.

Δl = length of the interaction area corresponding to the soil spring. This is the average length of elements connected to the node at the location of soil spring.

n = Poisson's ratio of the soil layer at the location of soil spring.

r_0 = radius of the pile.

r_m = distance from the axis of pile at which the shear stresses are negligible.

For the logarithmic yielding zone, the following equation for spring force f is used (based on Puzrin & Burland, 1996; Puzrin & Shiran, 2000)):

$$f = f_y + (w - w_y) \cdot \left(1 - \alpha \left\{\ln\left[1 + \left(\frac{w - w_y}{f_p - f_y}\right) \cdot k_{el}\right]\right\}^{\kappa}\right)$$

$$x_L = \left(\frac{w_p - w_y}{f_p - f_y}\right) \cdot k_{el}$$

$$R = \frac{c\,(1 + x_L)\ln(1 + x_L)}{x_L\,(x_L - 1)}$$

$$\alpha = \frac{x_L - 1}{x_L\,[\ln(1 + x_L)]^R}$$

where:

f = force in the soil spring for a deformation w in it.

f_y = yield force of the soil spring. It is expressed as a fraction ξ of the peak force, and marks the boundary between linear elastic zone and logarithmic yielding zone.

f_p = the peak force of the soil spring.

w_y = yield displacement of the soil spring.

c = 1.0 (to ensure gradient of function equals zero at f_p)

For the post-peak degrading portion, an exponential decay is assumed (based on Siedel and Coronel (2011)):

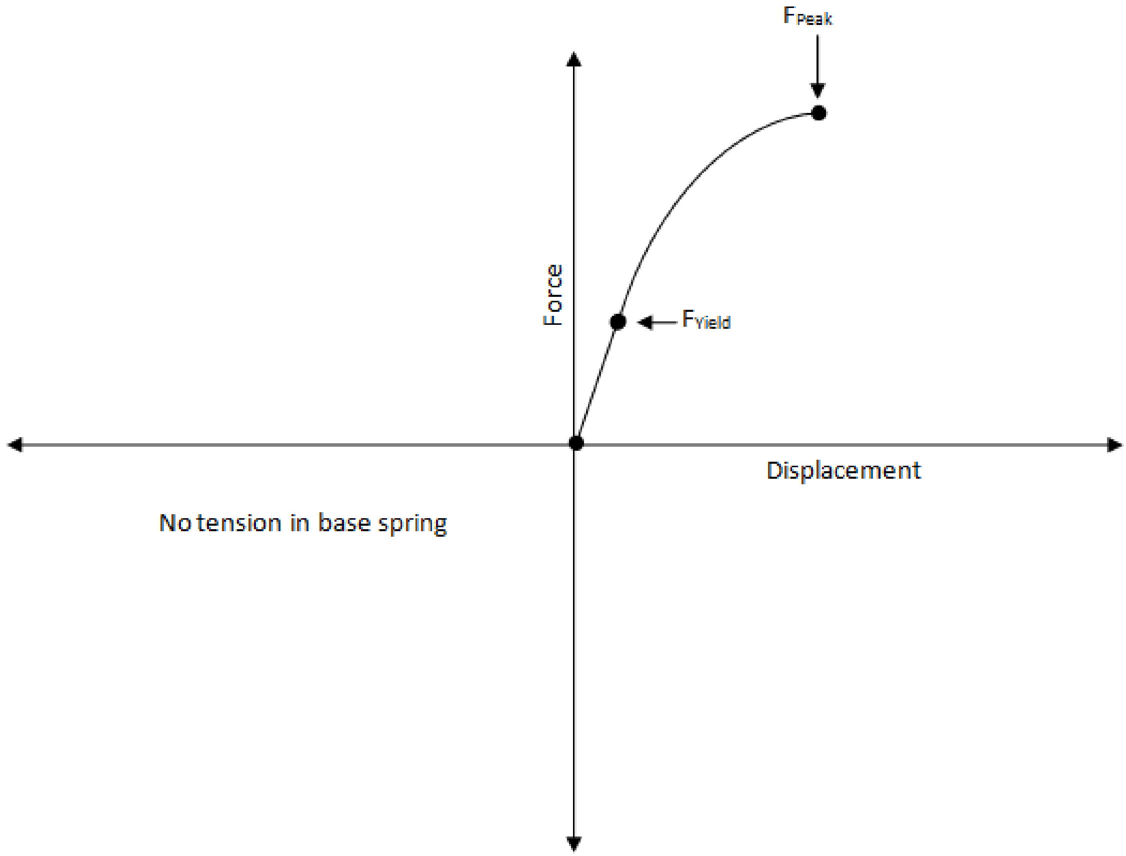
$$f_0 = f_p - 1.1 * (f_p - f_{deg}) * \left(1 - \exp\left(-2.4 * \left(\frac{\Delta w}{\Delta w_{res}}\right)^{\eta}\right)\right)$$

where:

f_0 is the force in soil spring for a post-peak deformation of Δw in the soil spring.

Δw_{res} is the total post-peak deformation in the soil spring leading to a residual force f_r in the soil spring.
f_{deg} is the minimum post-peak force of the soil spring.
f_p is the peak force of the soil spring.
w_y is yield deformation of the soil spring.

The tip load curves are treated in a similar way to the shaft curves described above. However, there is no softening portion for the base, as can be seen below:

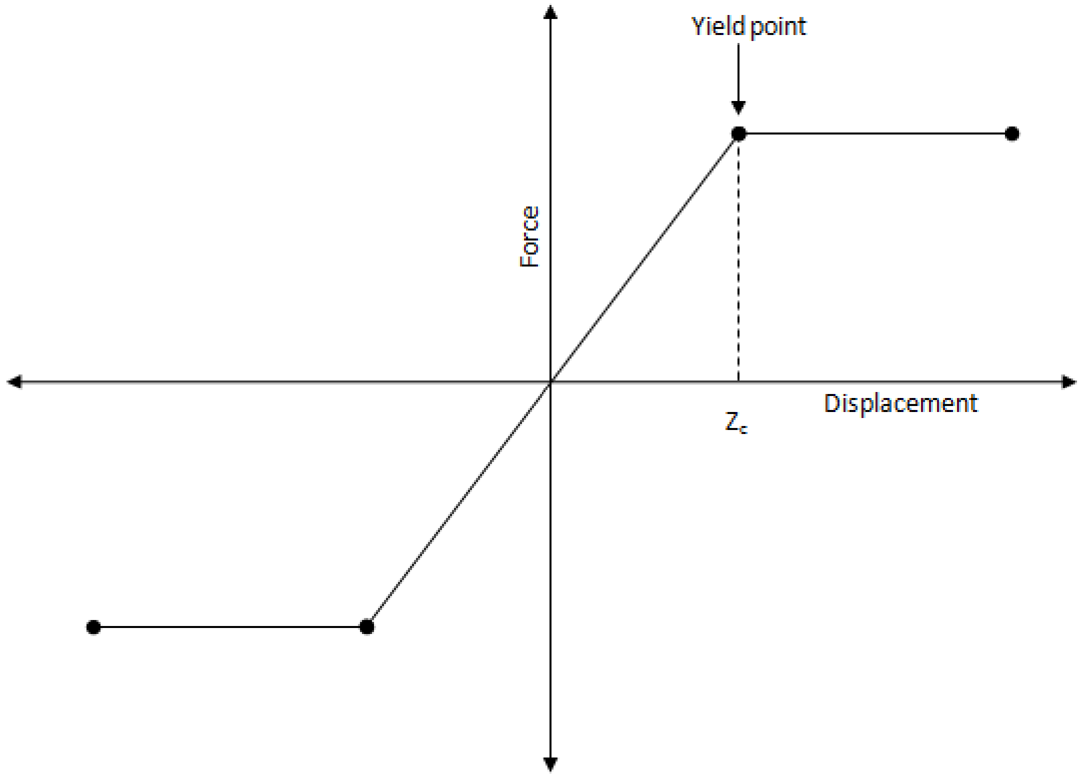


2.2.2.1.4 API

There are two different types of API curves for shaft -

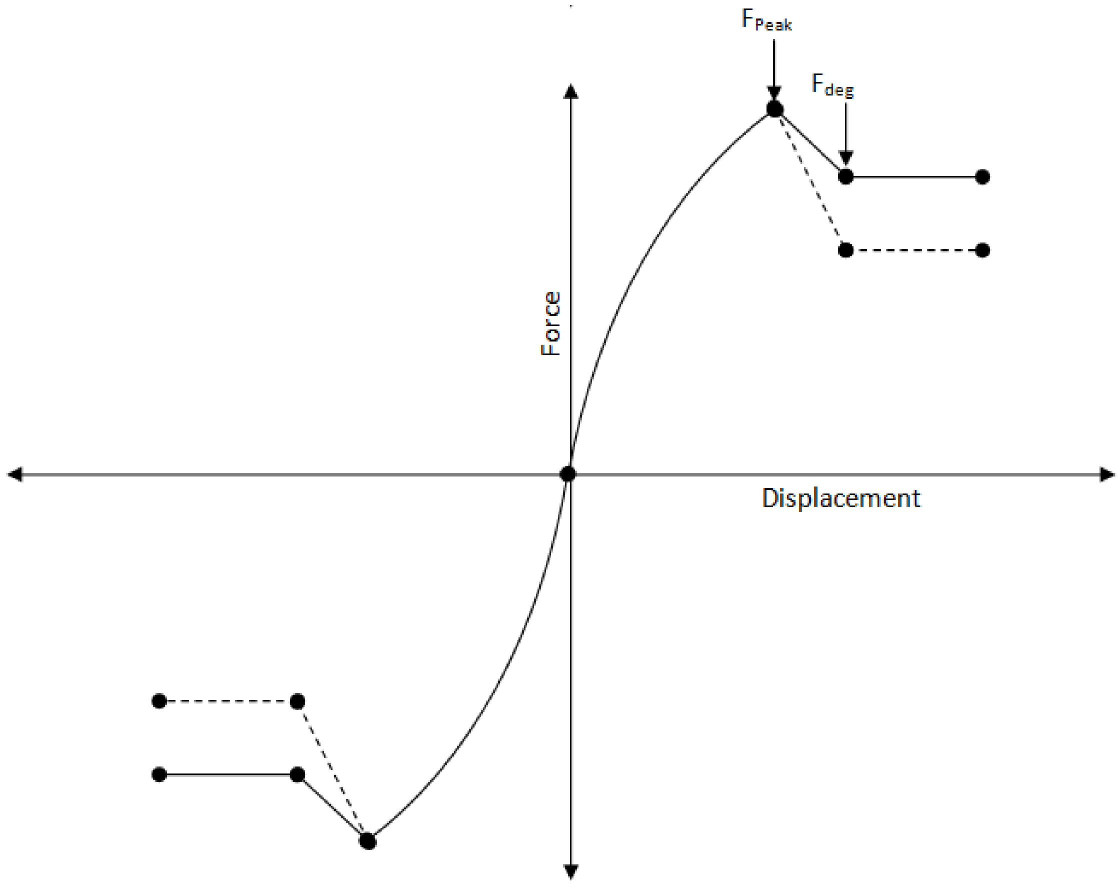
- Sand:

The shaft curves in this case are essentially elastic-plastic. The user just needs to specify the yield displacement z_c to define the curve.

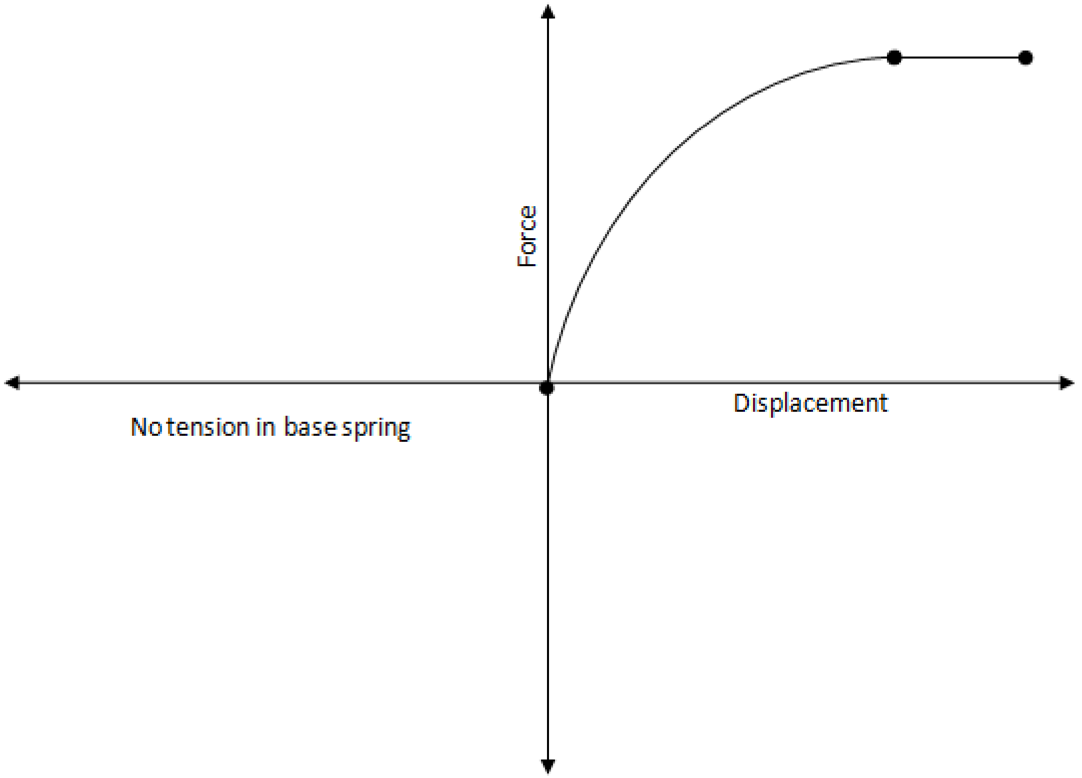


- Clay:

For clay, the program uses a set of multi-linear curves to model the pre-peak portion of the curve outlined in API 1993. The curve exhibits decreasing stiffness till peak, followed by softening behaviour. The user needs to enter the residual force as a fraction of the peak force to fully define the curve.



For base interaction, there is only one type of curve - same for both clay and sand. This is modeled by 5 points as specified in the API documentation.



2.2.2.1.5 Emperical (Vijayvergiya)

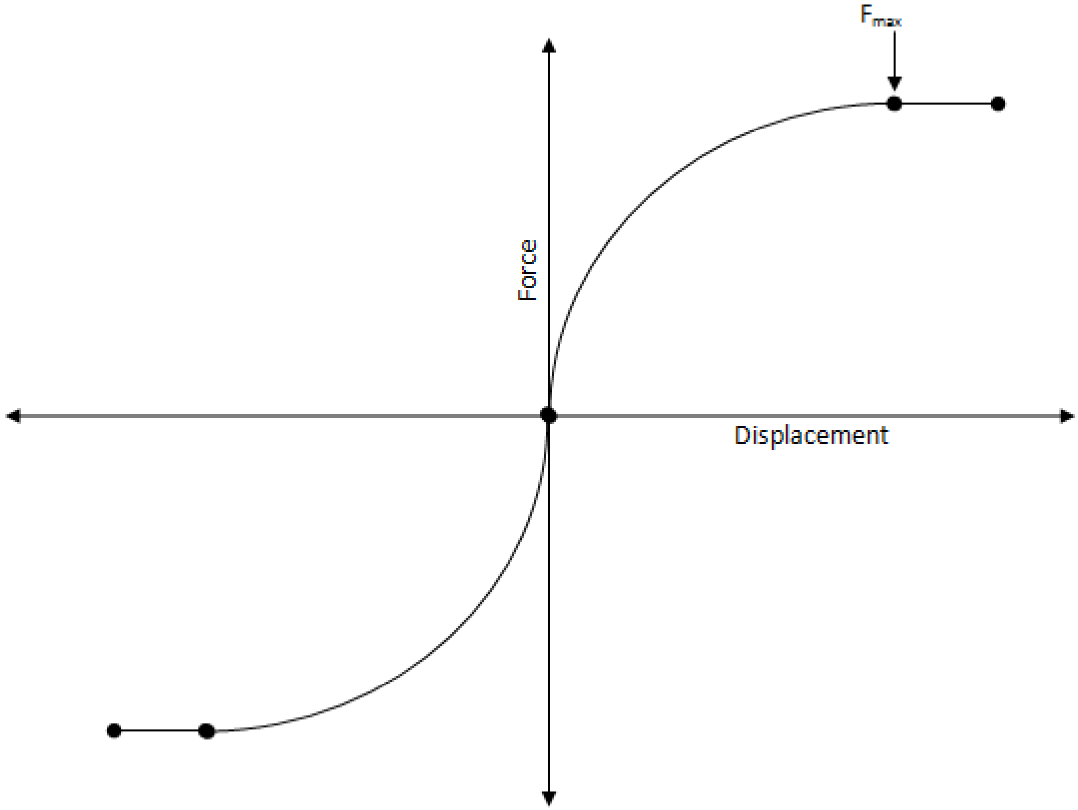
For the shaft, the t-z curve is parabolic. The equation for the t-z curve is given by

When $z < z_c$

$$F = F_{max} * \left(2 * \sqrt{\frac{z}{z_c}} - \frac{z}{z_c} \right)$$

When $z \geq z_c$

$$F = F_{max}$$



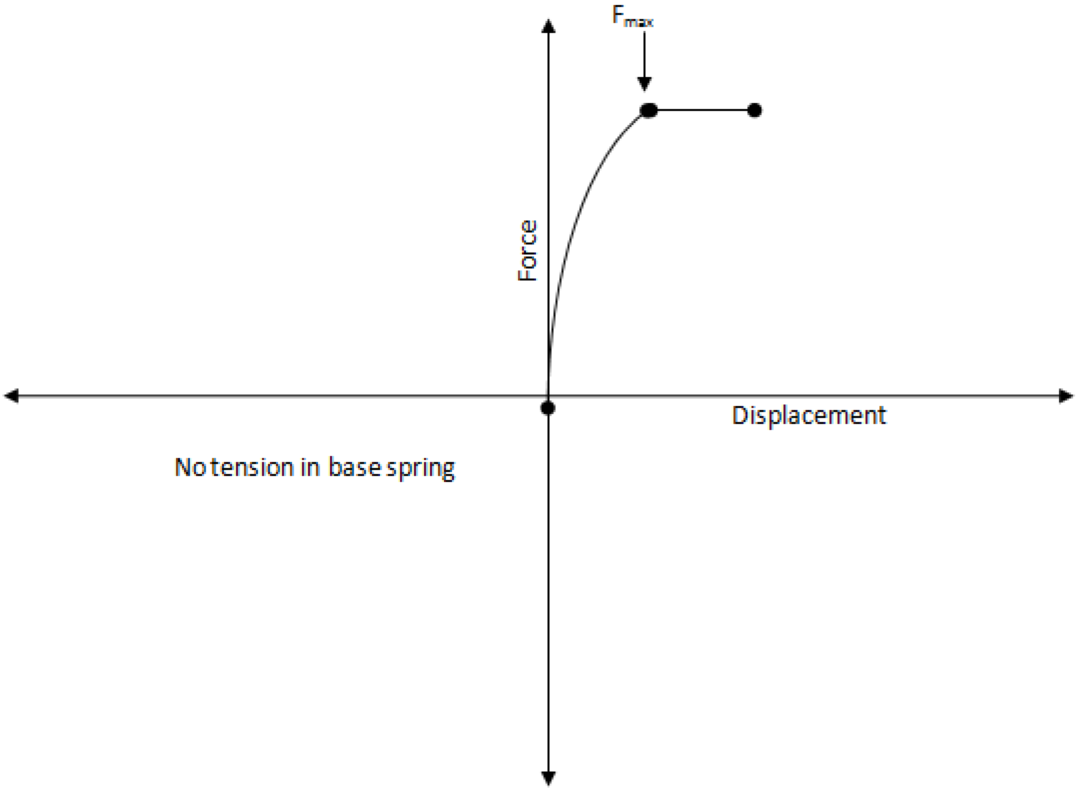
For the base, the tip load curve is given by

When $z < z_c$,

$$F = F_{max} * \left(\frac{z}{z_c} \right)^{\frac{1}{3}}$$

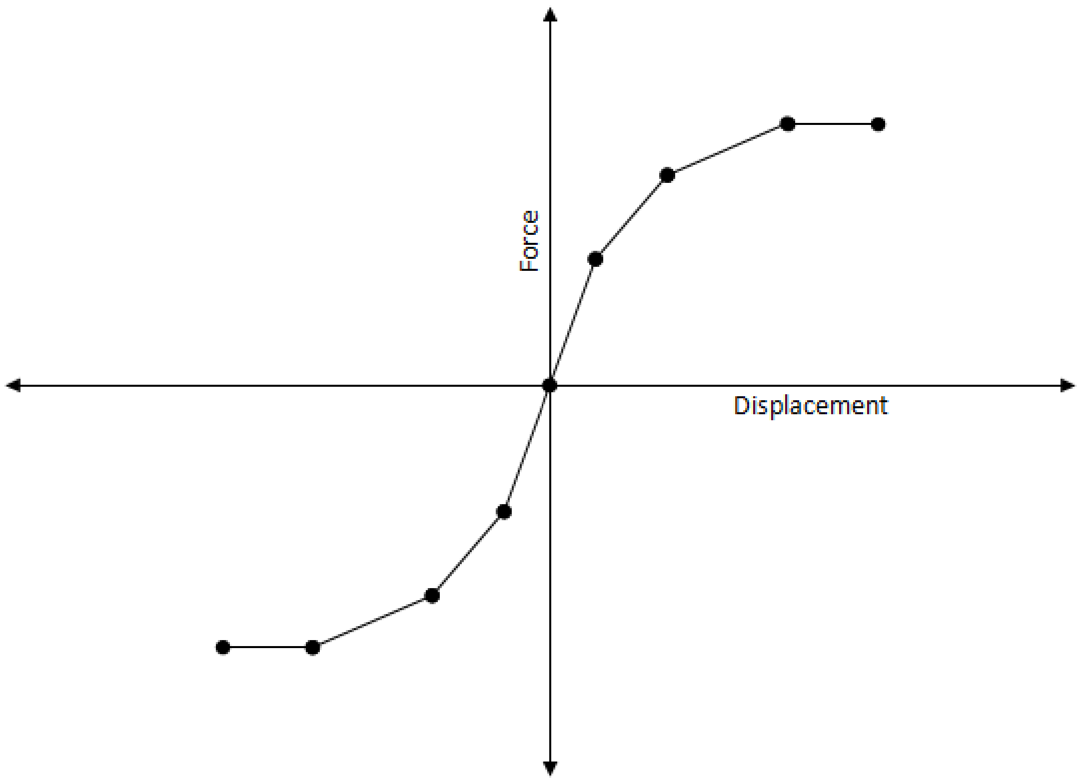
When $z \geq z_c$

$$F = F_{max}$$

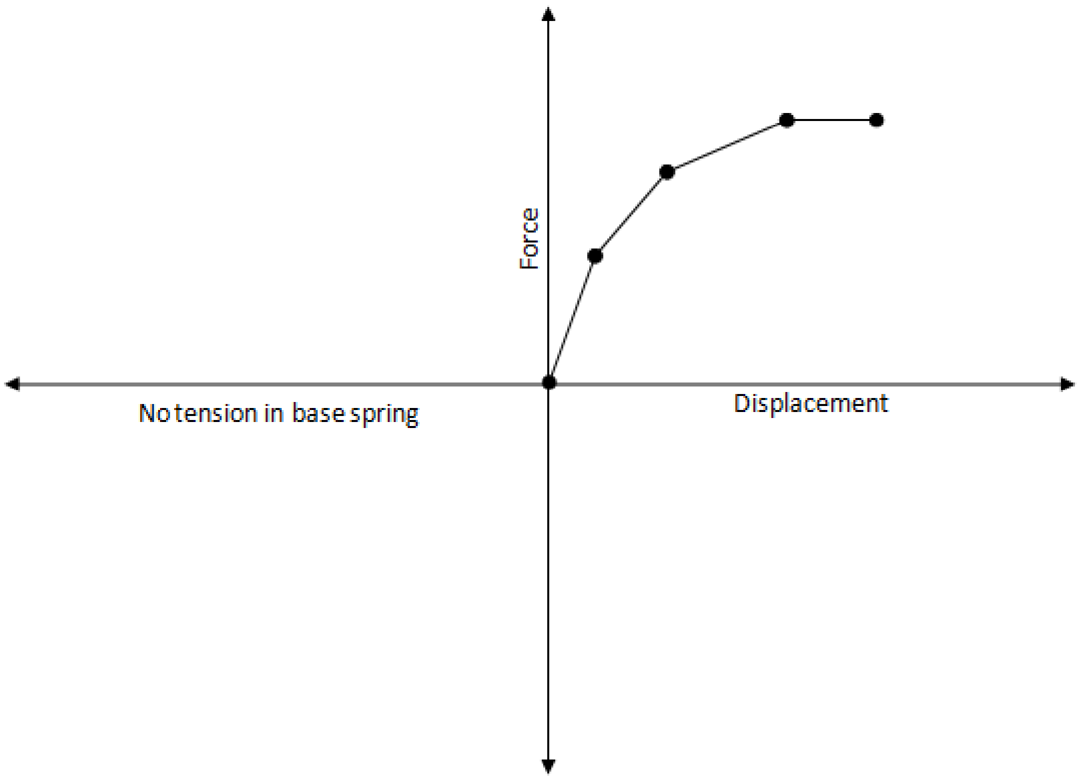


2.2.2.1.6 User-defined

When using this option, the user is required to enter a series of points to define a multi-linear force versus displacement curve.This curve is extended symmetrically into tension region for shaft curves.



For the base curves too, the user is required to enter a series of points as discussed above. However, the curve is not extended into the tension region i.e. base spring does not take tension.



2.2.2.2 Pile Stiffness Matrix

The pile is modelled as a series of axial elements i.e. one dimensional elements, where the stiffness matrix of each element(based on 1D finite element method) is given by:

$$\begin{bmatrix} AE/L & -AE/L \\ -AE/L & AE/L \end{bmatrix}$$

where,

A is the area of the element
E is the Young's modulus of the material
L is the element length

The total pile stiffness matrix of a pile with 'n' elements is of size (n+1) x (n+1) and is given by

$$\begin{bmatrix} k_{11}^{1} & k_{12}^{1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ k_{21}^{1} & k_{22}^{1}+k_{11}^{2} & k_{12}^{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & k_{21}^{2} & k_{22}^{2}+k_{11}^{3} & k_{12}^{3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & k_{21}^{3} & k_{22}^{3}+k_{11}^{4} & \dots & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & \dots & \dots & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & \dots & \dots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \dots & k_{22}^{i-1}+k_{11}^{i} & k_{12}^{i} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & k_{21}^{i} & \dots & \dots & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & \dots & \dots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & k_{22}^{n-1}+k_{11}^{n} & k_{12}^{n} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{21}^{n} & k_{22}^{n} \end{bmatrix}_{(n+1)\times(n+1)}$$

where the superscript indicates the element number.

This pile stiffness matrix is assembled with the soil stiffness matrix, and the resulting global stiffness matrix is used to calculate the displacements.

2.2.2.3 Effect of Cyclic Loading

There are currently 3 different ways in which the cyclic loading is handled in the program for t-z and tip load curves:

- Default behaviour (Elastic-plastic, User-defined, Vijayvergiya, and API curves)
- Logarithmic curves
- Chin-Poulos curves

The cyclic loading behaviour for these different cases is discussed next.

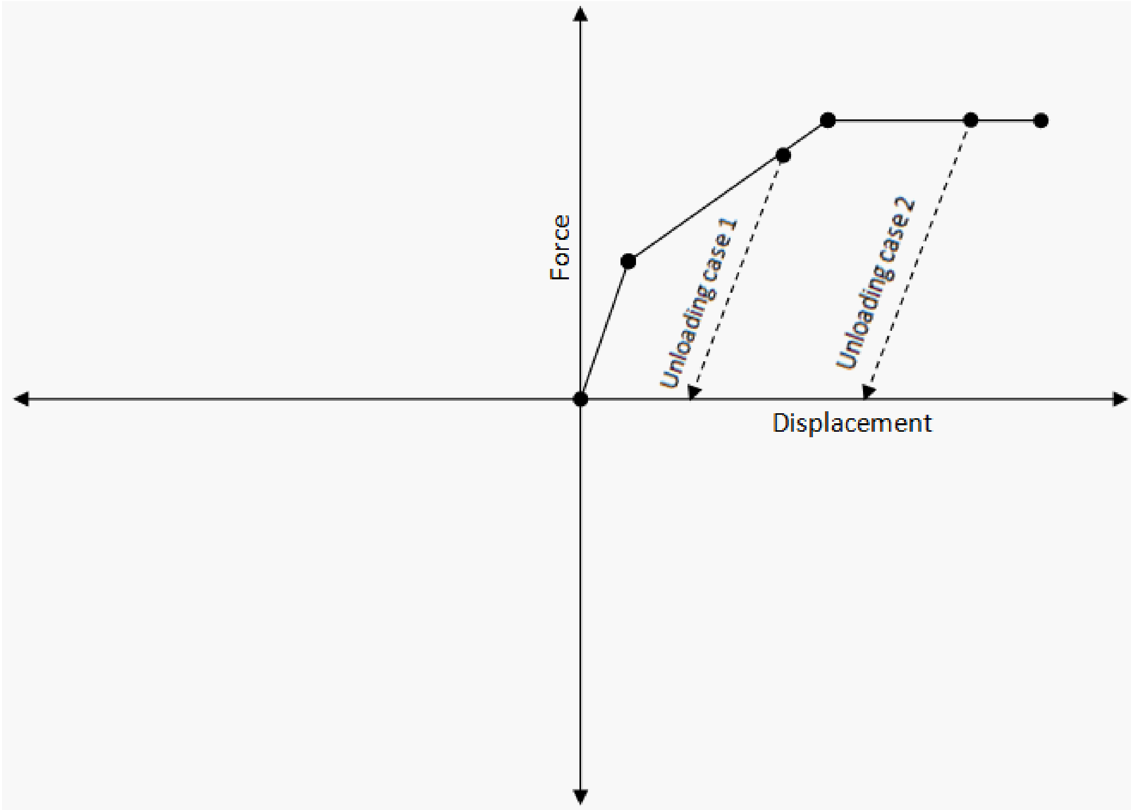
2.2.2.3.1 Default Behaviour

All types of t-z curves and tip load curves are updated after each loading stage to take into account load reversal and post yield behaviour. Internally, all the different types of curves are modelled as multi-linear force-displacement curves. For the Chin-Poulos curves and logarithmic curves, the equations of the curves for initial loading, unloading and reloading are explicitly given by equations.

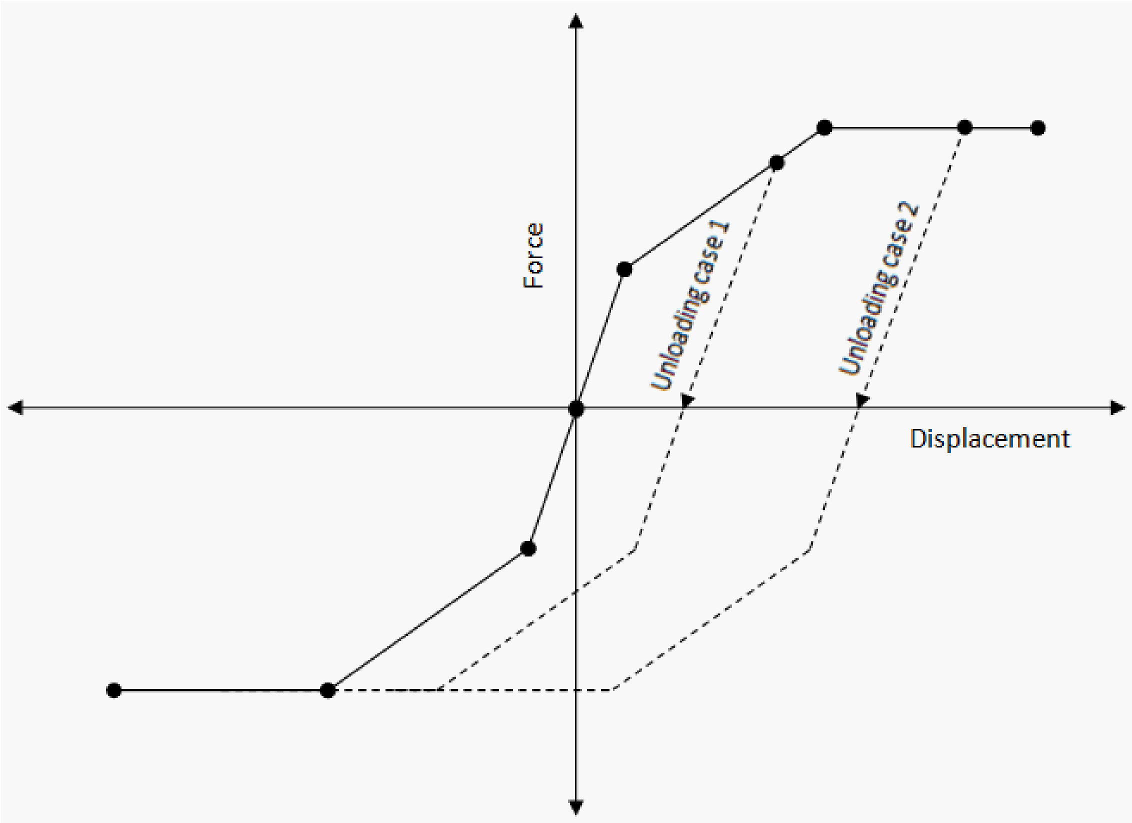
For all the other types of curves, the following assumptions are made to generate curves to account for yielding and load reversals. The Non-softening curves are discussed first.

- Only the first segment is considered to be the elastic segment. This holds for both tension and compression cases.

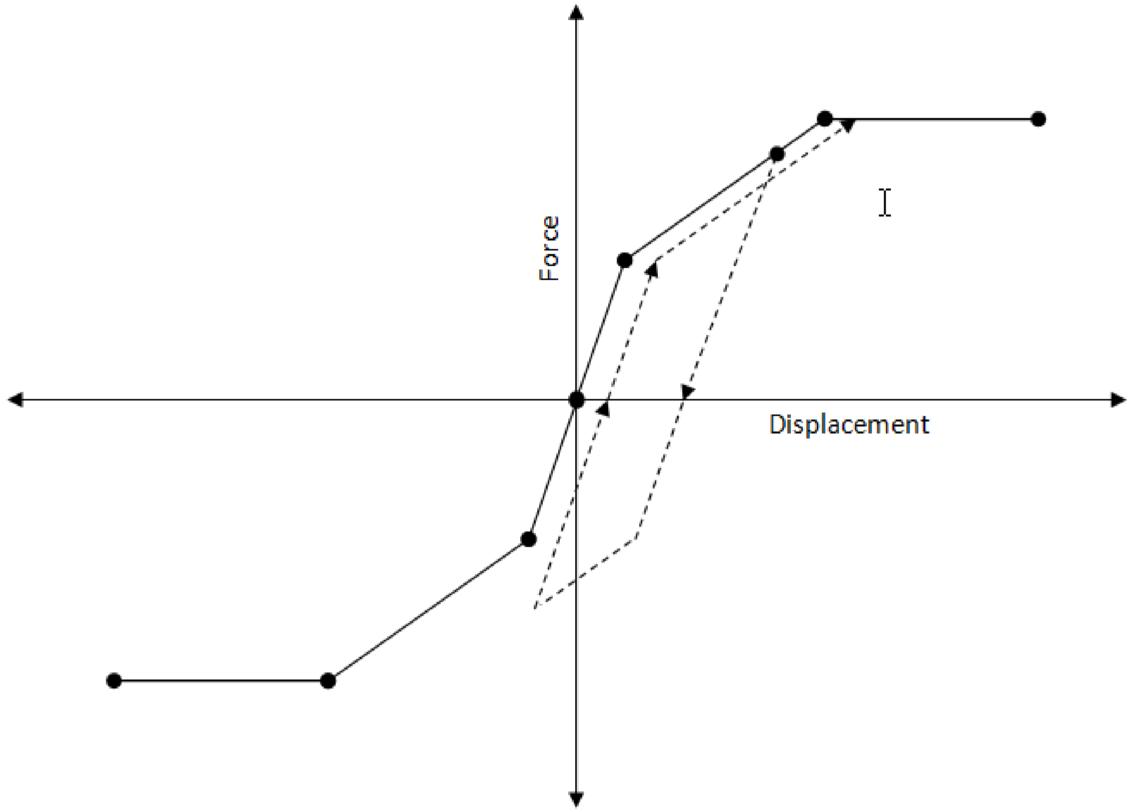
- When the spring is loaded beyond the first yield point, plastic deformations are introduced. The unload curve in these cases are obtained by unloading parallel to the initial elastic segment. This is similar to and an extension of the elastic-perfectly plastic case. The illustrations are given below.



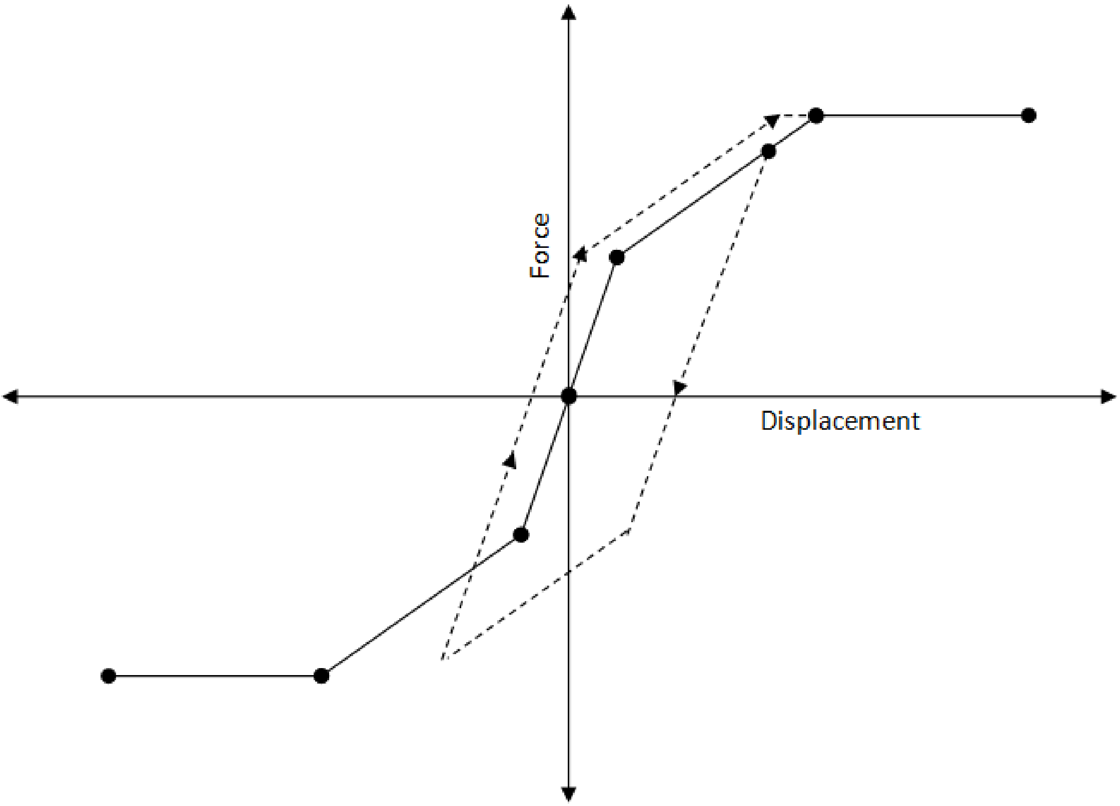
As a result, all the points on the unloading side of the curve shift parallel as shown below:



- If the spring is loaded untill plastic deformation in one direction, unloaded to plastic deformation again in the opposite direction, and again reloaded in the original direction, the reloading curve runs parallel to the initial loading curve and merges with the perfectly plastic zone of the inital loading curve.



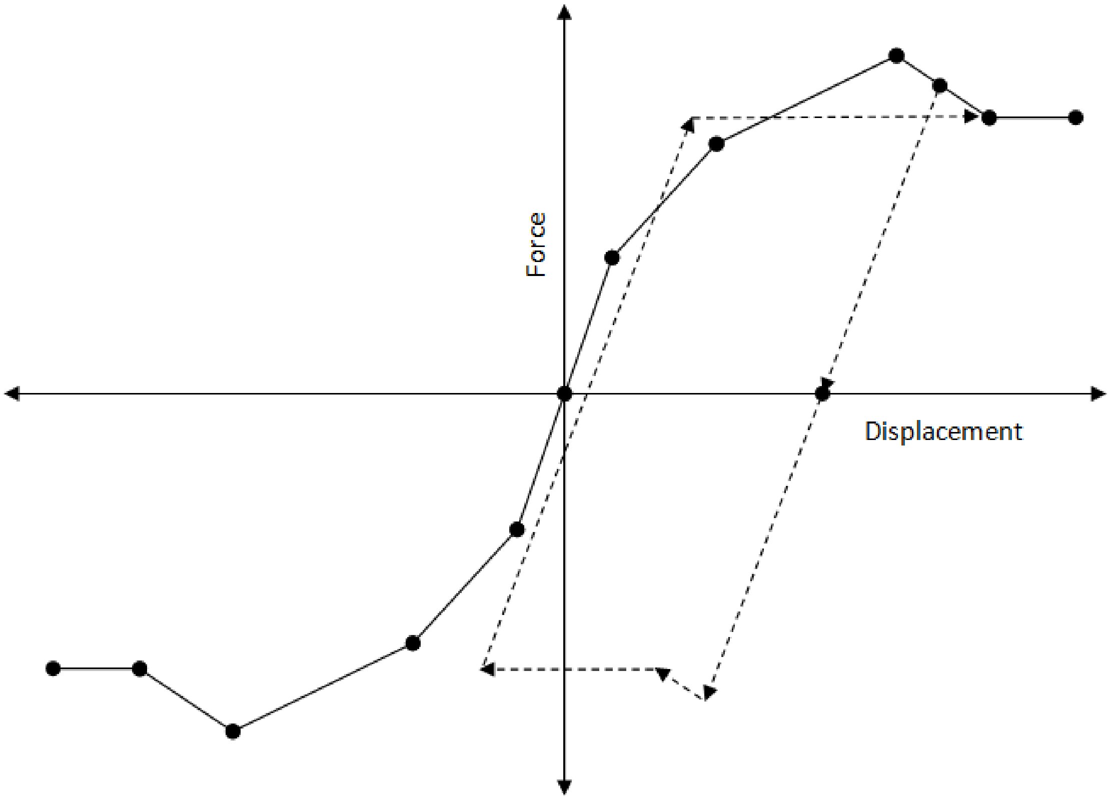
An alternative case where the the last load displacement curve shifts to the left of initial loading curve is given below:



- The slope of the unloading curve, after plastic deformation sets in, is given by the slope of the initial loading curve at the origin. This poses a a problem for the Vijayvergiya API curve since the slope of the parabolic force-displacement curve is infinity at the origin. Hence, the program uses the slope of the first segment of the 10 segments used in modelling this curve.

Post-peak behaviour - API Clay and other user defined curves with softening behaviour:

- For API Clay, the post-peak behaviour is as shown in the figure below:



As can be seen from the figure above, when the spring is loaded into the post-peak softening zone, the peak strength for the subsequent stage is reduced to the value of the current force in the spring. In the subsequent stage also, if the spring is loaded into post-peak zone, there is a further reduction in strength i.e. peak force. This reduction continues until peak spring force falls to residual value. Thereafter, the behaviour is similar to the non softening case described above.

Base curves (Tip load curves)

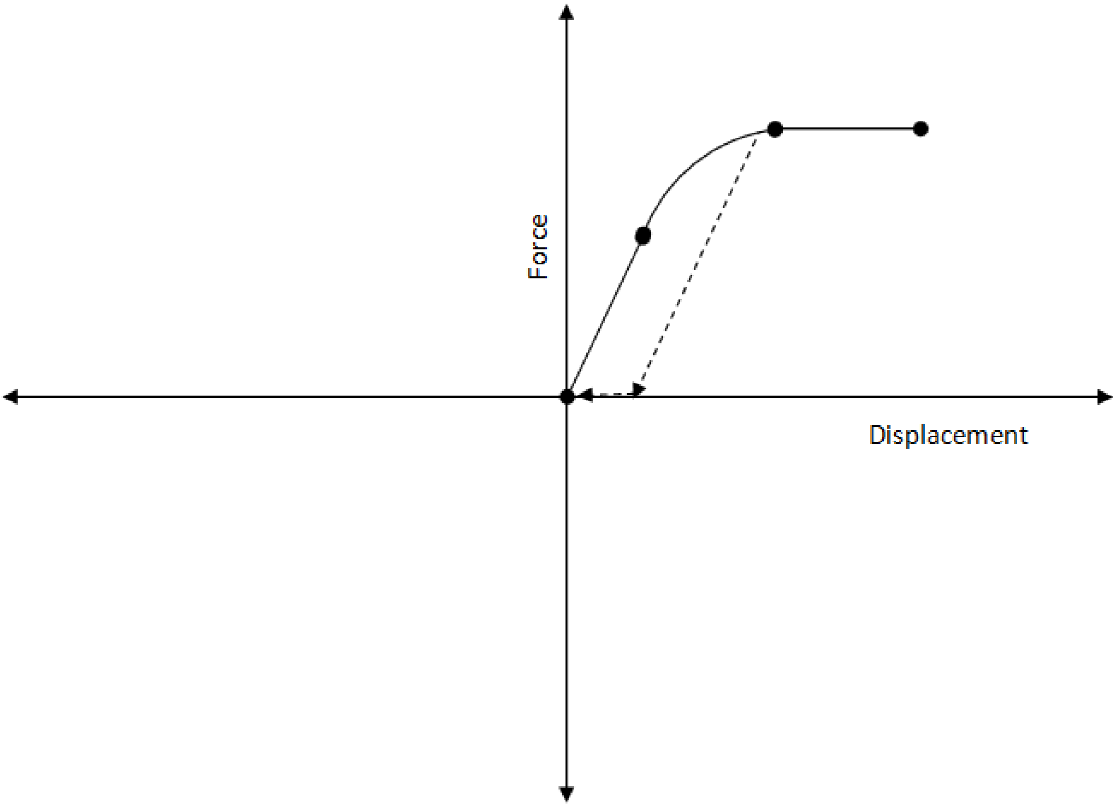
The Slope of elastic portion is defined by Timoshenko & Goodier (1970) as:

$$w_b = \frac{P_b * (1-\upsilon)}{4 * r_0 * G}$$

Where w_b is pile base displacement and P_b is pile base load (sb . π . r_0^2). The following input parameters are required:

r_0 pile radius
G shear modulus of soil [input as a value at top of layer and gradient with depth]
ν Poisson’s ratio

The tip load curves are treated in a similar way to the shaft curves described above. However, they neither carry tension nor exhibit softening behaviour.



The pile base response should be parallel to the initial elastic gradient on unloading, with no tension capability. Upon reloading, the displacement should accumulate displacement with no load carried until it reaches the elastic unloading path, retrace the unloading path in the opposite direction up to the previous maximum stress on the initial loading path, then follow the initial loading path to peak stress.

2.2.2.3.2 Chin-Poulos

For Chin-Poulos t-z curves, the following equations are used to model the unload- reloading behaviour:

- Unloading curve:

$$z - z_i = \frac{\tau_0^* r_0}{G_{max}} ln \left[\frac{\frac{r_m}{r_0} + \frac{\tau_0^*}{\tau_f} R'_{fu}}{1 + \frac{\tau_0^*}{\tau_f} R'_{fu}} \right]$$

$$R'_{fu} = \frac{R_f}{2R_u}$$

- Reloading curve:

$$z - z_i = \frac{\tau_0^* r_0}{G_{max}} ln\left[\frac{\frac{r_m}{r_0} - \frac{\tau_0^*}{\tau_f} R'_{fr}}{1 - \frac{\tau_0^*}{\tau_f} R'_{fr}}\right]$$

$$R'_{fr} = \frac{R_f}{2R_r \delta}$$

where :

z_i is the pile node displacement at load reversal.

R_u is a curve fitting constant for the unloading curve.

R_r is a curve fitting constant for the reloading curve.

R_f is a curve fitting constant for the shaft.

δ is the degradation factor for the reloading curve.

τ^*_0 is the difference between current shear stress and the stress at the load reversal point.

τ_f is the limiting shear stress

r_0 is the radius of the pile.

G_{max} is the initial shear modulus of the soil.

For the Chin-Poulos tip load curves, the following equations are used to model the unload-reload behaviour:

- Unloading curve:

$$z - z_i = \frac{(p_b - p_{b,i})}{k_i * \left(1 - \frac{(p_b - p_{b,i}) * R'_{fu}}{p_f}\right)}$$

$$R'_{fu} = \frac{R_f}{2R_u}$$

$$k_i = \frac{4G_{max} r_0}{(1 - \vartheta)} = \frac{2E_{max} r_0}{(1 - \vartheta^2)}$$

- Reloading curve:

$$z - z_i = \frac{(p_b - p_{b,i})}{k_i * \left(1 - \frac{(p_b - p_{b,i}) * R'_{fr}}{p_f}\right)}$$

$$R'_{fr} = \frac{R_f}{2R_r \delta}$$

$$k_i = \frac{4G_{max} r_0}{(1 - \vartheta)} = \frac{2E_{max} r_0}{(1 - \vartheta^2)}$$

where,

p_b is the current end bearing force.
z_i is the pile base displacement at load reversal.
$p_{b,i}$ corresponds to the load reversal point.
R_u is a curve fitting constant for the unloading curve.
R_r is a curve fitting constant for the reloading curve.
R_f is a curve fitting constant for the base.
δ is the degradation factor for the reloading curve.
p_f is the limiting end bearing force.
r_0 is the radius of the pile.
G_{max} is the initial shear modulus of the soil.
E_{max} is the initial Young's modulus of the soil.
ν is the Poisson's ratio of the soil.

2.2.2.3.3 Logarithmic Curves

Shaft curves

In the case of cyclic loading, the program keeps track of the elastic and irreversible deformation in the soil spring.

As long as the cumulative absolute irreversible displacement is less than the monotonic irreversible displacement to peak force, there is no degradation of the peak force in either tension or compression. However, when the accumulated irreversible displacement exceeds monotonic irreversible displacement, then degradation of peak force occurs.

The program deals with the pre-peak behaviour and post-peak behaviour separately. First the pre-peak behaviour is discussed.

Pre-peak behaviour:

When the spring is in the pre-peak zone, it unloads parallel to the linear elastic segment.

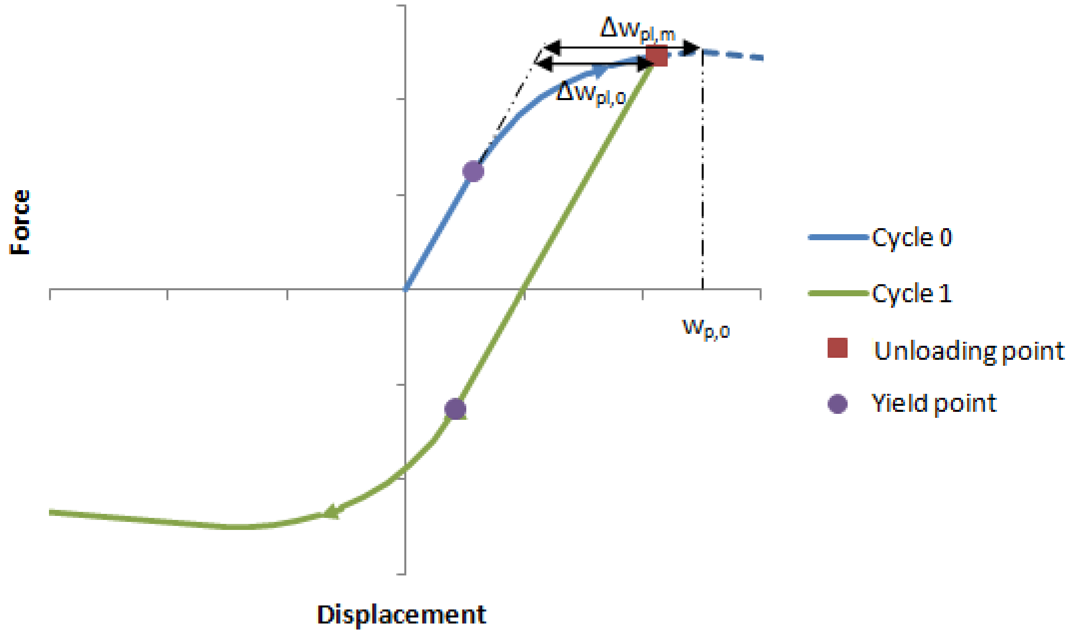
Even when the spring is in the pre-peak zone, when the cumulative absolute irreversible displacement exceeds the monotonic irreversible displacement required to mobilise peak force in a particular stage (such as after several cycles of pre-peak loading and unloading) , the program reduces the peak force in the spring in a similar manner to post-peak monotonic exponential decay. This is based on

$$f_{p,i} = f_p - 1.1\left(f_p - f_r\right)\left\{1 - e^{-2.4\left[\left(\Sigma\Delta w_{pl,i-1} - \Delta w_{pl,m}\right)/\Delta w_{res}\right]^{\eta}}\right]$$

In this equation, the subscript "i" denotes the half cycle number. Two consecutive half cycles correspond to a change in the direction of increasing force i.e. from increasing force to decreasing force or vice versa.

$\Sigma\Delta w_{pl,i-1}$ is the cumulative absolute irreversible displacement till the i-1th half cycle.
$\Delta w_{pl,m}$ is the monotonic irreversible displacement to the peak force. It is important to note that

this excludes elastic displacement to peak force.



Also, the yield force in a particular stage (half cycle), depends on the spring force (f_{max}) in the previous two half cycles (i.e. one tension stage and a compression stage).

$$f_{y,i} = f_{max,i-1} + 0.5\,(1 + \xi)\,(f_{max,i-2} - f_{max,i-1})$$

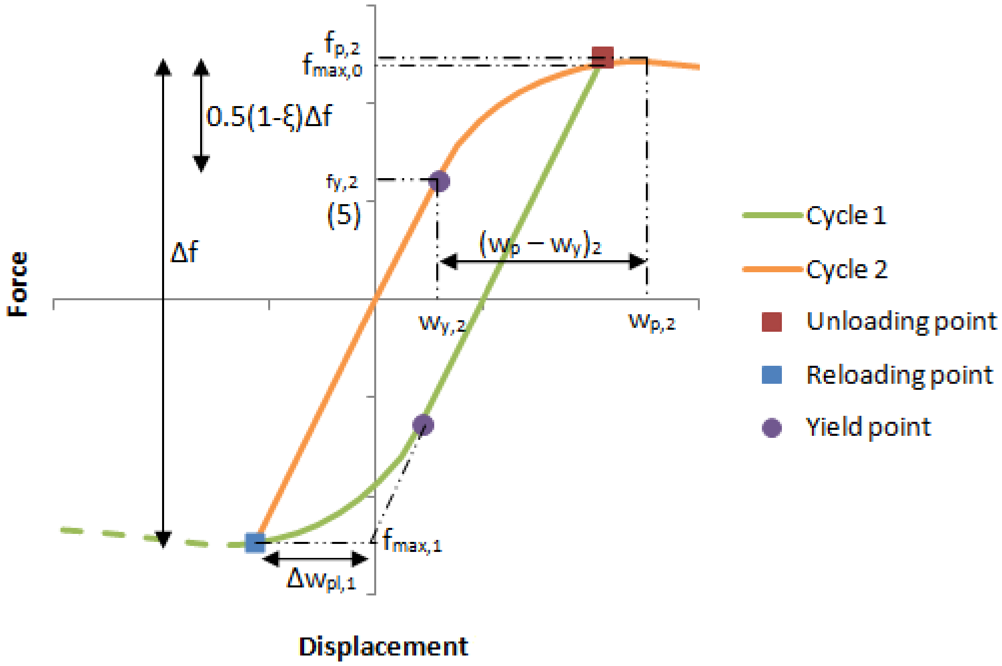
with the requirement that the yield force calculated using the above equation should not be below $\zeta{*}f_{peak}$.

In order to maintain a similar shape of logarithmic function during reloading and subsequent unloading stages, the displacement from yield force to peak force is a function of the amount by which the yield force has reduced from the maximum force, as well as the 'irreversible' displacement that has occurred according to the following equation, which applies provided the previous cycles have been in the pre-peak region of the t-z curve:

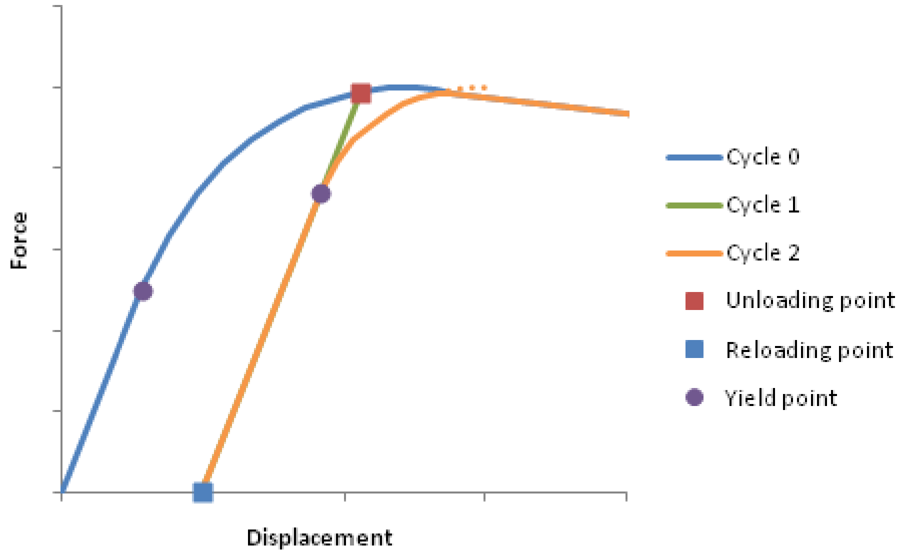
$$w_{p,i} = w_{p,i-2} - \Delta w_{pl,i-1} + \Delta w_{pl,i-2} \cdot \left(\frac{f_{max,i-2} - f_{y,i}}{f_{max,i-2} - f_{y,i-2}} \right)$$

When using this equation, if the yield force $f_{y,i}$ has decreased from its previous value on this side of the axis $f_{y,i-2}$ (due to degradation of peak force from accumulated 'irreversible' displacement), then $f_{y,i}$ is replaced with $f_{y,i-2}$ and the equation becomes:

$$w_{p,i} = w_{p,i-2} - \Delta w_{pl,i-1} + \Delta w_{pl,0}$$



The above graphs show symmetrical two-way cycling, however the above equations are also designed to model the behaviour of unsymmetrical cycling, such as one-way cycling, as shown below. When there is post-peak degradation of the monotonic loading curve, a check is made to ensure the force-displacement path is limited by the monotonic post peak exponential curve. This is more of an issue for one-way rather than two-way loading, as additional 'irreversible' displacement during two-way loading ensures that the peak force degrades more with absolute displacement than monotonic loading alone. This is described further in the post-peak section below.



As can be seen from the graph above, cycle 2 is limited by the initial monotonic curve i.e. blue curve for cycle 0.

Post-peak behaviour:

If the spring is loaded to a failure force f_f after passing through peak force f_p, then the first unloading curve is a scaled down version of the initial loading curve, factored by f_f/f_p as follows:

The unloading stage initially follows a path parallel to the linear elastic portion of the loading curve.

The unloading yield force lies on the negative side of the spring force axis, and is a proportion of the failure force ($-\xi f_f$) and is therefore less than ξf_p. The displacement at unloading yield ($w_{y,1}$) can be found from following the elastic gradient back from the displacement at maximum force (w_{max}).

The first unloading peak force lies on the negative side of the force axis, and is the same as the failure force of the initial loading stage ($-f_f$). The displacement of the peak stress point on unloading, $w_{p,0}$ is calculated based on the assumption that the displacement from zero force to peak force is always equal to the input value w_p which describes the monotonic displacement required to mobilise peak shaft resistance.

As before, on subsequent reloading and unloading stages, a detailed track of the yield and peak force points must be carried out.

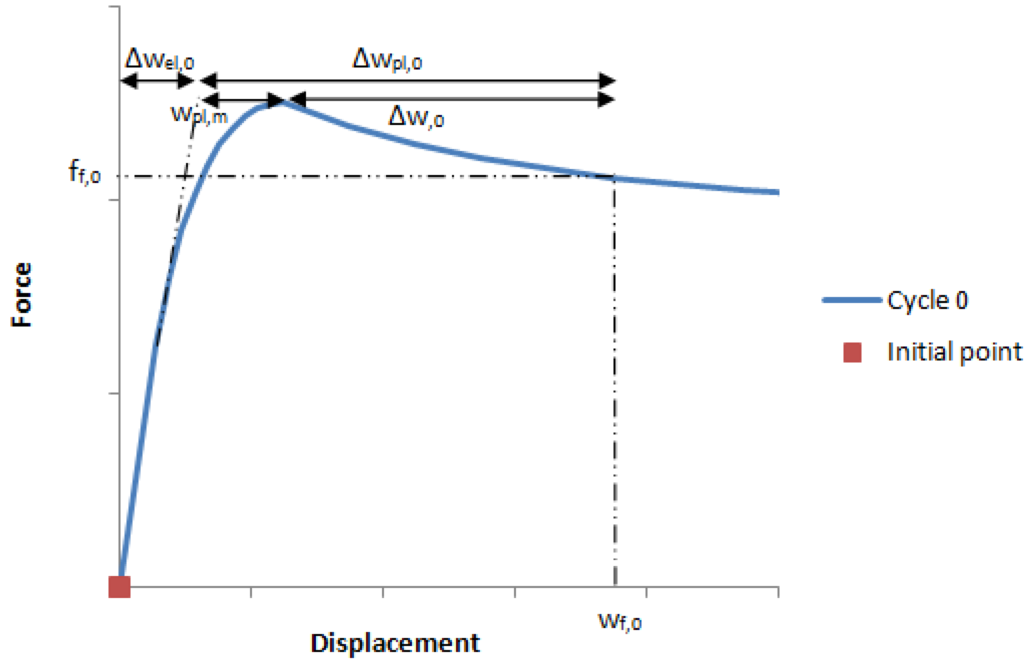
The peak force that can be reached on subsequent reloading and unloading stages is again a function of the amount of 'irreversible' displacement that has accumulated from previous cycles, with a limit placed on the peak force that it must not exceed the minimum post-peak failure force, f_f reached on previous cycles. Degradation of peak force in one direction also limits the peak force in the opposite direction to the same value. This is taken into account using the relationship for peak force based on accumulated 'irreversible' displacement as before.

$$f_{p,i} \leq f_{f,i-1} \leq f_{p,i-1}$$

When 'irreversible' displacement accumulates from two-way cycling

$$f_{p,i} = f_p - 1.1\left(f_p - f_{deg}\right)\left\{1 - e^{-2.4\left[\left(\sum \Delta w_{pl,i-1} - \Delta w_{pl,m}\right)/\Delta w_{res}\right]^{\eta}}\right\}$$

The post-peak 'irreversible' displacement that is accumulated on each cycle, Δw_{pl}, is the difference between the equivalent elastic displacement at peak force, $\Delta w_{el,p}$ (rather than the equivalent elastic displacement at current force) compared to the current post-peak displacement, w_f. This ensures that the peak force of the subsequent cycle calculated using the equation above equals the failure force of the previous cycle.



The yield force for the reloading stage again reduces with the unloading path as described earlier. During unloading, the yield force for the reloading cycle is initially at the maximum force obtained on initial loading, f_f, and decreases at half the rate of the unloading force point, to a minimum value of $\xi\ f_{p,i}$, where $f_{p,i}$ is the peak force of the reloading cycle (which will have degraded as a function of the amount of pre- and post-peak 'irreversible' displacement accumulated). The yield point for the subsequent reloading stage can therefore be defined in the same manner as before, where f_f is used in place of f_{max} when post-peak displacement has occurred:

$$f_{y,i} = f_{f,i-1} + 0.5\,(1 + \xi)\left(f_{f,i-2} - f_{f,i-1}\right)$$

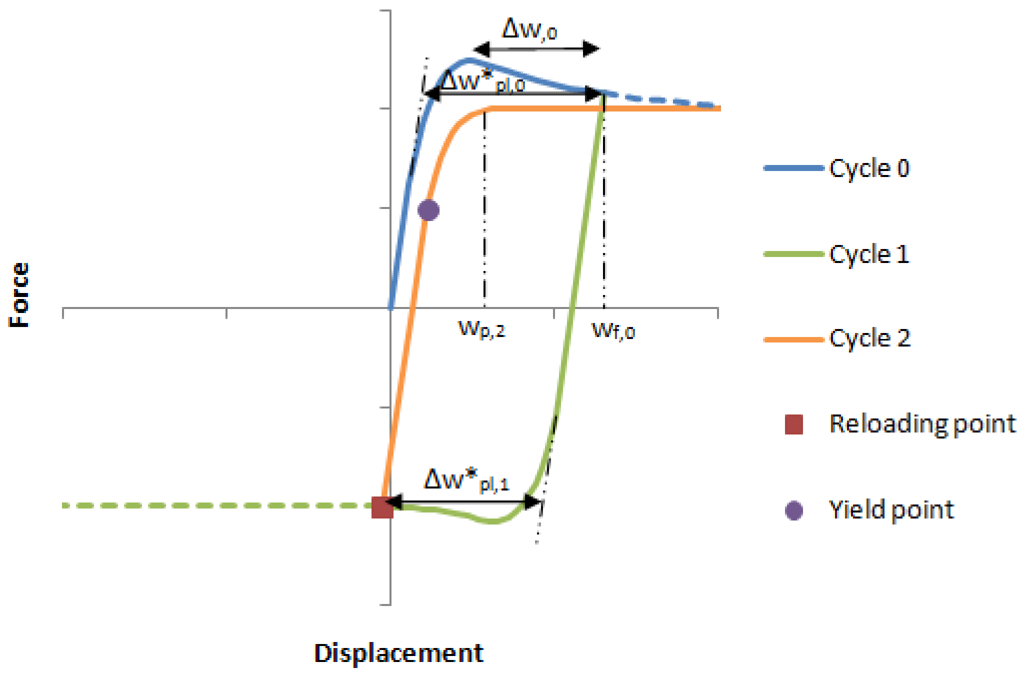
$$f_{y,i} \geq \xi\, f_{p,i}$$

In order to maintain a similar displacement to mobilise peak force during reloading and subsequent unloading stages, the displacement to peak force is proscribed as a function of the amount by which the yield force has reduced from the maximum force, as well as by following the amount of 'irreversible' displacement that has occurred according to the following equation, which applies to the post-peak region of the force-displacement curve, where w_f is the displacement at stress reversal points. w^*_{pl} is the difference between the equivalent elastic displacement at the current failure force (not peak force) and the displacement at the current failure force.

$$w_{p,i} = w_{p,i-2} + \Delta w_{pl,i-1} + \Delta w_{pl,i-2} \cdot \left(\frac{f_{max,i-2} - f_{y,i}}{f_{max,i-2} - f_{y,i-2}}\right)$$

When using this equation, if the yield force $f_{y,i}$ has decreased from its previous value on this side of the axis $f_{y,i-2}$ (due to degradation of peak stress from accumulated 'irreversible' displacement), then $f_{y,i}$ is replaced with $f_{y,i-2}$ and the equation becomes:

$$w_{p,i} = w_{p,i-2} + \Delta w_{pl,i-1} + \Delta w_{pl,0}$$



The above equations are used for both pre-peak and post-peak cycles by replacing the post-peak term with a pre-peak term for the cycle in question. The corresponding values for pre-peak instead of post-peak behaviour are: $w_{p,i-2}$ instead of $w_{f,i-2}$, $\Delta w_{pl,i-2}$ instead of $(\Delta w^*_{pl,i-2} - \Delta w_{i-2})$ and $f_{max,i-2}$ instead of $f_{f,i-2}$ for pre-peak displacement on load cycle i-2, while for pre-peak displacement on load cycle i-1 $\Delta w_{pl,i-1}$ should be used instead of $\Delta w^*_{pl,i-1}$.

Post-peak degradation

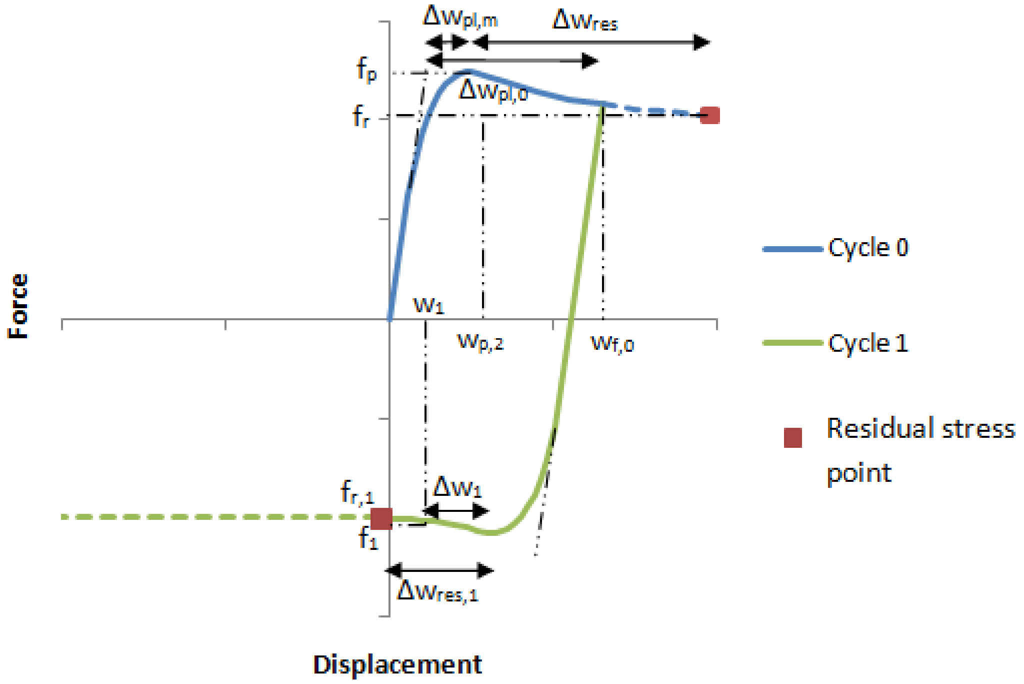
On every cycle, peak force degradation to minimum post-peak force force occurs after the spring is loaded beyond peak force. The degradation is of similar form to the monotonic post-peak degradation exponential curve, however the 'irreversible' displacements that have occurred over previous cycles must be accounted for in the degradation curve of the current cycle.

The displacement from peak to minimum force on the current cycle, $\Delta w_{res,i}$ is reduced by the sum of the accumulated 'irreversible' displacements, $?w_{pl,i-1}$ over and above the monotonic 'irreversible' displacement required to reach peak force for the first time, $w_{pl,m}$.

$$\Delta w_{res,i} = \Delta w_{res} - \left(\Sigma\Delta w_{pl,i-1} - \Delta w_{pl,m}\right)$$

The form of the equation for calculating the post-peak force similarly needs to account for the accumulated 'irreversible' displacements of previous cycles, and follows a similar shape of curve to the remaining portion beyond the maximum displacement reached on the previous cycle by referring to the values of monotonic peak and residual force, while accounting for the accumulating 'irreversible' displacements from all of the previous cycles:

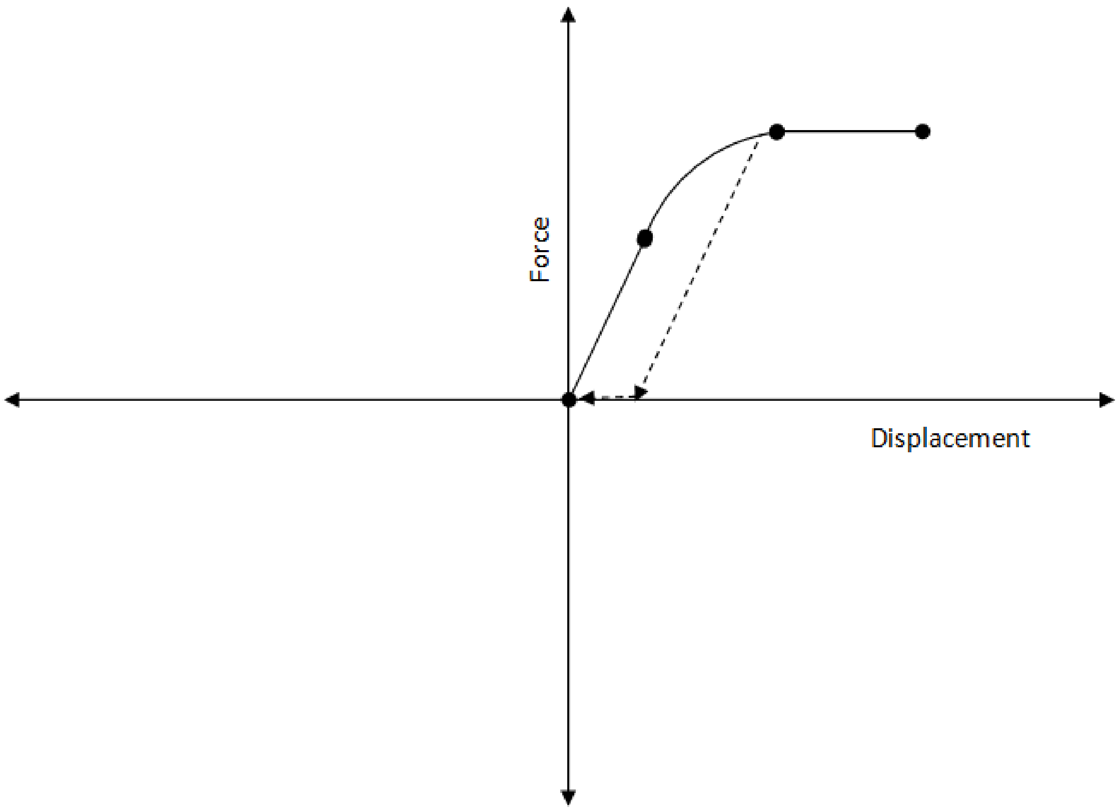
$$f_i = f_p - 1.1(f_p - f_r)\left\{1 - e^{-2.4\left[\left(\Delta w_i + \sum \Delta w_{pl,i-1} - \Delta w_{pl,m}\right)/\Delta w_{res}\right]^{\eta}}\right\}$$



As noted previously, the form of the equations for the current value of peak force and the degradation to post-peak minimum force mean that for one-way cycling it may be possible for the peak force value to lie above the monotonic curve as accumulating 'irreversible' strains of the previous cycles only (and not the current cycle) are accounted for, therefore a comparison of the top portion of the loading curve to the monotonic curve is made to ensure that accumulating displacement under one-way loading does not cause the current force point to go above the monotonic curve. Under two-way loading this is less of an issue as 'irreversible' displacements in both directions tend to degrade the peak force under low values of average absolute displacement and the monotonic curve is less critical to the behaviour.

Base curves (tip load curves)

The tip load curves are treated in a similar way to the shaft curves described above. However, there is no softening portion for the base. Further, the unloading behaviour is different as outlined below:



The pile base shows a response that is parallel to the initial elastic gradient on unloading, with no tension capability. Upon reloading, the displacement accumulates with no load carried until it reaches the elastic unloading path, retraces the unloading path in the opposite direction up to the updated yield stress on the initial loading path (as tracked using assumptions described for shaft curves), then follows the updated loading path to peak stress.

2.2.3 Different Young's Modulus for Compression and tension

Pile allows the input of different Young's modulus values for segments in compression and tension.

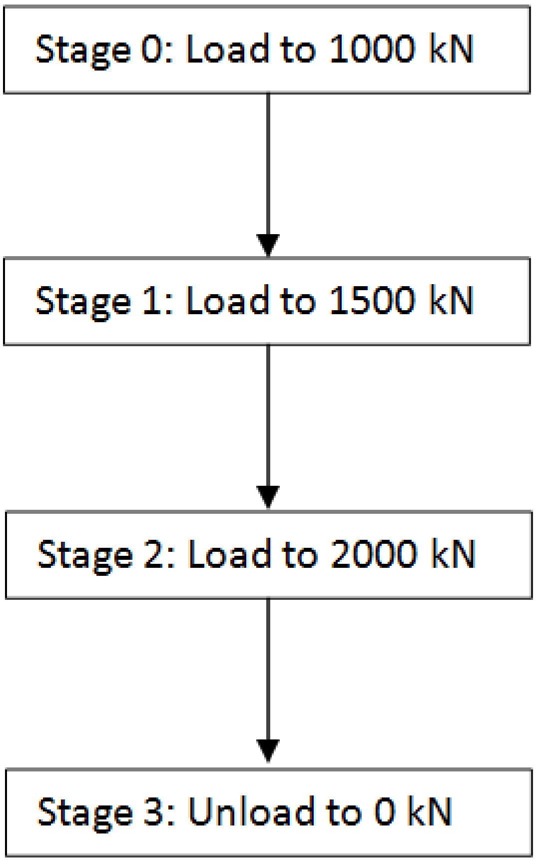
If the user selects this option in the Pile Properties' page, then the following action takes place in the solver.

- Initially all the segments are assumed to be in compression, hence, the Young's modulus value for compression is used for all the segments. Analysis is performed.
- After the analysis, if the sign of the stress of any segment is different from the initial sign, the Young's modulus of that segment is modified accordingly and the analysis is performed again.
- This procedure is repeated until the signs of stresses obtained for the segments (compression or tension) match the signs of the Young's modulus values that were assumed for that analysis iteration.
- However, if a segment is continuously oscillating between tension and compression after many iterations, the solver defaults its value to the Young's modulus in compression and a warning is given.

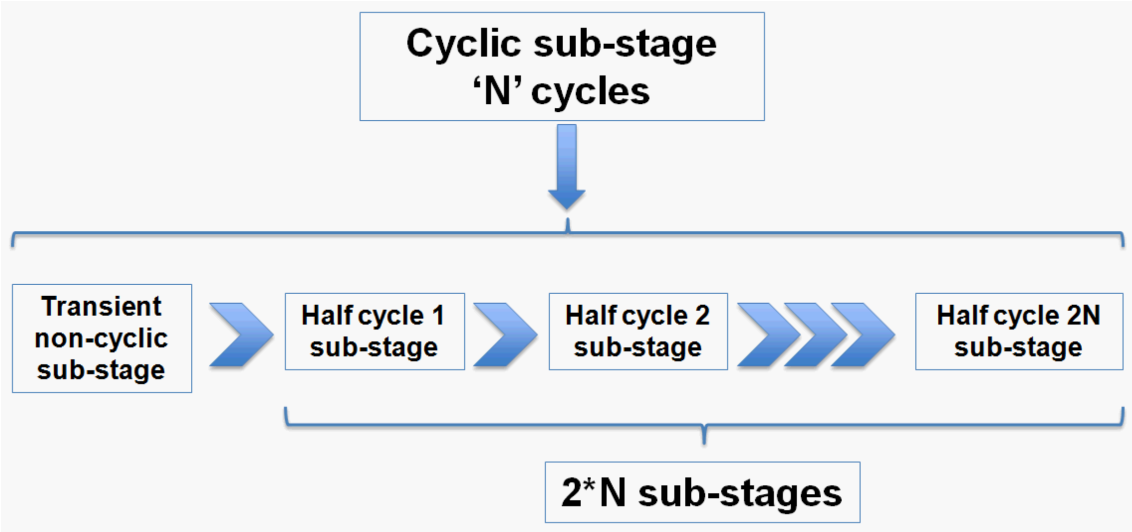
NOTE: In models with thermal loading, ONLY Young's modulus in compression is used i.e. the program does not consider different Young's moduli in tension and compression.

2.2.4 Staged Analysis and Cyclic Loading

When the t-z curves option is selected, a series of analysis stages that follow each other can be defined. In addition, cyclic thermal and mechanical loads can be defined in a particular stage.



During analysis, when the program encounters a stage that has cyclic loading specified for 'N' cycles, it generates 2N+1 sub-stages as shown below:

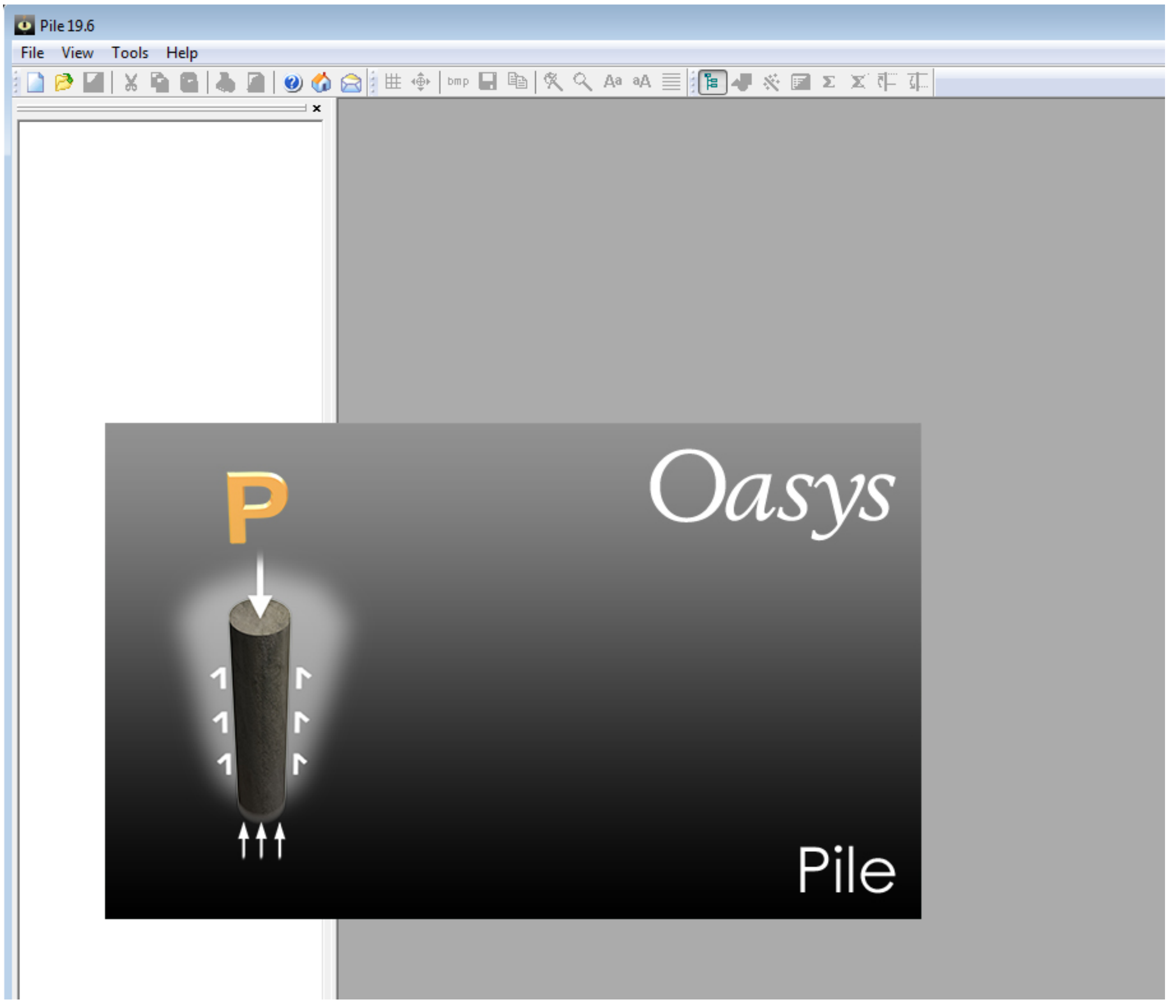


The transient sub-stage is inserted to explicitly apply non-cyclic loading component of the original loading stage. Then, in the subsequent sub-stages, additional cyclic loads are applied.

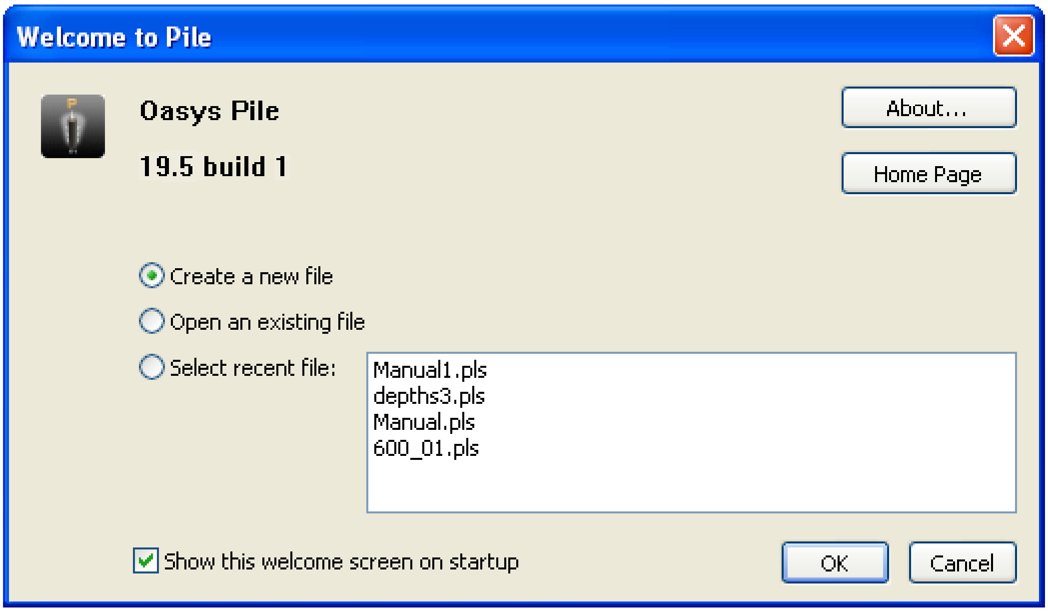
3 Opening the Program

The following provides details of all the information required to run the **Pile** program.

On selection of the **Pile** program the main screen will open.



To start a new project file select "Create a new file" option on the opening screen.



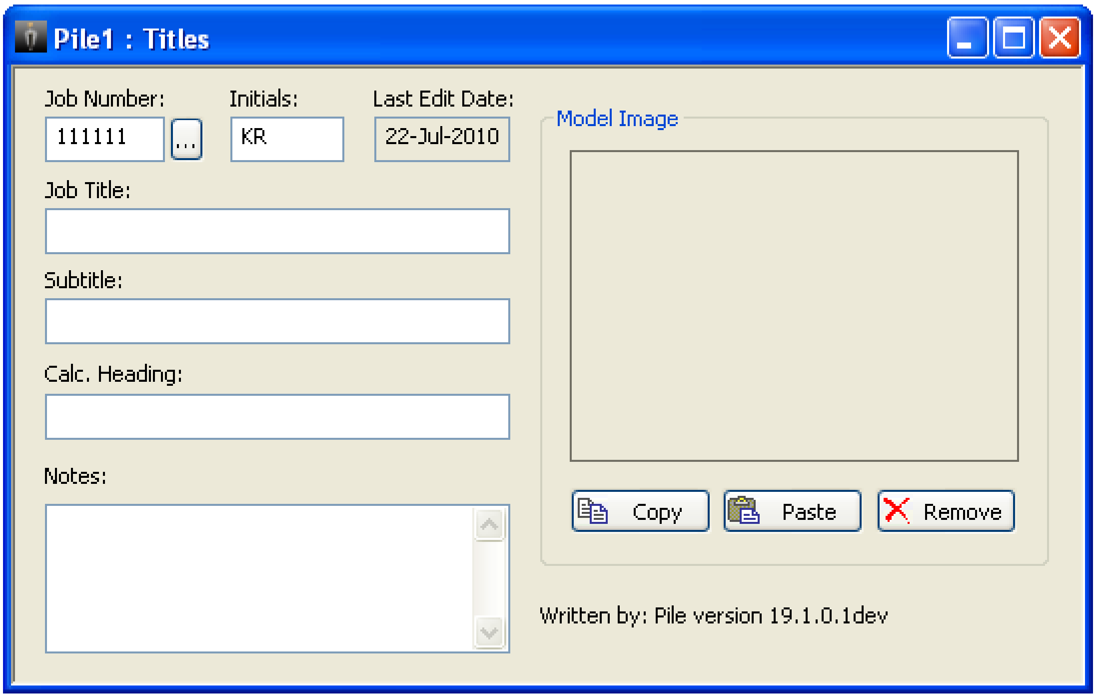
If the "Show this welcome screen on startup" option is unchecked then this dialog will not be displayed on startup. In that case a new data file may be created by clicking File | New on main menu or the corresponding icon  on toolbar.

This will open a new Titles window and allow you to proceed.

To display Welcome to Pile at startup, check "Show welcome screen" in the Preferences dialog. The Preferences dialog can be accessed via Tools | Preferences.

It is possible to open more than one data file at any one time. The file name is therefore displayed in the title bar at the top of each child window.

It is possible to open legacy Pile and Pilset files in this version. (In this version limiting shaft skin friction is calculated from the material properties, so reading of limiting shaft skin friction from a Pilset file is ignored.)



3.1 Intranet Link and Emails

To view the latest information regarding the **Pile** program or to contact the support team click on the internet  or  support team buttons on the Start screen or select them from the standard toolbar.

The list below gives information that should be gathered and action that should be taken before contacting the support team.

- version of **Pile** (see top bar of program or Help | About **Pile**)
- specification of machine being used

- type of operating system
- pre-check all input data
- access help file for information
- check web site for current information
- should a program malfunction be specified then attempt to repeat and record the process prior to informing the team

The web site aims to remain up to date with all data regarding the program and available versions. Should any malfunctions persist then the work-around or fix will be posted on the web site.

The input file can be emailed to the support team by choosing the 'Help | Email' from the program menu

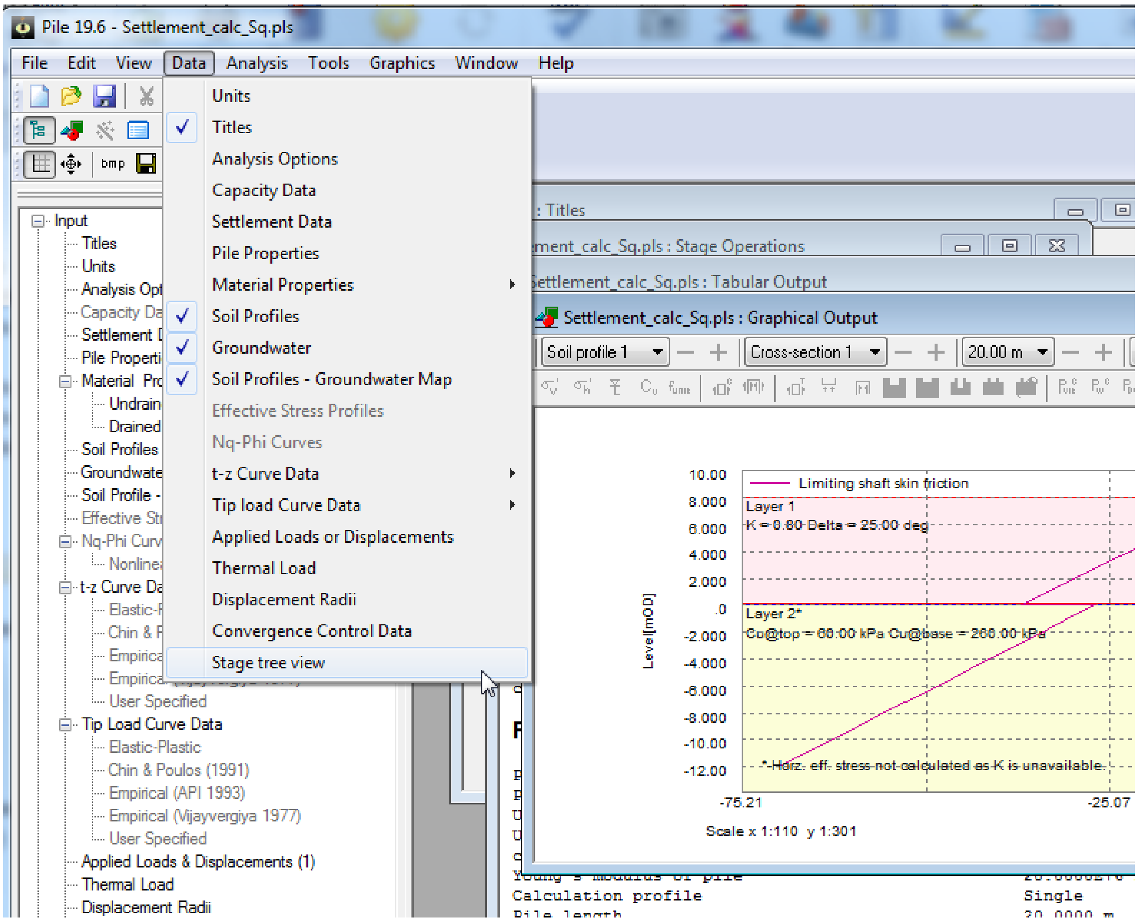
4 Assembling Data

Details of the following should be gathered:

- the drained/undrained parameters of the different soil materials at the proposed site;
- ground water data - phreatic surface location and piezometric pressure distribution elevations if needed;
- soil layer levels;
- geometry of the pile and cross-section information, and depth of the pile.

5 Input Data

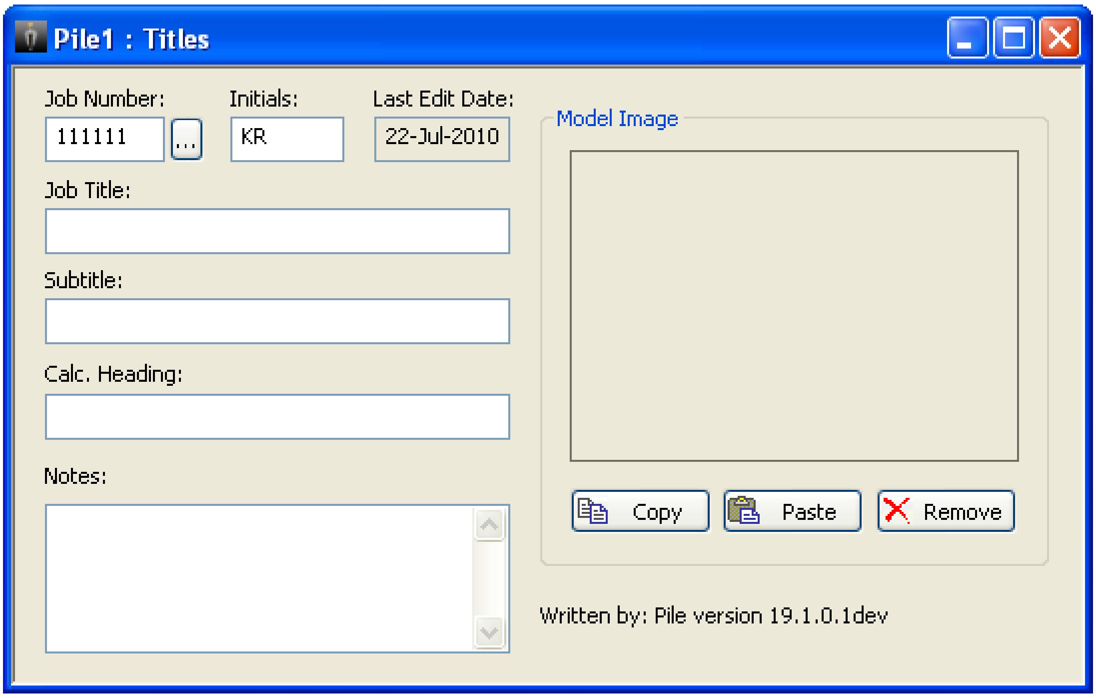
Data is input via options that are available in the Data menu, or via the Gateway.



For options other than "Units and Preferences" and "Analysis Options" a check mark is placed against the option once data has been entered.

5.1 Titles

The first window to appear, for entry of data into **Pile**, is the Titles window.



This window allows entry of identification data for each program file. The following fields are available.

Job Number allows entry of an identifying job number. By clicking the drop-down button, the job numbers previously used can be accesed.

Initials for entry of the user's initials.

Date this field is set by the program at the date the file is saved.

Job Title allows a single line for entry of the job title.

Subtitle allows a single line of additional job or calculation information.

Calculation Heading allows a single line for the main calculation heading.

The titles are reproduced in the title block at the head of all printed information for the calculations. The fields should therefore be used to provide as many details as possible to identify the individual calculation runs.

Notes allow the entry of a detailed description of the calculation. This can be reproduced at the start of the data output by selection of notes using File | Print Selection.

5.1.1 Titles window - Bitmaps

The box in the right of the Titles window can be used to display a picture beside the file titles.

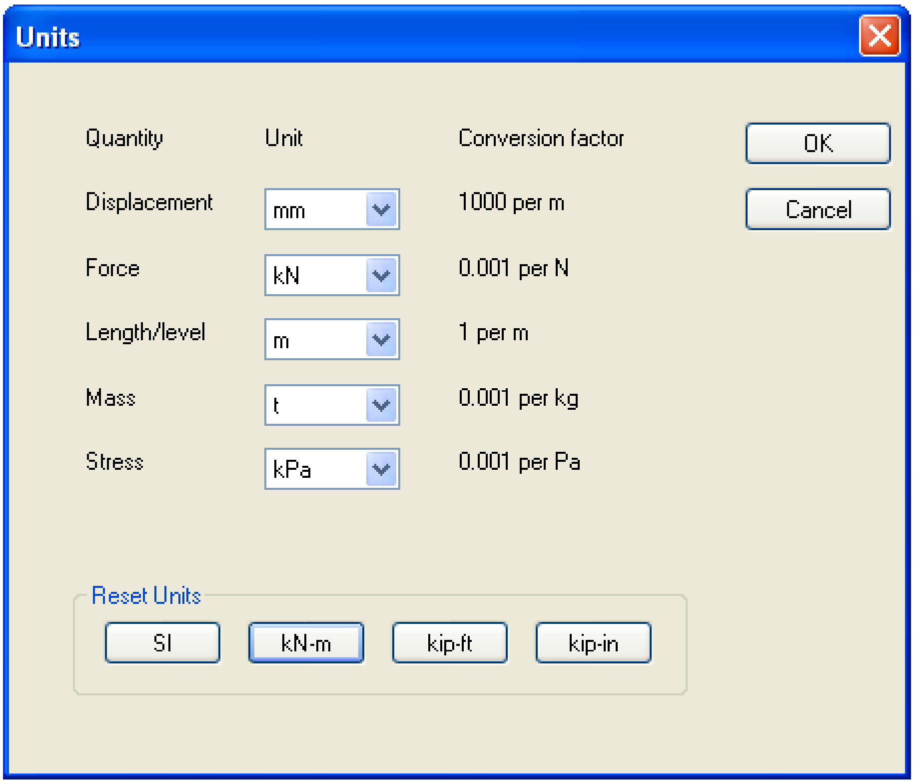
To add a picture, place an image on to the clipboard. This must be in a RGB (Red / Green / Blue) Bitmap format. Select the "Paste Bitmap" button to place the image in the box.

The image is purely for use as a prompt on the screen and can not be copied into the output data. Care should be taken not to copy large bitmaps, which can dramatically increase the size of the file.

To remove a bitmap select the button "Remove Bitmap".

5.2 Units

The Units dialog is accessible via the Gateway, or by choosing Data | Units from the program's menu. It allows the units for entering the data to be specified and reporting the results of the calculations. These choices are stored in, and therefore associated with, the data file.



Default options are the Système Internationale (SI) units - kN and m. The drop down menus provide alternative units with their respective conversion factors to metric.

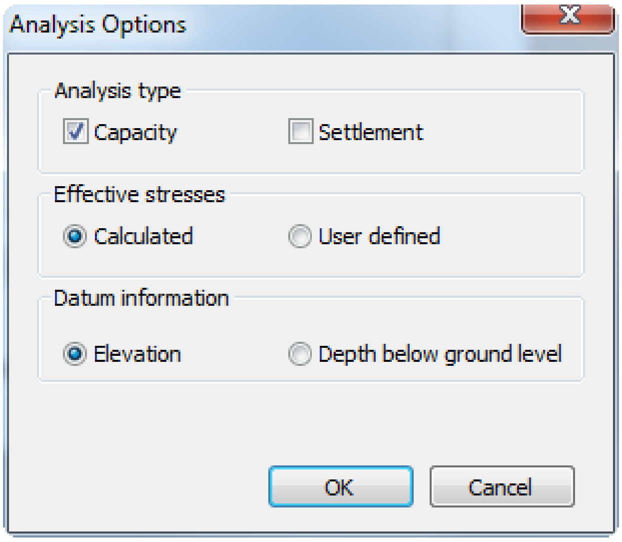
Standard sets of units may be set by selecting any of the buttons: SI, kN-m, kip-ft kip-in.

Once the correct units have been selected click 'OK' to continue.

SI units have been used as the default standard throughout this document.

5.3 Analysis Options

The following general data is entered to define the outline of the problem and type of analysis to be carried out.



Analysis type

Type of analysis can be selected - either Capacity or Settlement or both. If only Capacity analysis is selected then the data input for Settlement will be disabled, and vice versa.

Effective Stresses

Either of the following options can be selected:

Calculated - the effective stresses in the soil layers are calculated by the program.

User-defined - the effective stress profiles (both vertical stress profile and horizontal stress profile) to be used by the program in calculating the pile capacity are specified.

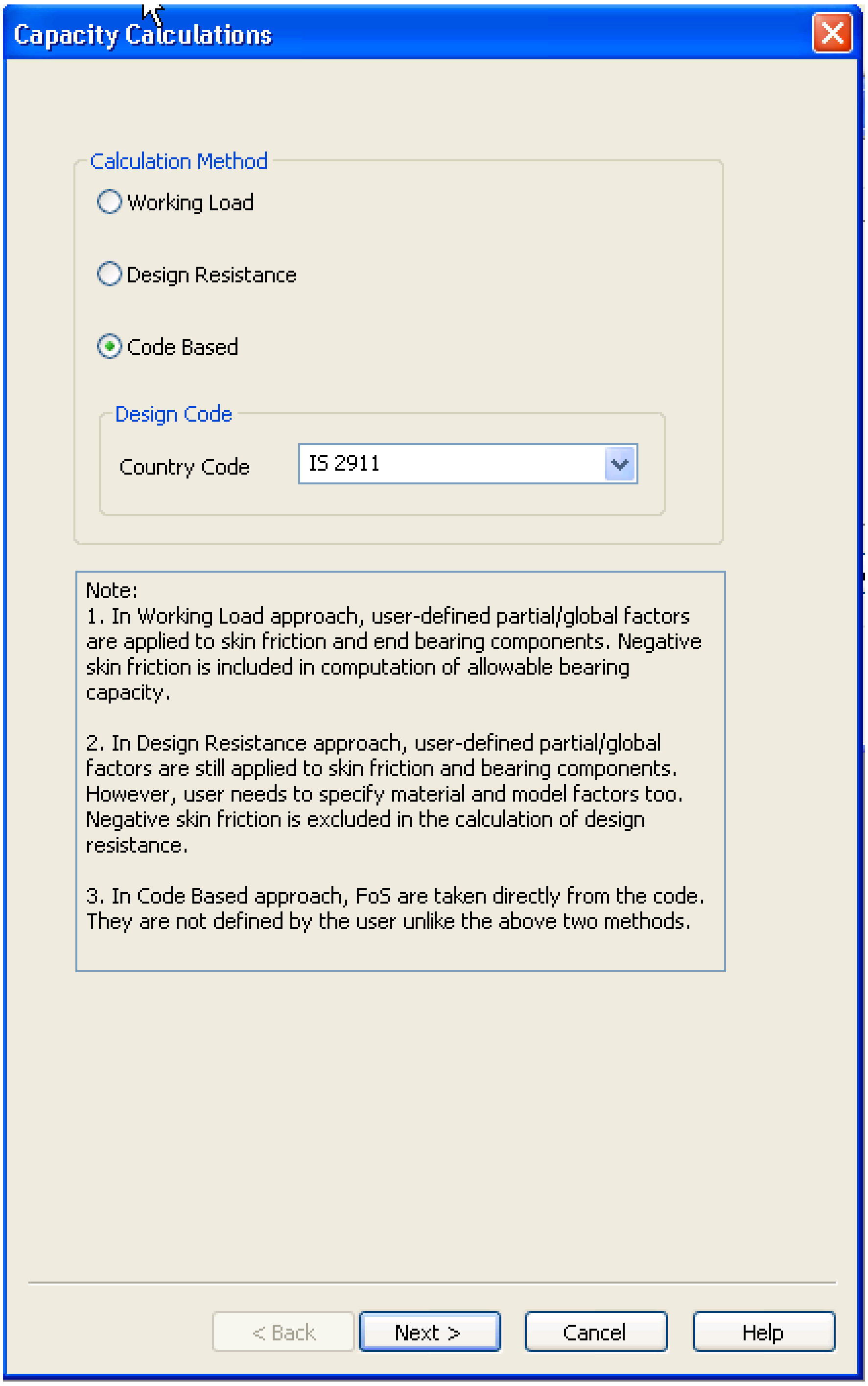
Datum Information

There are two choices for datum.

- Depth below Ground Level
- Elevation (above Ordnance Datum).

5.4 Capacity Data

The following data needs to be entered to specify the type of capacity calculations to be carried out:



Calculation Method

There are three options available:

- **Working Load**

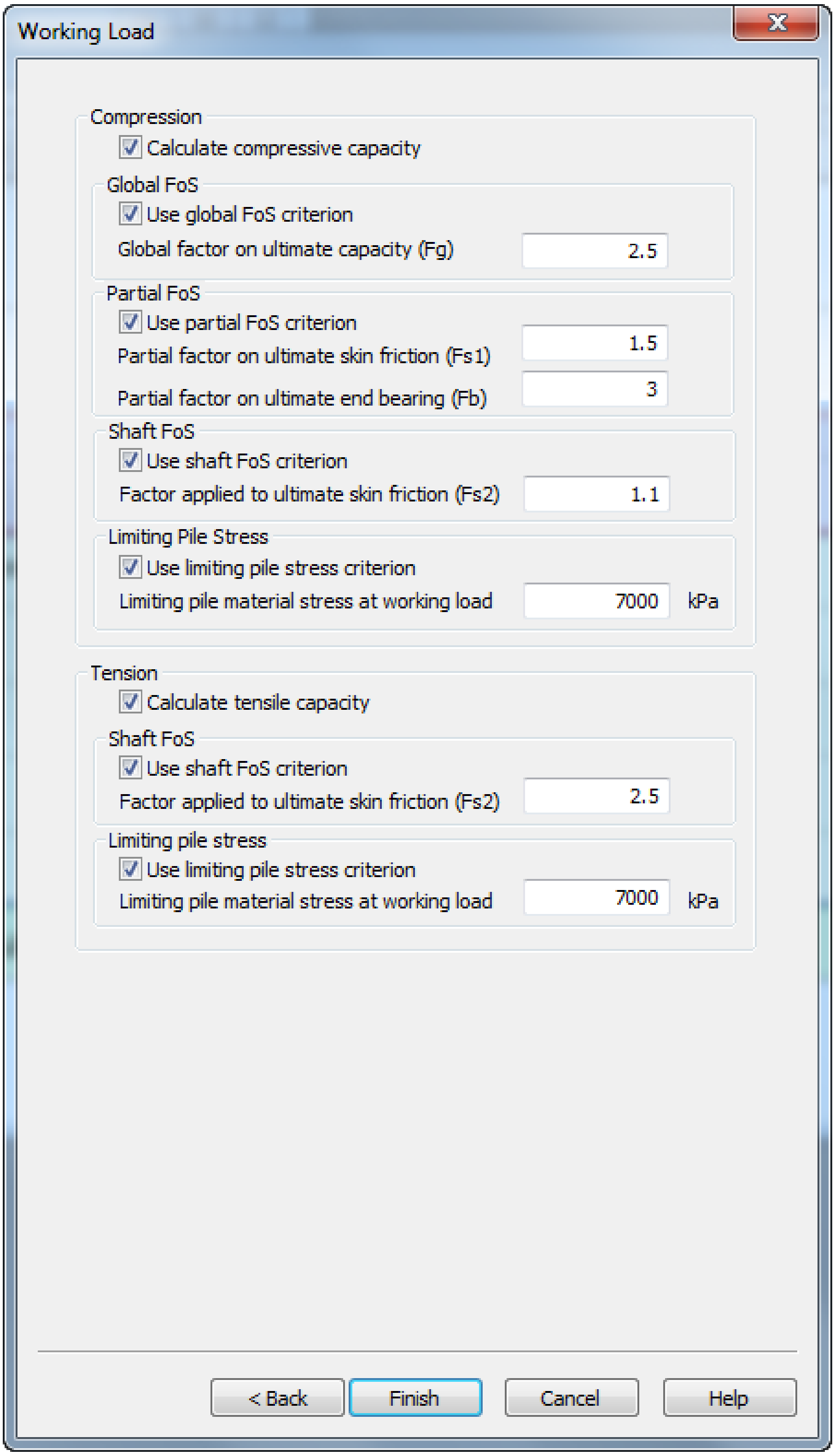
- **Design Resistance**

- **Code-based**
  In this method, the explicit design code has to be specified. Presently, EC7(No National Annex), EC7(United Kingdom) and IS 2911 are available.

For theory about each of the above approaches, refer the topics Working Load Approach, Limit State Approach and Code-Based.

5.4.1 Working Load

The following factors of safety must be specified:



In this approach, the following factors need to be specified:

Global factor on ultimate capacity

Partial factor on ultimate skin friction

Partial factor on end bearing

Factor applied to ultimate skin friction

In the working load option, at least one of the following combinations should be selected:

- global factor of safety on total bearing capacity

- partial factors of safety on shaft skin friction and end bearing

- factor of safety on shaft skin friction only

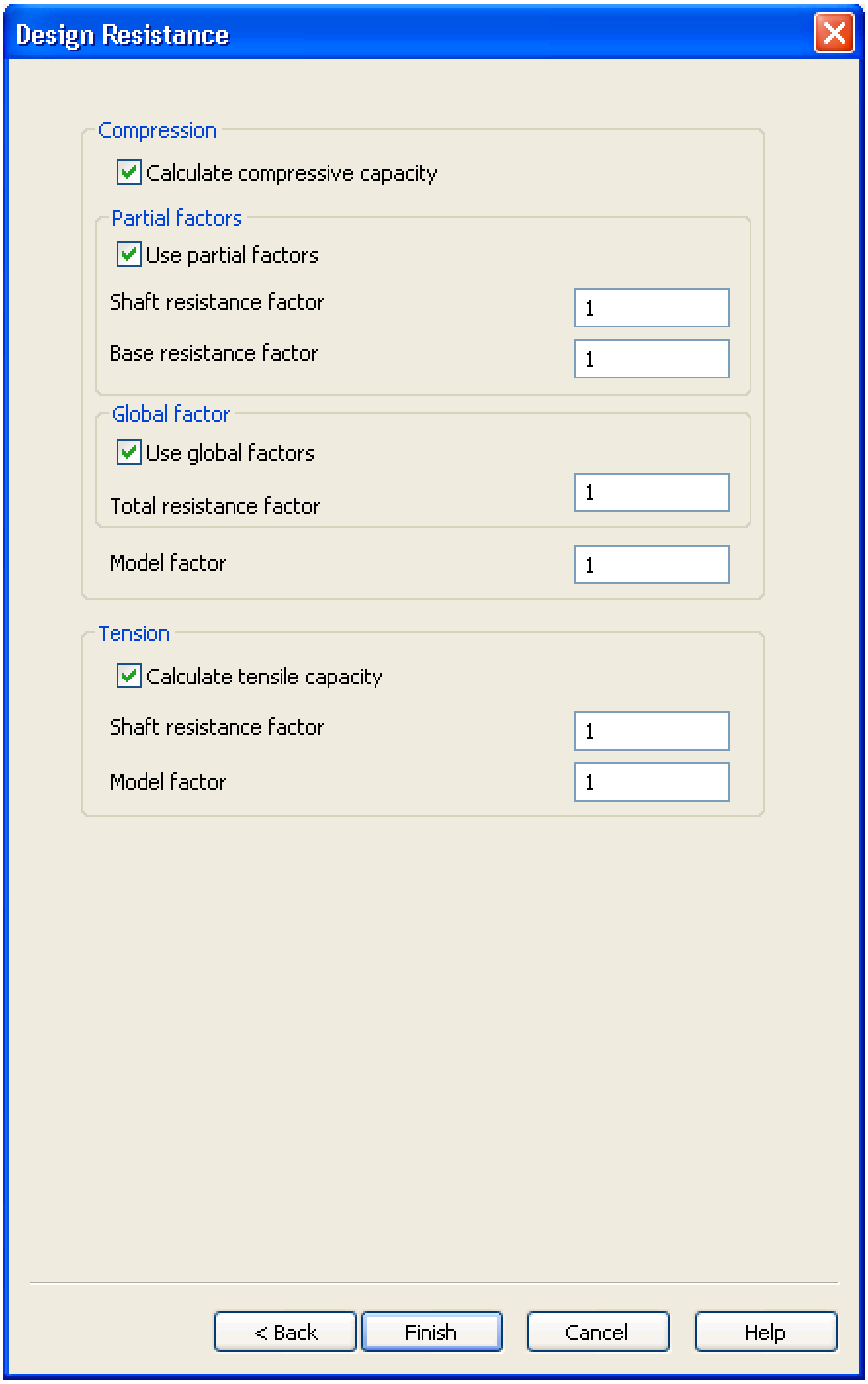
The limiting pile stress criterion can also be selected.

The program calculates the minimum capacity from all the selected combinations and prints it as the allowable capacity.

Also, compression and tension related parameters need to be specified separately. At least one of tension or compression capacity computations should be selected.

For more information, refer to Allowable Capacity - Working Load Approach

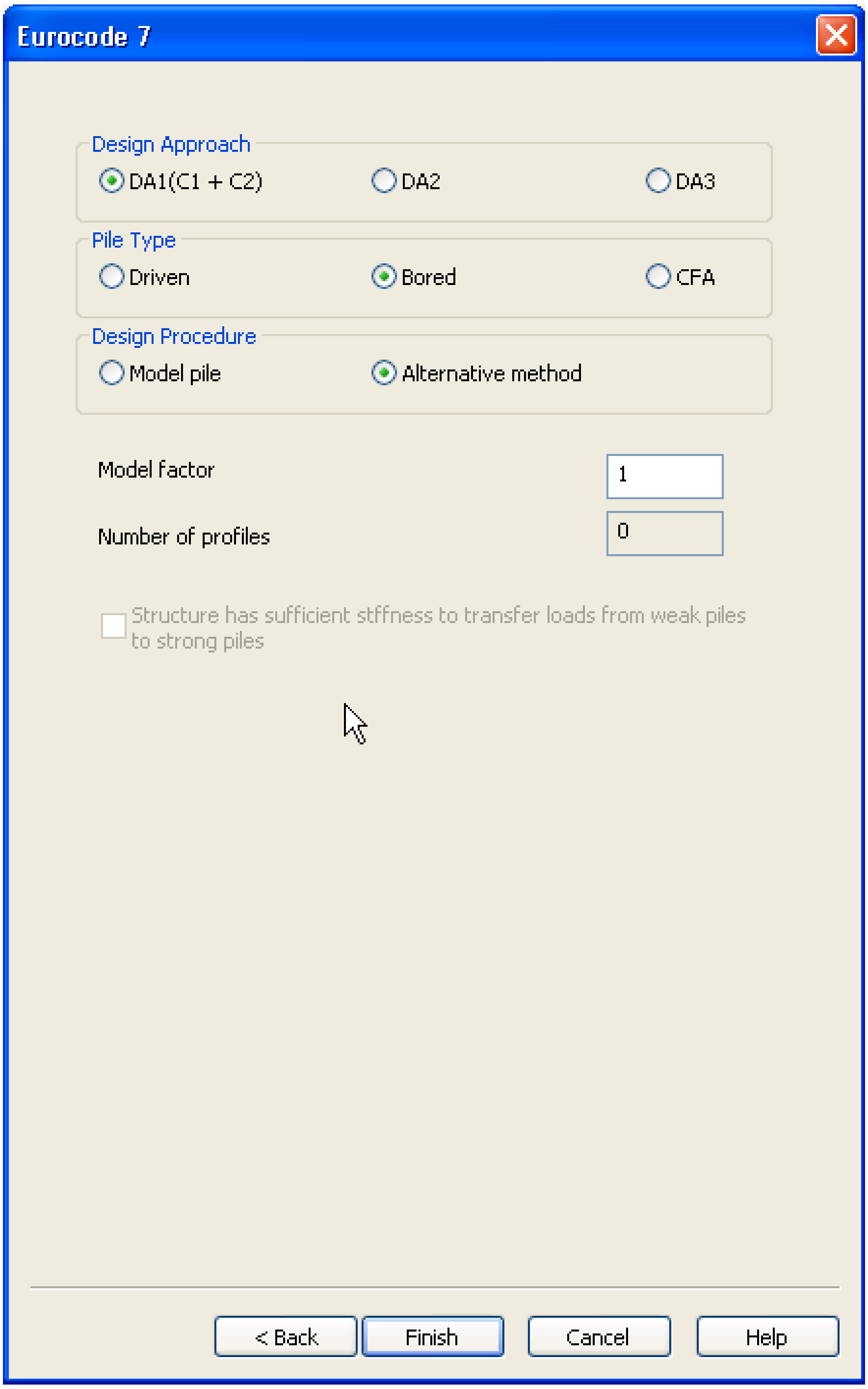
5.4.2 Design Resistance



In this approach, either compression or tension computations or both can be selected. For the compression case, the program computes the lowest capacity from the selected combinations (partial factors' combination and/or global factor combination), and reports it as the design capacity. Design resistance does not include any contribution from negative skin friction.

For more information, refer to Design Resistance - Limit State Approach

5.4.3 EC7 (No National Annex)

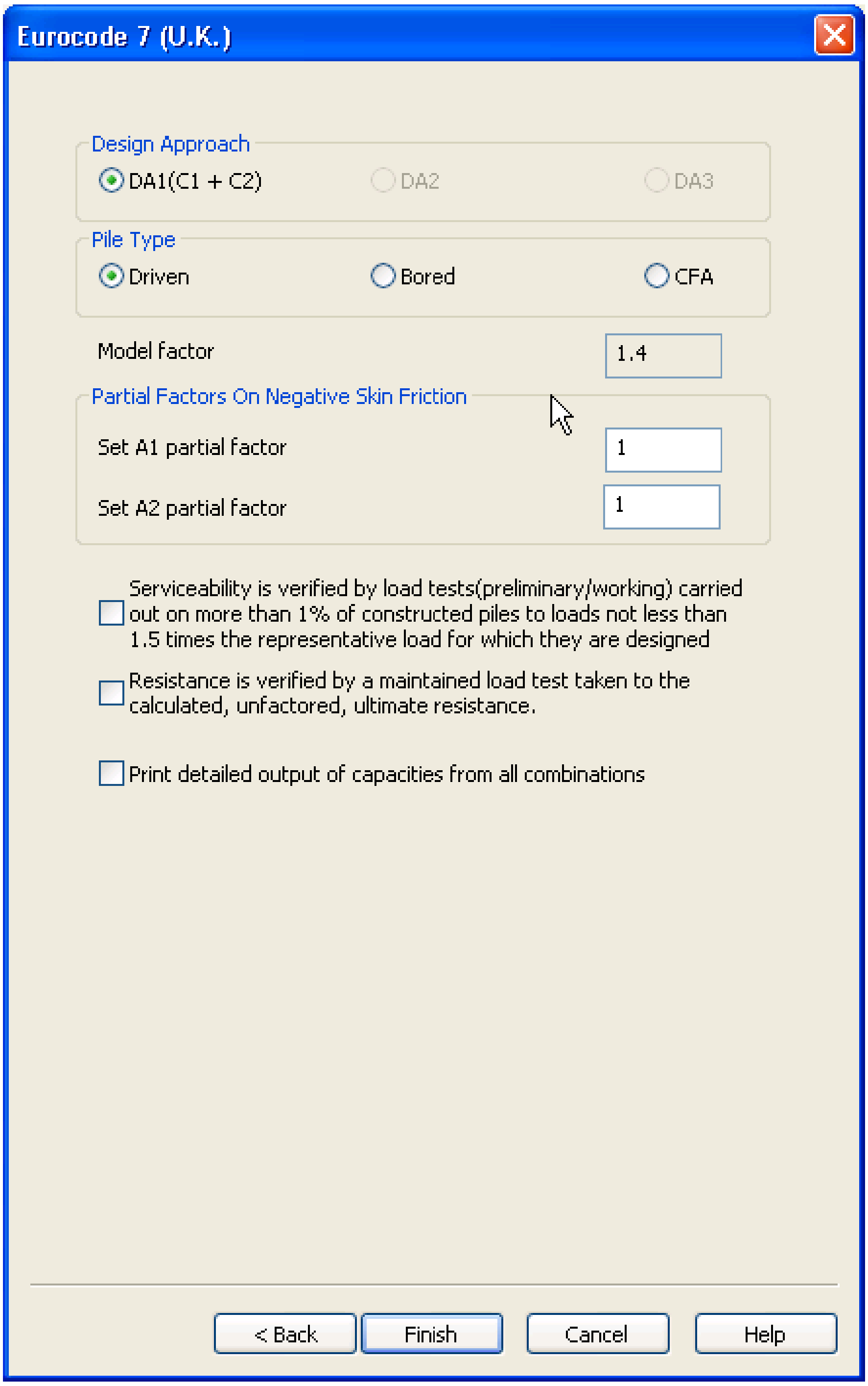


Code specific data should be specified in this dialog. Either of DA1, DA2 and DA3 can be specified. Further, either model pile procedure or alternate procedure can be specified.

The check box regarding stiffness is active only when the model pile procedure is selected.

The "Number of profiles" refers to number of soil profiles and is read-only.

5.4.4 EC7 (United Kingdom)

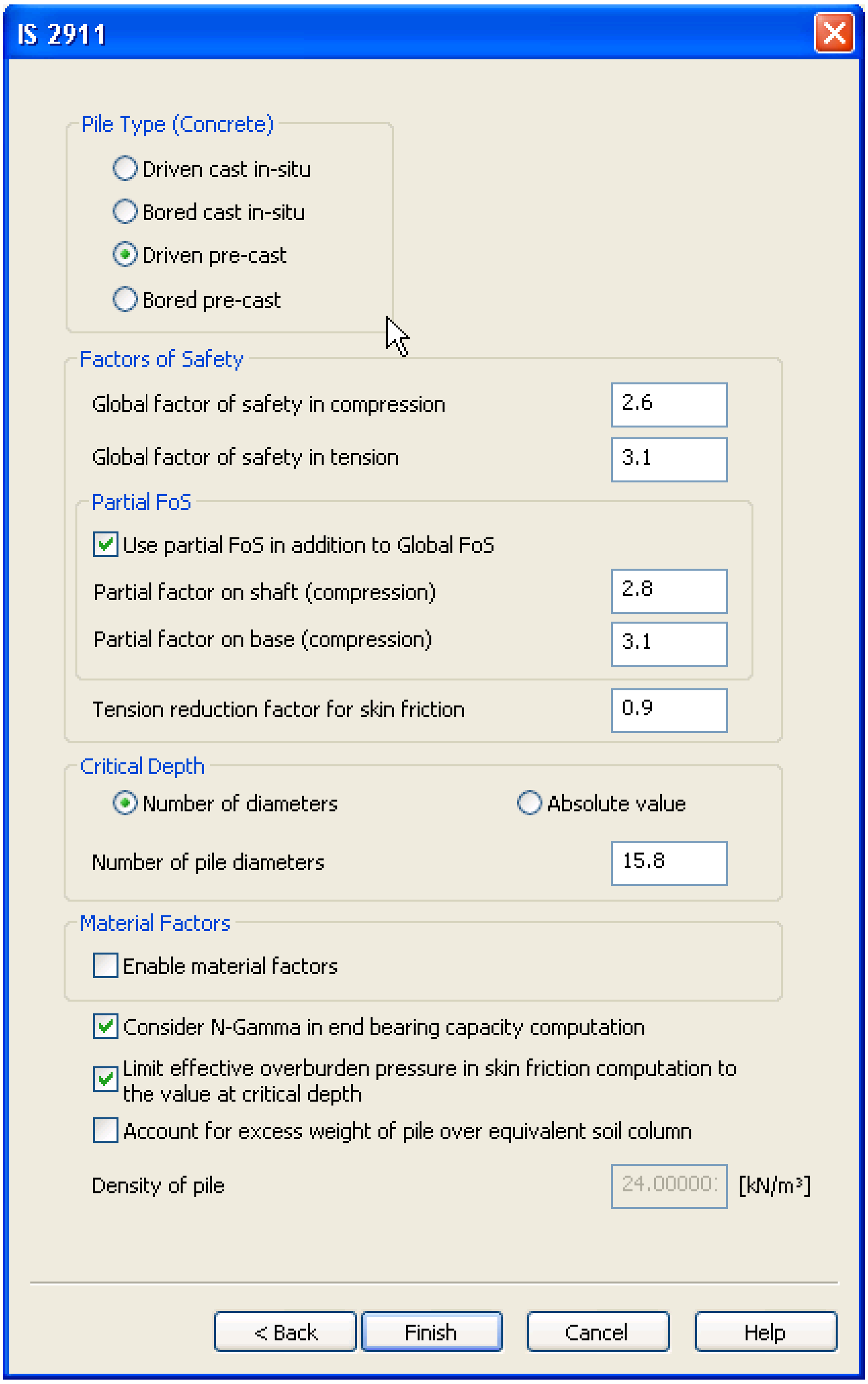


In this case, only DA1 is available. The model factor is read-only, and depends on whether the the second check box shown above is selected or not.

Also, partial factors on negative skin friction for the two action factor sets A1 and A2 respectively need to be specified. The negative skin friction is considered only in compression calculations as unfavourable permanent load. It is not considered at all in tension calculations. It is recommended to refer to A.3.1 section in the UK national annex for guidance on these factors. These values can be ignored if there is no negative skin friction in the model.

The calculations for both DA1 and DA2 combinations can be requested in the tabular output of results by selecting the relevant check box.

5.4.5 IS 2911



For IS 2911 the type of pile, factors of safety, and critical depth may be specified. The other parameters are optional.

As per IS 2911 the N_q values for a drained soil type are computed based on the type of pile selected, and minimum global factors of safety imposed. Partial factors may be chosen in addition to global factors of safety - but this is not mandatory. When the partial factors are also selected, the program computes the allowable load as the minimum from both the global factor approach and the partial factor approach.

A tension reduction factor for skin friction computation should be specified.

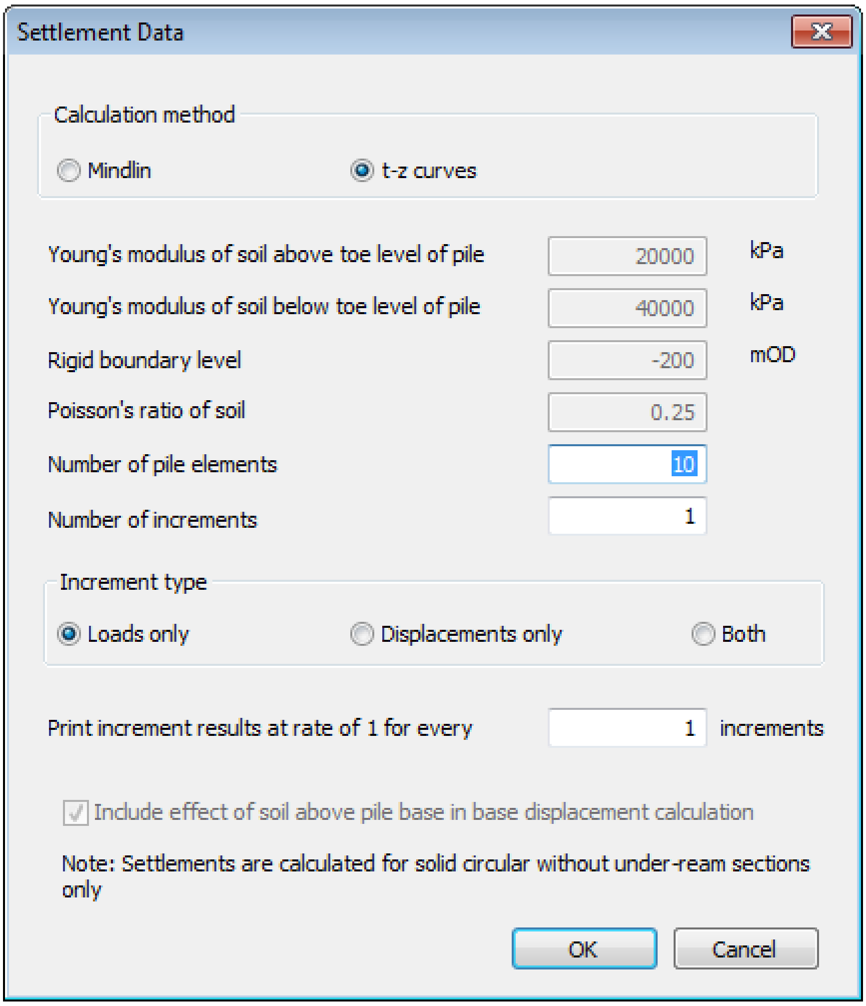
The critical depth can be entered either as an absolute value or in terms of the number of pile diameters.

Material factors may be optionally enabled. The program then uses the factored material parameters in pile capacity calculations. The material factors should be specified on a per material basis for $\tan\phi$ or cohesion, depending on the type of soil material. These values then would need to be entered in the drained/undrained materials table views.

The contribution of the $N\gamma$ term in the evaluation of end bearing capacity may be selected or ignored.

The excess weight of pile over the surrounding soil may also be optionally taken into account. This may be relevant for offshore piles or other piles which protrude above the ground. To model piles protruding out of the ground, dummy soil layers with nearly zero unit weights above the actual ground level should be defined. When exercising this option the density of pile material should be entered.

5.5 Settlement Data



Settlement data is enabled when settlement analysis is selected.

Calculation method - the calculation method to be used should be selected. The methods provided are Mindlin and t-z curves.

Young's Modulus of soil above toe level of pile and **Young's Modulus of soil below toe level of pile** are average values representing the soil stiffness above and below the pile toe respectively.

Poisson's ratio is the average value from the different soil layers around the pile.

Include effect of soil above pile base in base displacement calculation - whether the stiffness at the base node is to include the effect of soil above the base.

Depth of rigid boundary - the level at which the soil displacements are zero.

Number of pile elements - the pile is divided into the number of elements and Pile Stiffness is calculated for each element.

Number of increments - the load is applied in this number of equal increments

Increment type - i.e. whether load alone is incremented, the applied displacement alone is incremented, or both.

Increasing the increments helps to reduce any incompatibilities between relative displacements at the pile-soil interface, and the mobilised skin friction.

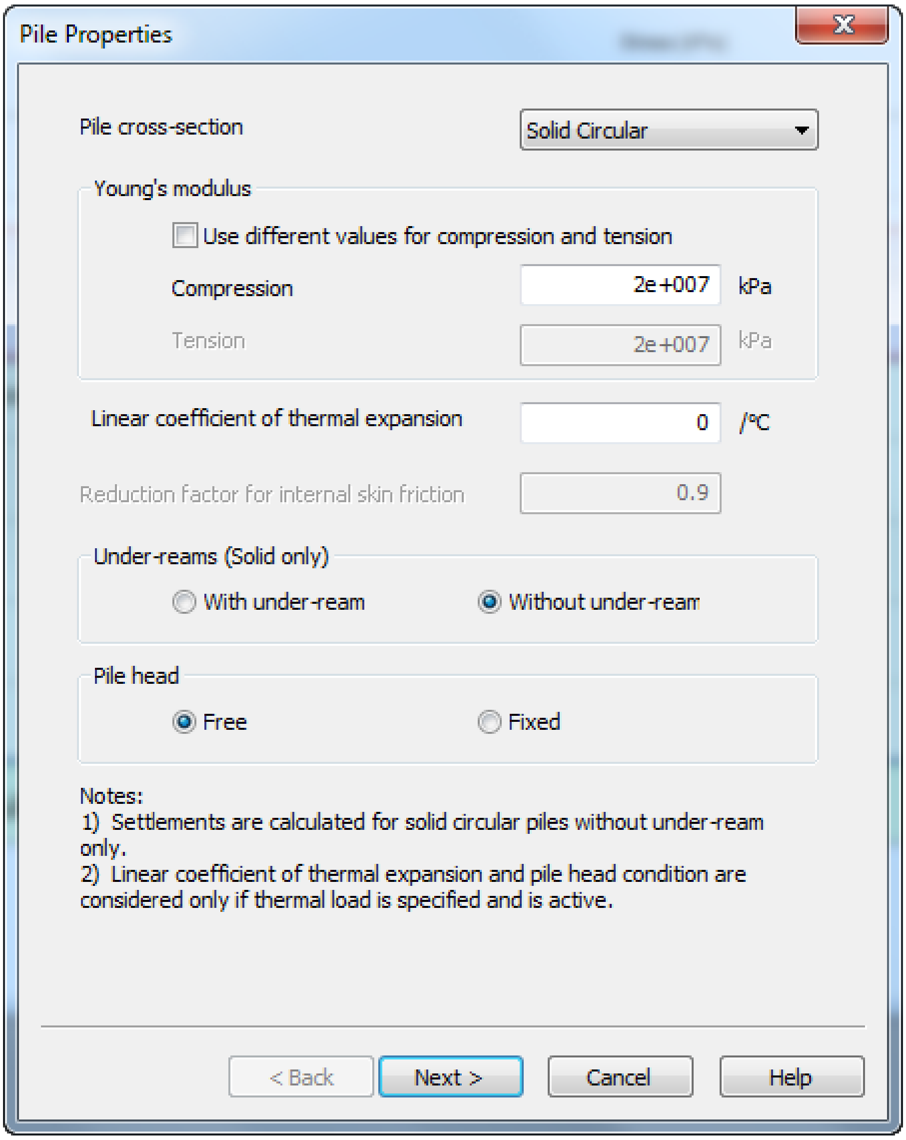
The rate at which the results from various increments need to be printed e.g. one in every 10 increments, can be specified. Irrespective of the frequency specified, the program always prints the last increment.

5.6 Pile Geometry

Pile Geometry contains information regarding the type of pile, the length of the pile, cross-section and under-ream dimensions.

5.6.1 Pile Properties

The **Pile Properties** dialog presents the following input data.



Pile cross-section

The different types of cross-sections available are Solid Circular, Hollow Circular, Solid Square, Hollow Square and H-Pile.

Settlements are calculated for solid circular and solid square sections without under-ream only. If other cross-section types are selected, an error message will appear upon analysis.

Young's modulus

This is used in the settlement calculation. Different Young's modulus values may be set for segments in compression and tension. If the "Use different values......." option is unchecked, the user may enter only one Young's modulus value for all segments.

Linear coefficient for thermal expansion - coefficient describing the relative change in length of pile per unit of temperature change. This is relevant only when thermal loading is applied to the Pile.

Under-reams (Solid only)

This option is available only if "Solid" pile type option is selected.

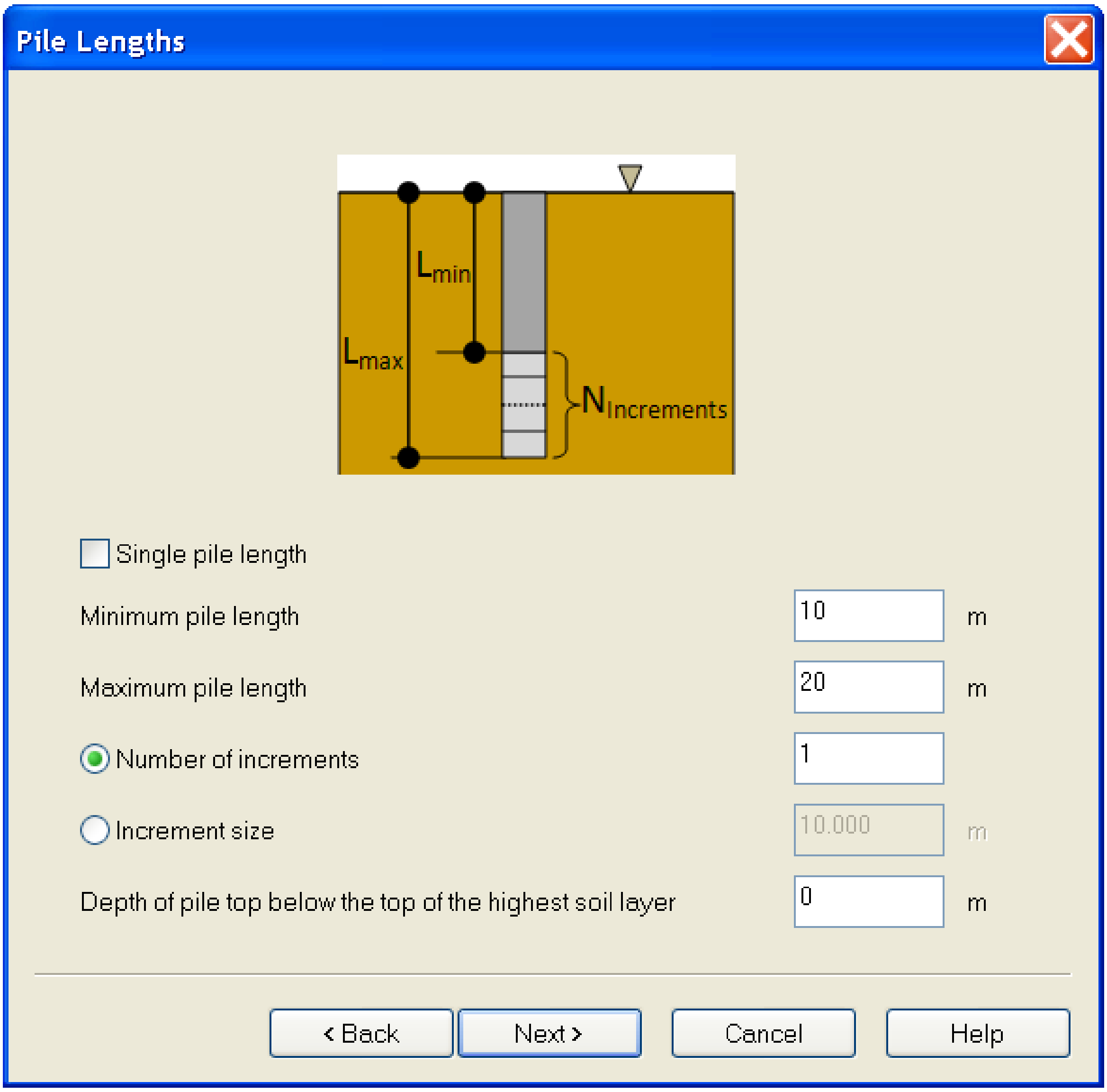
Reduction Factor for Internal Skin Friction

This factor is used in calculating the internal skin friction.

Pile head - fixed or free. By default it is free.

5.6.2 Pile Lengths

The **Pile Lengths** dialog presents the following input data.



Single pile length - If checked then capacity and settlements are calculated for one pile length only.

Minimum pile length - the minimum pile length for which the pile capacity to be calculated.

Maximum pile length - the maximum pile length for which the pile capacity to be calculated.

Number of increments - the number of increments between the minimum and maximum pile depth for which the pile capacity is to be calculated.

Quantities like skin friction, plugged capacity etc. do not vary linearly with depth. The accuracy of such calculations can be improved by choosing a sufficient number of increments.

Depth of pile top below the top of the highest soil layer - is the difference in height between the highest soil layer and the top of the pile. If this value is positive, it is used to represent basement piles. If this value is negative, it is used to represent general and local scour if the water table is above ground level.

5.6.3 Pile Cross-section Dimensions

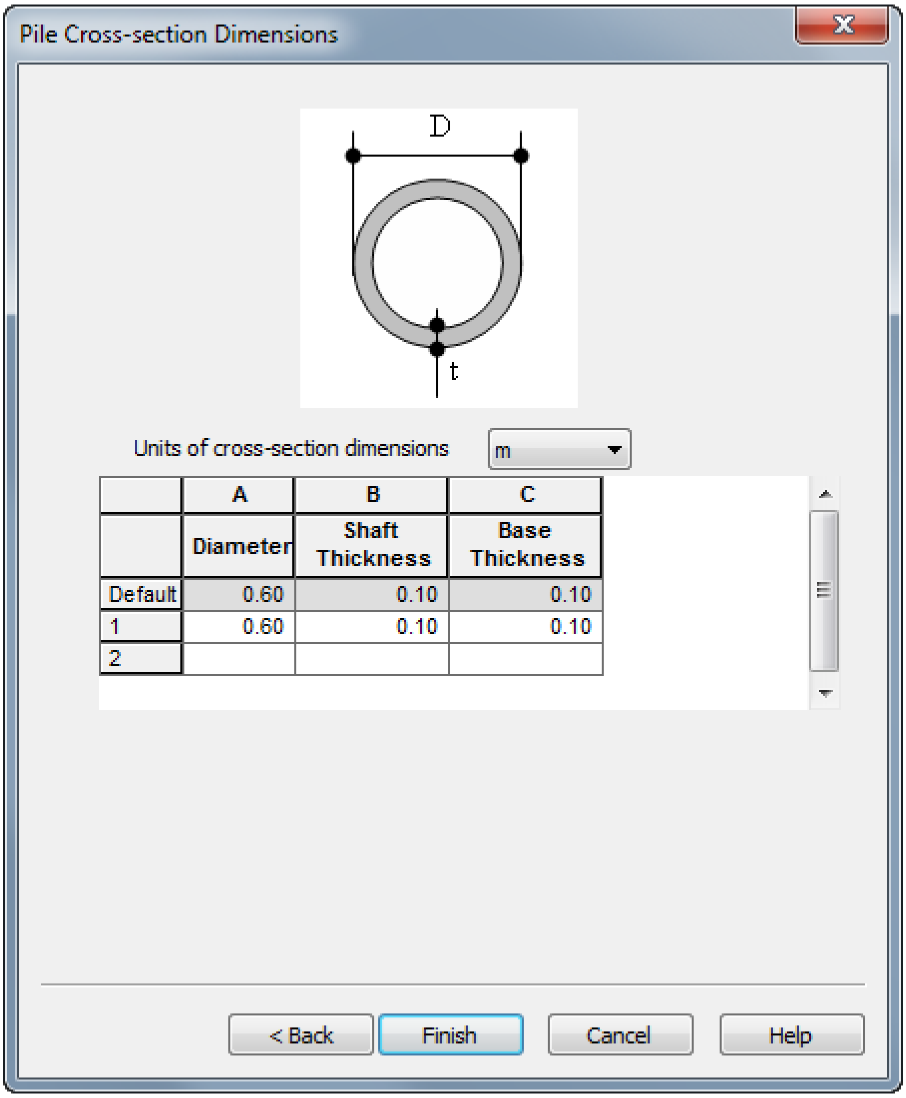
The **Pile Cross-section Dimensions** dialog allows the user to define the different pile cross-sections.

Multiple cross-sections can be entered - one per row of the table.

Units of cross-section dimensions - specifies the required units for entering cross-section data in this dialog.

There are 2 types of tables based on the pile cross section:

- **Uniform** - This option is for modeling piles that have a uniform cross section over the whole length of the pile. This applies to hollow piles and H-piles.



Circular cross-section

- Shaft Diameter outside
- Shaft Wall Thickness (for hollow piles only)
- Wall Thickness at Base (for hollow piles only)

Square cross-section

- External Side Width
- Shaft Wall Thickness (for hollow piles only)
- Wall Thickness at Base (for hollow piles only)

H-Pile

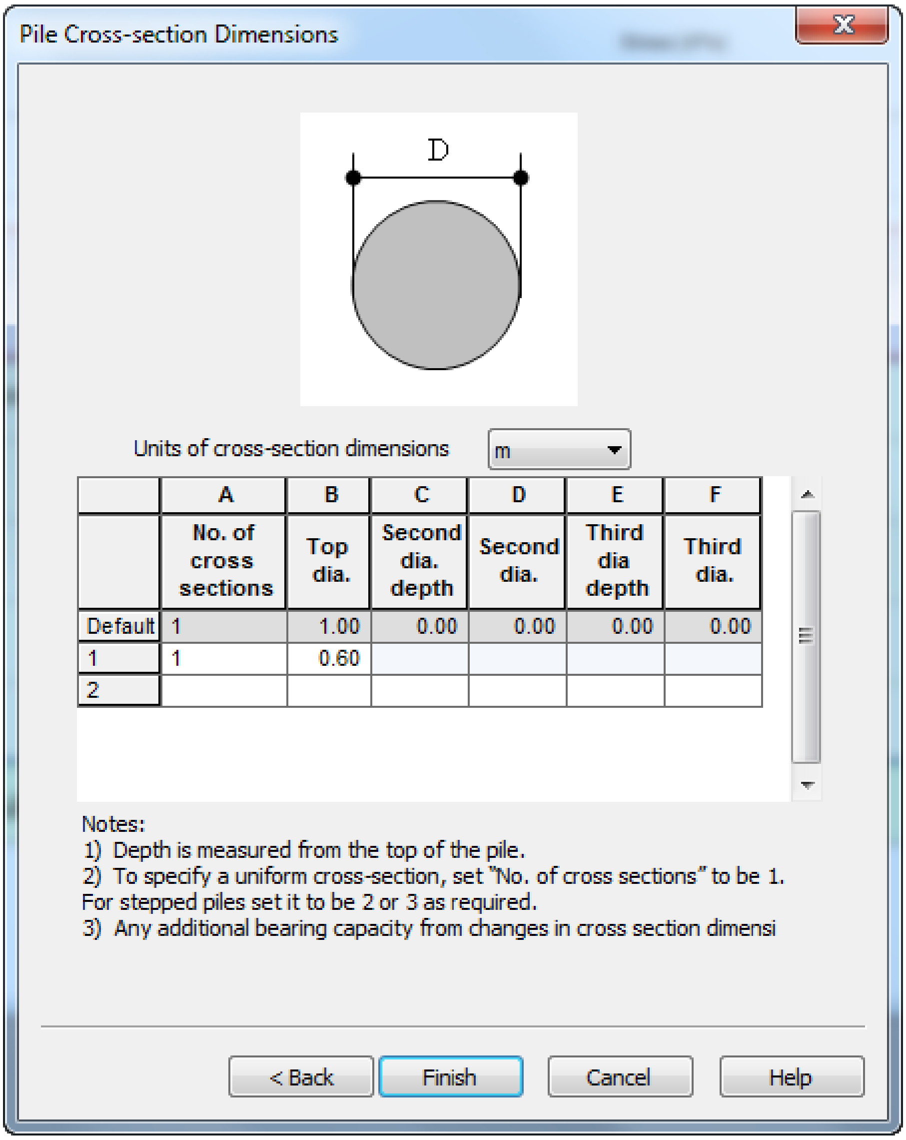
- Depth along Web
- Width along Flanges
- Average Web Thickness
- Average Flange Thickness

- **Varying -** This option is available for modeling piles that have step change in cross section at various depths down the pile.

This option is allowed only for solid circular/square piles. The user can enter a maximum of 3 widths down the pile.The fields "Second width location" and "Third width location" correspond to depths of cross section changes from the top of the pile.

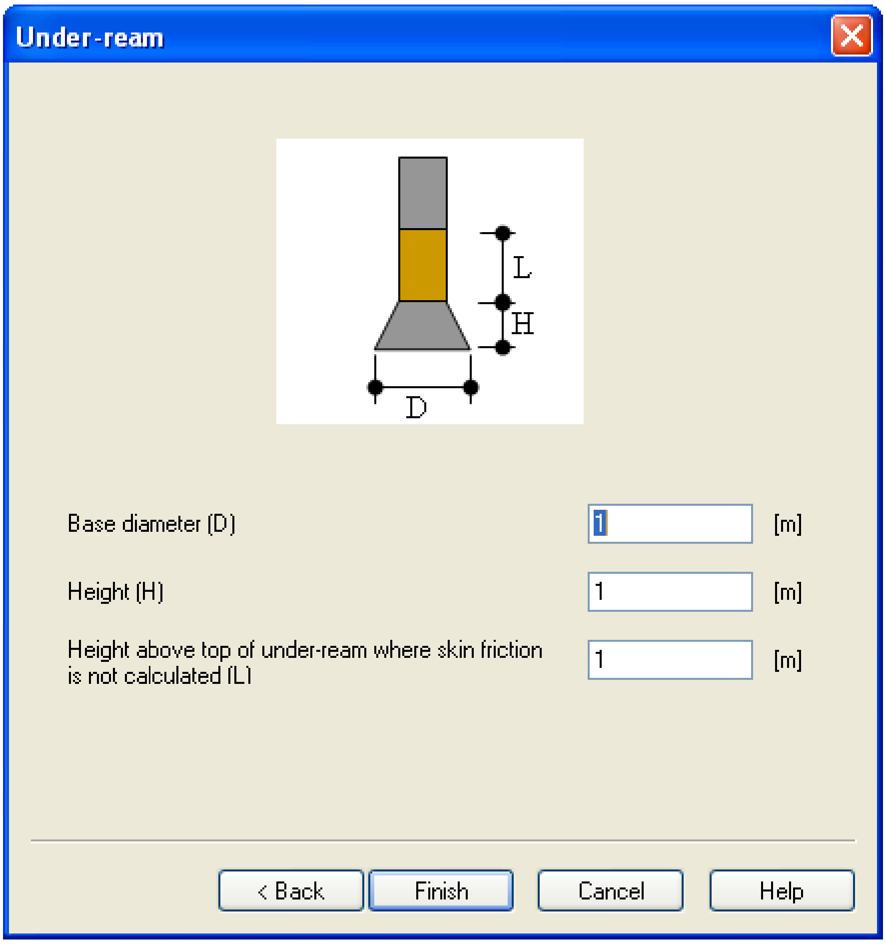
If the user wants to model a solid pile with uniform cross section, then he must enter the "No. of cross sections" as 1, and enter the top diameter or top width depending on the cross section.

The program does NOT, however, include any additional bearing capacity from step changes in cross section dimensions.


Pile Cross-section Dimensions
D
Units of cross-section dimensions
m
A B C D E F
No. of cross sections
Top dia.
Second dia. depth
Second dia.
Third dia depth
Third dia.
Default 1 1.00 0.00 0.00 0.00 0.00
1 1 0.60
2
Notes:
1) Depth is measured from the top of the pile.
2) To specify a uniform cross-section, set "No. of cross sections" to be 1.
For stepped piles set it to be 2 or 3 as required.
3) Any additional bearing capacity from changes in cross section dimensi
< Back
Finish
Cancel
Help

5.6.4 Under-ream

The **Under-ream** dialog presents the following input data.



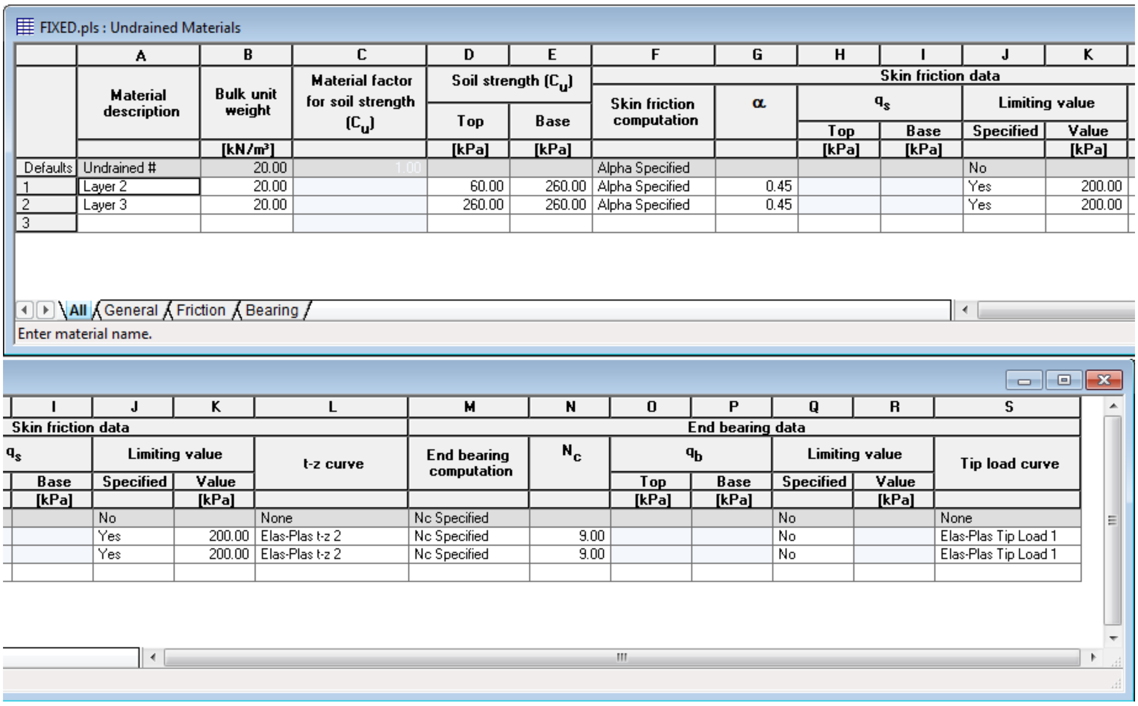
- Base diameter
- Height of the under-ream
- Height above top of under-ream where skin friction is neglected

5.7 Material Properties

The **Material Properties** section presents the following input data.

5.7.1 Undrained Materials

Each record in the **Undrained Materials** table view consists of the following items.



	A	B	C	D	E	F	G	H	I	J	K
	Material description	Bulk unit weight	Material factor for soil strength (C_u)	Soil strength (C_u) Top	Soil strength (C_u) Base	Skin friction data: Skin friction computation	α	q_s Top	q_s Base	Limiting value Specified	Limiting value Value
		[kN/m³]		[kPa]	[kPa]			[kPa]	[kPa]		[kPa]
Defaults	Undrained #	20.00	1.00			Alpha Specified				No	
1	Layer 2	20.00		60.00	260.00	Alpha Specified	0.45			Yes	200.00
2	Layer 3	20.00		260.00	260.00	Alpha Specified	0.45			Yes	200.00
3											

I	J	K	L	M	N	O	P	Q	R	S
Skin friction data: q_s Base	Limiting value Specified	Limiting value Value	t-z curve	End bearing data: End bearing computation	N_c	q_b Top	q_b Base	Limiting value Specified	Limiting value Value	Tip load curve
[kPa]		[kPa]				[kPa]	[kPa]		[kPa]	
	No		None	Nc Specified				No		None
	Yes	200.00	Elas-Plas t-z 2	Nc Specified	9.00			No		Elas-Plas Tip Load 1
	Yes	200.00	Elas-Plas t-z 2	Nc Specified	9.00			No		Elas-Plas Tip Load 1

Material description - brief descriptions for the material types can be entered here.

Bulk unit weight - bulk unit weight of the soil layer.

Material factor for soil strength - this factor that needs to be applied to cohesive strength or friction angle depending on the type of material.

When the "Working load" method is selected in the Analysis Options, the "Material factor for soil strength" field is greyed out completely. It is active only when the "Design resistance" method is chosen.

Soil strength (C_u)

Top - undrained shear strength of the total stress material at the top of the layer.

Bottom - undrained shear strength of the total stress material at the bottom of the layer.

When the bottom-most layer in the model is assigned a "Total stress" material, the cohesion within the layer is assumed to be constant with value of cohesion specified at the top of the layer - "C_u-Top". The cohesion at the bottom of layer, "C_u-Bottom" is ignored in this case.

The following fields relate to **Friction data**

Method - method of calculating Alpha, the adhesion factor. This is one of API method 1, API method 2, or user-specified value of Alpha.

α - adhesion factor, if user-specified.

Limiting value

Specified - select 'Yes' to specify the limiting value.

Value - friction value is limited to this value.

t-z curve - the stress-displacement curve to be used for calculations if the settlement calculation method selected is 't-z curves'. This column is active only when the analysis type in Analysis Options is 'Settlement' and, the calculation method in Settlement Data is 't-z curves'.

The following fields are related to **End bearing**

Method - method of calculating N_c, the bearing capacity factor. This is one of user-specified or calculated.

N_c - user-specified bearing capacity factor.

Limiting value

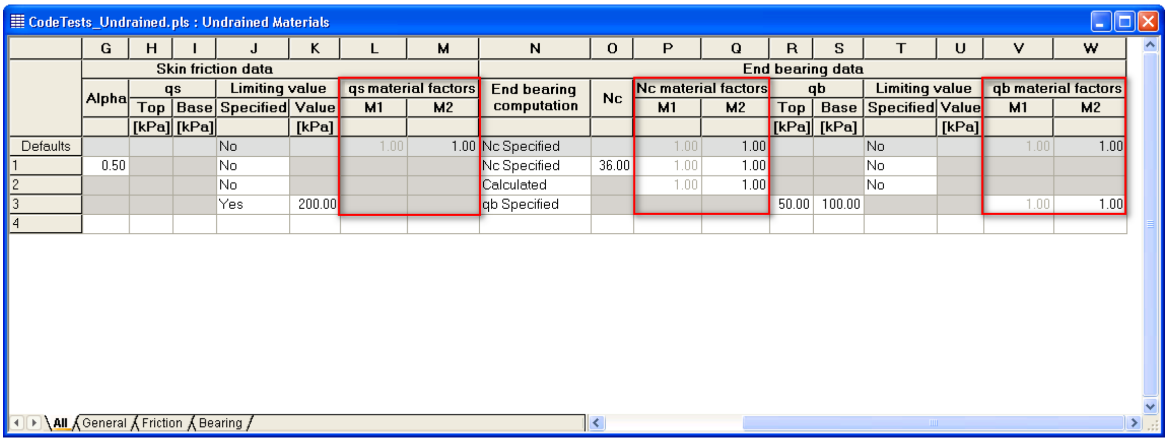
Specified - select 'Yes' to specify the limiting value.

Value - bearing value is limited to this value.

Tip load curve - the stress-displacement curve to be used for calculations if the settlement calculation method selected is 't-z curves'. This column is active only when the analysis type in Analysis Options is 'Settlement', and the calculation method in Settlement Data is 't-z curves'.

For information about the methods used to evaluate pile capacities using the total stress approach please refer to the topics: Shaft friction - Total stress approach and End bearing - Total stress approach.

When using code EC7, additional fields pertaining to material factor sets are available.


CodeTests_Undrained.pls : Undrained Materials

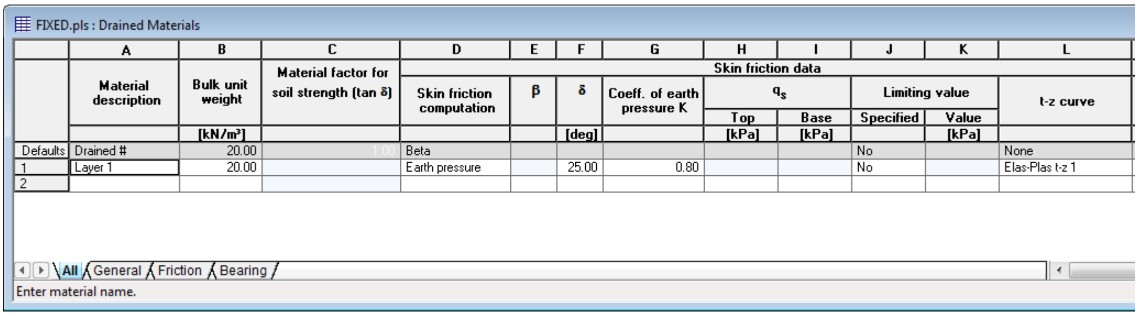
	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
	Skin friction data							End bearing data									
	Alpha	qs		Limiting value		qs material factors		End bearing computation	Nc	Nc material factors		qb		Limiting value		qb material factors	
		Top	Base	Specified	Value	M1	M2			M1	M2	Top	Base	Specified	Value	M1	M2
		[kPa]	[kPa]		[kPa]							[kPa]	[kPa]		[kPa]		
Defaults				No		1.00	1.00	Nc Specified		1.00	1.00			No		1.00	1.00
1	0.50			No				Nc Specified	36.00	1.00	1.00			No			
2				No				Calculated		1.00	1.00			No			
3				Yes	200.00			qb Specified				50.00	100.00			1.00	1.00
4																	

The M1 set values are always 1.00. M2 set values are different from 1.00, and are specified in the code for only some parameters (C_u, Phi etc.). However, skin friction and end bearing computations can be specified that do not explicitly depend on these parameters. For example, q_s, or q_b can be specified directly, or N_c can be used to calculate them. In these situations, the corresponding M2 parameters would need to be specified, as these are not available in the code. The program uses these M2 values in end bearing/skin friction computations.

Note: The M2 parameters are used for certain design approaches e.g. DA1 Combination 2 and DA3.

5.7.2 Drained Materials

Each record in the **Drained Materials** table view consists of the following items

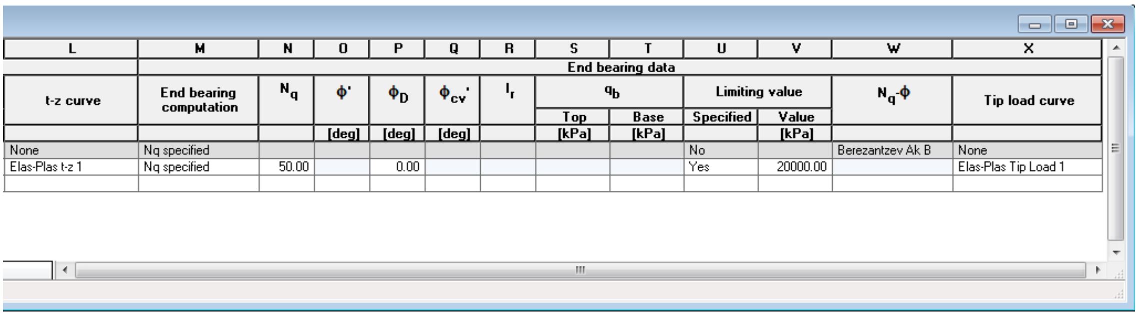


FIXED.pls : Drained Materials

	A	B	C	D	E	F	G	H	I	J	K	L
				Skin friction data								
	Material description	Bulk unit weight	Material factor for soil strength (tan δ)	Skin friction computation	β	δ	Coeff. of earth pressure K	q_s Top	q_s Base	Limiting value Specified	Limiting value Value	t-z curve
		[kN/m³]				[deg]		[kPa]	[kPa]		[kPa]	
Defaults	Drained #	20.00	1.00	Beta						No		None
1	Layer 1	20.00		Earth pressure		25.00	0.80			No		Elas-Plas t-z 1
2												

All / General / Friction / Bearing

Enter material name.



L	M	N	O	P	Q	R	S	T	U	V	W	X
	End bearing data											
t-z curve	End bearing computation	N_q	φ'	$φ_D$	$φ_{cv}$'	I_r	q_b Top	q_b Base	Limiting value Specified	Limiting value Value	N_q-φ	Tip load curve
			[deg]	[deg]	[deg]		[kPa]	[kPa]		[kPa]		
None	Nq specified								No		Berezantzev Ak B	None
Elas-Plas t-z 1	Nq specified	50.00		0.00					Yes	20000.00		Elas-Plas Tip Load 1

Material description - brief descriptions for each of the material types can be entered here.

Bulk unit weight - bulk unit weight of the soil layer.

Material factor for soil strength - the material factor that needs to be applied to cohesive strength or friction angle depending on type of material.

When the "Working load" method is selected in the Analysis Options, the "Material factor for soil strength" field is greyed out completely. This is active only when the "Design resistance" method is chosen.

The following fields relate to **Friction data**.

Skin friction computation method - either Beta Method or Earth Pressure Method.

β - value of beta

δ - friction angle

Coefficient of earth pressure K - is used to calculate horizontal effective stress from vertical effective stress.

This field is enabled when "Effective stresses" are selected in the Analysis Options.

Limiting value

Specified - select 'Yes' to specify a limiting value.

Value - the friction value is limited to this value.

t-z curve - the stress-displacement curve to be used for calculations, if the settlement calculation method selected is 't-z curves'. This column is active only when the analysis type in the Analysis Options is 'Settlement' and, the calculation method in the Settlement Data is 't-z curves'.

The following fields relate to **End bearing.**

N_q computation method - any of user-specified, Bolton or Berezantzev.

N_q - value of bearing capacity factor Nq.

ϕ' - value of effective friction angle for the soil profile.

ϕ_D - value of angle of internal friction corresponding to the soil of overburden. Refer to Berezantzev method.

ϕ_{cv}'- value of critical state angle of friction.

I_r - value of the corrected relative density (0 to 1).

Limiting value

Specified - select 'Yes' to specify limiting value.

Value - the bearing value is limited to this value.

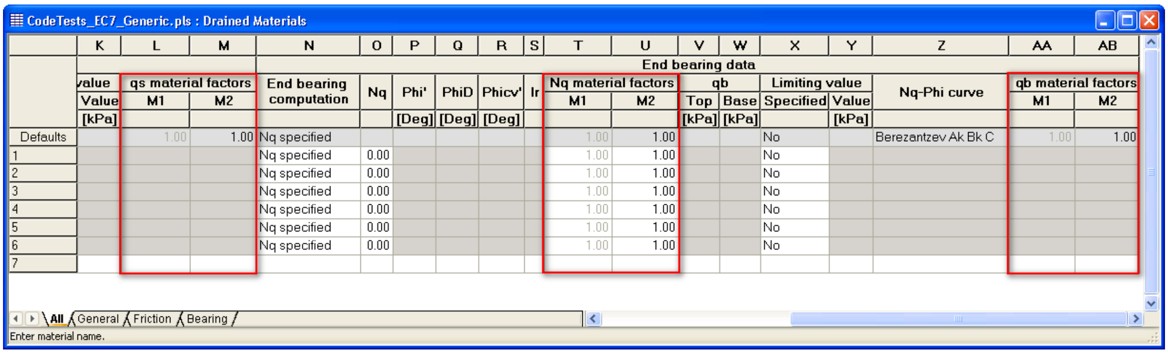
N_q-ϕ Curve - used for calculating the value of N_q from friction angle, ϕ.

Tip load curve - the stress-displacement curve to be used for calculations if the settlement calculation method selected is 't-z curves'. This column is active only when the analysis type in the Analysis Options is 'Settlement' and, the calculation method in the Settlement Data is 't-z curves'.

This option becomes available for Berezantzev and Bolton methods. "Berezantzev Ak Bk Curves" or user-defined N_q-ϕ curves may be selected.

For information about the methods used to evaluate pile capacities using the effective stress approach refer to the topics: Shaft friction - Effective stress approach and End bearing - Effective stress approach.

When using code EC7, additional fields pertaining to material factor sets are available.



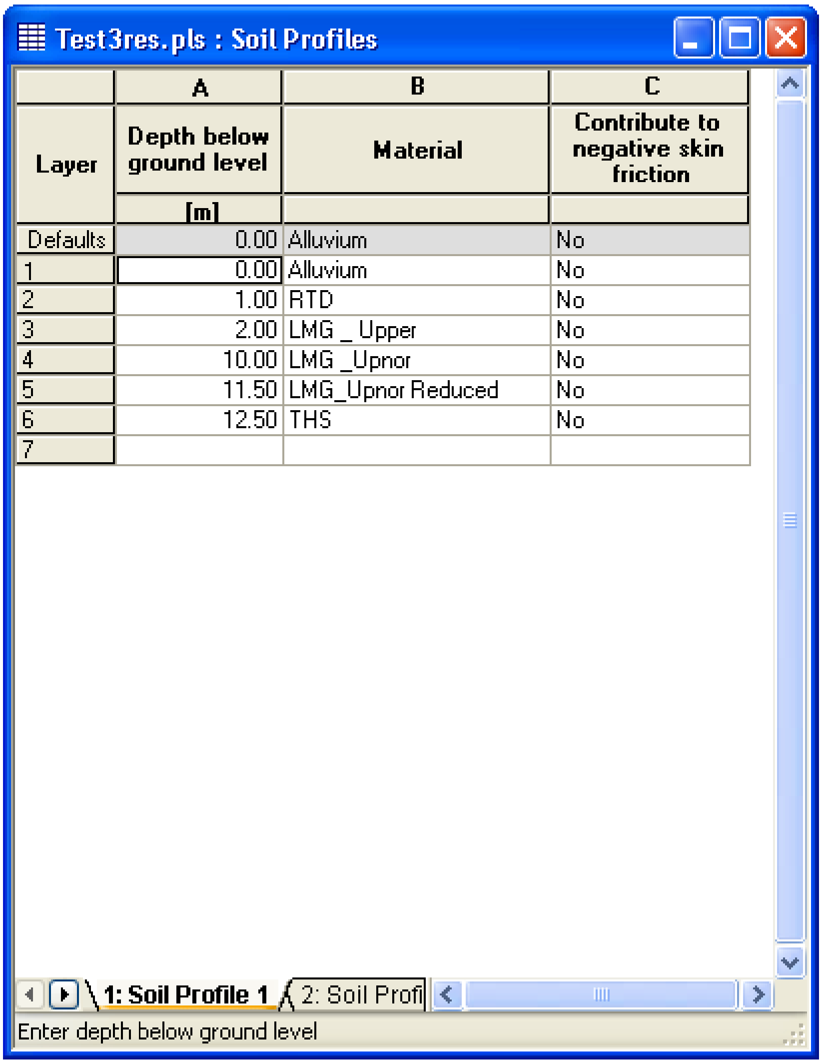
The M1 set values are always 1.0. M2 set values are different from 1.00, and are specified in the code for only some parameters (Cu, ϕ etc.) However, skin friction and end bearing computations can be specified that do not explicitly depend on these parameters. For example, q_s, or q_b can be specified directly, or N_q can be used to calculate the same. In these situations, the corresponding M2 parameters would need to be specified, as these are not available in the code. The program uses these M2 values in end-bearing/skin friction computations.

Note: The M2 parameters are used for certain design approaches eg. DA1 Combination 2, DA3.

5.8 Soil Profiles

Multiple soil profiles can be selected in the Soil Profiles table view. Each tab corresponds to one soil profile. Existing soil profiles can be edited or deleted and new soil profiles can be added using the context menu obtained by right-clicking on any tab.

Each record in the table view consists of the following items.



Level at Top/Depth below ground level - level of the top of each layer according to the datum chosen.

The levels must be entered in decreasing order if datum information is elevation in Analysis options dialog.

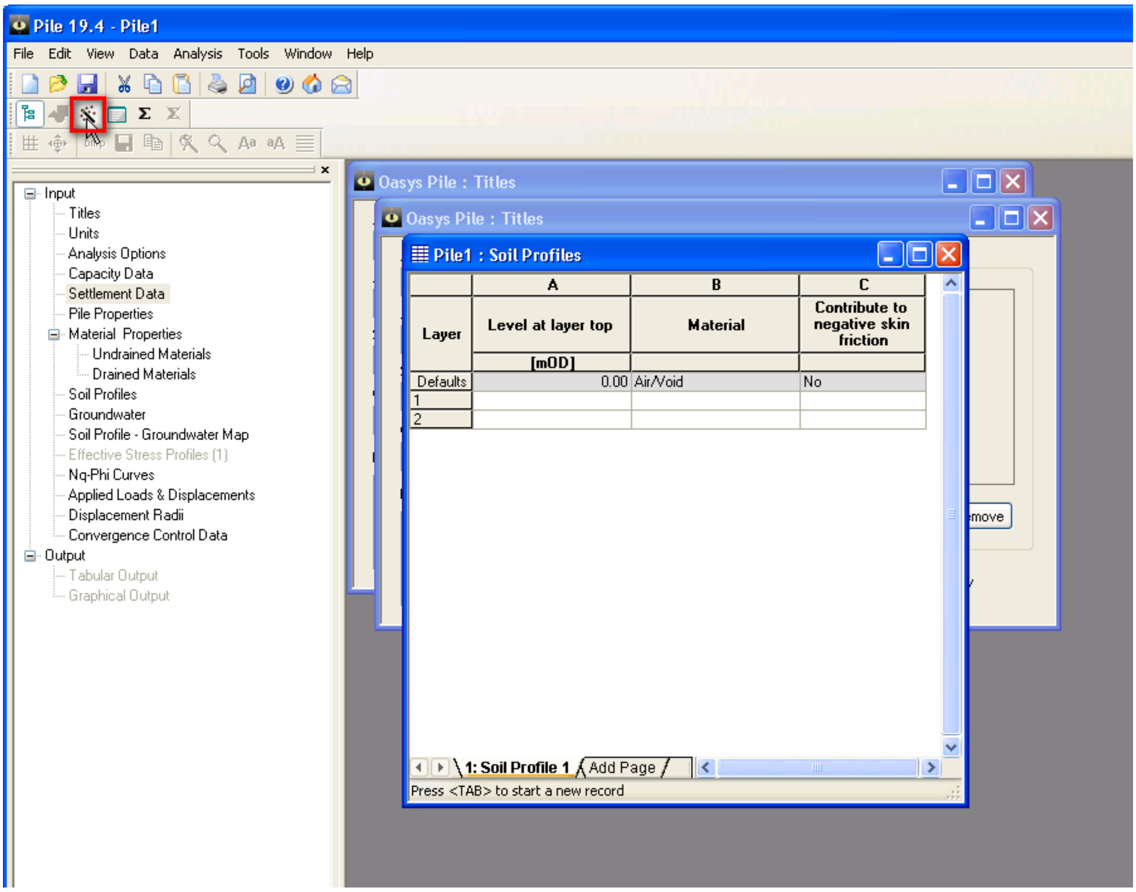
The depths must be entered in increasing order if datum information is depths in Analysis options dialog.

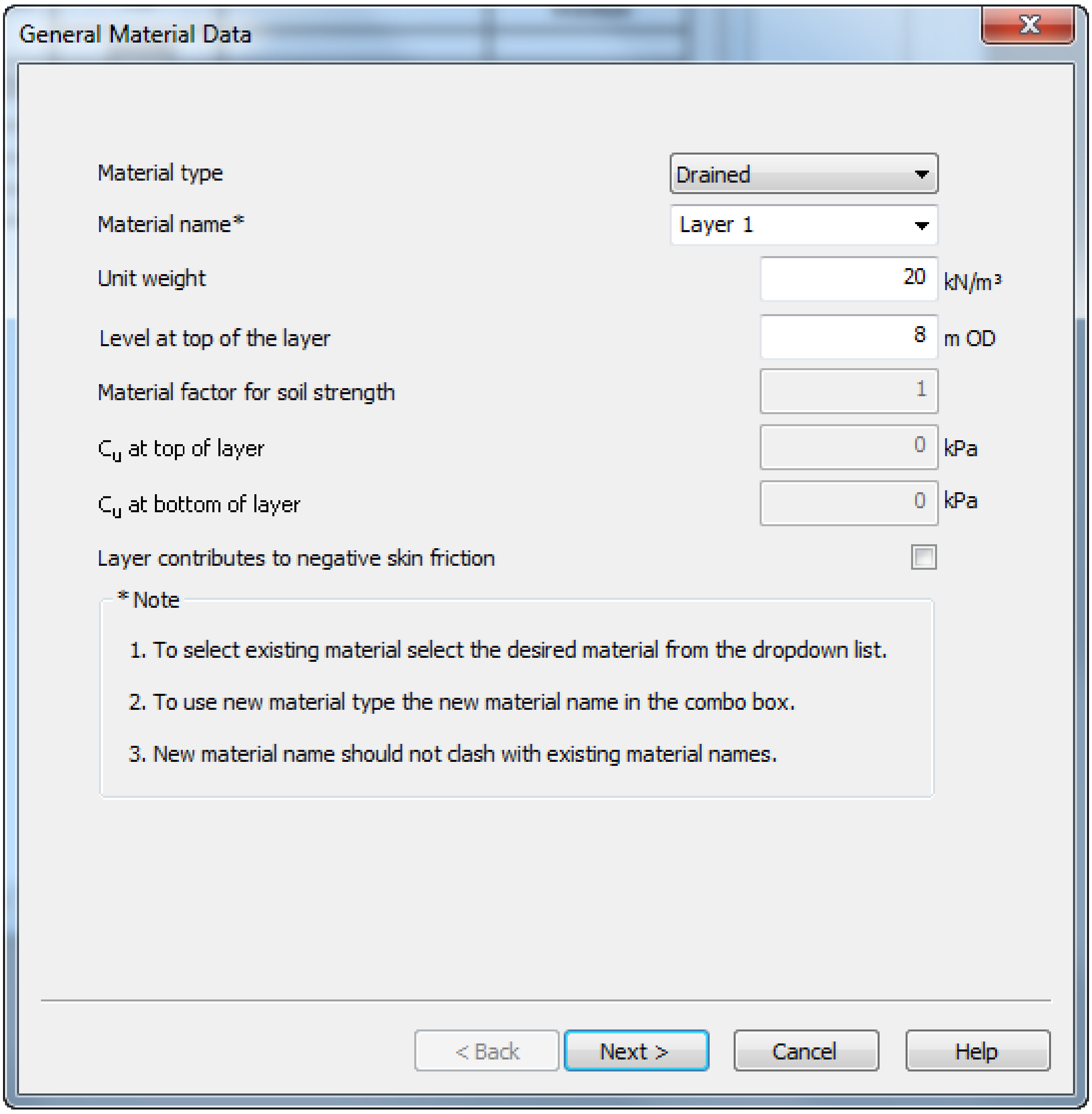
Material - the soil material that is present in the layer.

Contribute to Negative Skin Friction - whether the layer contributes to negative skin friction.

This was material specific in earlier versions of Pile, it is now layer specific.

The material properties can be defined when entering new layer data using the new material wizard. This wizard can be invoked by clicking the wizard toolbar button.


Pile 19.4 - Pile1
File Edit View Data Analysis Tools Window Help
Input
Titles
Units
Analysis Options
Capacity Data
Settlement Data
Pile Properties
Material Properties
Undrained Materials
Drained Materials
Soil Profiles
Groundwater
Soil Profile - Groundwater Map
Effective Stress Profiles (1)
Nq-Phi Curves
Applied Loads & Displacements
Displacement Radii
Convergence Control Data
Output
Tabular Output
Graphical Output
Oasys Pile : Titles
Oasys Pile : Titles
Pile1 : Soil Profiles
A
B
C
Layer
Level at layer top
Material
Contribute to negative skin friction
[mOD]
Defaults
0.00
Air/Void
No
1
2
1: Soil Profile 1
Add Page
Press <TAB> to start a new record



This wizard contains pages to allow definition of layer properties and material properties.

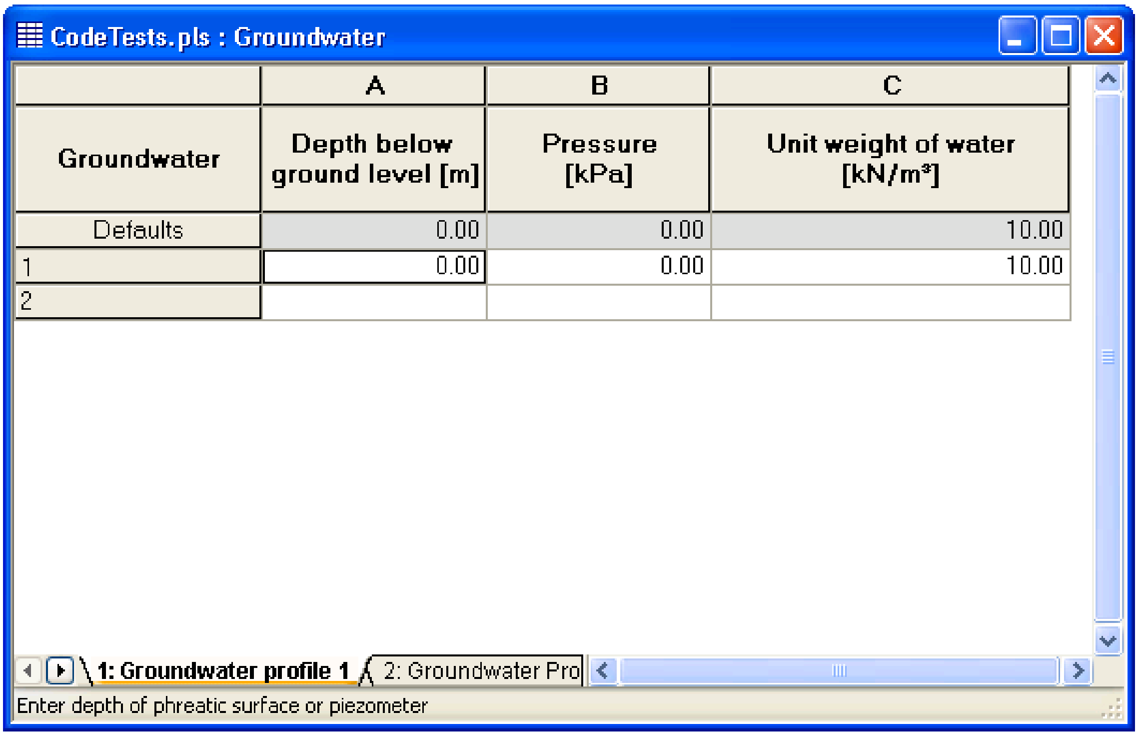
The initial page allows definition of the layer data as well as general material data. The type of material has to be specified in this page. Depending on the type of material selected, relevant pages to define other "Drained" or "Undrained" material properties will be shown.

5.9 Groundwater

Multiple groundwater profiles can be defined in the Groundwater Data table view. Each tab corresponds to one groundwater profile. Existing groundwater profiles can be edited or deleted, and new groundwater profiles can be added using the context menu obtained by right clicking on any tab.

This can be hydrostatic or piezometric.

Each record in the **Groundwater** table view consists of the following items.



Level/Depth below ground level - level/depth at which the pressure is the specified.

Pressure - pressure at the level/depth when a piezometric profile is entered.

Unit weight of water - the value of unit weight of water. The entry in the first record alone is available for input.

This first line of the table view allows a single value for the unit weight of water to be added. On subsequent lines levels/depths and pressures can be entered to create a piezometric profile. Interpolation between the points is linear and the water profile beneath the lowest point is assumed to be hydrostatic.

If only one data point is entered the program will also assume a hydrostatic groundwater distribution.

For hydrostatic distributions the water pressure (u) is calculated from:

$$u = z_w \gamma_w$$

where:

z_w - depth below water table level

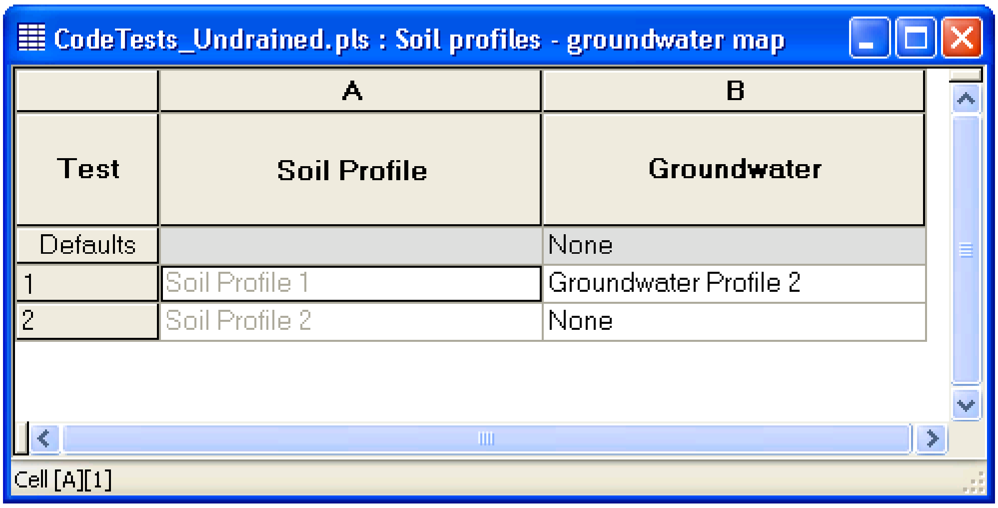
γ_w - specified unit weight of water

Thus a partial hydrostatic condition can be modelled by specifying a value of γ_w less than 10kN/m^3.

For piezometric profiles the level/depth and pressure at each known point must be entered. If more than one data point is entered, the program will assume that the points represent piezometers, and the ground water pressure will be interpolated vertically between the specified points. Below the lowest point, groundwater pressure will be assumed to extend hydrostatically.

5.10 Soil Profiles Groundwater Map

The groundwater profile needs to be specified for each soil profile using this table view.



CodeTests_Undrained.pls : Soil profiles - groundwater map

	A	B
Test	Soil Profile	Groundwater
Defaults		None
1	Soil Profile 1	Groundwater Profile 2
2	Soil Profile 2	None

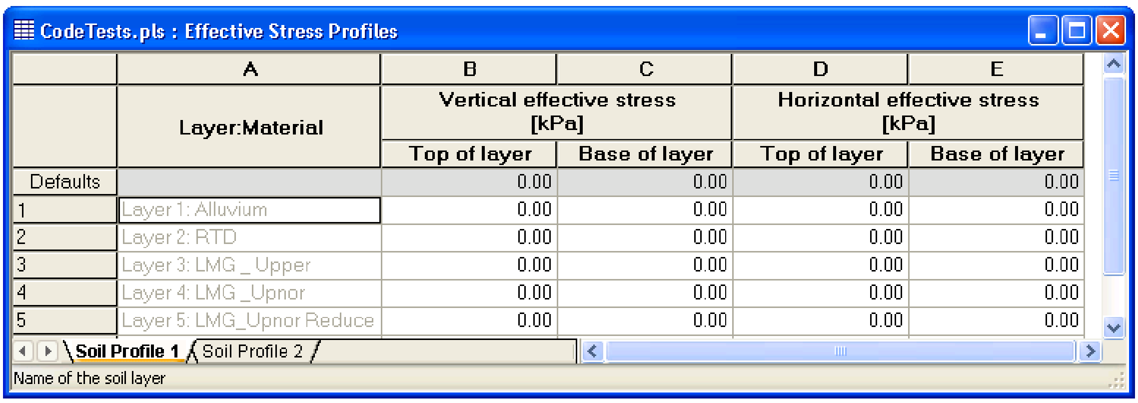
Cell [A][1]

The number of records in this table view is fixed and is the same as the number of soil profiles.

5.11 Effective Stress Profiles

A separate effective stress profile needs to be specified for each soil profile. Each tab corresponds to one soil profile. The tabs in this table view cannot be edited as there is a one-to-one relation between this table view and the Soil Profiles table view.

Each record in the **Effective Stress Profiles** table view consists of the following items.



CodeTests.pls : Effective Stress Profiles

	A	B	C	D	E
	Layer:Material	Vertical effective stress [kPa]		Horizontal effective stress [kPa]	
		Top of layer	Base of layer	Top of layer	Base of layer
Defaults		0.00	0.00	0.00	0.00
1	Layer 1: Alluvium	0.00	0.00	0.00	0.00
2	Layer 2: RTD	0.00	0.00	0.00	0.00
3	Layer 3: LMG _Upper	0.00	0.00	0.00	0.00
4	Layer 4: LMG _Upnor	0.00	0.00	0.00	0.00
5	Layer 5: LMG_Upnor Reduce	0.00	0.00	0.00	0.00

Soil Profile 1 | Soil Profile 2

Name of the soil layer

Layer:Material - the soil material that is present in the layer.

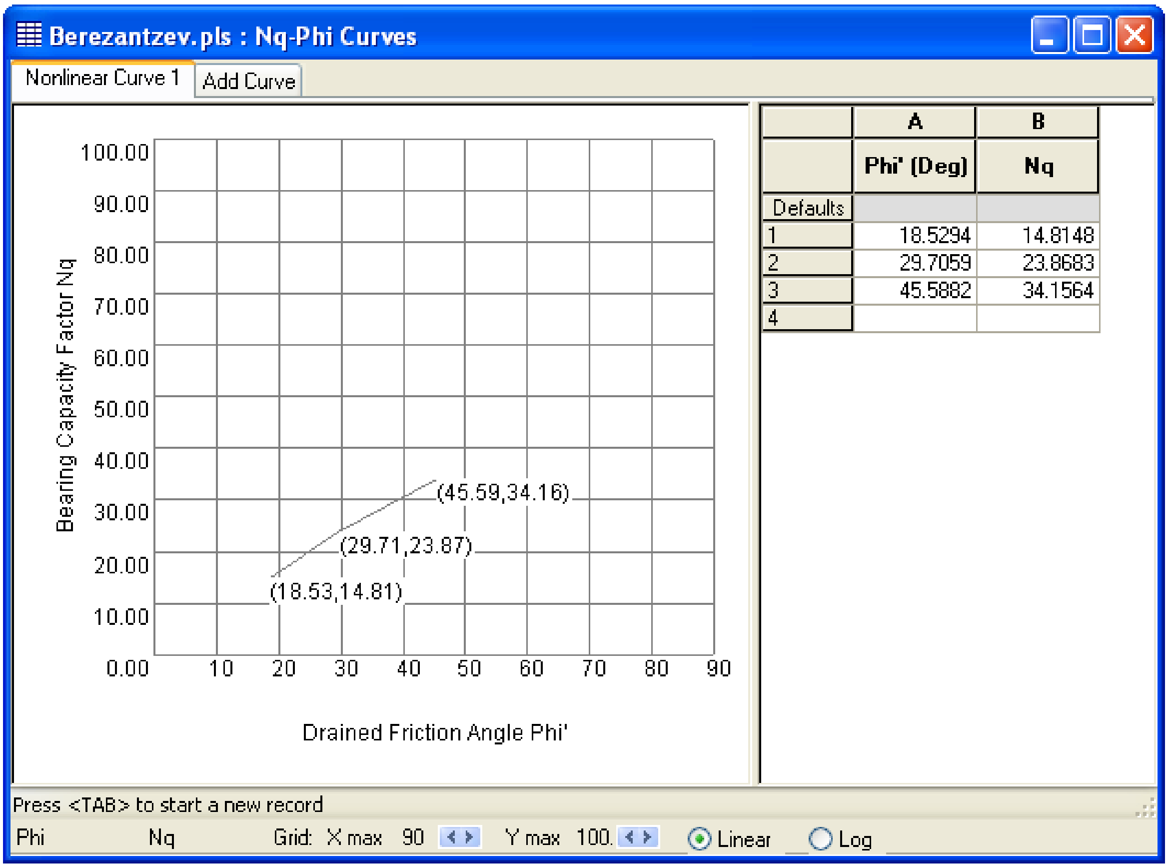
Vertical effective stress - user-defined vertical effective stress profile.

Horizontal effective stress - user-defined horizontal effective stress profile.

The vertical and horizontal effective stresses at any intermediate level are linearly interpolated between the top and bottom of layer.

5.12 Nq-Phi Curves

Each record in the **N_q-Phi** table view consists of the following items.



Phi' - the effective friction angle.

N_q - the value of bearing capacity factor at the given friction angle.

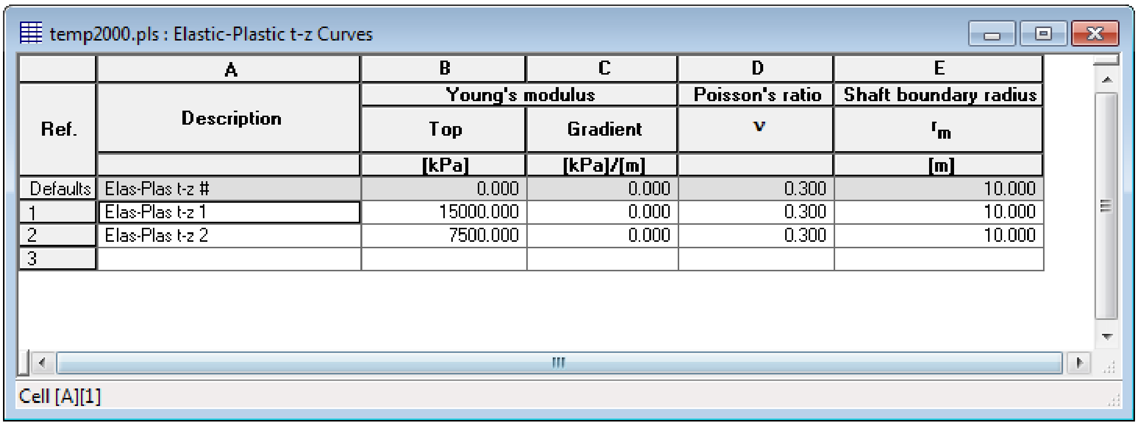
This table view is used by the Berezantzev (1961) and Bolton (1984) methods for calculating N_q.

5.13 t-z Curve Data

There are 6 types of t-z curves currently supported by the program. The following sections will cover these options in detail.

5.13.1 Elastic-Plastic

Each record in the **Elastic-Plastic t-z Curves'** table view consists of the following items.


temp2000.pls : Elastic-Plastic t-z Curves

	A	B	C	D	E
Ref.	Description	Young's modulus		Poisson's ratio	Shaft boundary radius
		Top	Gradient	ν	r_m
		[kPa]	[kPa]/[m]		[m]
Defaults	Elas-Plas t-z #	0.000	0.000	0.300	10.000
1	Elas-Plas t-z 1	15000.000	0.000	0.300	10.000
2	Elas-Plas t-z 2	7500.000	0.000	0.300	10.000
3					

Cell [A][1]

Description - the name of the curve.

Young's modulus

Top - the Young's modulus at top of the soil layer.

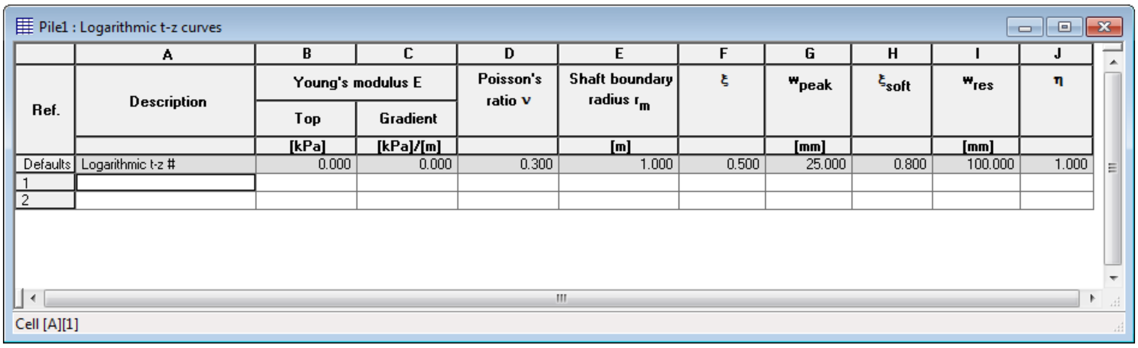
Gradient - the rate at which the modulus changes down the layer.

Poisson's ratio - the Poisson's ratio of the material.

r_m - the radial distance at which the shear stress in the soil becomes negligible.

5.13.2 Logarithmic

Each record in the **Logarithmic t-z Curves'** table view consists of the following items.


Pile1 : Logarithmic t-z curves

	A	B	C	D	E	F	G	H	I	J
Ref.	Description	Young's modulus E		Poisson's ratio ν	Shaft boundary radius r_m	ξ	w_{peak}	$ξ_{soft}$	w_{res}	η
		Top	Gradient							
		[kPa]	[kPa]/[m]		[m]		[mm]		[mm]	
Defaults	Logarithmic t-z #	0.000	0.000	0.300	1.000	0.500	25.000	0.800	100.000	1.000
1										
2										

Cell [A][1]

Description - the name of the curve.

Young's modulus E

Top - the Young's modulus at top of the soil layer.

Gradient - the rate at which the modulus changes down the layer.

Poisson's ratio - the Poisson's ratio value of the material.

r_m - the radial distance at which the shear stress in the soil becomes negligible.

ξ - proportion of peak force which is yield force.

w_{peak} - displacement at peak force.

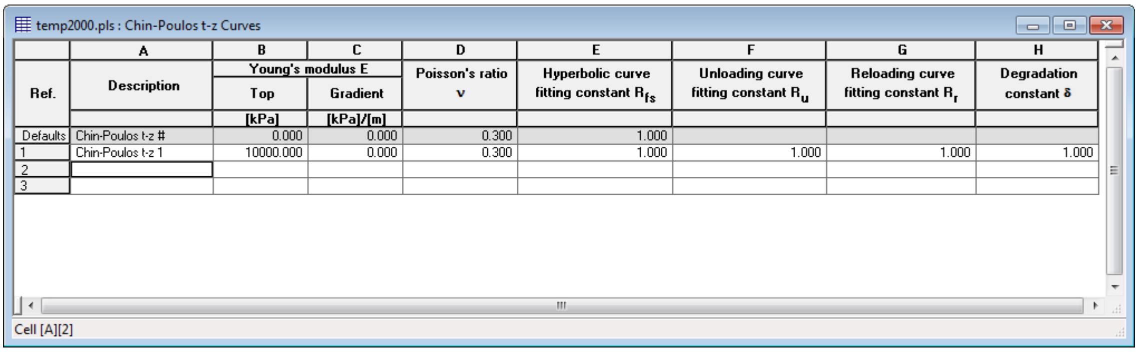
$ξ_{soft}$ - fraction of minimum post-peak force.

w_{res} - post-peak displacement to minimum post-peak force.

? - shape parameter controlling the rate of degradation

5.13.3 Chin and Poulos

Each record in the **Chin and Poulos t-z Curves'** table view consists of the following items.


temp2000.pls : Chin-Poulos t-z Curves

	A	B	C	D	E	F	G	H
Ref.	Description	Young's modulus E Top [kPa]	Young's modulus E Gradient [kPa]/[m]	Poisson's ratio v	Hyperbolic curve fitting constant R_{fs}	Unloading curve fitting constant R_u	Reloading curve fitting constant R_r	Degradation constant δ
Defaults	Chin-Poulos t-z #	0.000	0.000	0.300	1.000			
1	Chin-Poulos t-z 1	10000.000	0.000	0.300	1.000	1.000	1.000	1.000
2								
3								

Cell [A][2]

Description - the name of the curve.

Young's modulus E

Top - the Young's modulus at top of the soil layer.

Gradient - the rate at which the modulus changes down the layer.

Poisson's ratio - the Poisson's ratio of the material.

Hyperbolic curve fitting constant R_{fs} - the hyperbolic constant for pile shaft elements.

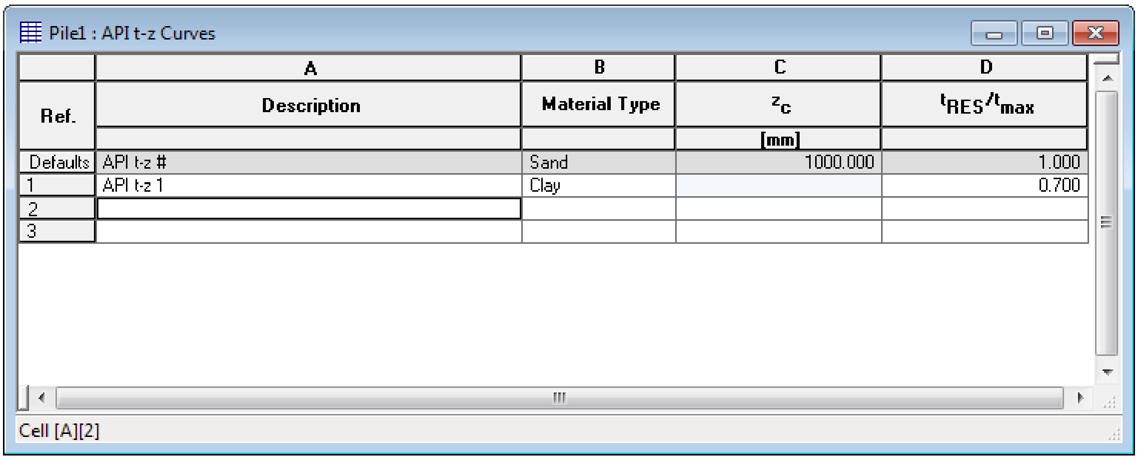
Unloading curve fitting constant R_u - the curve fitting constant for the unloading curve.

Reloading curve fitting constant R_r - the curve fitting constant for the reloading curve.

Degradation constant δ - the secant modulus degradation value due to cyclic loading.

5.13.4 API

Each record in the **Empirical t-z Curves'** table consists of the following items.



Description - the name of the curve.

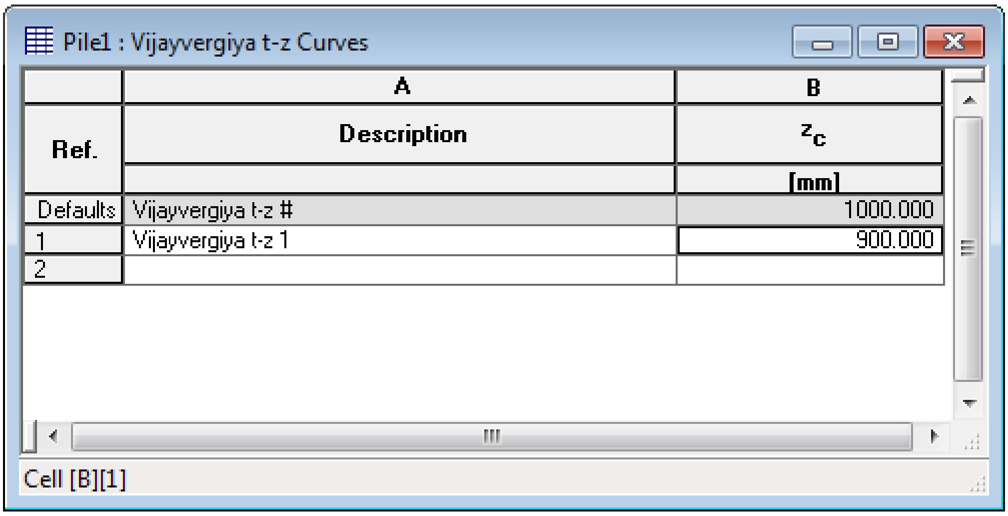
Material Type - selection has to be made between two materials: sand and clay.

z_c - the movement required to mobilise maximum stress. This is active only when the material type is sand.

t_{RES}/t_{max} - the ratio of mobilised stress to maximum stress. This is active only when the material type is clay.

5.13.5 Vijayvergiya

Each record in the **Vijayvergiya t-z Curves'** table view consists of the following items.

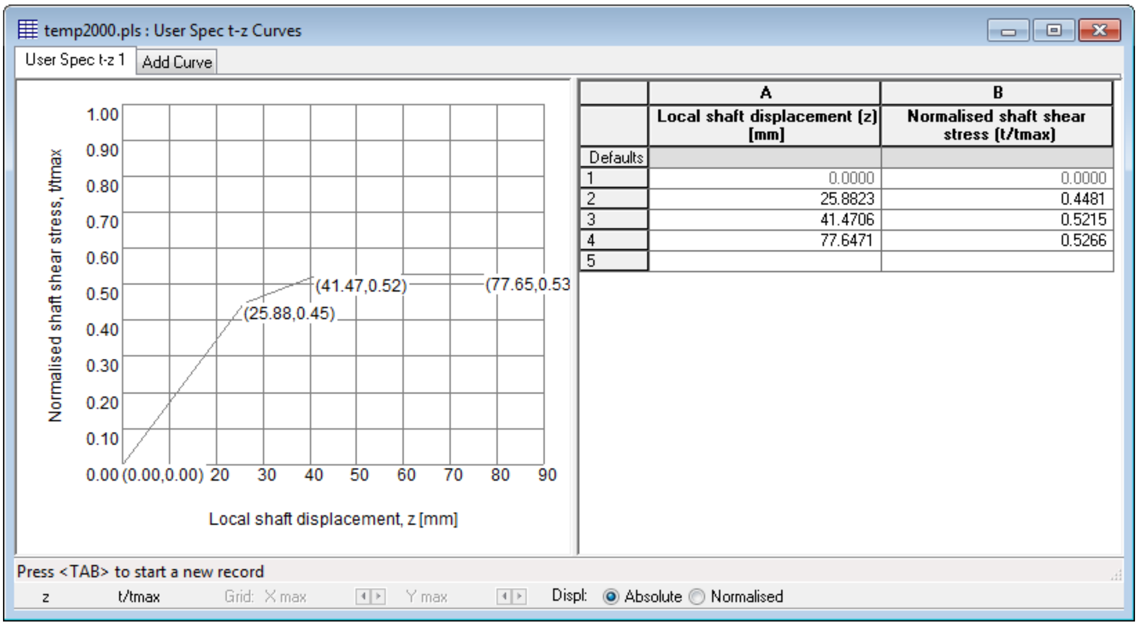


Description - the name of the curve.

z_c - the movement required to mobilise maximum stress. This value is often around 0.3 inches for sands.

5.13.6 User Specified

Each record in the **User Specified t-z Curves'** table view consists of the following items.



Local shaft displacement z - the shaft displacement. This can also be normalised by selecting the normalised radio button. By default, it is absolute.

Normalised shaft shear stress t/tmax - the ratio of mobilised shear stress to maximum shear stress.

5.14 Tip Load Curve Data

There are 6 types of tip load curves supported by the program. The following sections cover these options in detail.

5.14.1 Elastic-Plastic

Each record in the **Elastic-Plastic Tip Load Curves'** table view consists of the following items.

temp2000.pls : Elastic-Plastic Tip-Load Curves

	A	B	C	D	E
Ref.	Description	Young's modulus		Poisson's ratio	Base curve coefficient
		Top	Gradient	ν	η
		[kPa]	[kPa]/[m]		
Defaults	Elas-Plas Tip Load #	0.000	0.000	0.300	1.000
1	Elas-Plas Tip Load 1	15000.000	0.000	0.300	1.000
2					

Cell [E][0]

Description - the name of the curve.

Young's modulus

Top - the Young's modulus at top of the soil layer.

Gradient - the rate at which the modulus changes down the layer.

Poisson's ratio - the Poisson's ratio value of the material.

η - the base curve coefficient which allows for the depth of the pile base below the surface.

5.14.2 Chin and Poulos

Each record in the **Chin and Poulos Tip Load Curves'** table view consists of the following items.

temp2000.pls : Chin-Poulos tip load curves

	A	B	C	D	E	F	G	H
Ref.	Description	Young's modulus E		Poisson's ratio	Hyperbolic curve fitting constant R_{fb}	Unloading curve fitting constant R_u	Reloading curve fitting constant R_r	Degradation constant δ
		Top	Gradient	ν				
		[kPa]	[kPa]/[m]					
Defaults	Chin-Poulos Tip Load #	0.000	0.000	0.300	1.000			
1	Chin-Poulos Tip Load 1	10000.000	0.000	0.300	1.000	1.000	1.000	1.000
2								
3								

Cell [A][2]

Description - the name of the curve.

Young's modulus E

Top - the Young's modulus at the top of the soil layer.

Gradient - the rate at which the modulus changes down the layer.

Poisson's ratio - the Poisson's ratio value of the material.

Hyperbolic curve fitting constant R_{fb} - the hyperbolic constant for pile base element.

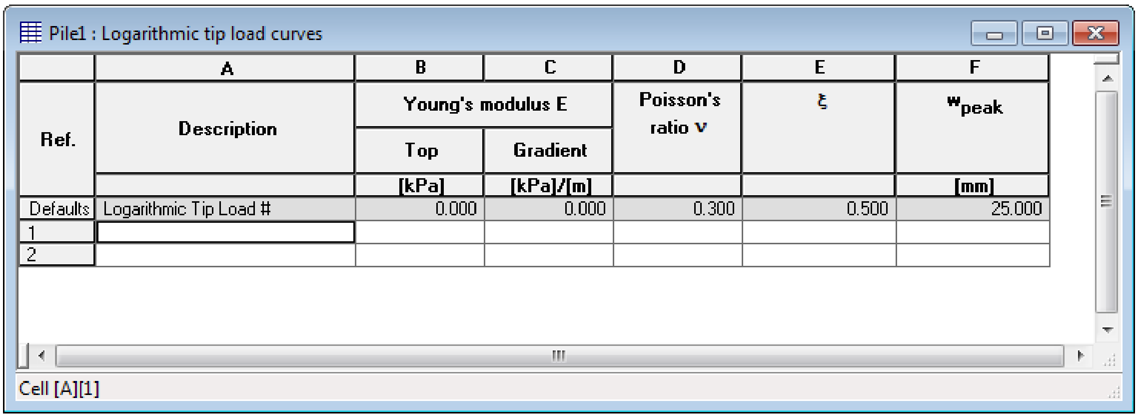
Unloading curve fitting constant R_u - the curve fitting constant for the unloading curve.

Reloading curve fitting constant R_r - the curve fitting constant for the reloading curve.

Degradation constant δ - the secant modulus degradation value due to cyclic loading.

5.14.3 Logarithmic

Each record in the **Logarithmic tip load Curves**' table view consists of the following items.



Description - the name of the curve.

Young's modulus E

Top - the Young's modulus at the top of the soil layer.

Gradient - the rate at which the modulus changes down the layer.

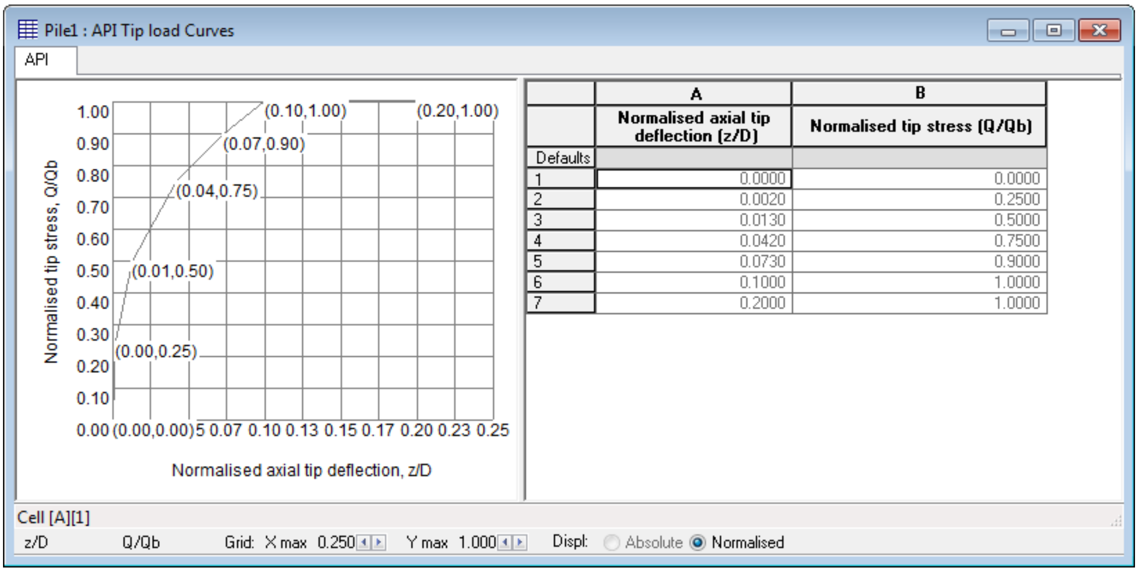
Poisson's ratio - the Poisson's ratio value of the material.

ξ - proportion of peak force which is yield force

w_{peak} - displacement at peak force

5.14.4 API

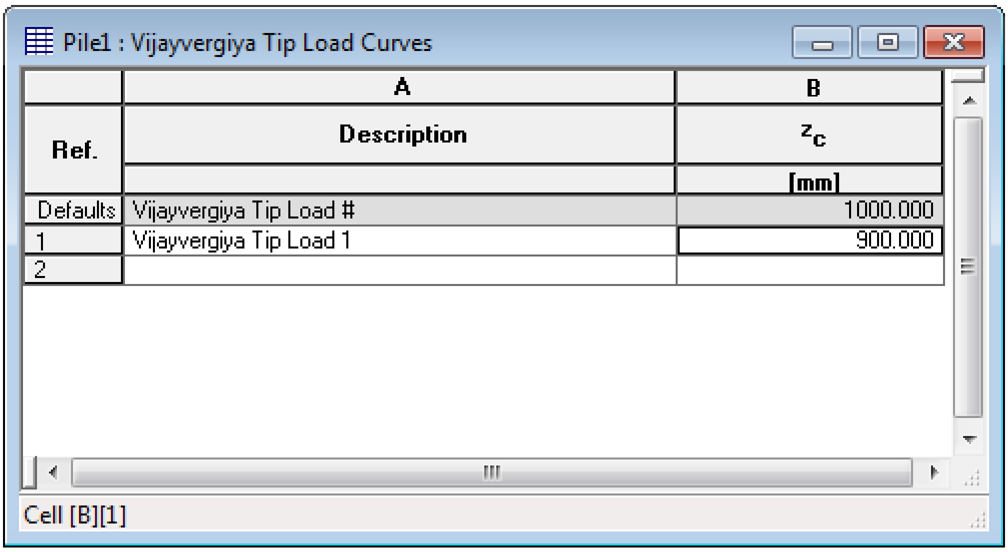
API Tip Load Curve is a standard curve and is non-editable.



	A	B
	Normalised axial tip deflection (z/D)	Normalised tip stress (Q/Qb)
Defaults		
1	0.0000	0.0000
2	0.0020	0.2500
3	0.0130	0.5000
4	0.0420	0.7500
5	0.0730	0.9000
6	0.1000	1.0000
7	0.2000	1.0000

5.14.5 Vijayvergiya

Each record in the **Vijayvergiya t-z Curves'** table view consists of the following items.



	A	B
Ref.	Description	z_c [mm]
Defaults	Vijayvergiya Tip Load #	1000.000
1	Vijayvergiya Tip Load 1	900.000
2		

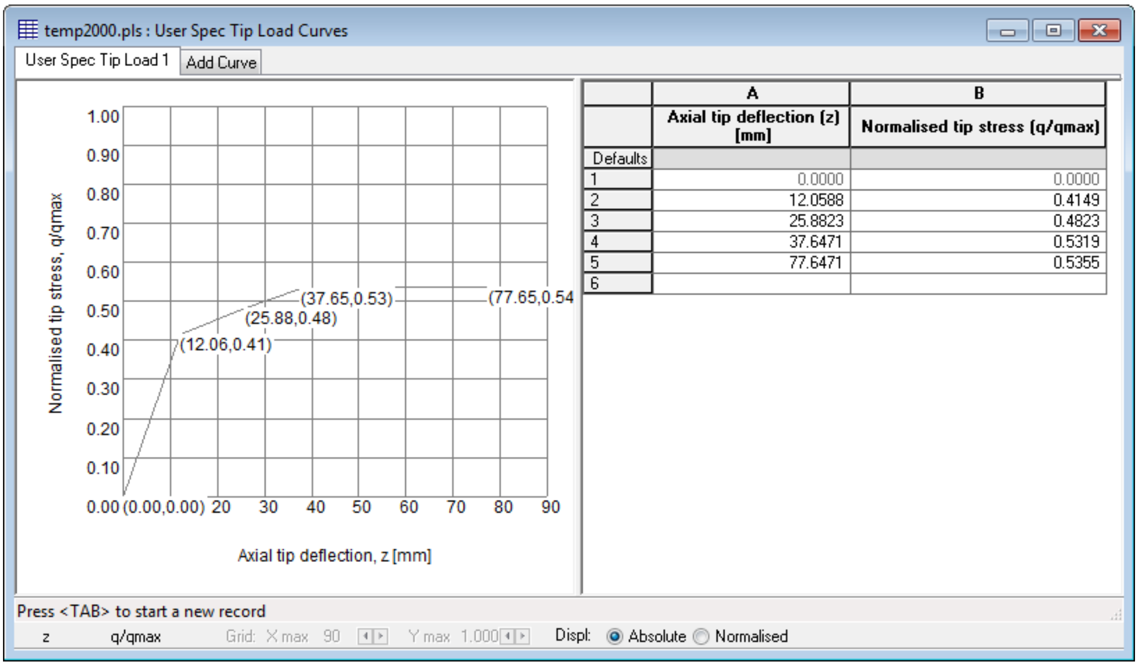
Description - the name of the curve.

z_c - the movement required to mobilise maximum tip resistance. This value is often around 0.25

inches for sands.

5.14.6 User Specified

Each record in the **User Specified t-z Curves'** table view consists of the following items.

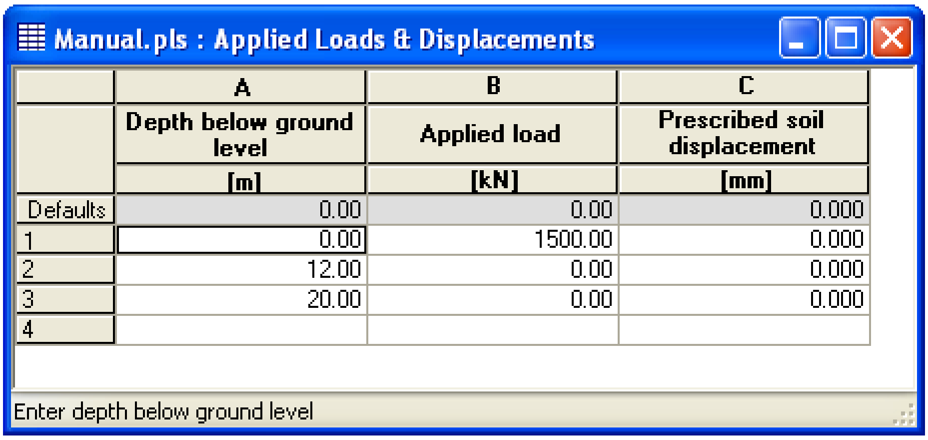


Axial tip deflection z - the deflection at the tip. It can also be normalised by selecting the normalised radio button. By default, it is absolute.

Normalised tip stress q/q_{max} - the ratio of mobilised tip stress to maximum tip stress.

5.15 Applied Loads & Displacements

Each record in the **Applied Loads & Displacements** table view consists of the following items.



	A	B	C
	Depth below ground level	Applied load	Prescribed soil displacement
	[m]	[kN]	[mm]
Defaults	0.00	0.00	0.000
1	0.00	1500.00	0.000
2	12.00	0.00	0.000
3	20.00	0.00	0.000
4			

Level/ Depth below ground level - level/depth at which the pressure is the specified.

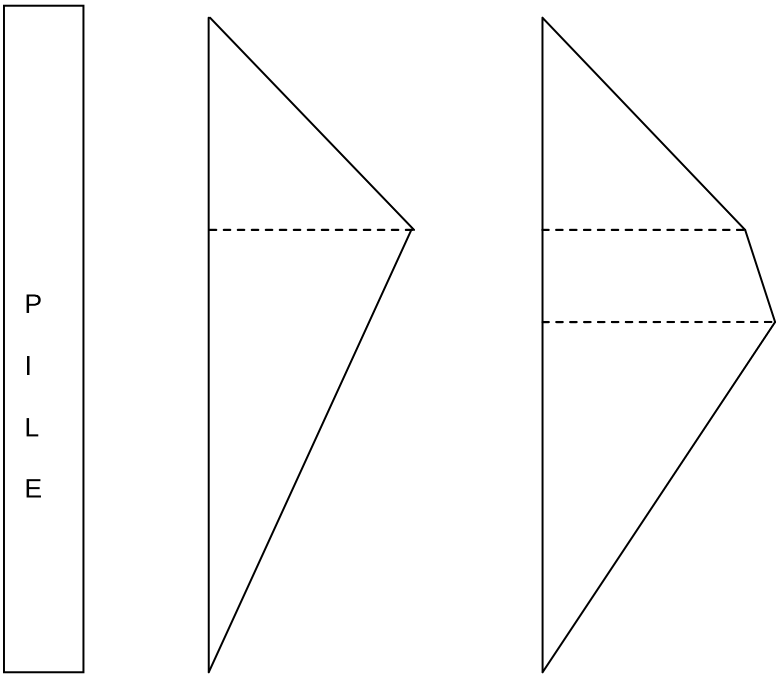
Applied load - downward positive and upward negative.

Prescribed soil displacement - heave is defined as negative displacement and settlement as positive displacement. i.e soil moving upward negative and downward positive.

Note: Prescribed soil displacement is only available for settlement calculations.

The data are specified at appropriate levels down the pile. The data can be entered in any order, the program internally arranges levels and interpolates between the levels to determine the values of prescribed soil displacement at each node down the pile. It assumes zero displacement at top and bottom of pile if not entered.

Interpolation of prescribed displacement down the pile shown below.

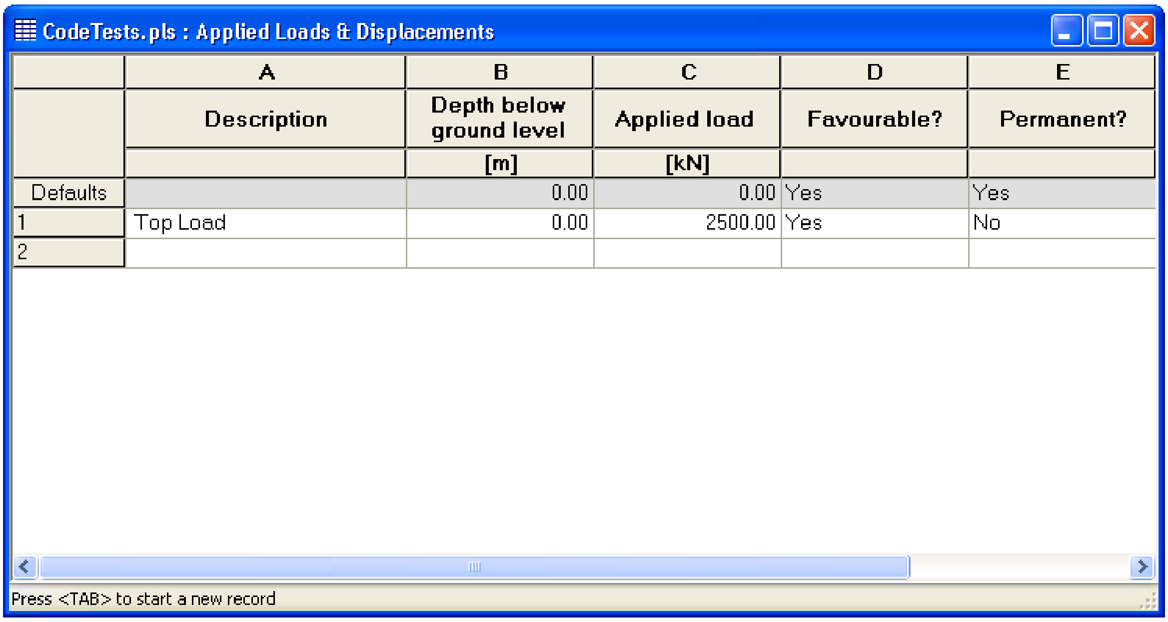


Single data is entered for prescribed displacement

Multiple data is entered for prescribed displacement

This table view changes when Code-based capacity calculations are selected, as shown below.

<u>EC7 (No National Annex)</u>

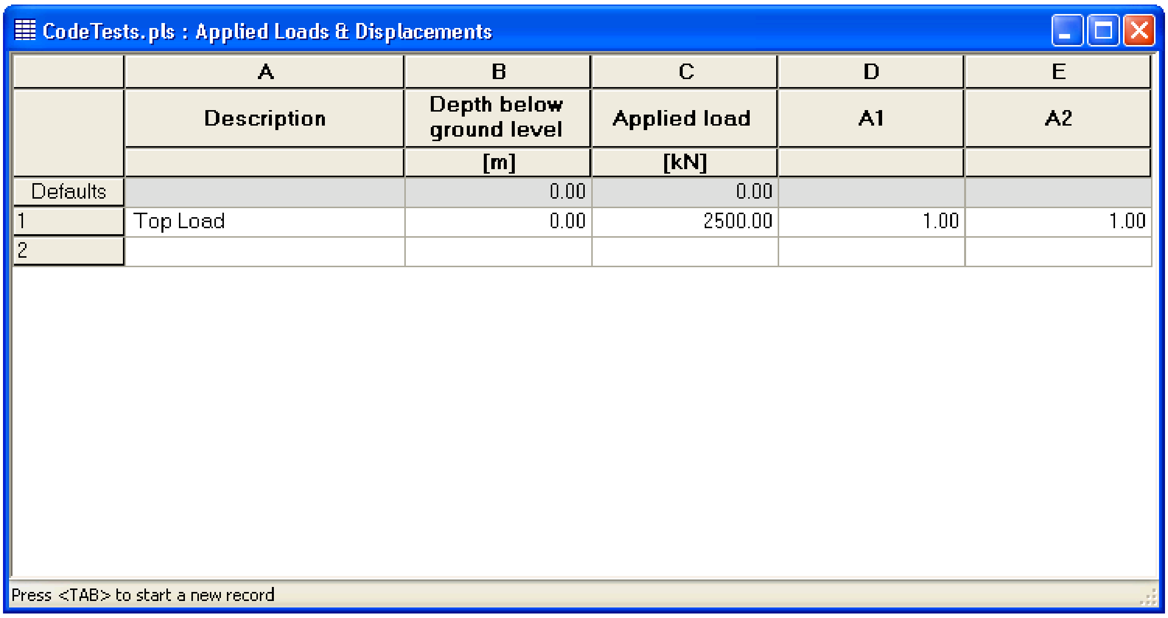

CodeTests.pls : Applied Loads & Displacements

	A	B	C	D	E
	Description	Depth below ground level	Applied load	Favourable?	Permanent?
		[m]	[kN]		
Defaults		0.00	0.00	Yes	Yes
1	Top Load	0.00	2500.00	Yes	No
2					

Press <TAB> to start a new record

For this case whether a load is permanent, and whether a load is favourable need to be specified.

EC7 (United Kingdom)

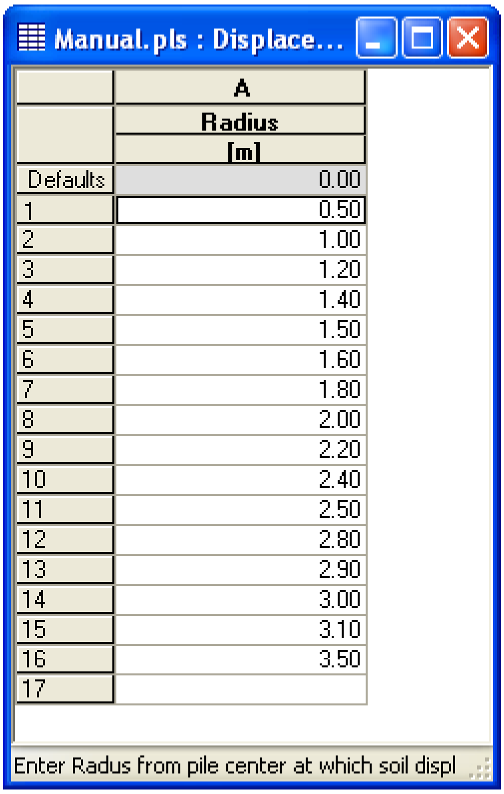


	A	B	C	D	E
	Description	Depth below ground level	Applied load	A1	A2
		[m]	[kN]		
Defaults		0.00	0.00		
1	Top Load	0.00	2500.00	1.00	1.00
2					

In this case the explicit load factors for A1 and A2 load factor sets need to be specified.

5.16 Displacement Radii

Each record in the **Displacement Radii** table view consists of the following items.



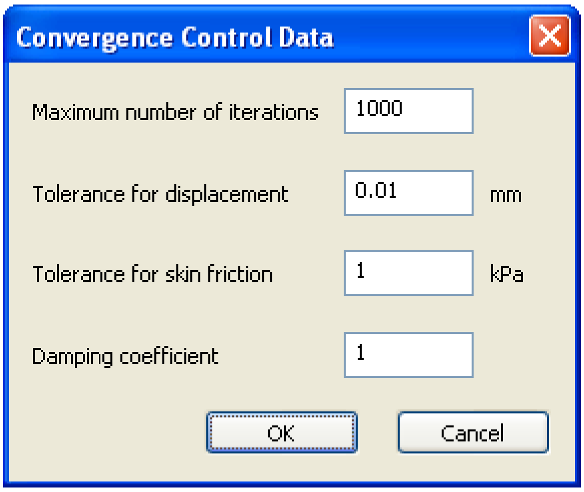
	A
	Radius
	[m]
Defaults	0.00
1	0.50
2	1.00
3	1.20
4	1.40
5	1.50
6	1.60
7	1.80
8	2.00
9	2.20
10	2.40
11	2.50
12	2.80
13	2.90
14	3.00
15	3.10
16	3.50
17	

Radius - the radius from the pile at which soil displacements are to be calculated.

If the displacement radius entered is less then the shaft/base radius, the displacements are calculated at the interface of pile and soil (i.e. at the radius of shaft/base)

5.17 Convergence Control Data

The **Convergence Control Data** dialog presents the following input data.



Tolerance for displacement - the maximum change of displacement between successive iterations. The absolute error will be considerably larger (typically by a factor of 100).

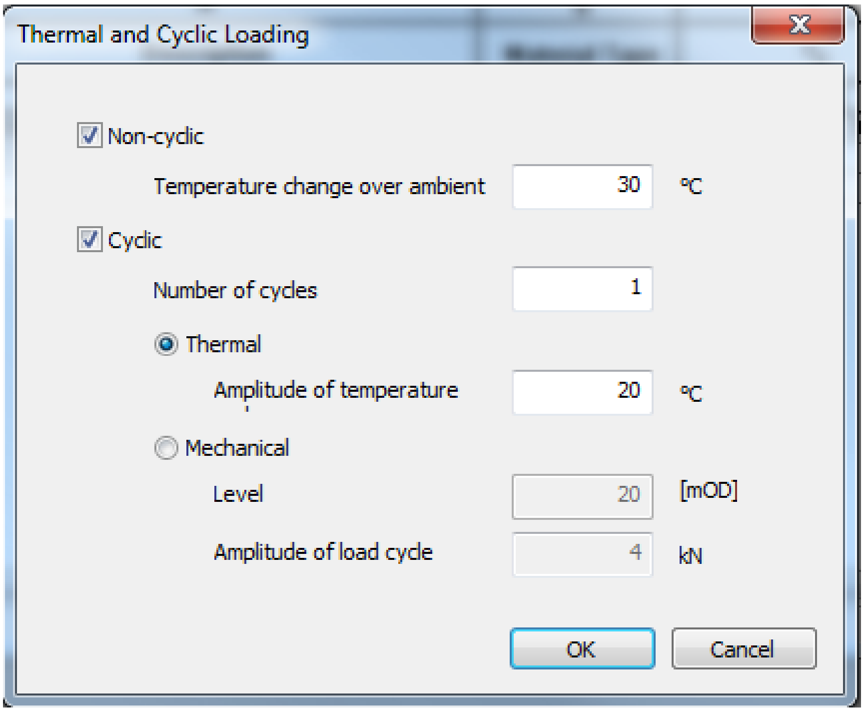
Tolerance for skin friction - the maximum error in the shaft skin friction (i.e. how much the skin friction exceeds the limiting value). This is an absolute value.

Damping coefficient - can be enhanced if convergence is slow.

If instability is apparent it may possibly be solved by reducing this coefficient.

5.18 Thermal and Cyclic Loading

The **Thermal and Cyclic Loading** dialog presents the following input data.



Non-cyclic - if checked, non-cyclic thermal load will be applied

Temperature change over ambient - the change in pile temperature from the ambient temperature.

Cyclic - if checked, cyclic thermal load or cyclic mechanical load will be applied depending on the selection.

Number of cycles - the number of loading cycles to be applied

Thermal - if selected, thermal loading cycles will be applied

Amplitude of temperature change- the change in temperature from the mean temperature

Mechanical - if selected, mechanical loading cycles will be applied

Level - level at which the mechanical load is to be applied

Amplitude of load cycle - the load to be applied

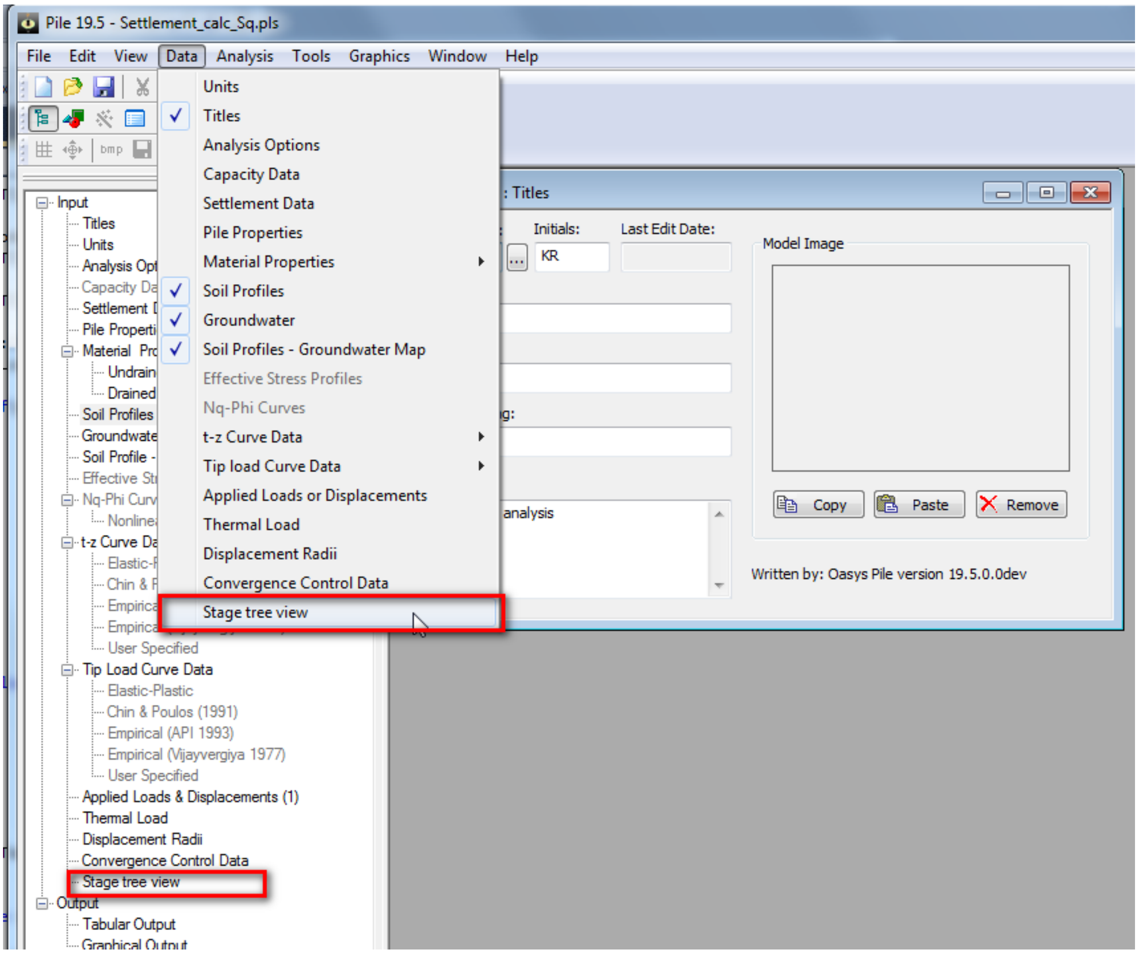
6 Staged Analysis

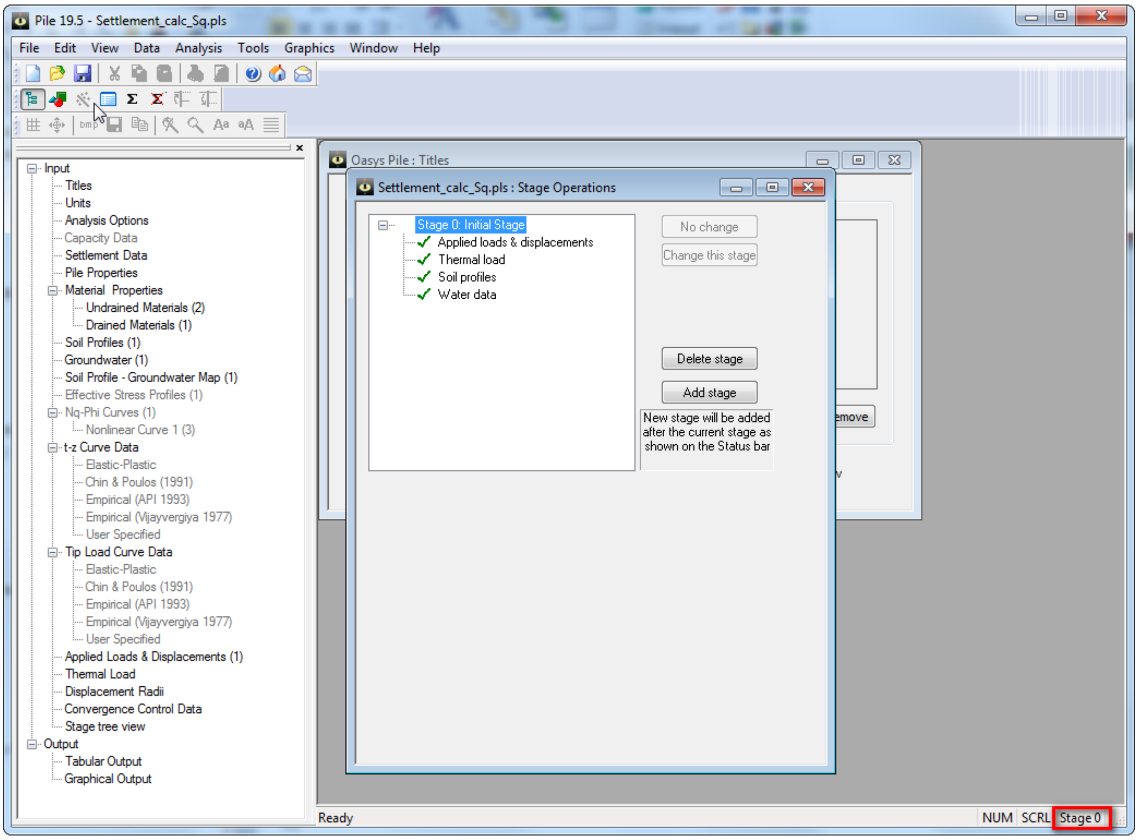
Oasys Pile program allows the users to analyse different stages which follow one another. This is available **only** when t-z curves option is selected.

The following data can be changed between different stages:

- Applied loads and displacements
- Thermal loads
- Soil profile
- Groundwater data

When a new file is created, the program inserts the default "Initial stage" (Stage 0). The user can set up further stages from the Stage tree view. This can be invoked from the Gateway or menu as shown:





The current stage index is displayed in the "Stage indicator" located at the bottom right corner of the application window.

The Stage data menu allows the data to be modified for individual stages using the Stage Operations window. This opens a tree diagram, which allows access to all available options for each stage. Ticks are placed against those options which have been changed.

This window also allows the creation of new stages and the deletion of those no longer required. When "Add stage" is selected the new stage can be inserted after a highlighted stage.

Parameters can also be set to change in a particular stage.

Note: Left-click on the boxes to open or close the tree diagram for each stage. The dialog or view corresponding to stage specific data i.e. Soil profiles, Applied loads & displacements etc. can be accessed either from this tree view or from the gateway.

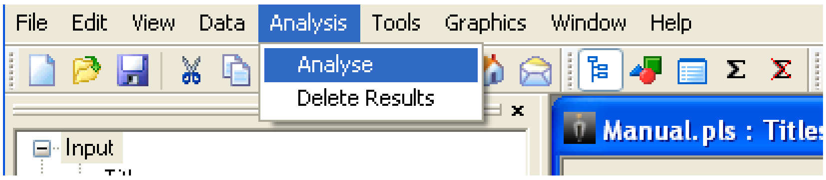
The program calculates the pile capacity and settlement for each stage, based on whether the user has selected capacity analysis or settlement analysis. For the settlement analysis, the program treats the pile and soil displacements obtained from analysis of a particular stage as the initial displacements for the next stage.

The initial t-z curves are generated and used for the first load increment of the initial stage. The program updates the t-z curves for each node after each load increment. When there is no material change at a particular node, the t-z curve of the node from the last increment of the last stage is used. However, it the node is in a drained material, and effective stress changes between stages, the program generates the new t-z curve for this revised stress state, and uses the same for the new stage.The same procedure is followed if the material changes at a node between stages.

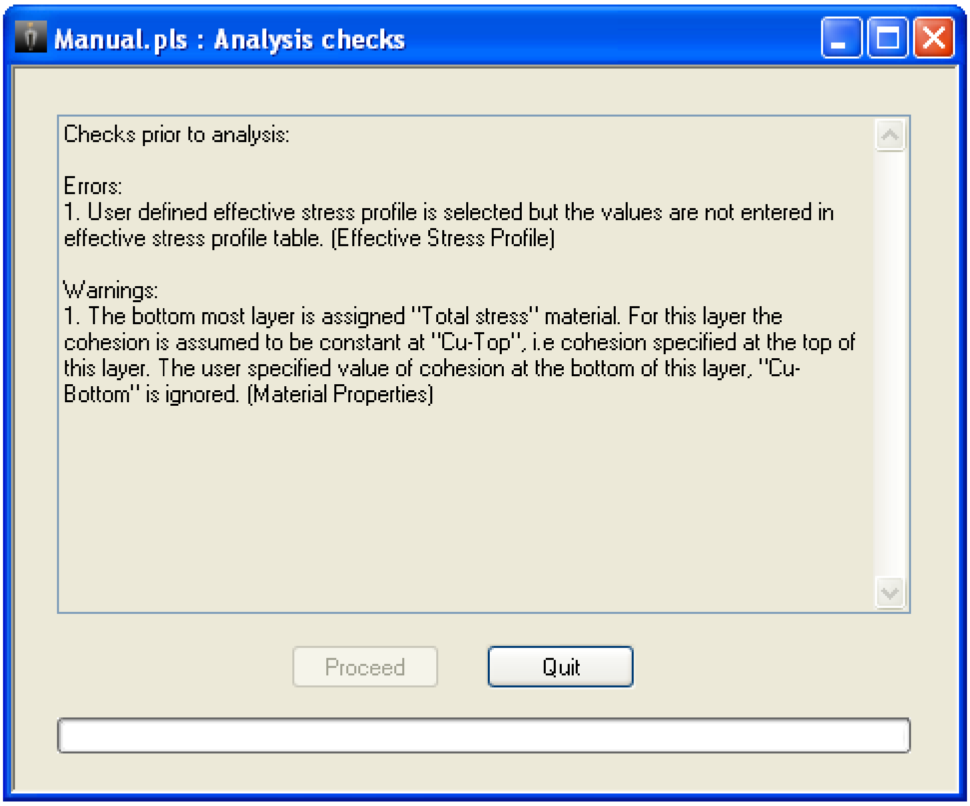
7 Output

7.1 Analysis and Data Checking

The data can be analysed via Analysis | Analyse from the program menu or the analysis button  on the analysis toolbar.

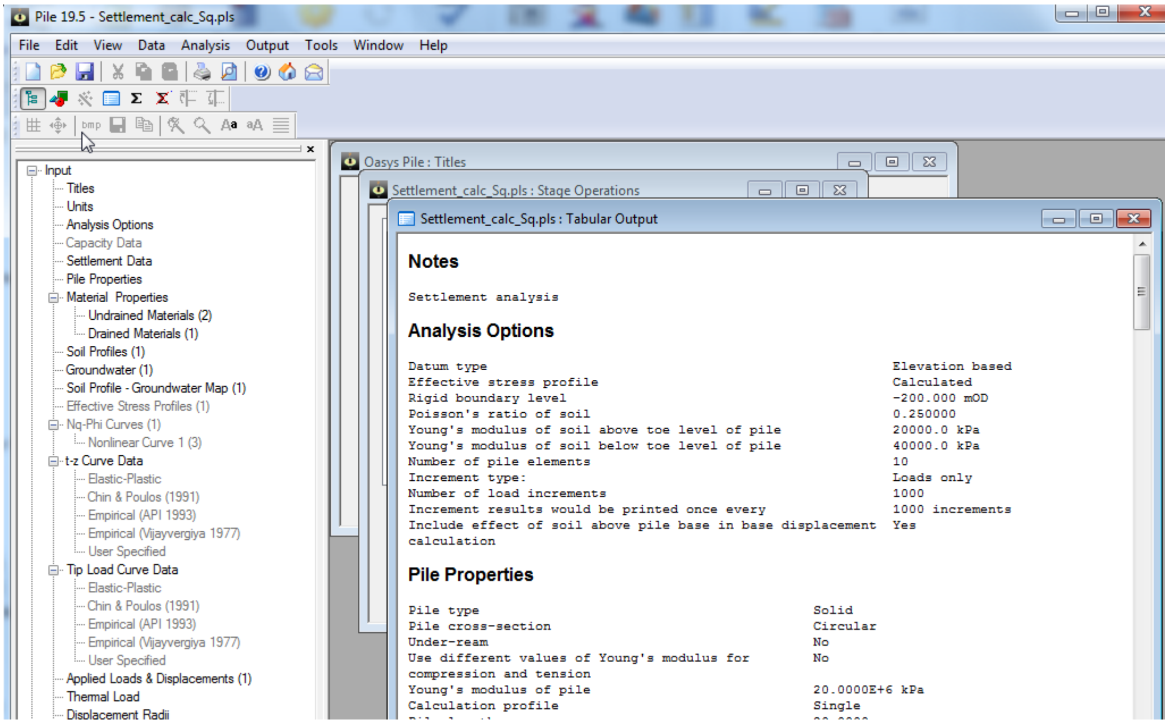


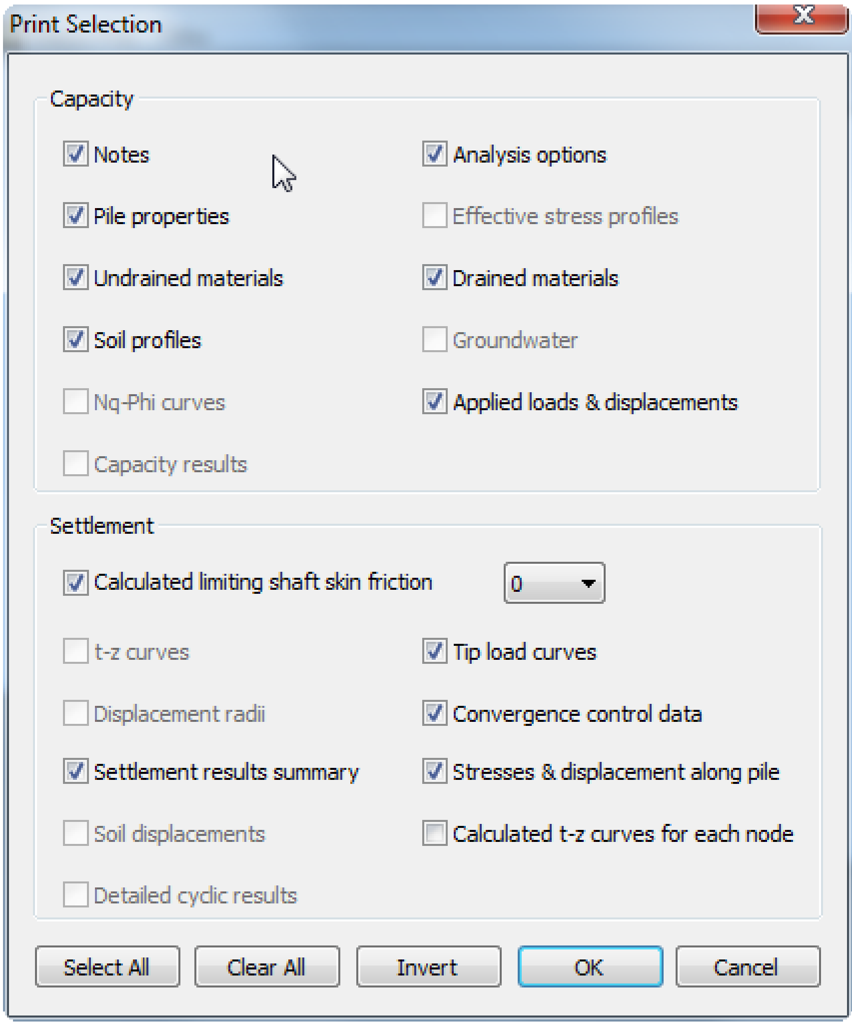
Prior to analysing the data, the program performs various checks and gives warnings/errors if the data is not consistent. Warnings do not prevent an analysis. Errors do and must be corrected before an analysis may proceed.



7.2 Tabular Output

Tabulated output is accessible from the View menu, the Gateway or the Pile toolbar. This output may include input data and results if an analysis has been performed.





The results are provided in a tabular form, containing the levels corresponding to the depth(s) of the pile and the various load capacities at the given level.

The results are printed for all the soil profiles.

However, for model pile procedure, the design capacity results are printed separately after the ultimate capacity results etc. are printed from all the soil profiles.

The pile limiting shaft skin friction, shaft skin friction, pile stress, pile and soil displacement at the given level are tabulated for each pile length and each cross-section and for each load increment.

The number of outputs of calculated limiting shaft skin friction within a layer can be selected in the Print Selection dialog.

The analysis warnings may also be viewed in the results.

Manual.pls : Tabular Output

Cross-section 1 results:

Results - Compression

Level [mOD]	Pile length [m]	Ultimate base capacity (Q_b) [kN]	Cumulative external Friction (Q_s) [kN]	Negative skin friction (Q_{nsf}) [kN]	Ultimate capacity [kN]	Allowable capacity [kN]	Limiting criterion #
3.0000	5.0000	989.60	144.15	0.0	1133.8	288.30	3
2.0000	6.0000	1131.0	196.89	0.0	1327.9	393.78	3
1.0000	7.0000	1272.3	256.66	0.0	1529.0	513.32	3
0.0	8.0000	1413.7	323.46	0.0	1737.2	646.92	3
0.0	8.0000	152.68	323.46	0.0	476.14	190.46	1
-1.0000	9.0000	173.04	377.75	0.0	550.79	220.31	1
-2.0000	10.000	193.40	438.82	0.0	632.22	252.89	1
-3.0000	11.000	213.75	506.68	0.0	720.43	288.17	1
-4.0000	12.000	234.11	581.32	0.0	815.43	326.17	1
-5.0000	13.000	254.47	662.75	0.0	917.22	366.89	1
-6.0000	14.000	274.83	750.97	0.0	1025.8	410.32	1
-7.0000	15.000	295.18	845.97	0.0	1141.2	456.46	1
-8.0000	16.000	315.54	947.76	0.0	1263.3	505.32	1
-9.0000	17.000	335.90	1056.3	0.0	1392.2	556.89	1
-10.000	18.000	356.26	1171.7	0.0	1527.9	611.18	1
-11.000	19.000	376.61	1293.8	0.0	1670.5	668.18	1
-12.000	20.000	396.97	1422.8	0.0	1819.7	727.90	1
-13.000	21.000	417.33	1558.5	0.0	1975.8	790.33	1
-14.000	22.000	437.69	1701.0	0.0	2138.7	855.47	1
-15.000	23.000	458.04	1850.3	0.0	2308.3	923.33	1
-16.000	24.000	478.40	2006.3	0.0	2484.8	993.90	1
-17.000	25.000	498.76	2169.2	0.0	2668.0	1067.2	1

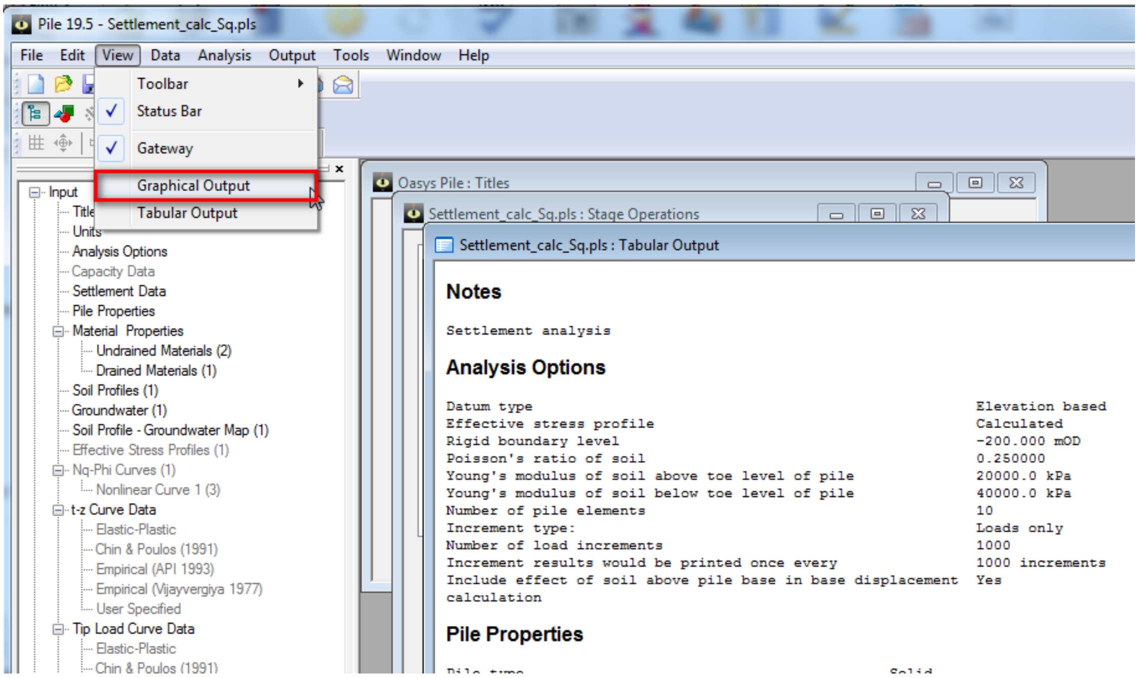
The lists of tabulated output can be highlighted and then copied to the clipboard and pasted into most Microsoft Windows type applications e.g. Microsoft Word or Excel. The output can also be directly exported to various text or HTML formats by choosing 'File | Export' from the program menu.

Sign conventions are as follows:

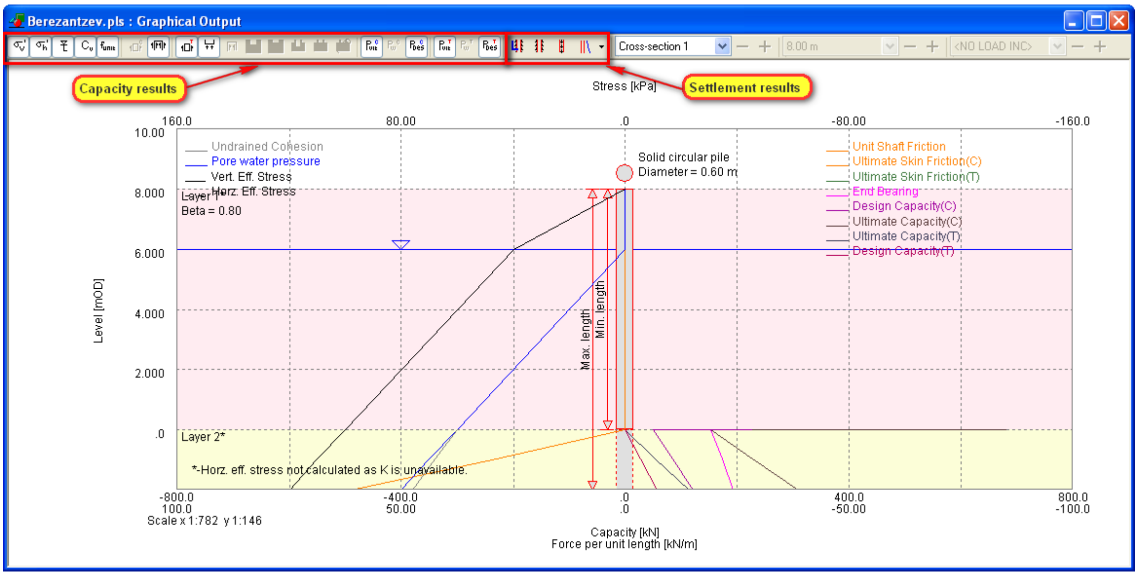
- Displacements - negative movement is upwards (e.g. soil heave), and positive is downwards (e.g. pile or soil settlements)
- Applied load - downward positive and upward negative
- Pile stress - compression positive and tension negative
- Base pressure - downwards positive and upward negative

7.3 Graphical Output

Graphical output of data and results is accessed via the View menu, the Gateway or the Pile toolbar.

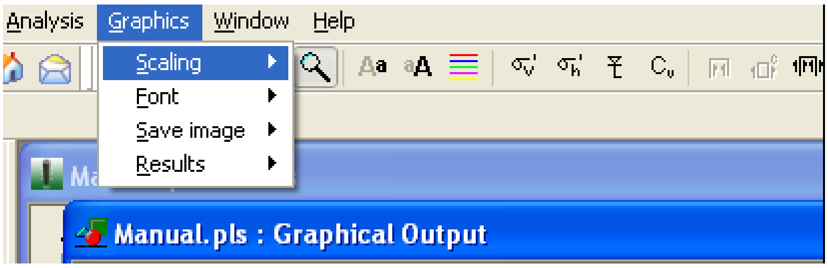


The graphical representation of the soil layers, the pile and the cross-section of the pile is shown.



Introduction to Graphics menu

When the Graphical Output View is open the graphics menu shows the following options.



Graphical toolbar buttons

Axis - provides a reference grid behind the drawing.

Set Scale - this allows switch between the default 'best fit' scale, the closest available engineering scale. e.g. 1:200, 1:250, 1:500, 1:1000, 1:1250, 1:2500, or exact scaling. The same options are available via the View menu's "Set exact scale" command.

Save Metafile - this save icon allows the image to be saved in the format of a Windows metafile. This retains the viewed scale. The metafile can be imported into other programs such as word processors, spreadsheets and drawing packages.

Zoom Facility - select an area to 'zoom in' to by using the mouse to click on a point on the drawing and then dragging the box outwards to select the area to be viewed. The program will automatically scale the new view. The original area can be restored by clicking on the 'restore zoom' icon as shown here.

Smaller/Larger font - adjusts font sizes on the Graphical Output View.

Edit colours - allows line and fill colours to be edited.

Save BMP - saves the file as a bitmap.

Copy - copies the graphical view to the clip board.

Capacity

Vertical effective stress - toggles the vertical effective stress plot.

Horizontal effective stress - toggles the horizontal effective stress plot.

Pore water pressure - toggles the pore water pressure plot.

Undrained cohesion - toggles the undrained cohesion plot.

Unit shaft friction - toggles the unit shaft friction plot.

External skin friction compression - toggles the external skin friction compression plot.

Total skin friction compression - toggles the total skin friction compression plot.

Total skin friction tension - toggles the total skin friction tension plot.

 **Axis** - provides a reference grid behind the drawing.

 **End bearing capacity** - toggles the end bearing capacity plot.

 **Internal skin friction** - toggles the internal skin friction plot.

 **Wall end bearing** - toggles the wall end bearing plot.

 **Plugged end bearing** - toggles the plugged end bearing plot.

 **Plugged capacity** - toggles the plugged capacity plot.

 **Unplugged capacity** - toggles the unplugged capacity plot.

 **Unplugged capacity - auto plugged** - toggles the unplugged capacity - auto plugged plot.

 **Ultimate load compression** - toggles the ultimate load compression plot.

 **Working load compression** - toggles the working load compression plot.

 **Design load compression** - toggles the design load compression plot.

 **Ultimate load tension** - toggles the ultimate load tension plot.

 **Working load tension** - toggles the working load tension plot.

 **Design load tension** - toggles the design load tension plot.

Settlement

 **Limiting Shaft Skin Friction -** toggles the limiting shaft skin friction plot.

 **Shaft Skin Friction -** toggles the shaft skin friction plot.

 Pile Stress - toggles the pile stress plot.

 **Pile/Soil Displacement -** toggles the displacements for pile or soil.

 **Envelope -** toggles whether or not envelope of results is plotted for cyclic loading sub stages.

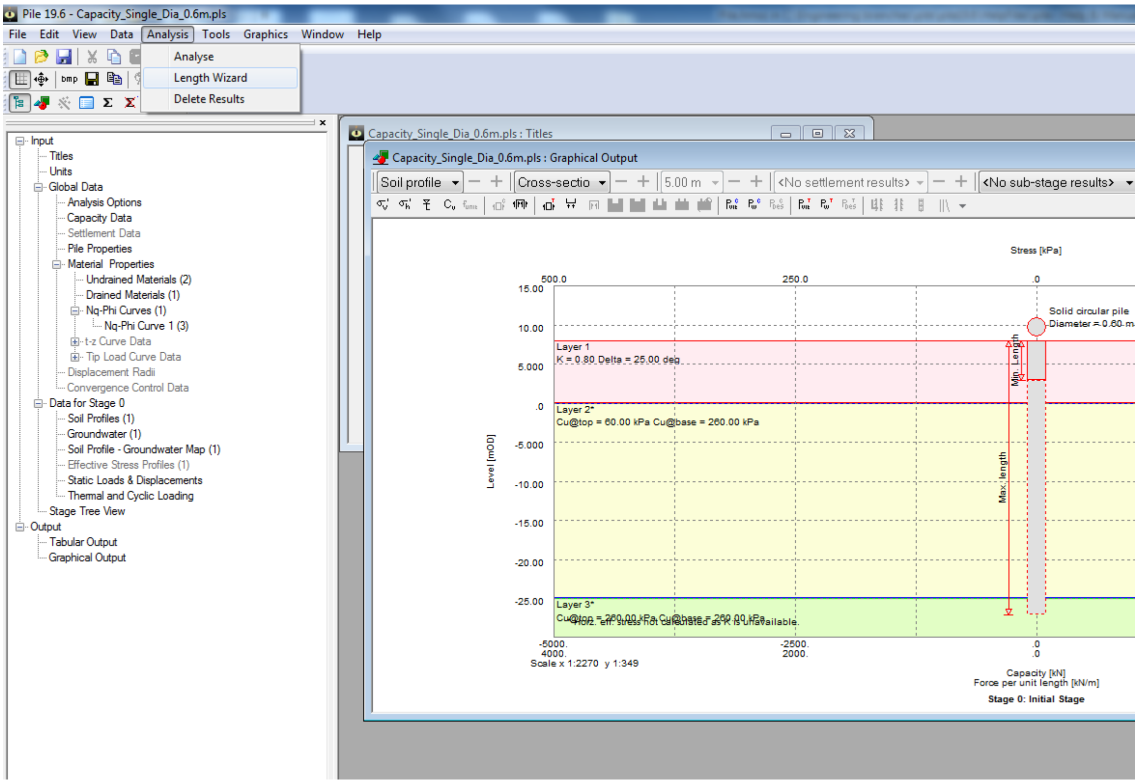
Drop lists above the Graphical Output View allow selection of capacity and settlement results according to selected soil profiles, pile cross-sections, pile lengths, applied load/displacement increments and sub-stages.

The plot can be exported in WMF format via the "Graphics->Save image->Save WMF" menu item.

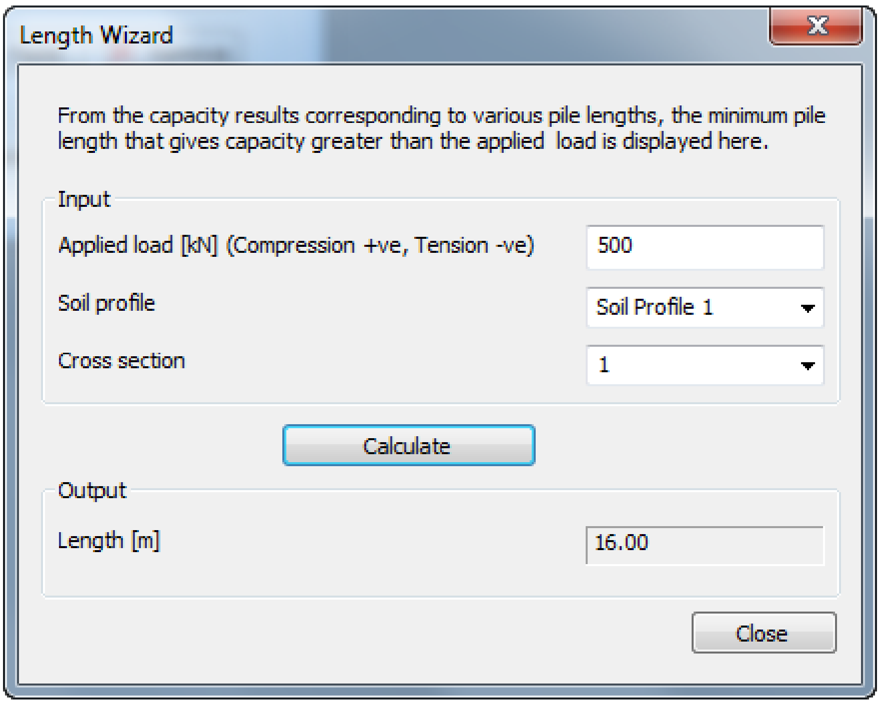
7.3.1 Length Wizard

The user can also invoke a pile length calculator to find out the required length of a pile for a given applied load. From the available results, the program gives the lowest pile length whose capacity is greater than the applied load.

This can be invoked by clicking the wizard button as shown below:



After this dialog is invoked, the user needs to enter the soil profile, and pile cross section of interest, and then press the "Calculate" button to view the result.



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9 Manual Example

9.1 General

The data input and results for the **Pile** manual examples are available in the 'Samples' sub-folder of the program installation folder. The examples have been created to show the data input for all aspects of the program and do not seek to provide any indication of engineering advice.

These examples can be used by new users to practise data entry and get used to the details of the program.

10 Brief Technical Description

10.1 Pile

Pile is a program which calculates the vertical load carrying capacities and vertical settlements of a range of individual piles in a layered soil deposit. The theory is based on both conventional and new methods for drained (frictional) and undrained (cohesive) soils. Currently the settlements are calculated for solid circular sections without under-ream.

The main features of **Pile** are summarised below.

Either capacity analysis, settlement analysis, or both can be performed for a range of pile lengths and cross-sections.

Settlements are calculated for only solid circular cross-sections without under-ream.

The soil is specified in layers. Each layer is set to be drained (frictional) or undrained (cohesive) and appropriate strength parameters are specified. Maximum values can be set for ultimate soil/ shaft friction stress and end bearing stress within each layer.

Levels may be specified as depth below ground level or elevation above ordnance datum (OD).

Porewater pressures within the soil deposit can be set to hydrostatic or piezometric.

Pile capacities may be calculated for a range of pile lengths and a range of cross-section types such as circular, square and H-section. The circular and square cross-sections may be hollow or solid, whereas the H-section is only solid. Under-reams or enlarged bases may be specified.

Pile settlements may be calculated for a range of pile lengths and a range of solid circular cross-sections without under-ream.

There are two approaches available to calculate the capacity of the pile - working load approach and limit-state approach.

The graphical output depicts the variation of different pile capacities such as shaft resistance, end bearing, total bearing with pile depth and settlements of pile or soil. This may be exported in WMF format.

The text output contains the tabular representation of the input data and results. They may be exported to CSV format.

Legacy Pile and Pilset files may be read. Limiting shaft skin friction is calculated from the material properties, so the reading of limiting shaft skin friction from legacy Pilset files is ignored. results in CSV format.

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