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Strain Wedge Model Computer Program for Piles and Large Diameter Shafts with LRFD Procedure

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16. Abstract

The research evaluated strain wedge model computer program (SWM6.2) for piles and large diameter shafts with LRFD procedure. It illustrated program capability, input data, and output data. It also provided some examples and publications for various applications.

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REPORT AND USER MANUAL

ON

STRAIN WEDGE MODEL COMPUTER PROGRAM FOR PILES AND LARGE DIAMETER SHAFTS WITH LRFD PROCEDURE

CCEER 07-07

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REPORT/MANUAL CONTENTS

PROGRAM CAPABILITIES

The current SWM6.2 computer program has the following capabilities:

- Based on the Strain Wedge (SW) Model Analysis, the computer program SWM6.2 allows the assessment of:
  - **Lateral/Axial response of isolated (single) pile and large diameter shaft**
    - Pile/shaft classification (short, intermediate or long) based on soil and pile properties
    - Pile head lateral load-deflection behavior
    - Lateral response of the isolated pile that includes (lateral deflection, bending moment, shear force and soil reaction) at particular values of pile head lateral load
    - Excess porewater distribution along a single pile in liquefied soil
    - Effect of lateral soil spreading on the pile response
    - p-y curves at different points on the isolated pile (max. 5 curves per run)
    - t-z curve for each soil layer along the pile length
    - Pile lateral, axial and rotational (spring) stiffnesses
    - Axial response of the pile (Load-settlement curve)
    - Skin and tip axial resistance of the pile
    - Moment-curvature relationship for the pile/shaft cross section(s)
    - Moment-pile bending stiffness (EI) relationship for the pile/shaft cross section(s)
    - Curvature-pile bending stiffness (EI) relationship for the pile/shaft cross section(s)
    - Linear and nonlinear modeling for pile/shaft materials.

  - **Lateral response of pile/shaft group**
    - The advantage to use the LRFD procedure in the analysis
    - Lateral resistance of a pile group with or without pile cap
    - Pile head lateral load-deflection behavior for different individual piles in the pile group
    - Lateral response (lateral deflection, bending moment, shear force and soil-pile reaction) for individual piles in the pile group
    - Pile group lateral, axial and rotational (spring) stiffnesses (with/without pile cap)
    - Excess porewater distribution along individual piles in the group in liquefied soil
    - Effect of lateral soil spreading induced by soil liquefaction on the pile group response
    - Lateral Resistance of average pile in a group compared to a similar isolated pile

The program accounts for a pile/shaft of varying diameter, bending stiffness (EI) and type (short, intermediate or long). The linear and nonlinear behavior of pile/shaft material is part of the program analysis options. Linear behavior represents a fixed value for the bending stiffness (EI) of the pile cross-section(s) which is the initial EI. Nonlinear behavior allows the EI of each pile section to vary with the level of loading based on the moment-curvature relationship.

INPUT DATA

The SWM6.2 is a window-based program that works under Windows 95, 98, 2000, ME, XP and NT. The program has different windows (forms) with different titles to enter the pile/shaft and soil properties, and the basic characterization of the problem. The program has the following basic windows:

- Window # 1 (Problem Configuration) [**Fig. 1**]
    - Define the type of the targeted problem (Single Pile or Pile Group)
    - Choose the units used for input and output data (the program can covert the input data if another unit system has been chosen)
    - Click *p-y Curve* to open ***Window # 1-1*** for the desired p-y curve of a single pile using the ***SW model analysis*** (see Fig. 2 for Window 1-1).
    - If Pile Group problem is checked, *Pile Group* option in the Menu Bar will be enabled. Click Pile Group option in the Menu Bar to open ***Window # 1-2*** for pile group input data (see Fig. 3 for Window 1-2).

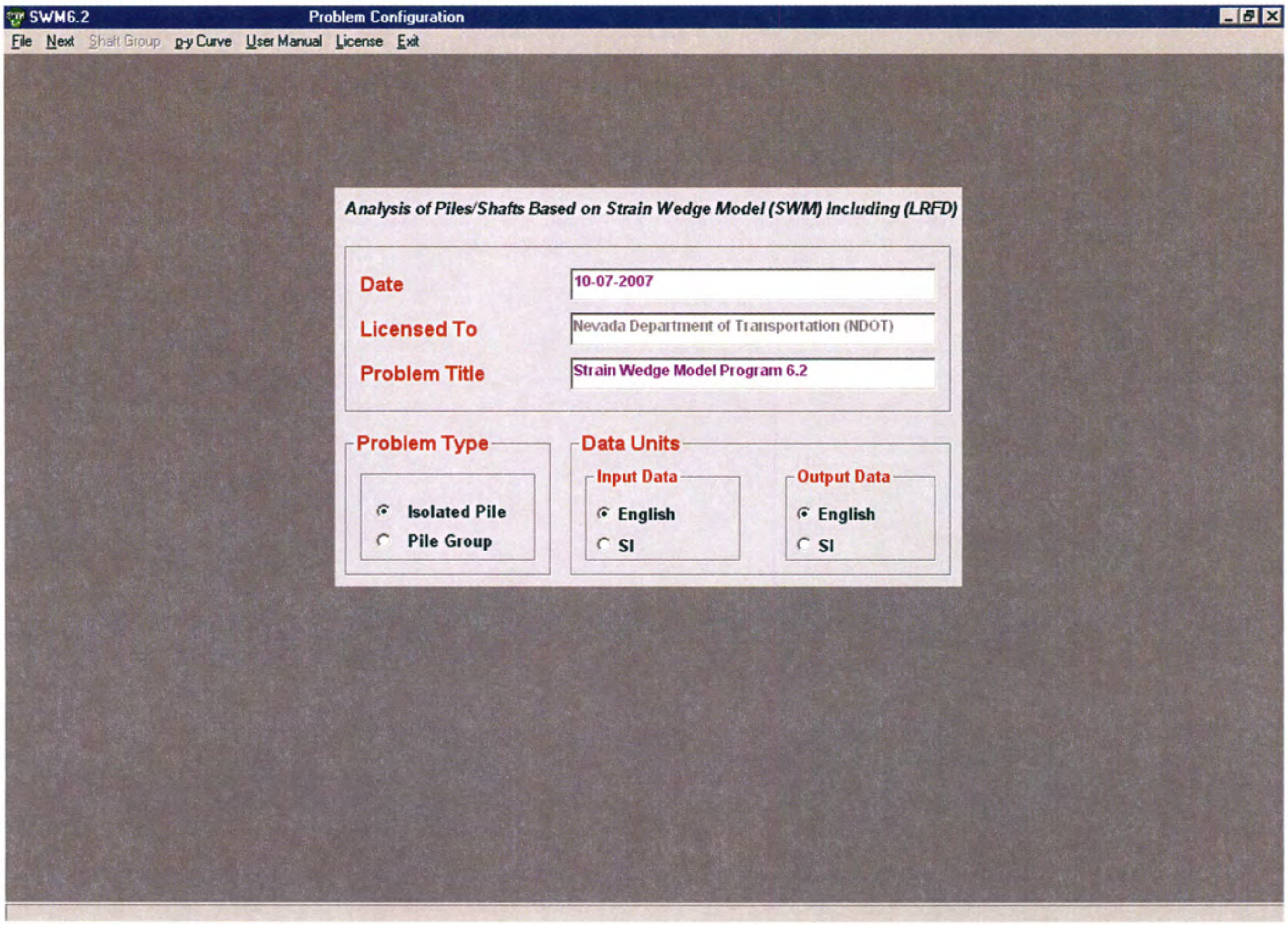


Fig. 1 Window #1 (Problem Configuration)

- Window # 1-1 (p-y Curves) [**Fig. 2**]

  This window is available with the SW model Analysis and accessed only from ***Window # 1***. The SW model does not need to enter p-y curves. p-y curves in the SW model analysis are determined and provided as output. The SW model analysis constructs its own p-y curves and gives them as output. No p-y curves may be assigned in Window # 1-1 for output plotting.

  - **Number of p-y Curves.** Define the total number of p-y curves desired from the SW model analysis to be plotted. This governs the number of p-y curves in the next step. Maximum of 5 p-y curves may be plotted each run
  - **p-y Curve No.** Click the no. of p-y curve in question and enter its depth below pile head in the next step

- **Depth of p-y Curve Below Pile Head.** Enter the depth of the p-y curve assigned by the **p-y Curve No**. *Depth of the p-y curve is measured from pile head.*

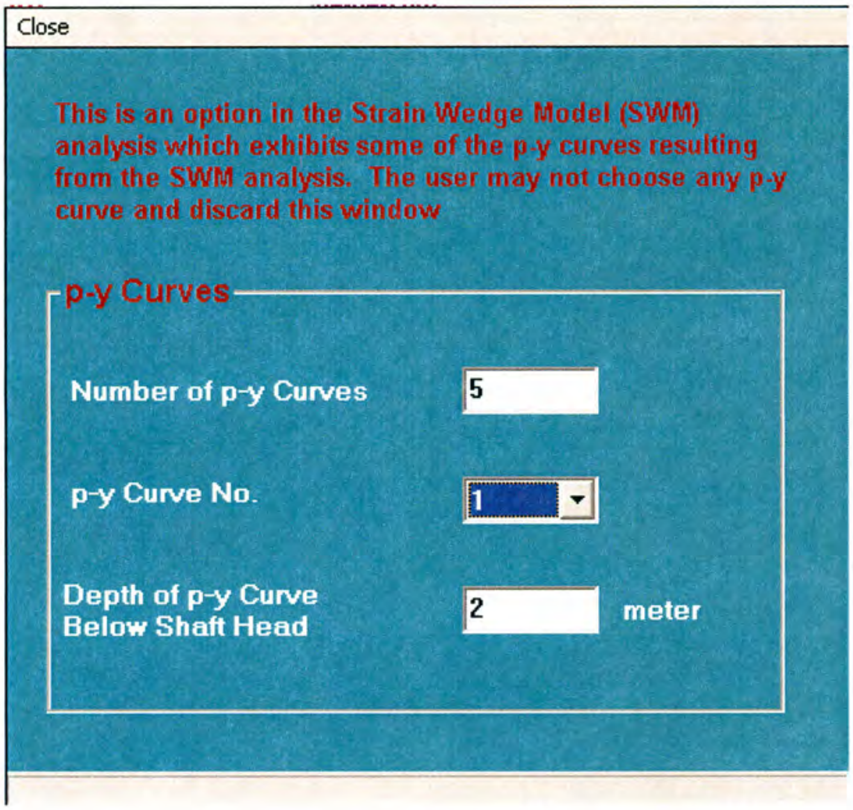


Fig. 2 Window # 1-1 (p-y curves) in the Strain Wedge Model Analysis

- Window # 1-2 (Pile Group) [**Fig. 3**]
  - This window is available in pile group analysis. Click *Pile Group* in the Menu Bar in any window to open this window. Pile Group in the Menu Bar will be disabled with the single pile/shaft analysis. The following points are shown in **Fig. 3**
  - Click the **Loading Direction** to identify the direction of the analysis and the output data (Longitudinal X-X or Transverse Y-Y)
  - **Number of Pile/Shaft Rows Parallel to the X-X Axis**: Enter the number of shaft/pile rows aligned parallel to the X-X axis that represents the longitudinal direction of the bridge.
  - **Number of Pile/Shaft Rows Parallel to the Y-Y Axis**: Enter the number of shaft/pile rows aligned parallel to the Y-Y axis that represents the transverse direction of the bridge.

- **Pile Spacing (S1)**: Enter the center-to-center shaft/pile spacing of the piles/shafts in the X-X direction.
- **Pile Spacing (S2)**: Enter the center-to-center shaft/pile spacing of the piles/shafts in the Y-Y direction.

  Based on the specified loading direction, the program automatically distributes the piles/shafts and pile/shaft spacing to be consistent with the loading direction.

- **Pile Cap**: Check *Pile Cap Effect* to include the shaft cap influence on the structural system of the whole pile group. Based on the loading direction, the existence of a shaft cap converts the external moment (M) on the pile/shaft group to axial compression/tension forces on the piles of the group. Check the Pile Cap effect to enable the entry of cap properties **(Figs. 3 and 4)**.

  - **Cap Contribution to Lateral Resistance (Yes / No)**: Once Pile Cap Effect is checked, the Pile Cap properties will be accessible. The option "Yes" provides evaluation of passive and side resistance of soil as applied to the pile cap. Option "No" neglects the effect of the soil resistance around the cap but the program still accounts for the presence of cap and its effect (frame action) on load/moment distribution. This is also true for caps located above ground surface.
  - **Pile Cap W-Width**: Enter the length of pile cap side in the X-X direction direction.
  - **Pile Cap L-Length**: Enter the length of the shaft cap side in the Y-Y direction.
  - **Pile Cap Thickness (T)**: Enter the thickness (depth) of the pile cap.
  - Depth of Pile Cap Surface below Ground Surface (d): Enter the location of the top of the pile cap below ground surface.
  - **Depth of Pile Cap Surface Below Ground Surface (d).** Enter the location of the top of the pile cap below ground surface.

- Click *the Pile Distribution* in the Menu Bar to show the plot of distribution of the piles in a group with or without pile cap, pile spacing, and numbers.
- Click *Pile Definitions* in the Menu Bar to show the different types of pile in the pile group according to the location of the pile in the group and the direction of loading (**Fig. 5**).

- NOTES:

- The two illustrative figures for pile group shown in Window 1-2 help the user to identify the loading direction.
- Pile spacing is the same in a given direction.
- The pile group matrix is always square or rectangular in shape.
- The piles in the group are identical (i.e. have the same properties).

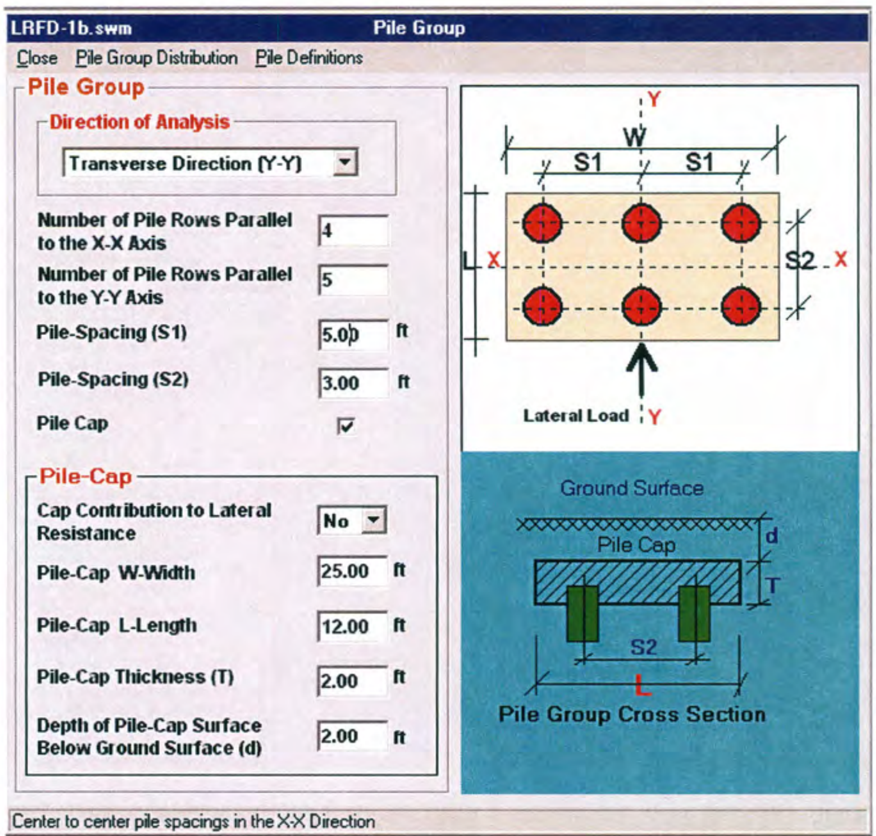


Fig. 3 Window # 1-2 (Pile Group)

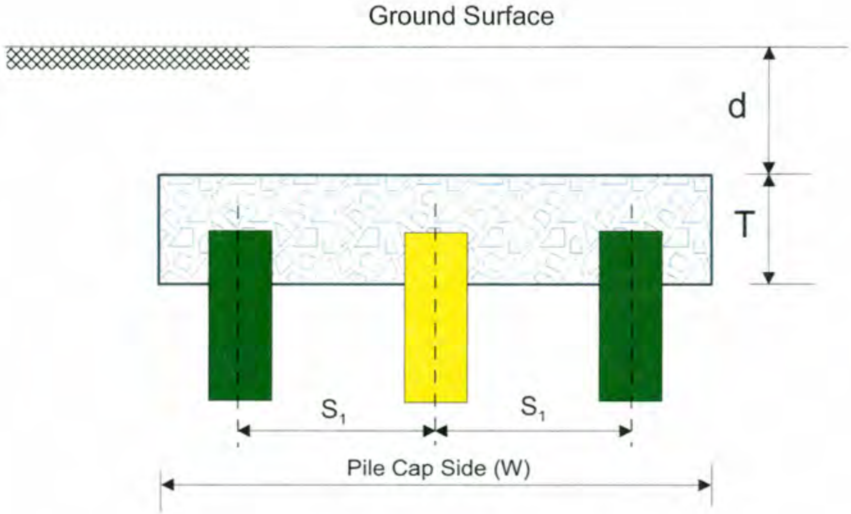


Fig. 4 Configuration of the Pile Cap

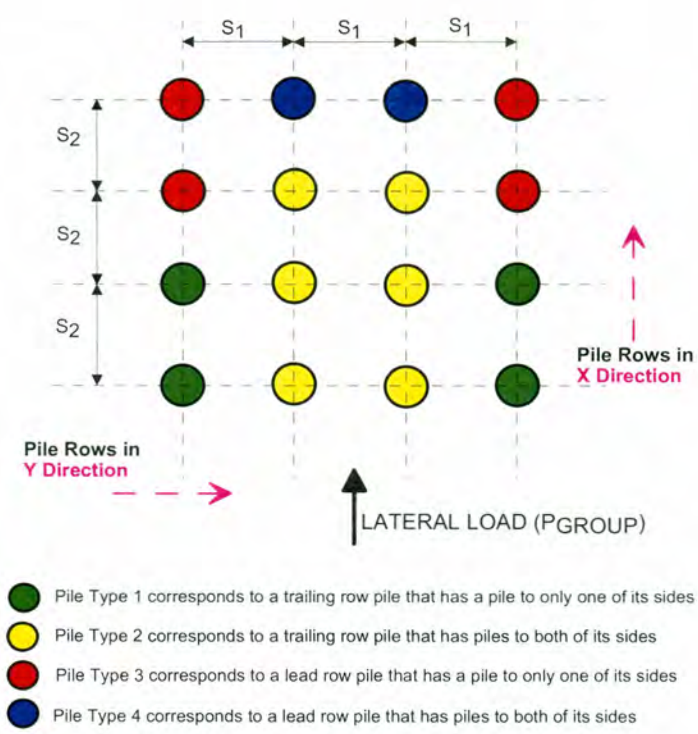


Fig. 5 Description and Distribution of Piles in a Group

- Window # 2 (Pile Properties) **[Fig. 6]**

See **Fig. 7** for more details on the pile/shaft properties and its relationship to the surrounding soil profile.

- **Total length of Pile**: Enter the total length of the pile (above and below ground surface). Figure 6 provides more description on the pile/shaft geometry.
- **Total Number of pile Segments**: Enter the total number of the pile segments those of different cross sections and/or properties along the pile length. The user can use up to 5 different sections for the same pile. The pile/shaft sections may differ in dimensions and/or material properties (steel and/or concrete). For a pile/shaft with a uniform section, enter 1.
- **Location of Pile-Head above or below Ground**: This represents the vertical distance of the pile head, where the lateral load is applied, above or below ground surface. This value has a negative sign if the pile head is located below ground surface, and a positive value for the pile head located above ground.
- **Pile Head Condition:** The following options of pile-head conditions are available in the SWM6.2 program (**Fig. 8**):
    1. *Free-head pile* for a pile-head that is allowed to rotate and deflect freely. Shear (lateral) force, moment and axial load can be applied at the head of the pile. A one-row pile group normal to the direction of loading can not maintain fixed-head conditions and must have free-head conditions.
    2. *Fixed-head pile* for a pile-head that is allowed to deflect but is completely restrained from rotation. The external (applied) bending moment at the top of the isolated fixed-head pile has no effect on pile response. The external bending moment on the pile cap will be internally converted to axial loads.
    3. *Pile-head rotation = 0* (applied only with a single pile). This is similar to the fixed-head condition. Only shear force from the column will be applied at the pile head to obtain Kd and K(d-r). Any applied (external) moment at the top of the pile will not be considered in the analysis.
    4. *Pile-head deflection = 0* (applied only with a single pile). Only moment at the pile head is entered to obtain Kr and K(r-d). The moment must have a negative sign in order to work against the lateral load that is internally generated by the program in order to develop zero deflection. Any applied (external) lateral load at the top of the pile will not be considered in the analysis.

Notes:

* Kd is the pile-head lateral displacement stiffness.

* Kr is the pile-head rotational stiffness.

* K(d-r) is the pile-head rotational stiffness against the shear force applied at the pile head (i.e. the off-diagonal element of the pile-head stiffness matrix).

* K(r-d) is the pile head displacement stiffness against the moment applied at the pile head (i.e. the off-diagonal element of the pile-head stiffness matrix).

In linear material analysis associated with the Stiffness Matrix employed in the Finite Element analysis, K(d-r) should be equal to K(r-d).

Behavior of Pile Material (Type of Analysis)

The user must choose one of the following analysis options:

1. **Linear Analysis (Constant EI):** The bending stiffness (EI) of the pile cross-section is constant and does not vary with pile deformations (i.e. no pile material failure criteria). Based on the geometrical and material properties of the pile segments, the program internally determines the values of the bending stiffness for each segment. The EI value calculated by the program represents the initial EI of that pile cross-section. The user may use a lesser value for the concrete uniaxial strength in order to get a reduced EI value for the cracked section. However, the use of a constant reduced EI for the cracked concrete section is fictitious and does not reflect reality. Click Input data option in the Menu Bar of Window # 3 after executing the program to see the determined value of the initial EI(s).
2. **Non-Linear Analysis (Varying EI):** The bending stiffness (EI) of the pile cross-section varies with loading based on the moment-curvature relationship of that pile cross-section. The degradation in the pile stiffness is considered in the analysis and thus allows the identification of failure of the pile material (concrete and/or steel). Output file ***Mcurve.txt*** contains the values of the varying moment, curvature and bending stiffness (from the moment-curvature relationship) for each pile segment.

- **Pile Segment No.:** Click the number of the desired pile/shaft segment to show/enter the cross-section properties of that pile/shaft segment. The number of the last pile segment is automatically equal to the total number of pile segments.
- **Properties of pile Segment No. #**
  The title of this set of the input data will carry the number of the pile segment in question that was clicked in the option "**Pile Segment No.**" shown above. All data entered below will be related to the cross section of that particular pile segment. Some of the following input data are automatically disabled according to the type of the analysis (linear or non-linear) and the material of pile segment. The EI of each pile

segment cross-section (Fig. 9) will be determined by the program based on the data provided in the input data section shown below.

- **Steel Pile** (steel shell)
- **Concrete in Steel Casing**
- **Reinforced Concrete in Steel Casing**
- **Reinforced Concrete**
- **H-Pile (Case-1)**
- **H-Pile (Case-2)**

A schematic figure is automatically linked to each one of the above cross sections to detail the data needed. It should be mentioned that the type of pile material (i.e. its skin roughness) affects the level of adhesion/friction between the surrounding soil and pile skin.

- **Length of Pile Segment:** Enter the length of the pile segment in question.
  The sum of the lengths of all entered pile segments must equal the full length of the pile that was given earlier by the user (checked by the program).
- **Outer Diameter of Pile Segment:** Enter the outer width of the cross section of the current pile segment.
- **T-Shell (Steel Casing) or Transverse Steel Ratio:** This label changes according to the type of the chosen pile segment cross-section. With the Reinforced Concrete, the transverse steel ratio (hoops/stirrups) is visible and calculated as ($2\ A_{s'}/d\ h_s$). $A_{s'}$ is the steel area of the hoop's cross-section. d and h_s are the hoop's diameter and spacing, respectively.
- **Uniaxial Compressive Strength of Concrete:** Enter the unconfined strength of concrete after 28 days.
- **Longitudinal Steel Ratio (A_s/A_c):** Enter the percentage of the area of longitudinal steel in terms of the whole area of the concrete section.
- **Yield Stress of Longitudinal Steel:** Enter the yield stress (f_y) of the steel used with the longitudinal reinforcement.
- **Yield Stress of Steel Shell:** Enter the yield stress of the steel used for the steel casing.
- **Thickness of Concrete Cover:** Enter the outer cover of concrete on the steel rebar.
- **I_{x-x} and I_{y-y} of the H-Pile:** H-Pile (1) and H-Pile (2) depends of the direction of loading on the H-Pile cross-section that has different moment inertia in each direction. The program automatically picks the associated moment of inertia.

NOTES:

- Some of the cells in this window are enabled/disabled according to the type of analysis and the material of the specified cross-section.

- Click Help to see the Characterization of the four pile-head conditions (**Fig. 7**).

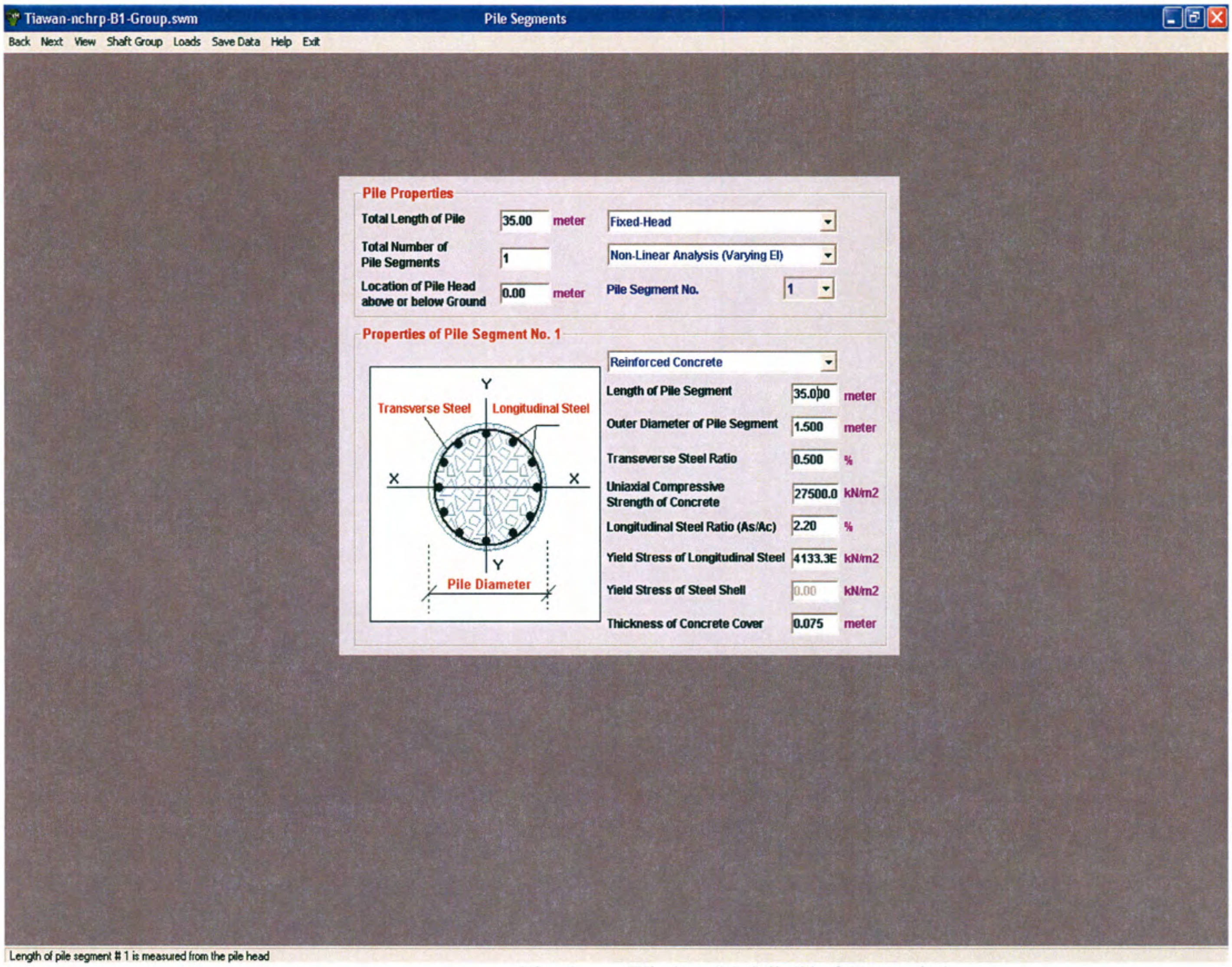


Fig. 6 Window # 2 (Pile/Shaft Properties)

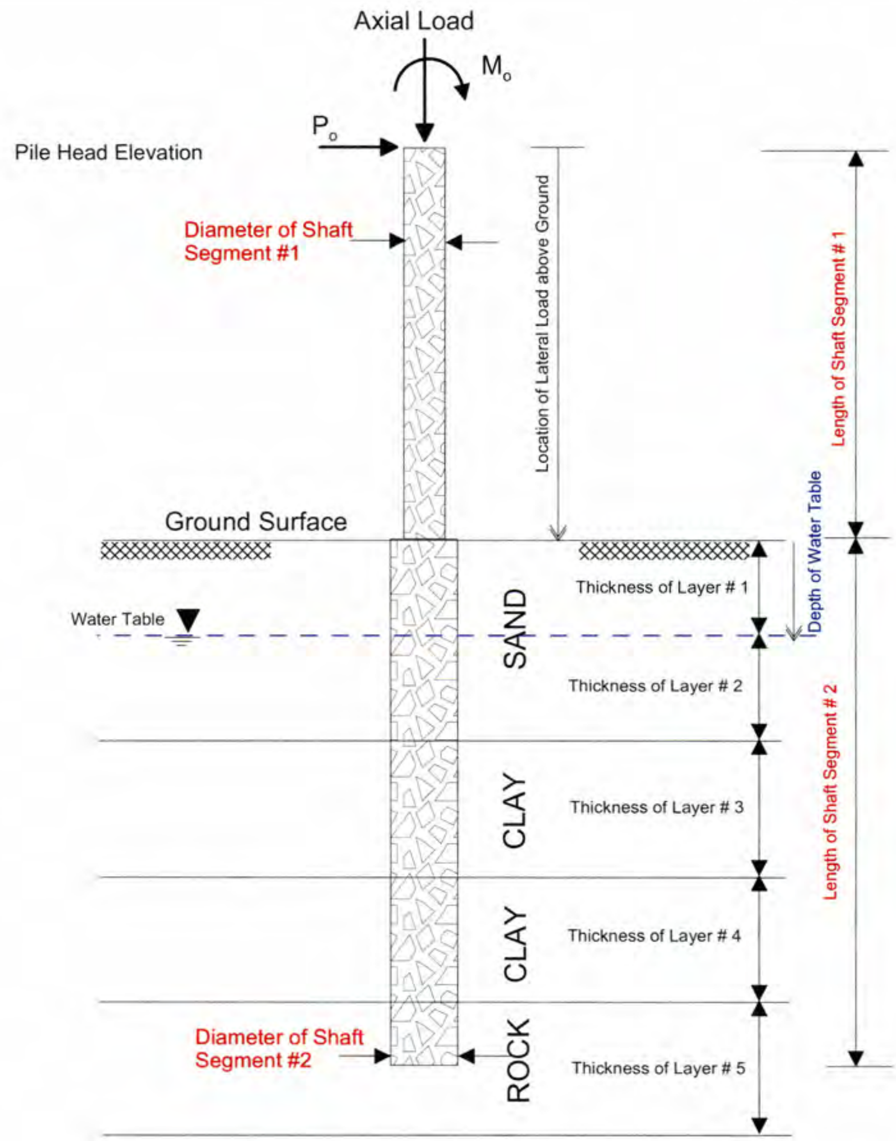


Fig. 7a Geometry of a Pile/Shaft and Surrounding Soil Profile, Shaft Head above Ground

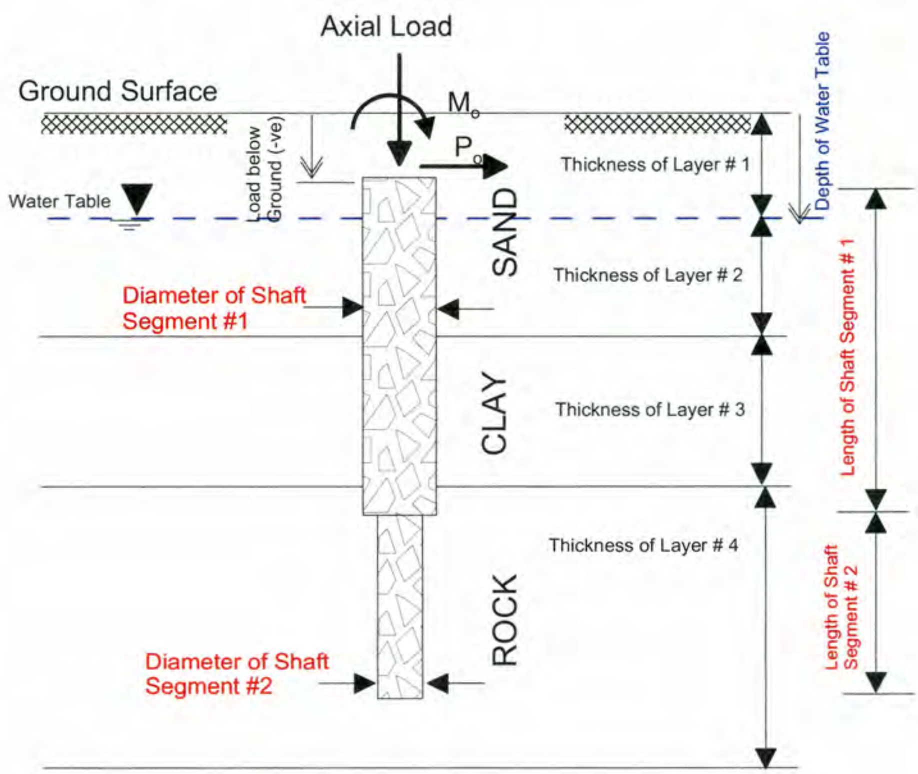


Fig. 7b Geometry of a Shaft and Surrounding Soil Profile, Shaft Head below Ground

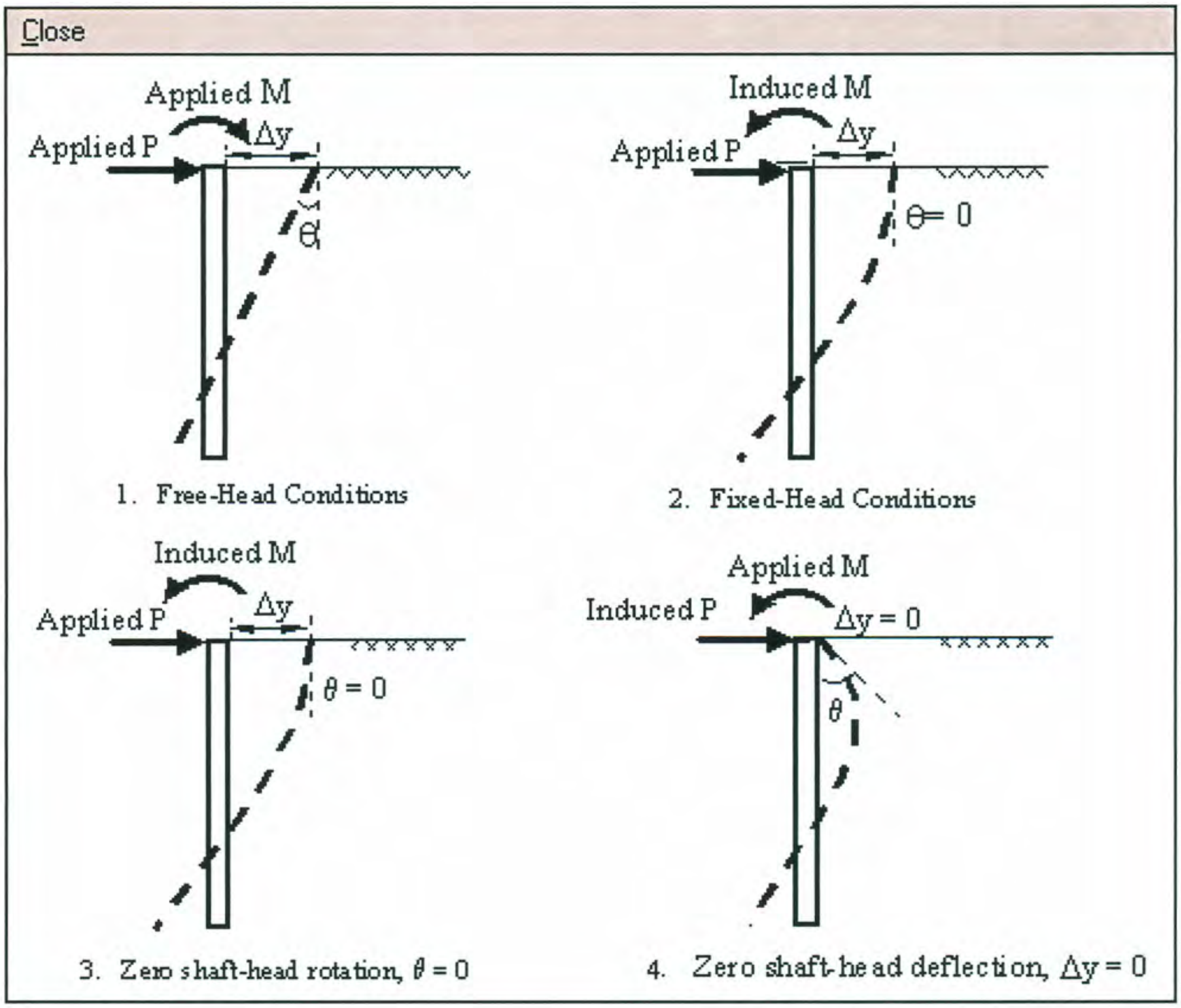


Fig. 8 Pile/Shaft-Head Conditions

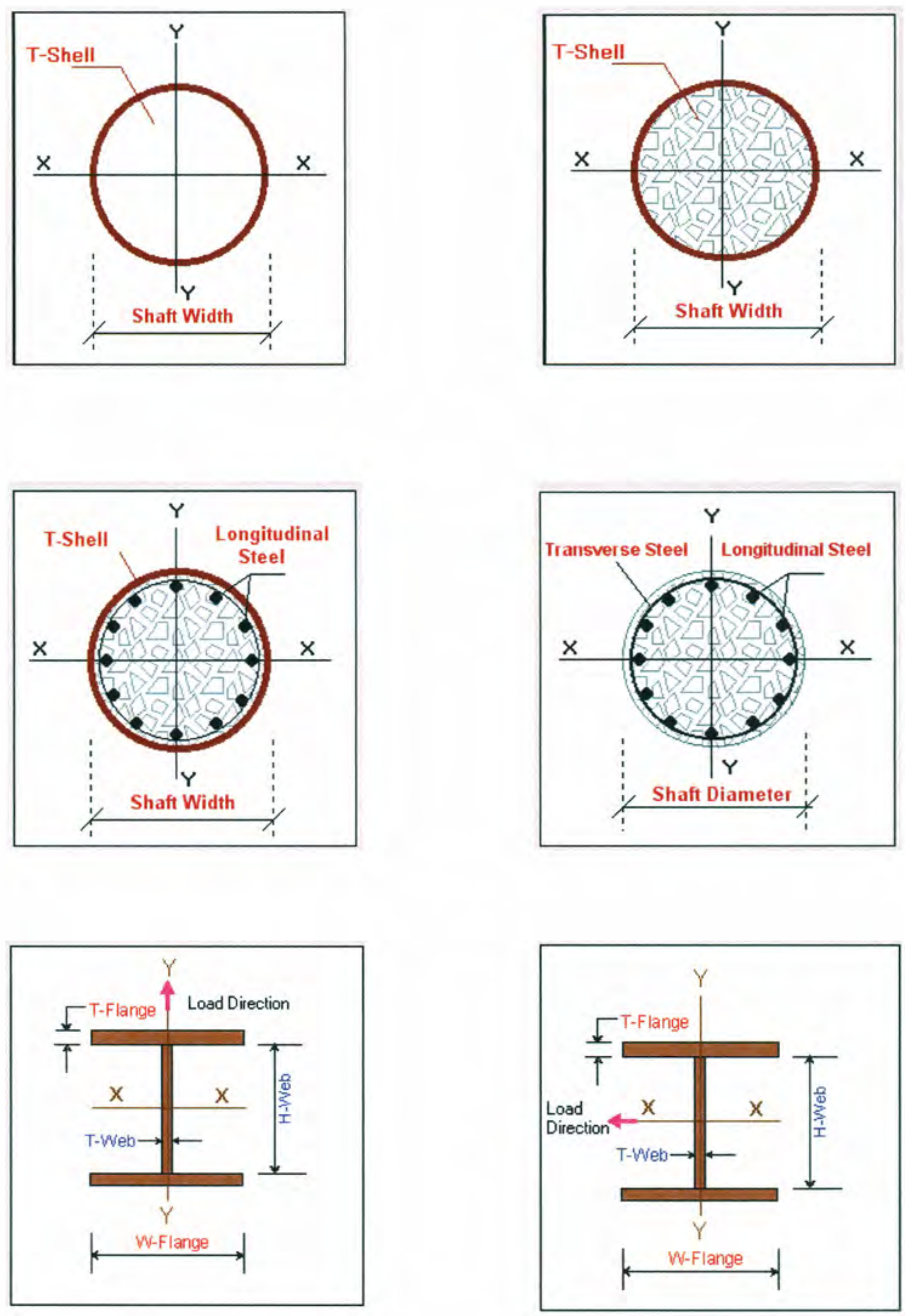


Fig. 9 Different Pile/Shaft Cross-Sections

- Window # 2-1 (Loads) **[Fig. 10]**

This Window can be accessed from Windows # 2 and 4. The user should define the desired values of load (at the top of the isolated pile or the pile group) at which the lateral response (*deflection, bending moment and shear force*) will be plotted along the isolated pile or individual pile in the pile group. The axial load, moment, and the lateral load at the top of the pile or pile group have single values for each run.

Loads at Isolated (Single) Pile Head or Loads on Pile Group

The upper title automatically changes according to the type of the problem (Single pile or Pile group). In the case of pile group, loads and moments acting on the pile group in both directions are entered to evaluate the axial load on every individual pile in the group. However, the program performs the analysis in the assigned direction (longitudinal X-X, or transverse Y-Y). The user must follow the sign convention of the applied moments and loads presented in the Window # 2-1 (Fig. 10)

a. Isolated (Single) Pile

- **Loading Direction:** Assign the loading direction in which the analysis will be performed. The pile/shaft head stiffnesses obtained for the analysis will be described based on the direction of loading (X-X and Y-Y direction)
- **Axial Load (P_z):** Enter the total value of the axial load (from the superstructure) on the. The program takes only one value for each run. Compression axial load has negative value and tension axial load has a positive value.
- **Bending Moment:** Enter the value of the driving moment (from the superstructure) applied at the top of the single pile. The moment value should be negative when the moment is acting opposite to the direction of the lateral load (shear force).
- **Pile Head Lateral Load (Shear Force).** Enter the values of the pile head load applied on the isolated pile. *This value is always positive in the case of single pile.*
- **Shaft-Base / Pile-Tip Efficiency:** Enter the percentage of the pile-tip resistance efficiency against the axial load. Enter zero if the tip/base resistance is not considered in the axial load analysis and the axial load is carried only by the shaft/pile skin resistance. For example, enter 30% if the axial load analysis accounts for only 30% of the pile-tip/shaft-base actual resistance (mobilized soil resistance) at any current step of the axial loading.

b. Pile Group

- **Loading Direction:** Assign the loading direction in which the analysis will be performed. The pile/shaft head stiffnesses obtained for the analysis will be described based on the direction of loading (Longitudinal X-X or Transverse Y-Y direction) in **Fig. 10.** Changing the loading direction in the load window automatically changes the loading direction in the group window and vise versa.
- **Axial Load:** Enter the total value of the axial load (from the superstructure) on the. The program takes only one value for each run. **As seen in Fig. 10**, the compression axial load has negative value and tension axial load has a positive value
- **Pile Head Lateral Load (Shear Force), P_x:** Enter the value of the pile head load applied on the group in the X-X direction. Follow the sign convention given in **Fig. 10.**
- **Pile Head Lateral Load (Shear Force), P_y:** Enter the value of the pile head load applied on the group in the Y-Y direction. Follow the sign convention given in **Fig. 10.**
- **Moment about X-X (M_x) :** Enter the value of the moment about the X-X axis (from the superstructure) applied at the top of the pile cap or on group. Follow the sign convention given in **Fig. 10**.
- **Moment about Y-Y (M_y) :** Enter the value of the moment about the Y-Y axis (from the superstructure) applied at the top of the pile cap or on group. Follow the sign convention given in **Fig. 10**.
- **Shaft-Base / Pile-Tip Efficiency:** Enter the percentage of the pile-tip resistance efficiency against the axial load. Enter zero if the tip/base resistance is not considered in the axial load analysis and the axial load is carried only by the shaft/pile skin resistance. For example, enter 30% if the axial load analysis accounts for only 30% of the pile-tip/shaft-base actual resistance (mobilized soil resistance) at any current step of the axial loading.

NOTES:

- The value of the lateral load on the pile group will be taken in part by the cap resistance if the soil resistance for the cap is considered in the analysis (as noted in **Fig. 3**).
- No resistance is considered between the bottom of the cap and the soil below.

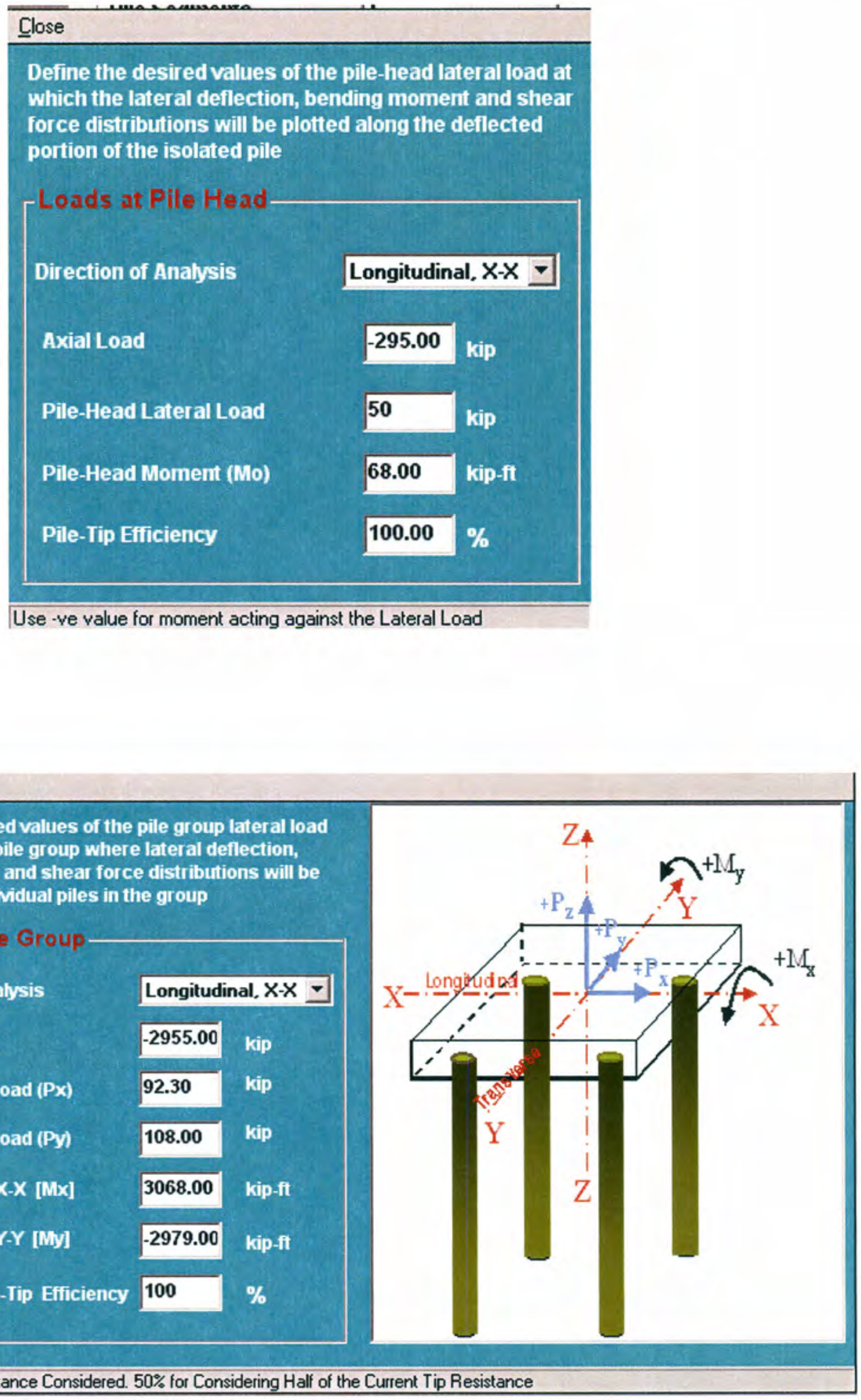


Fig. 10 Window # 2-1 (single pile/pile group loads)

- Window # 3 (Soil Properties) **[Fig. 11]**
  - **Number of Soil Layers** (Maximum of 15 layers): Enter the total number of soil layers that have different properties. If the water table falls within a soil layer, it should be treated as two different layers of different effective unit weights (total unit weight above and buoyant unit weight below the water table).
  - **Surcharge at Ground Surface:** Enter any surcharge (uniformly distributed load) that may exist at ground surface. Surcharge = 0 if there is no extra load at the ground surface.
  - **Water Table below Ground Surface:** The depth of water table is measured from the ground surface and is always 0. The water table above ground surface will have a zero value.
  - **Slope of Ground Surface (in Degrees):** Enter zero for level ground. For sloping ground, enter negative slope angle for down-hill lateral loading and positive slope angle for loading up-hill (**Fig. 12**)

  - **Soil Layer No**. Click to choose a particular soil layer.
  - **Soil Type:** Define the type of soil layer in question (Sand, Clay, C-ϕ Soil or Rock). The list of soil properties, shown below in this window, changes according to the checked soil type (**Figs. 11a, 11b, 11c, and 11d**).
  - **Layer Thickness:** Enter the thickness of the soil layer in question.
  - **Effective Unit Weight:** Enter the effective unit weight of the soil layer in question (Effective unit weight excludes the weight of water if soil layer exists below water table).
  - **Effective Friction Angle:** This value must be entered for sand and C-ϕ Soil.
  - $\boldsymbol{\varepsilon_{50}}$ (axial strain of soil at stress level of 50%). Enter 0 for ε_{50} to use the program default or click Help in this window to exhibit the curves that can be employed to evaluate the associated $\boldsymbol{\varepsilon_{50}}$ for Sand, Clay, C-ϕ Soil and Rock (**Fig. 13a**). It is recommended that site specific experimental data be used when available. The curves seen in **Fig. 13b** can be extrapolated to cover the range of the rock mass strength.
  - **$\boldsymbol{S_u}$ at the Top of Layer**: Enter the value of the undrained shear strength of clay at the top of the saturated clay layer in question.
  - **$\boldsymbol{S_u}$ at the Bottom of Layer**: Enter the value of the undrained shear strength of the saturated clay at the bottom of the clay layer in question. S_u at the top and the bottom of the clay layer may be equal.
  - **Compressive Strength of Rock Mass:** Enter the value of the unconfined compressive strength (q_u) of the rock mass. Note that the compressive strength of the weathered or fissured/fractured rock is much less than that of the intact rock mass.

- **Soil Cohesion, C:** Enter the cohesion of the C-ϕ Soil that represents the intercept of the Mohr-Coulomb failure envelope with the vertical shear stress axis.
- **Liquefaction:** This option is only applied with submerged sand (below water table). Once the liquefaction option is checked, the Liquefaction menu in the Menu Bar is enabled. Click Liquefaction in the Menu Bar to access the window of liquefaction data (Window # 3-1).
- Click ***Layout*** to plot the pile/shaft-soil profile based on the entered data.

- Window # 3-1 (Liquefaction) [**Fig. 14**]

The number of the current soil layer will be displayed in the window.

- **SPT Corrected Blow counts:** Enter the average of the corrected blow count, $(N_1)_{60}$, of the Standard Penetration Test (SPT) of the sand layer in question.
- **Percentage of Fines in Sand**: Enter the percentage of fine material passing the # 200 sieve (from sieve analysis).
- **Shape of Sand Grains:** Based on visual inspection choose the appropriate description of the shape (roundness) of the sand grains. If the user can not define this variable, "subangular" may be chosen as an average case. Particle comparison charts are presented in **Fig. 15** and can be displayed on the screen by clicking ***Help*** in the Menu Bar of this window (Window # 3-1).

- **Loading Type:** Two loading scenarios are available pile response in liquefiable soils.
  - **Earthquake Excitation:** This type of loading accounts for water pressure that develops in surrounding soil due to earthquake shaking (***Free-Field*** water pressure) and lateral load from the superstructure (additional ***Near-Field*** water pressure).
    - **Lateral Spreading:** Check the Lateral Spreading option to account for lateral spreading of the soil induced by earthquake shaking and developing liquefaction.
  - **Vessel Impact:** This type of loading accounts for pore water pressure that develops in soil surrounding the pile (***Near-Field***) due to impact loading from a ship, barge or floating objects.

- **Earthquake (EQ)**

  Enter the following basic earthquake data:
  - **Magnitude of the Earthquake (Moment magnitude, M_M)**
  - **Ground Acceleration Coefficient in (g):** Enter the maximum horizontal ground acceleration (a_{max}) that is expected at the ground surface based on seismic analysis of the

site under consideration. This value is the acceleration of gravity (g) at zero period (T = 0) in the acceleration response spectrum.

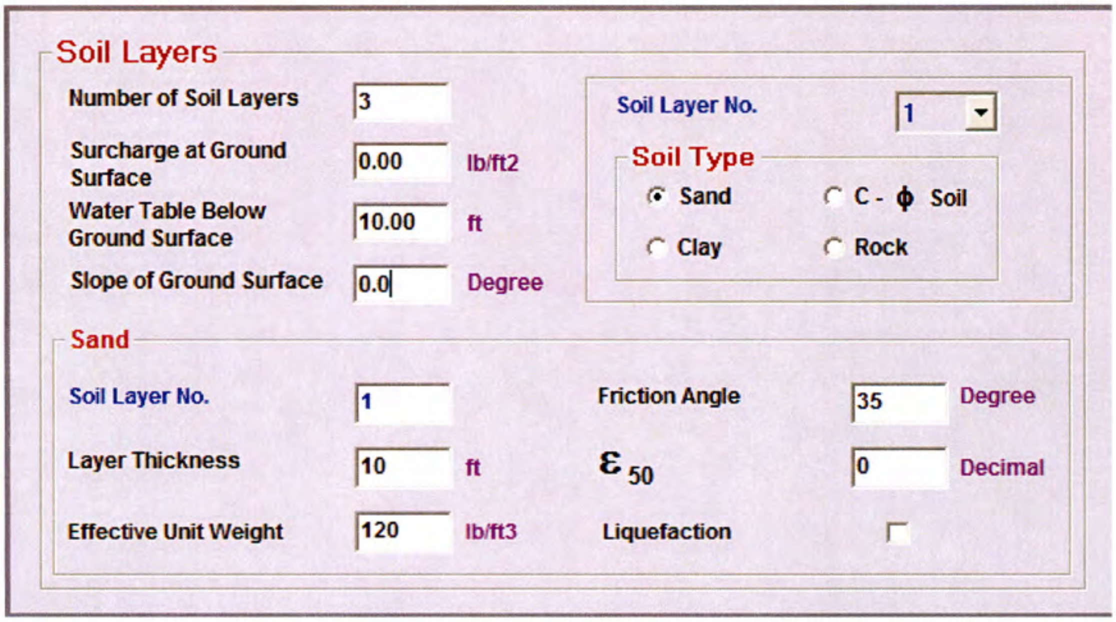


Fig. 11a Sand Properties

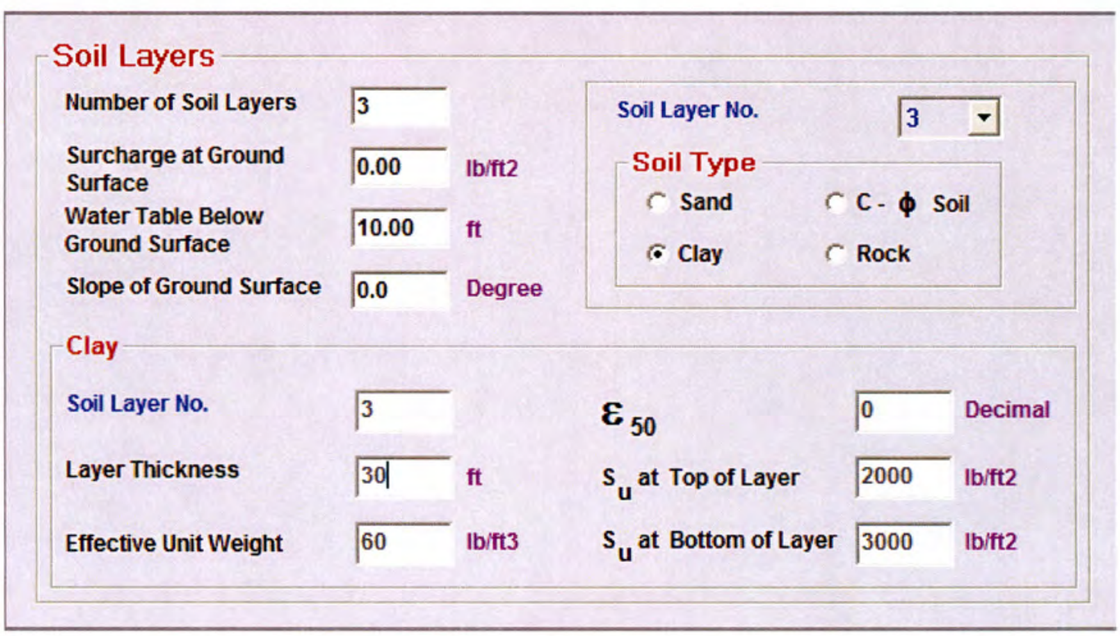


Fig. 11b Clay Properties

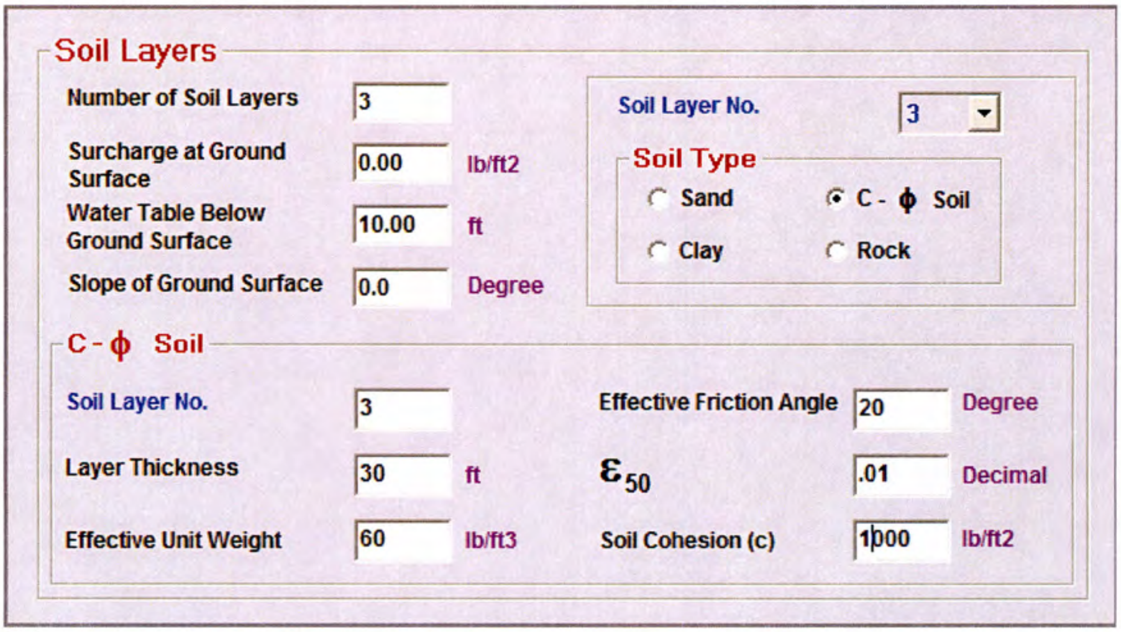


Fig. 11c C-φ Soil Properties

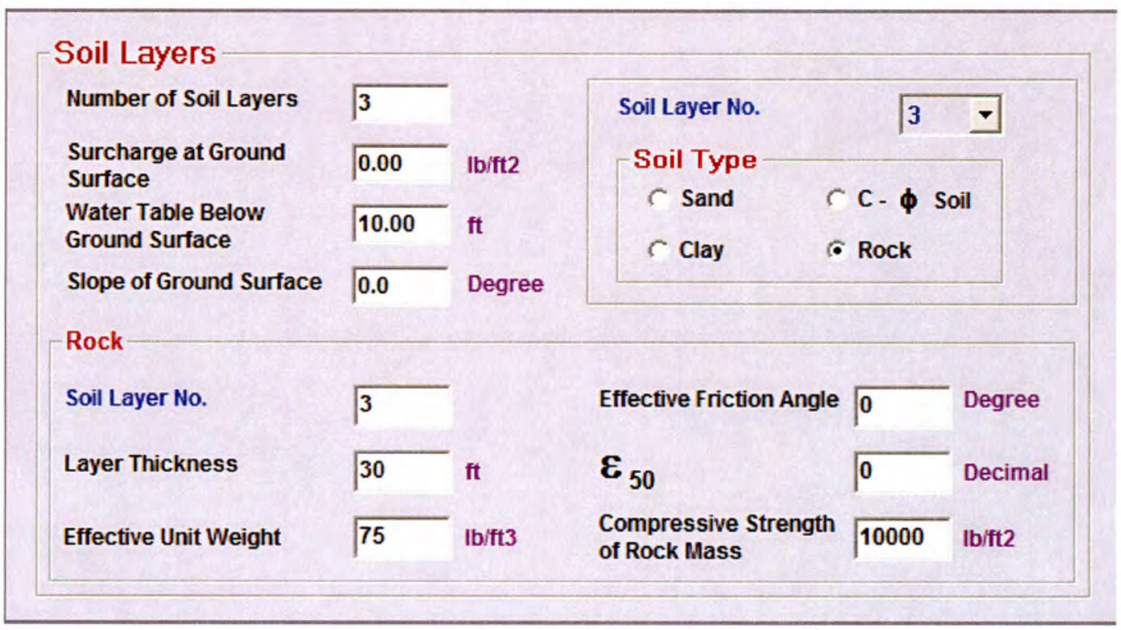


Fig. 11 Rock Properties

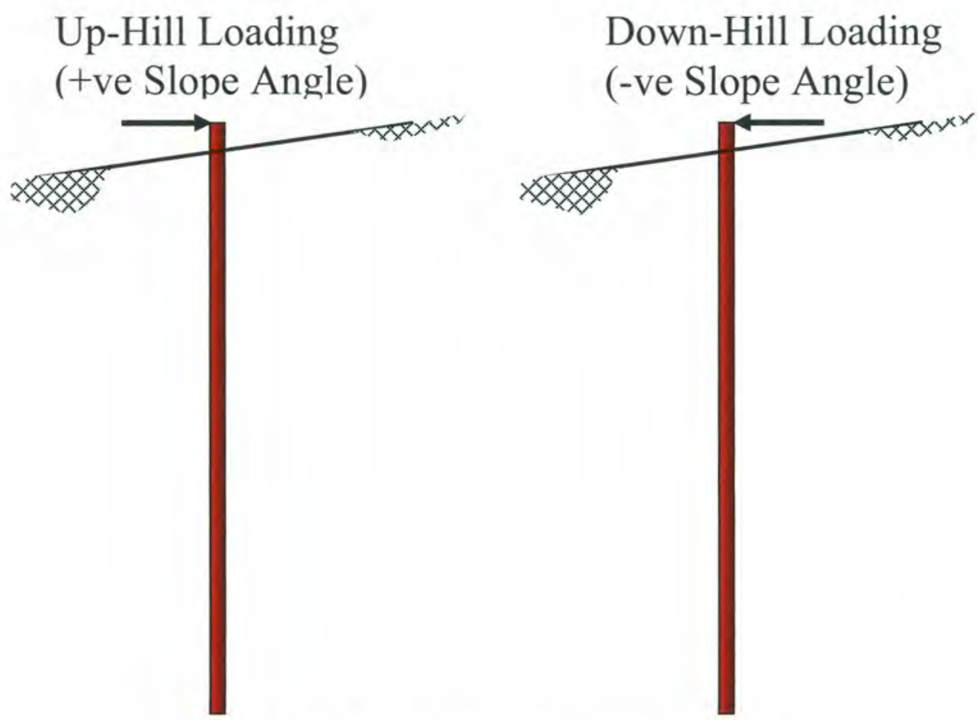


Fig. 12 Sloping Ground and Lateral Loading Direction

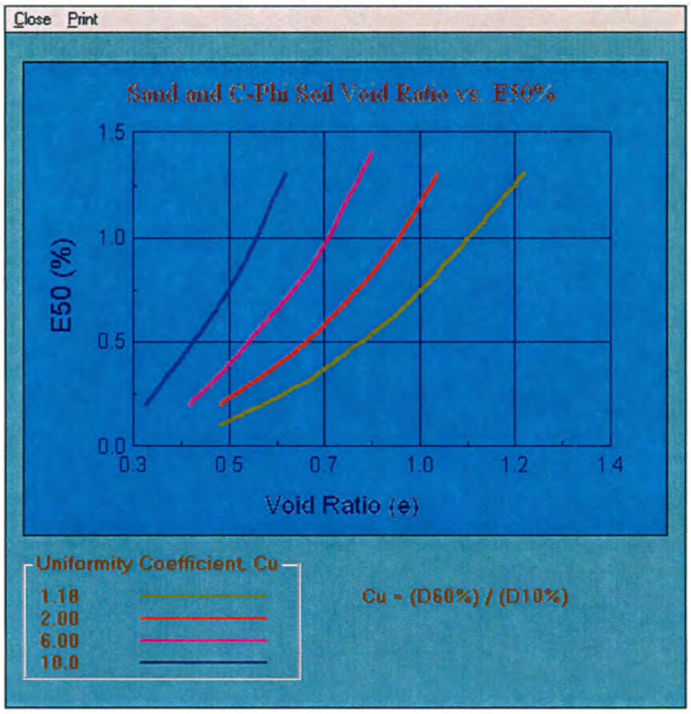


Fig. 13a Help Curves to Evaluate ε_{50} of Sand and C-φ Soil

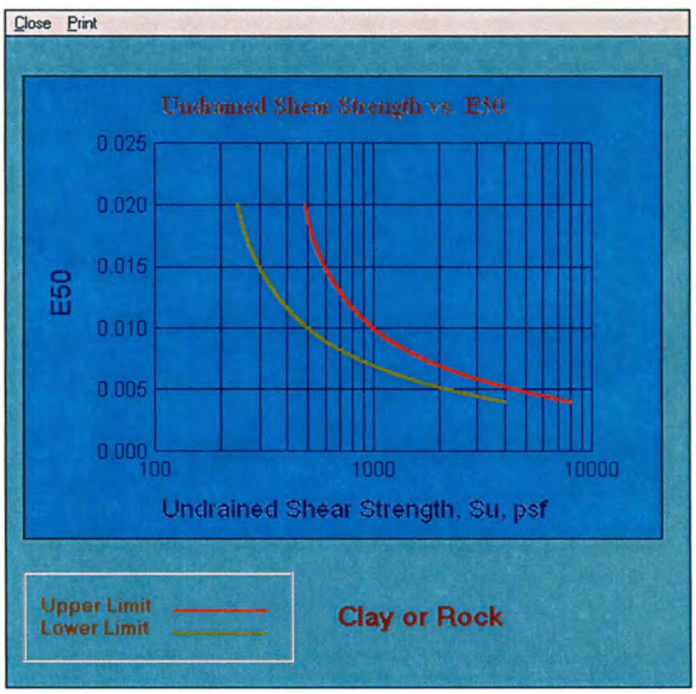


Fig. 13b Help Curves to Evaluate ε_{50} of Clay and Rock

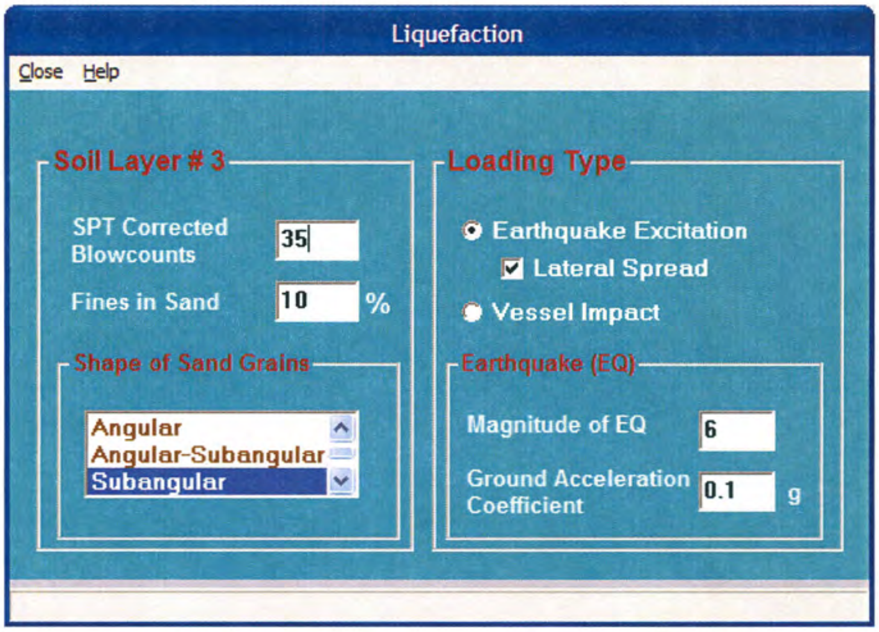


Fig. 14 Window 3-1 (Data Required for Soil Liquefaction)

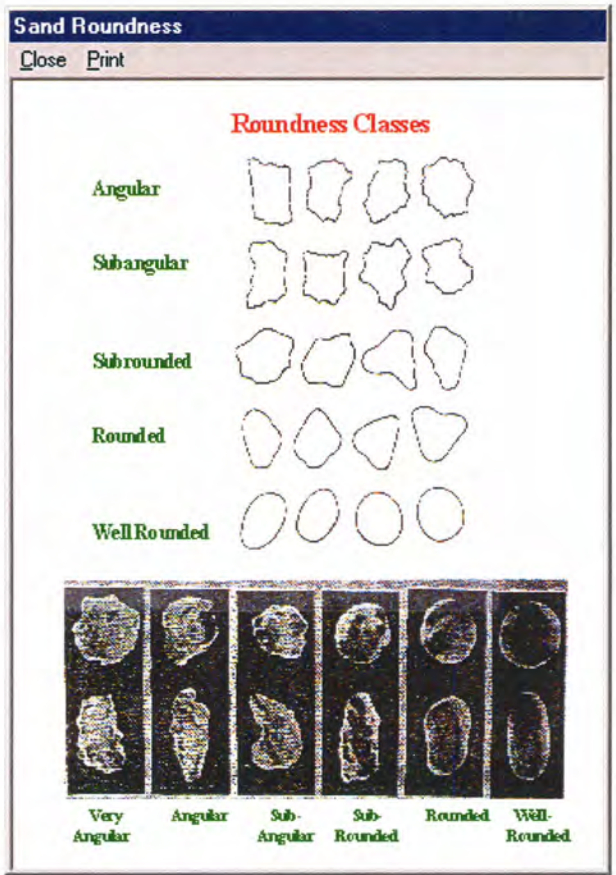
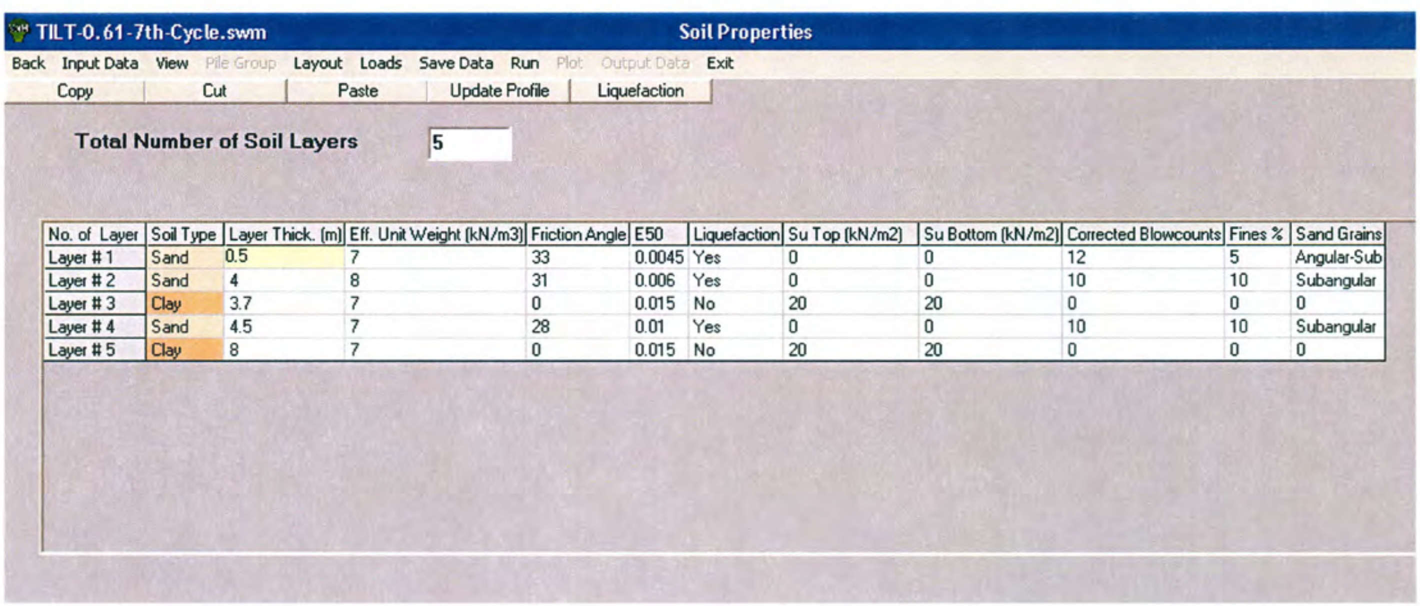


Fig. 15 Characterization of Roundness of Sand Grains

- Window # 4 (Soil Profile) [**Fig. 16**]

  This window shows the values of the soil properties employed. For quick editing, the user can review and modify any of the soil properties seen in the soil profile grid that was entered previously via Windows # 3 and 3-1. Any change made to the soil properties in the soil profile grid displayed in this window will be saved instantaneously.

  - The properties of soil layers can either be deleted or copied and pasted using the buttons seen in **Fig. 16**.
  - **Total Number of Soil Layers:** Add or remove soil layers by changing the value of total number of soil layers and clicking **Update Profile.**
  - Click **Layout** to plot the pile-soil profile based on the entered data.
  - Click **Input Data** in the Menu Bar (after running the program) to open a text file that contains the data input that may be printed and attached to reports.
  - Click **Run** in the Menu Bar to run the program.
  - Click **Plot** in the Menu Bar to show printable graphs of the output data.
  - Click **Save Data** at any time to save the data entered.



No. of Layer	Soil Type	Layer Thick. (m)	Eff. Unit Weight (kN/m3)	Friction Angle	E50	Liquefaction	Su Top (kN/m2)	Su Bottom (kN/m2)	Corrected Blowcounts	Fines %	Sand Grains
Layer # 1	Sand	0.5	7	33	0.0045	Yes	0	0	12	5	Angular-Sub
Layer # 2	Sand	4	8	31	0.006	Yes	0	0	10	10	Subangular
Layer # 3	Clay	3.7	7	0	0.015	No	20	20	0	0	0
Layer # 4	Sand	4.5	7	28	0.01	Yes	0	0	10	10	Subangular
Layer # 5	Clay	8	7	0	0.015	No	20	20	0	0	0

Fig. 16 Editable Table for Soil Properties and Conditions

OUTPUT DATA

- Window # 4 (Soil Profile) **[Fig. 17]**

  The program is executed from this window. Click Run to execute the program. Once the program is executed, the type of the pile/shaft analyzed will be printed on the screen (Long, Intermediate or short). The Ratio L/T (Pile length / Pile relative stiffness) defines the type of the pile.

  $L/T < 2$ for short pile

  $2 < L/T < 4$ for intermediate pile

  $L/T > 4$ for long pile

  - Click Input Data in the Menu Bar to open the input data file. This text file lists all the entered soil and pile properties. This file can be printed out for use in a report. The user can also check the initial values of the bending stiffness of the pile segments that are calculated by the program based on the entered pile properties. The type of pile (short, intermediate or long) predicted by the program is based on the initial bending stiffness of the pile cross-section(s).

  The user can access the output data files and plot the results via this window.

  - Click Output Data in the Menu Bar to open the output data files listed below:

- **Single.txt**. This file contains the response of the laterally loaded isolated pile or the average pile (in the case of pile group) that includes
  - Type of the analyzed pile (short or intermediate)
  - Type of the pile-head conditions specified in the input data
  - Pile head deflection (Y_o)
  - Pile head lateral load (P_o)
  - Maximum bending moment (M_{max}) in each load step
  - Location of M_{max} below the pile head
  - Location of the associated zero-lateral deflection point below pile head in each load step
  - Pile deflection at ground surface when the pile head is located above ground

- **pys.txt**. This file shows the p-y curves of the single pile that are defined in the input data (Window # 1-1). The points of each p-y curve are described in two columns (y vs. p). The depth (location) of each p-y curve below the pile head is shown at the top of the two columns.

- **Profile.txt**. This file shows the predicted values of the element stiffness matrix (Kd, Kr, Kv, Kt) for the isolated pile/pile.

This file also contains the distribution of the lateral pile deflection (y), moment (M), shear force (V), pile slope (s), line load or soil-pile reaction (p) and the excess porewater pressure (PWP) along the length of the pile and are evaluated at the load values specified in the input data (Window # 2-1).

- **Mcurve.txt**. This file shows the curvature, bending moment and bending stiffness (EI) of the pile cross section for each pile segment. This file is available only with the nonlinear analysis of the pile material. The number of output sets of data (curvature, moment and EI) is equal to the number of pile segments.

- **Group.txt**. This file presents the response of the pile group and the individual piles in the group (**Fig. 18**).

  - Pile head deflection for the whole group (pile cap lateral displacement), Y_o.
  - Pile head load, P_o, and the associated M_{max} for the isolated (single) pile at pile head deflection Y_o
  - Pile head load, P_1, and the associated $(M_{max})_1$ for the pile type # 1 at pile head deflection Y_o
  - Pile head load, P_2, and the associated $(M_{max})_2$ for the pile type # 2 at pile head deflection Y_o
  - Pile head load, P_3, and the associated $(M_{max})_3$ for the pile type # 3 at pile head deflection Y_o
  - Pile head load, P_4, and the associated $(M_{max})_4$ for the pile type # 4 at pile head deflection Y_o
  - Pile group load (P-Group) at group deflection Y_o. This accounts for the pile cap contribution to the system resistance
  - Average load per pile in the group, $\mathbf{P_{ave}}$. For this evaluation P-Group does not include the pile cap contribution to the system resistance. It is equal to P-Group divided by the number of piles in the group.

- **PileG1, PileG2, PileG3, and PileG4**. These files are similar to file **Profile.txt** of a single pile. However, each file represents the lateral response of an individual pile in the pile group. For example, file **PileG1** shows the lateral response (y, M, V, S, p and PWP) of Pile type # 1 in the group at the pile/pile group load defined previously in ***Window 2-1 (Fig. 10)***.

It should be noted that at any value of Y_o (or deflection increment) all individual piles in the group have the same pile head deflection (Y_o) but different values of pile head load (P_1, P_2, P_3, and P_4) due to pile interference. The pile head load (P_1, P_2, P_3 or P_4) at any load increment is equal to the shear force at the individual pile head.

The pile group deflection increases until it reaches the largest value of P_g specified in (***Window #2-1 in Fig. 10***). Messages from the program appear on the screen when this does not fully occur (the largest value of the group load solved is less than the specified value of P_g).

- **Axial1.txt**. This file shows the t-z curves of a single pile/pile for each soil layer in the soil profile along the length of the pile/pile in question. The points of each t-z curve are presented in two columns (z vs. t). Each t-z curve is automatically calculated at the mid of each soil layer below the pile/pile head.

- **Axial2.txt**. This file contains the axial skin resistance (axial shear force) vs. settlement/displacement for the pile/pile segment along the pile/pile length starting from the pile-tip / pile base up to the pile/pile top at each step of axial loading. The program performs such analysis in association with the assessment of the t-z curves. The SWM6.2 computer program performs up to 100 increments of axial load or until the pile/pile fails. The axial load distribution along the pile/pile length at the axial load specified in **Fig. 10** is also determined.

- **NOTES**

  The Isolated Pile option shown in **Fig. 17** represents the output data of a single (isolated) pile in the same soil profile of the group and under loads equal to the external loads divided by the number of piles (no group action). Such a type of output data allows the user to compare between the response of an individual pile in the group and response of the response of the same pile with no group action (isolated).

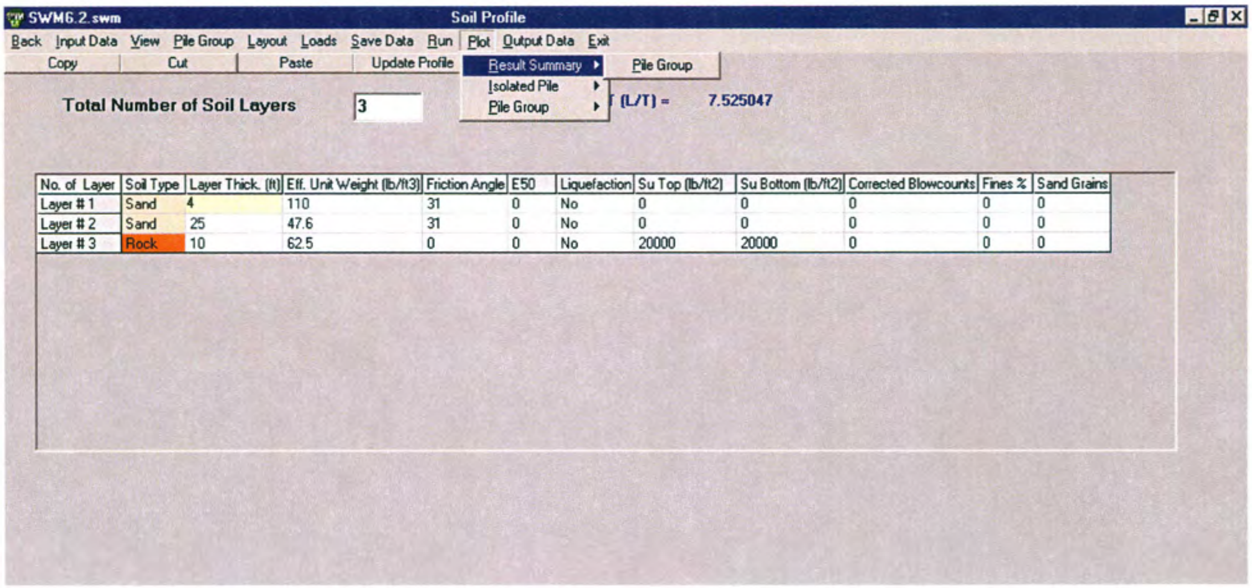
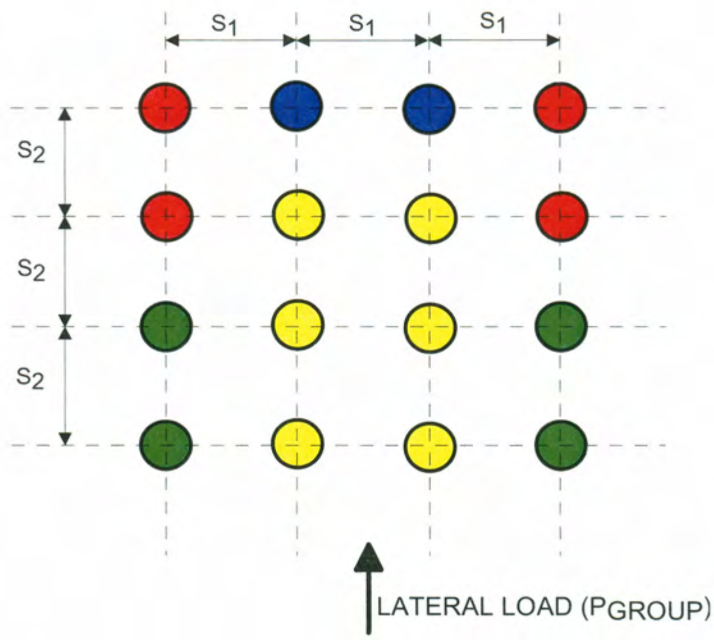


Fig. 17 Window # 4



corresponds to a trailing row pile that has a pile to only one of its sides

: corresponds to a trailing row pile that has piles to both of its sides

3 corresponds to a lead row pile that has a pile to only one of its sides

Pile Type 4 corresponds to a lead row pile that has piles to both of its sides

Fig. 18 Description and Distribution of Piles in a Group

- Plot
    - Result Summary [**Fig. 19**]

      The key parameters of the pile response including the elements of the stiffness matrix for an isolated pile and pile group are listed in a table to facilitate the use of the results obtained.

    - Isolated Pile/Shaft

      The table seen in **Fig. 19a** show the following sets of output data:

      1. The applied external load at the top of the isolated pile
          - Lateral load (shear force) on isolated pile head (P_o)
          - Moment at the pile head (M_o)
          - Axial (Vertical) load at the isolated pile haed (P_z)
      2. Pile/Shaft response
          - Pile-head deflection (Y_{head})
          - Pile deflection at ground surface (Y_{ground})
          - Pile-head slope
          - Lateral Load (shear load) on isolated pile.
          - Maximum bending moment in pile (M_{max}) due to applied external loads
          - Location of M_{max} below pile head.
      3. Pile-head stiffnesses
          - For pile-head conditions (Case 1 and 2, Fig. 8)
            Kd, Kr, Kv and Kt
          - For pile-head conditions (Case 3, Fig. 8)
            Kd, K(d–r), Kv and Kt
          - For pile-head conditions (Case 4, Fig. 8)
            Kr, K(r-d), Kv and Kt

        - Pile/Shaft Group

          The table seen in **Fig. 19b** exhibits the following sets of output data:

1. The applied external load at the top of the pile group
   - Lateral load (shear force) on pile group including the cap (P_x or P_y) that depends on the direction of the analysis identified in the loading or group window (X-X or Y-Y)
   - Moment on pile group (M_y or M_x) based on the direction of the analysis identified in the loading or group window (X-X or Y-Y)
   - Axial load at the top of the pile group (P_z)

2. Group response
   - Group deflection ($Y_{g\text{-}head}$)
   - Group deflection at ground surface ($Y_{g\text{-}ground}$)
   - Lateral Load (shear load) on average pile (P_{ave})
   - Lateral load carried by cap (P_{cap})
   - Lateral load carried by piles in the group (P_{group}). Pile-cap contribution is not accounted in the value P_{group}.

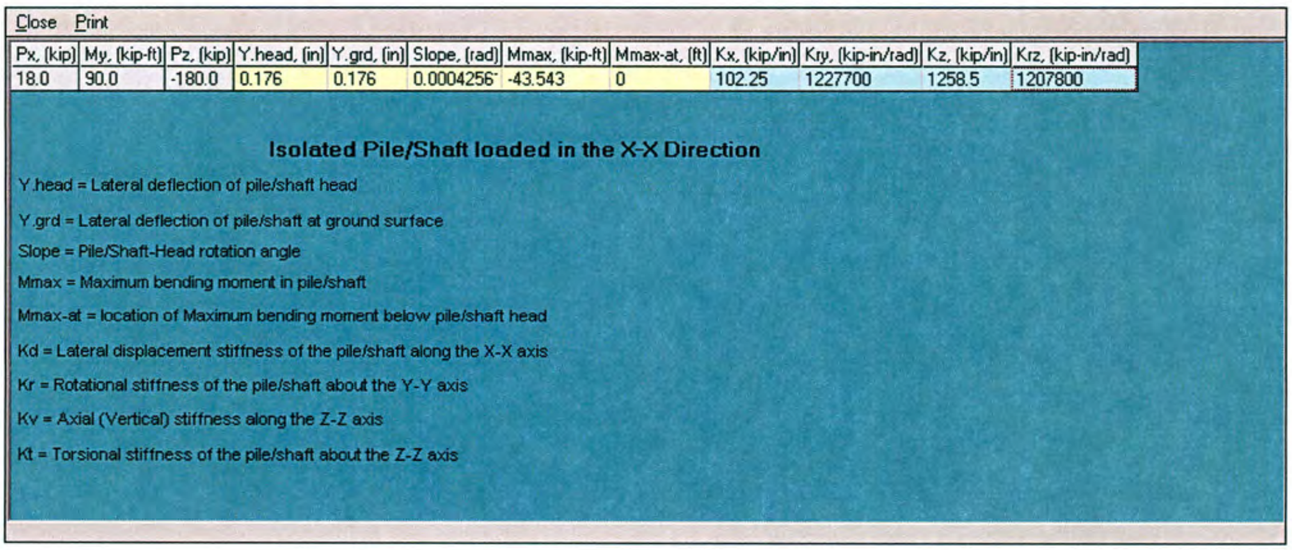
3. Pile group stiffnesses
   - For pile-head conditions (Case 1 and 2)
     Kx, Kry, Kz and Kt of the group if the analysis is performed in the X-X direction, or Ky, Krx, Kz and Kt of the group if the analysis is performed in the Y-Y direction.
     It should be noted that torsional moment (i.e. Kt) of a group with a cap is converted to lateral forces on piles and cap.
   - Pile-head conditions (Case 3) are not applicable with the pile group
   - Pile-head conditions (Case 4) are not applicable with the pile group

4. Critical Piles in the group
   Click Critical Piles in **Fig. 19b** to show the critical piles in the group as shown in **Fig. 19c**. Figure 19.c shows the piles that take the largest and smallest axial and lateral loads in the pile group.
   Click the table colored cell to plot the deflection, moment and shear force of the critical pile in question (**Fig. 19d**).
5. Axial Load distribution on the piles in the group

Click Axial Load bottom in **Fig. 19b** or **Fig. 19d** to plot the pile group and the share of the axial load applied on every individual pile in the group (**Fig. 19e**). The pile distribution and numbers (**Fig. 19e**) are plotted from the Group Window #1-2 in **Fig. 3**

NOTES:

- Pile group stiffness accounts for the group effect (pile lateral interaction) and cap resistance.
- The <u>one-row</u> pile group under lateral loads (P_g, M_g, P_v) can not achieve fixed-head conditions (Case 2) in the direction normal to the pile/pile row and must be analyzed as free-head conditions (Case 1).



Px, (kip)	My, (kip-ft)	Pz, (kip)	Y.head, (in)	Y.grd, (in)	Slope, (rad)	Mmax, (kip-ft)	Mmax-at, (ft)	Kx, (kip/in)	Kry, (kip-in/rad)	Kz, (kip/in)	Krz, (kip-in/rad)
18.0	90.0	-180.0	0.176	0.176	0.0004256	-43.543	0	102.25	1227700	1258.5	1207800

Fig. 19a Tabulated Results of an Isolated (Single) Pile

Close Print Group Critical Piles Axial Loads

Py, (kip)	Mx, (kip-ft)	Pz, (kip)	Yg.head, (in)	Yg.ground, (in)	Pave., (kip)	Pcap, (kip)	Pgroup, (kip)	Ky, (kip/in)	Krx, (kip-in/rad)	Kz, (kip/in)	Krz, (kip-in/rad)
-209.1	3196.5	-3594.0	0.39281	0.39281	10.53	0	210.6	521.94	24553000.0	25128	24157000

Pile/Shaft Group Loaded in the Y-Y Direction

Yg.head = Lateral deflection at the top of the pile group

Yg.ground = Lateral deflection of the pile group at ground surface

Py = Total lateral load applied on piles/shafts group including the cap in the Y-Y direction

Pgroup = Lateral load carried by piles/shafts only

Pave. = Average lateral load per pile in the group (Pgroup/Number of Piles)

Ky = Lateral displacement stiffness of the pile group about the Y-Y axis

Krx = Rotational stiffness of the pile group about the X-X axis

Kz = Axial (Vertical) stiffness of the pile group under Pz

Krz = Torsional stiffness of the pile group (about z-z axis)

Fig. 19b Tabulated Results of Pile Group

Close Print Group Critical Piles Axial Loads

Pile Loading State	Pile No.	Axial Load, Pz (kip)	Lateral Load, Fy (kip)	Max. Moment Mx, (kip-ft)	Deflection, Dy (in.)	Show
Most Critcal	1	-180.	21.003	-66.397	0.3928	Graphs
Least Critcal	20	-180.	8.3429	-40.477	0.3928	Graphs
Least Critcal	16	-180.	6.8507	-36.325	0.3928	Graphs

Analysis in the Loading Direction Y-Y

Fig. 19c Tabulated Results of the Critical Piles in the Pile Group

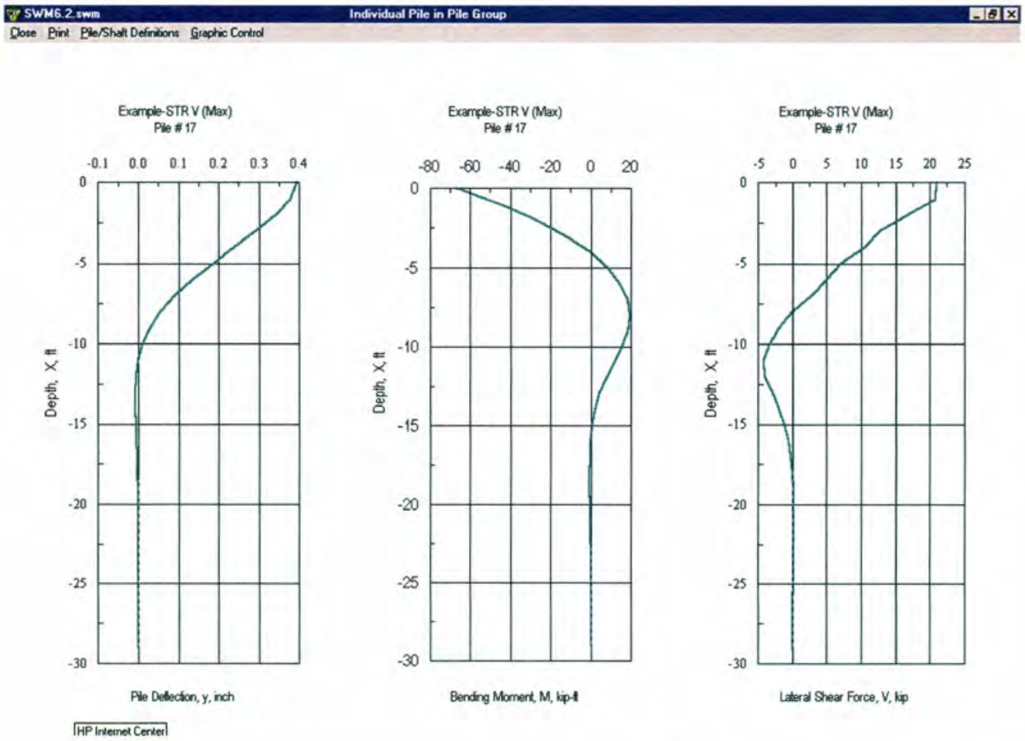


Fig. 19d Deflection, Moment and Shear Force along a Critical Pile.

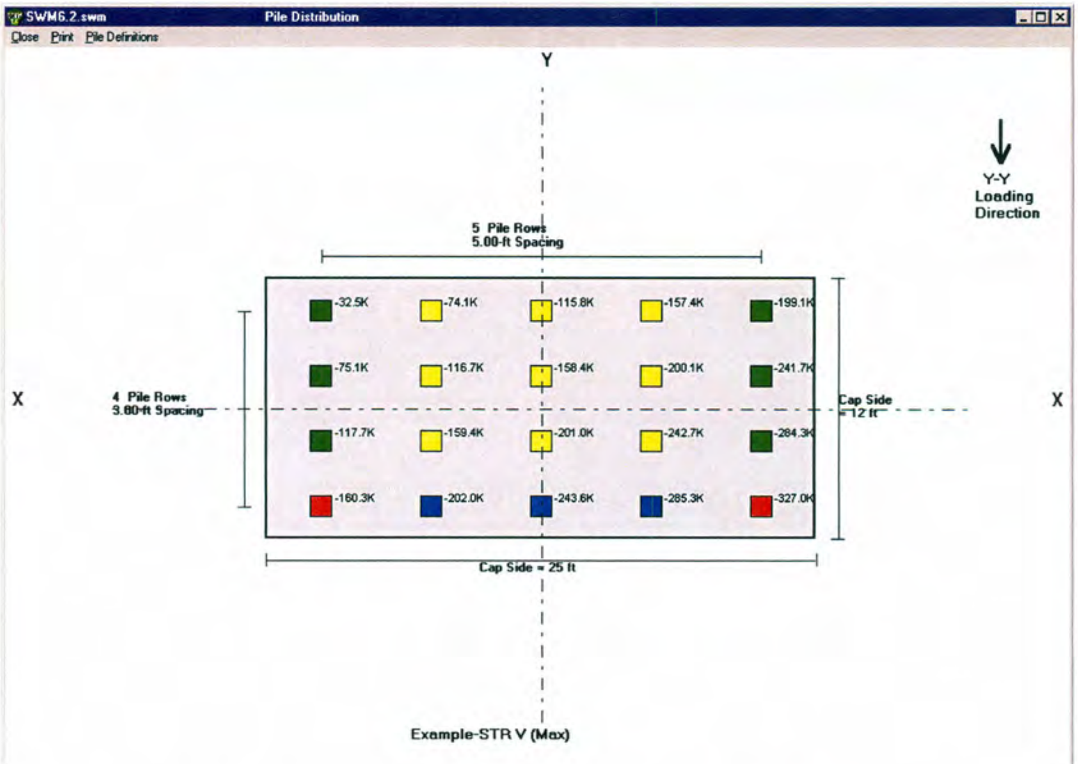


Fig. 19e Axial loads Distribution on Individual Piles in the Group.

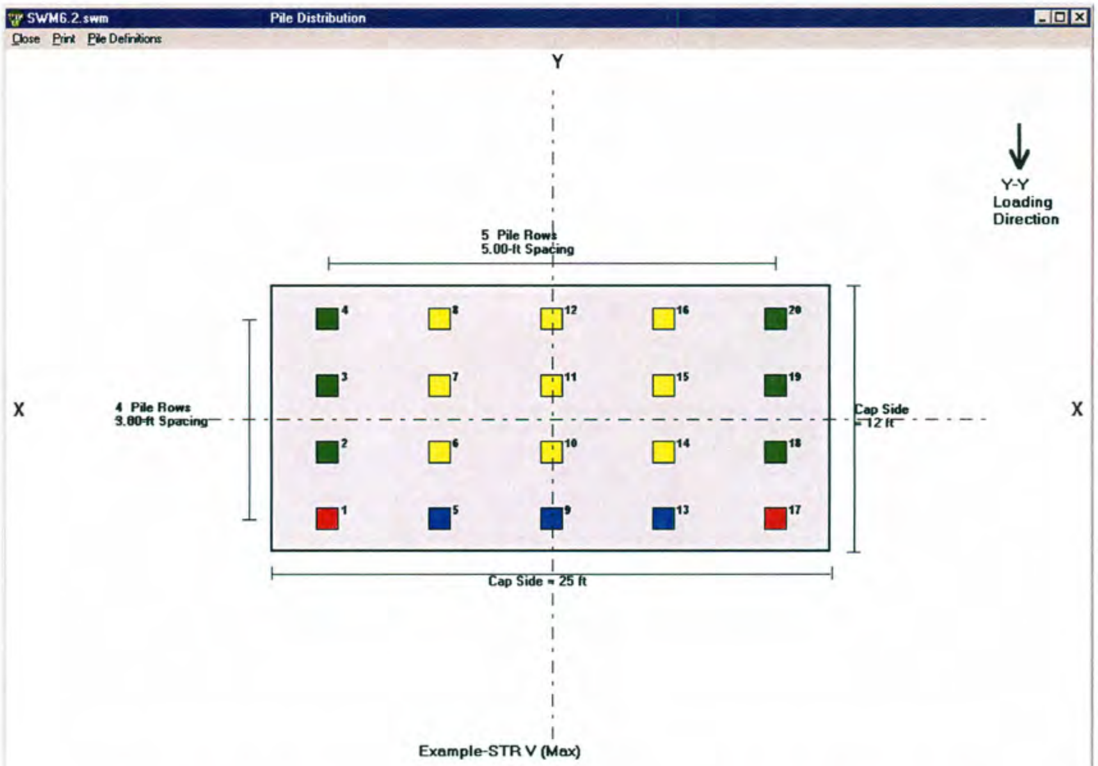


Fig. 19f Pile Numbers in the Pile Group (Accessed from the Pile Group Window)

- Lateral Pile Response **[Fig. 20]**

  This option allows the user to plot and print out the following pile responses along the length of the single pile/pile at the loads specified in Window #1-2

  - Lateral Deflection, Bending Moment, and Shear Force [Fig. 20a]
  - Lateral Deflection, Bending Moment, Shear Force, and Excess pore water pressure ratio (r_u) in liquefied soil [Fig. 20b] (in case of soil liquefaction).

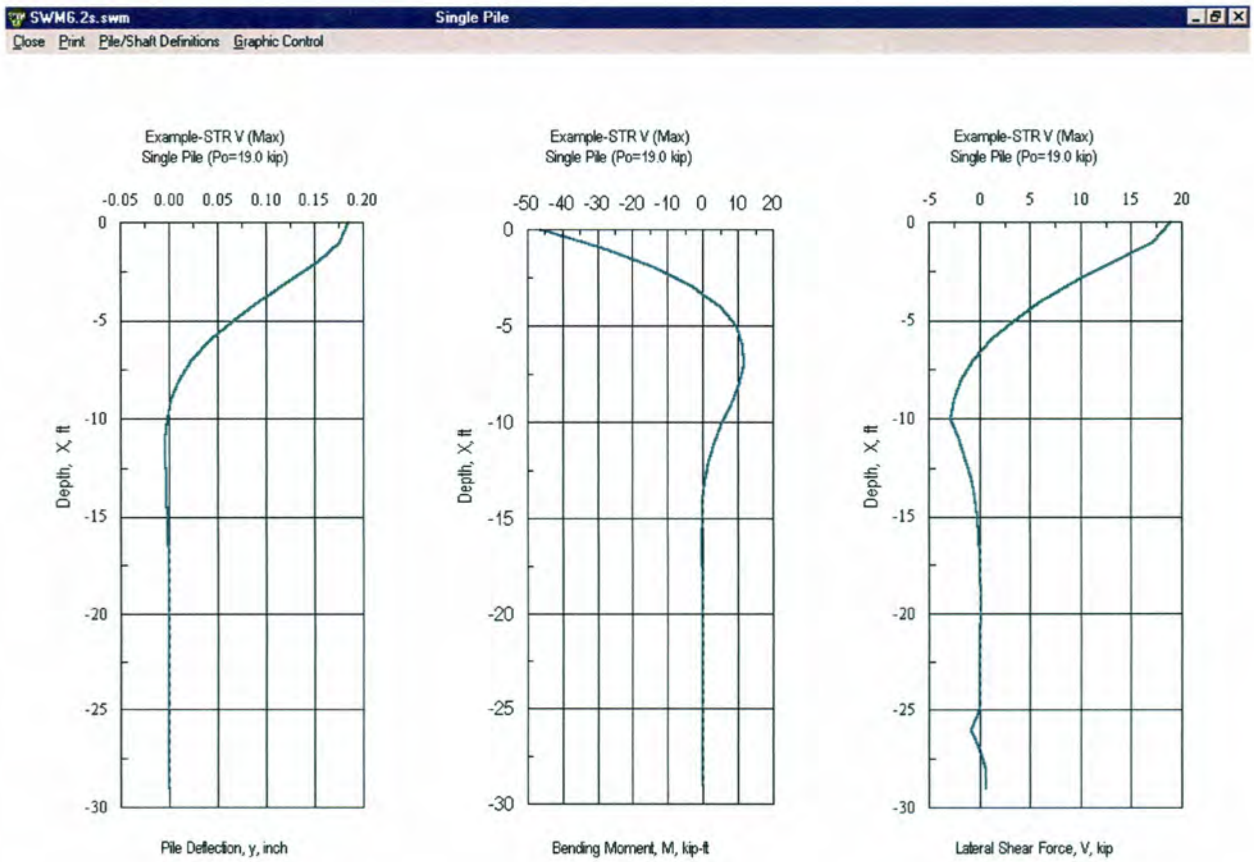


Fig. 20a Lateral Deflection, Moment and Shear Force along the Pile Length at the Given Loads

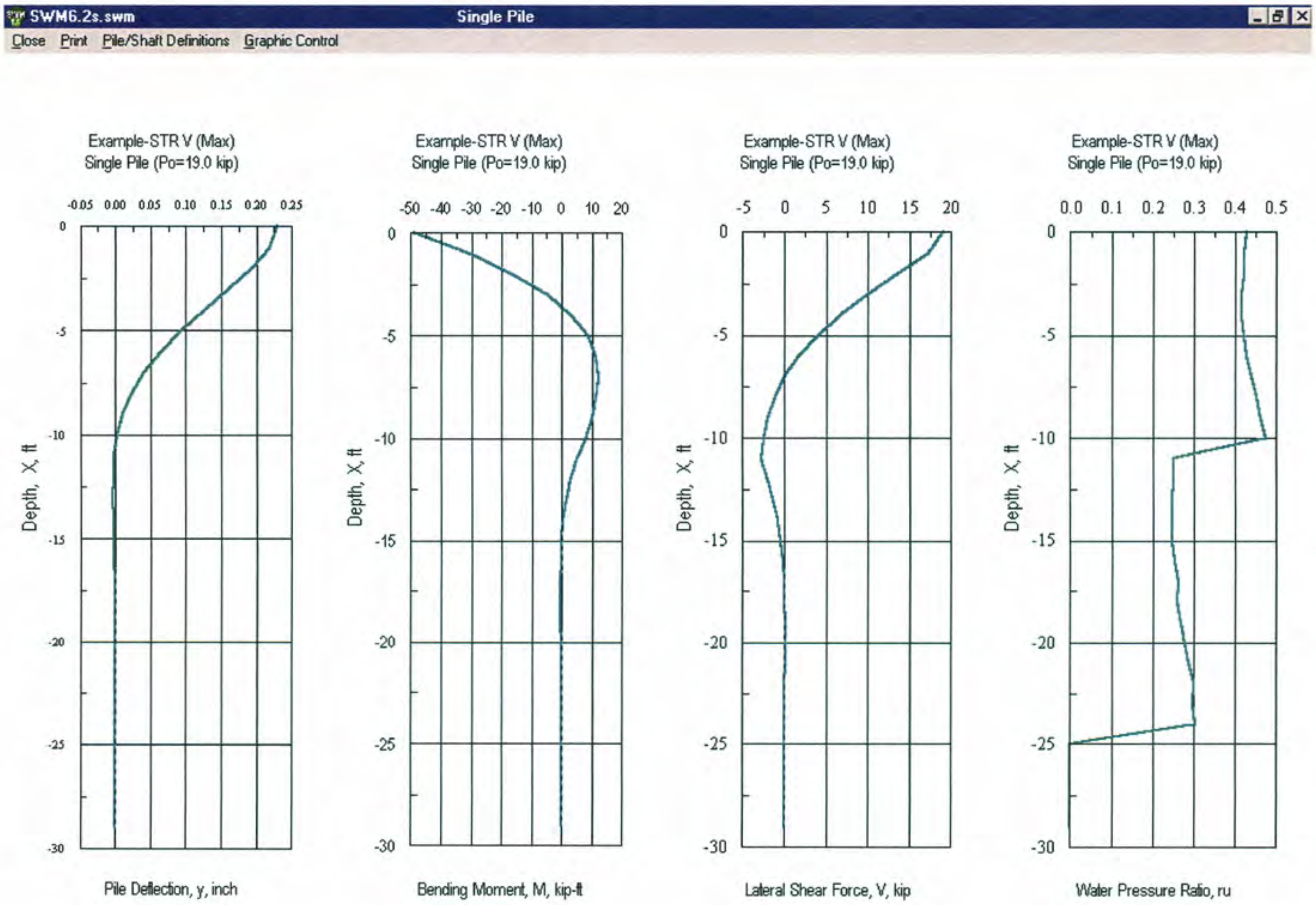


Fig. 20b Lateral Deflection, Moment, Shear Force, and Water Pressure Ration (ru) along the Pile Length at the Given Loads (Case of Soil Liquefaction)

NOTES:

- Click Graphic Control to modify the configuration of the plots seen above (**Fig. 21**). The properties of the above figures (colors, titles, borders, scale, line thickness, etc.) can be modified if desired via the browser of the Graphic Control.
- A copy of the plot can be stored in the clipboard and pasted into other software (such as MSWord). Click Graphic Control and then click System to open the window shown in **Fig. 21**. Choose BMP, Clipboard and then click Copy. Now the figure is ready to be pasted as a picture in any file.

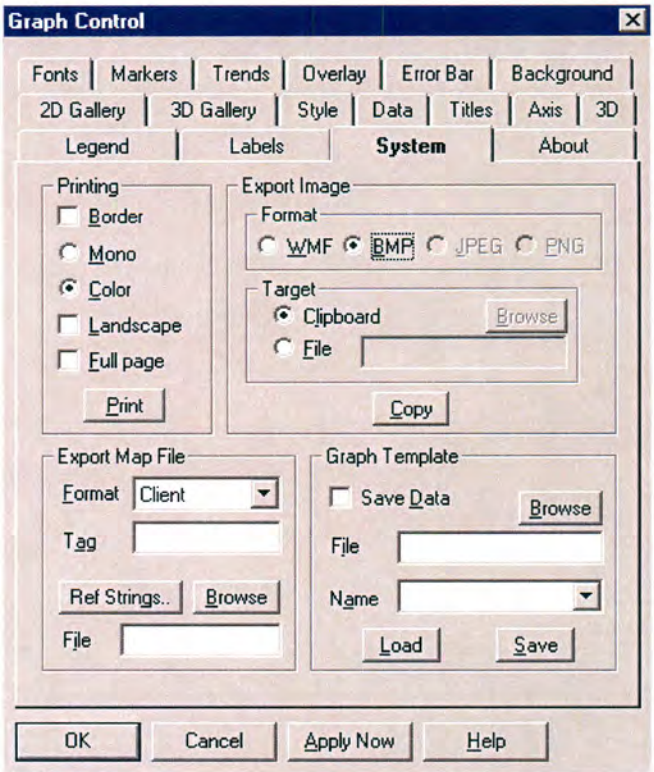


Fig. 21 Graphic Control to Modify the Configurations of the Plots

- p-y Curves (as defined in Window # 1-1) [**Fig. 22**]

Click p-y Curve in the Plot pull-down menu (Fig. 17) to show the shape of the p-y curves that are desired at particular depths during data entry via Window # 1-1. This option will be disabled in the case where no p-y curves were identified by the user in Window # 1-1. The p-y curves are an output data option. The depths of the p-y curves below pile head are shown next to the plot. It should be noted that the range of each p-y curve is governed by the maximum lateral deflection that the pile experiences under the given loads. A Larger pile head load/deflection results in a greater range of the p-y curves.

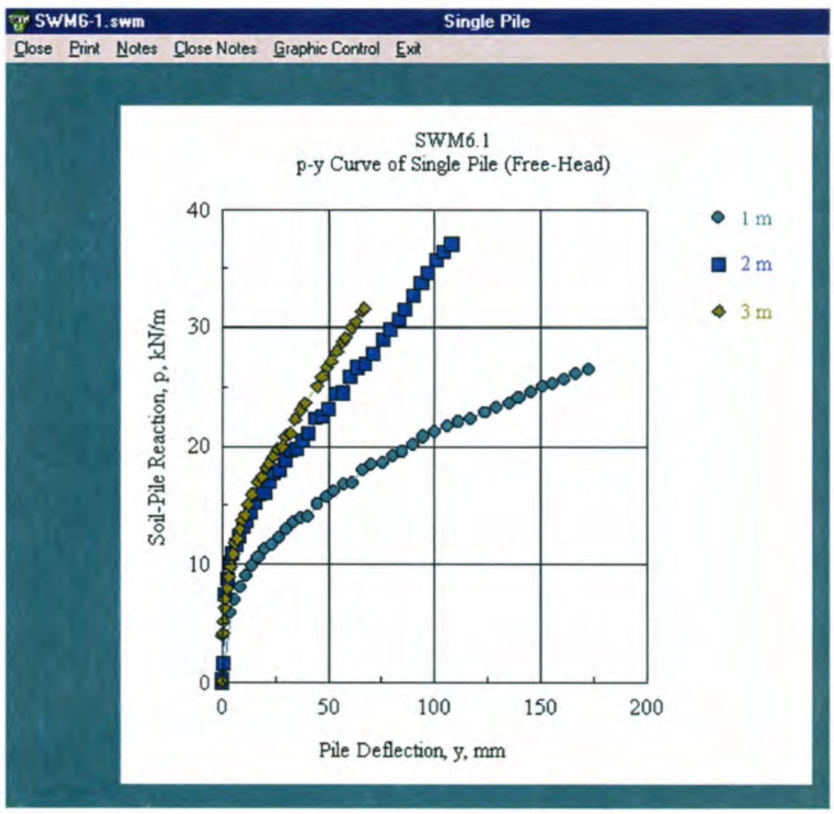


Fig. 22 p-y Curves for a Single Pile at Different Specified Depths

- t-z Curve **[Fig. 23]**

Click t-z Curves in the Plot pull-down menu (Fig. 17) to show the shape of the t-z curve for each soil layer along the length of the pile. No t-z curves will be shown for the soil layers above or below the pile. As with the p-y curve, the t-z curve is affected by developing liquefaction.

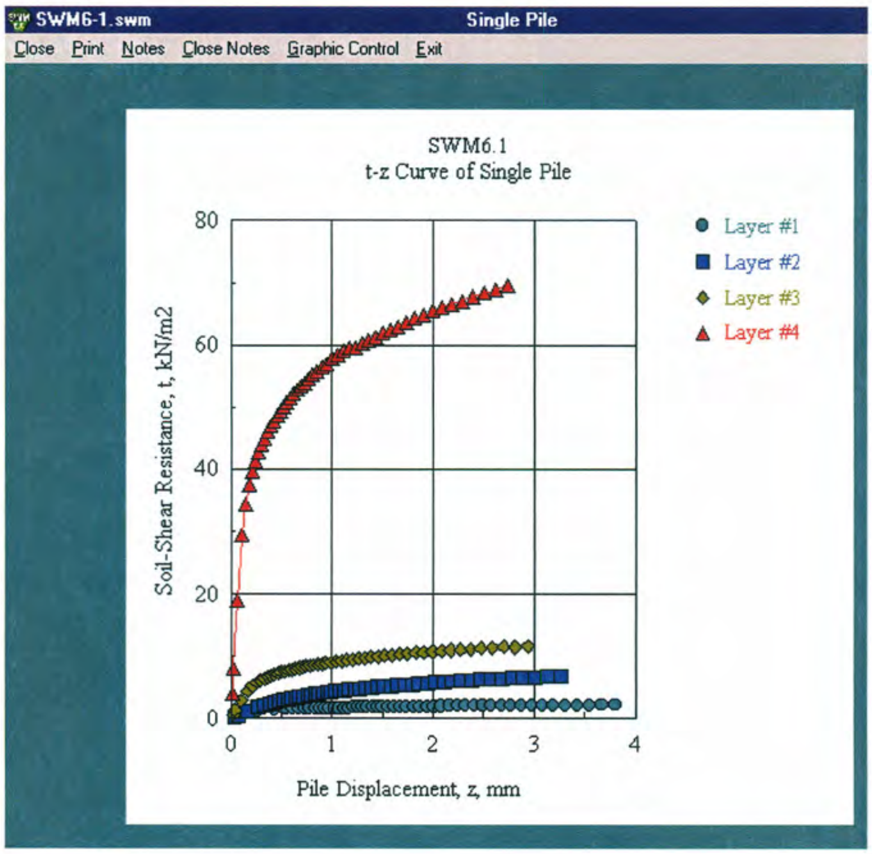


Fig. 23 T-Z Curves Mid Depth in the Soil Layers along the Pile Length

- Load-Settlement Curve [**Fig. 24**]

Click Load-Settlement Curve under Axial Load in the Plot pull-down menu (Fig. 17) to show the Axial Load vs. Pile/Pile head settlement for a varying axial load. The axial load represents the vertical load P_y plus or minus any contributing load due to applied moment acting on the cap.

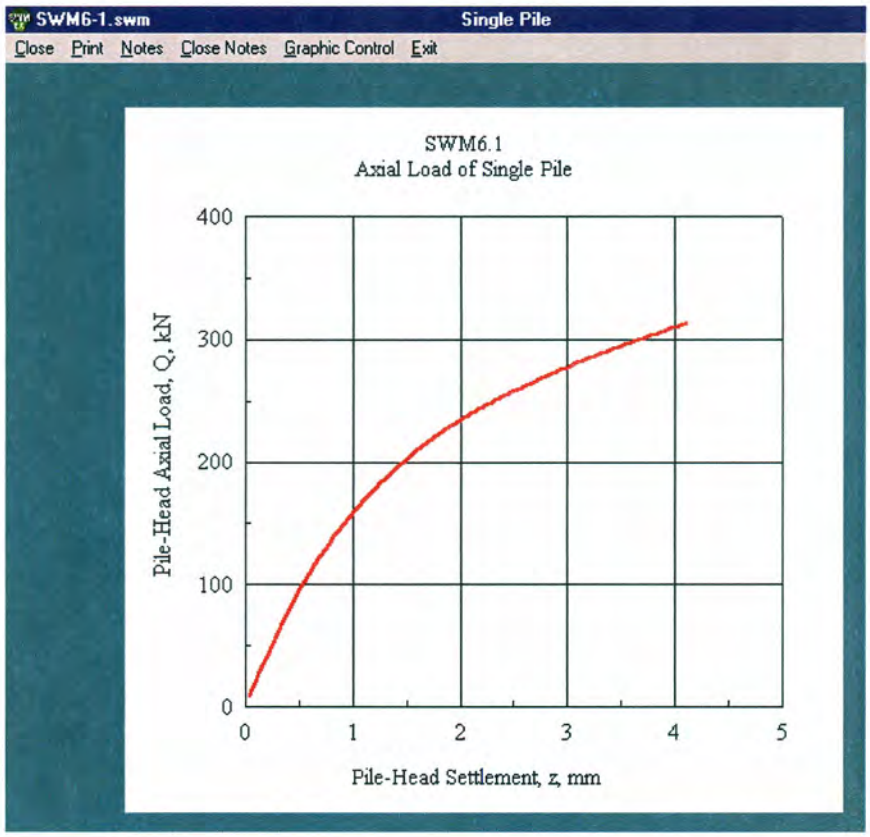


Fig. 24 Axial Load vs. Pile/Pile Head Settlement

- Axial Load Distribution [**Fig. 25**]

Click Axial Load Distribution under Axial Load in the Plot pull-down menu (Fig. 17) to show the Axial Load Distribution vs. Pile Depth at the axial load specified in the pile head load entry (Fig. 10). The plot shows the axial load carried by skin friction and pile-tip.

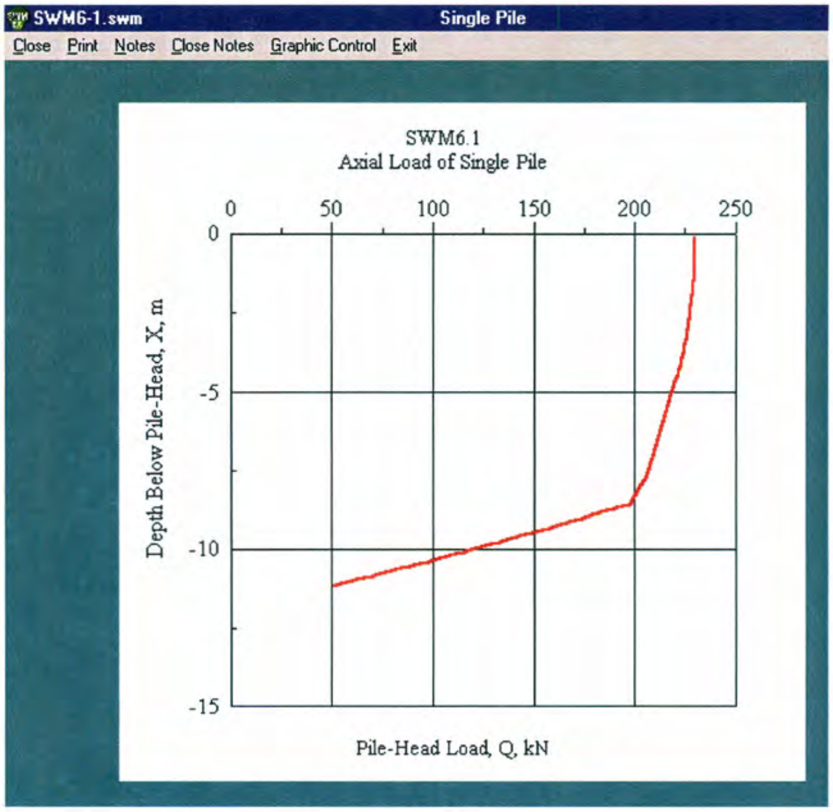


Fig. 25 Axial Load Distribution along Pile/Pile Length

- Moment–Curvature-Bending Stiffness (M - ϕ - EI). **[Figs. 26 and 27]**

  This output data is available only with the nonlinear analysis. The following set of relationships will be plotted for each pile segment. For example, if the pile has 2 different cross-sections (2 segments), the program plots 2 sets of the following curves:

  - Moment – Bending Stiffness (M – EI) [Fig. 27a]
  - Moment – Curvature (M - ϕ) [Fig. 27b]
  - Bending Stiffness – Curvature (EI - ϕ) [Fig. 27c]

  The above relationships show the degradation in pile stiffness (EI) due to the increasing bending moment and the associating curvature in the nonlinear analysis.

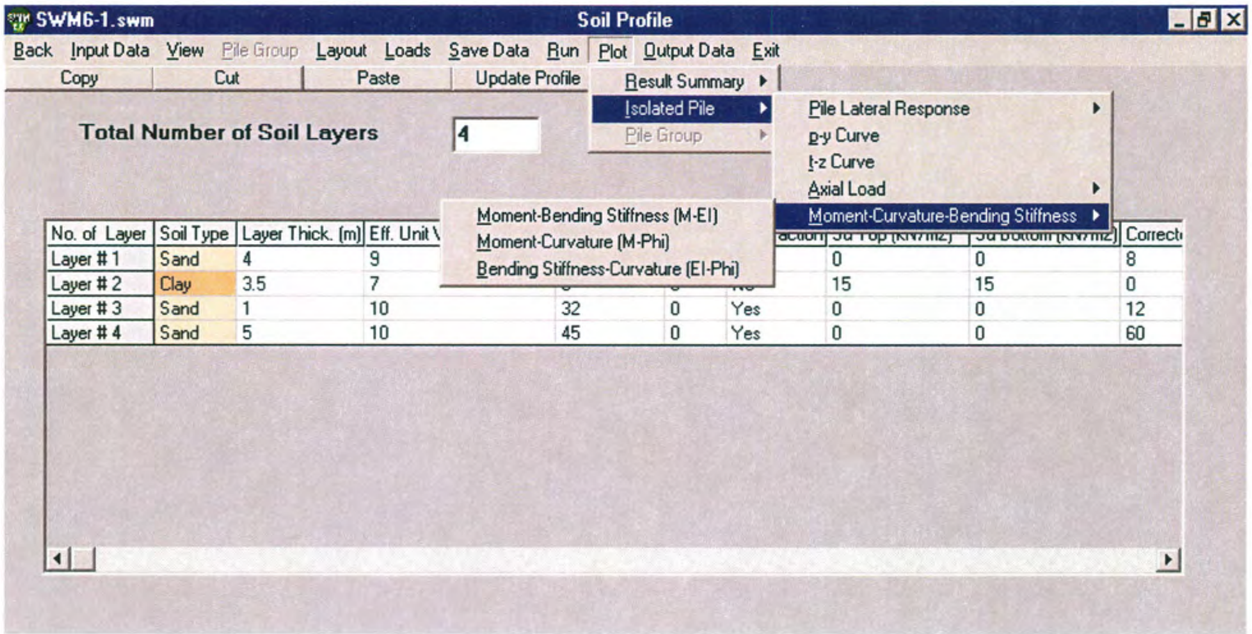


Fig. 26 Pull-Down Menu for the Moment-Curvature-Bending Stiffness Relationships

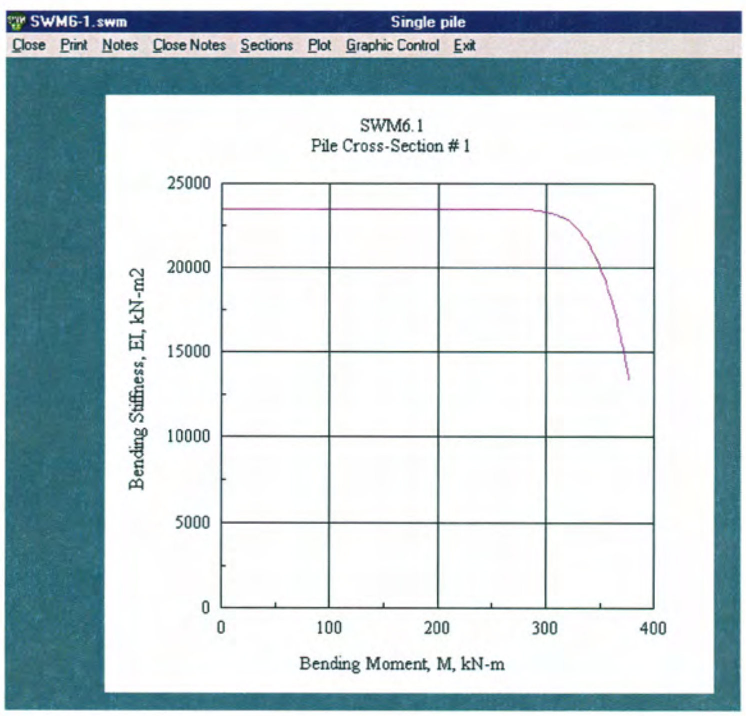


Fig. 27a Moment vs. Bending Stiffness for the Pile Cross Section(s) (Steel Pipe)

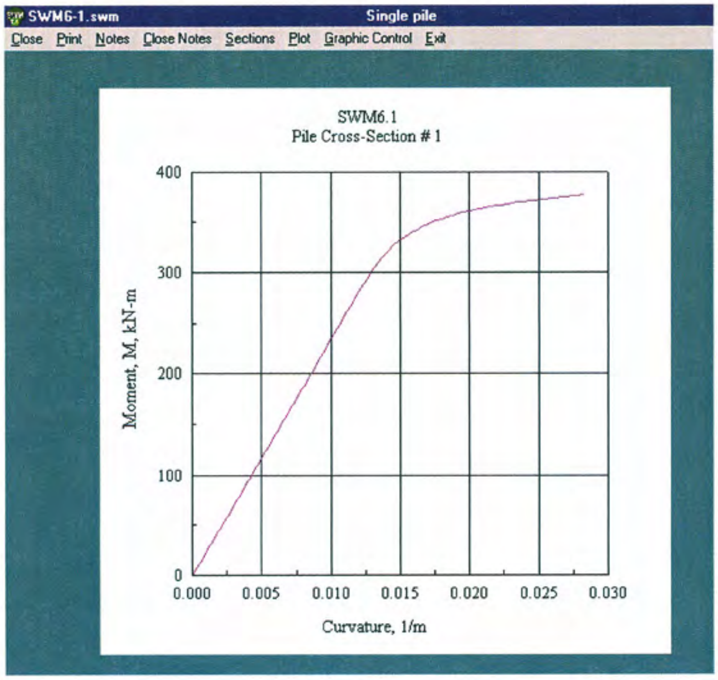


Fig. 27b Curvature vs. Moment for the Pile Cross Section(s)

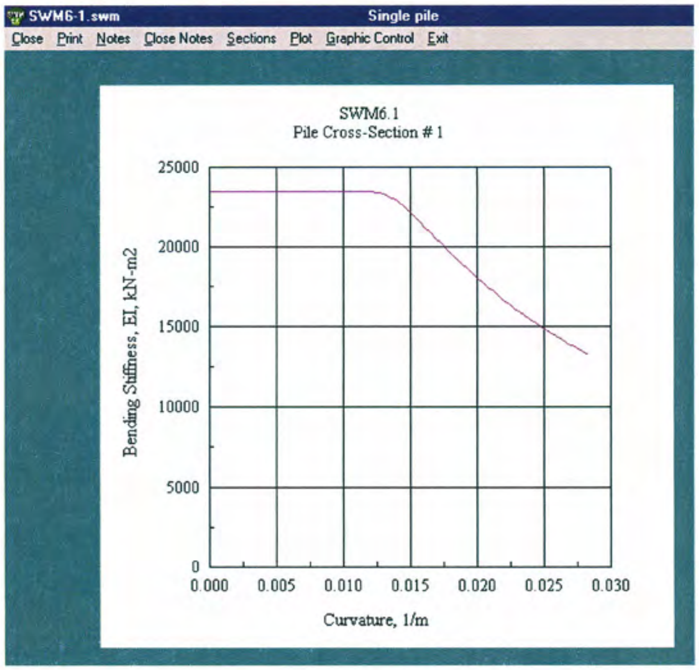


Fig. 27c Curvature vs. Bending Stiffness for the Pile Cross Section(s)

- Pile Group Lateral Response [**Fig. 28 thr. 31**]

This option allows the user to plot and print out the following responses for individual piles in a pile group (Pile Type # 1, Pile Type # 2, Pile Type # 3 or Pile Type # 4) along the pile/pile length at the loads entered in Window #1-2.

- Lateral Deflection, Bending Moment, Shear Force for every Pile Type in the group[Fig. 29]
- Pile-Group Lateral Load vs. Displacement for pile group with and without cap. [**Fig. 30**].
- Pile-Head Lateral Load vs. Displacement for isolated and average pile of a pile group without cap contribution. [**Fig. 31**].

Figure 32 shows the pile-type classifications in the pile group based on the loading direction and the pile locations in the group. Click *Pile/Shaft Definitions in the Menu Bar* in Fig. 29 to see Fig. 32.

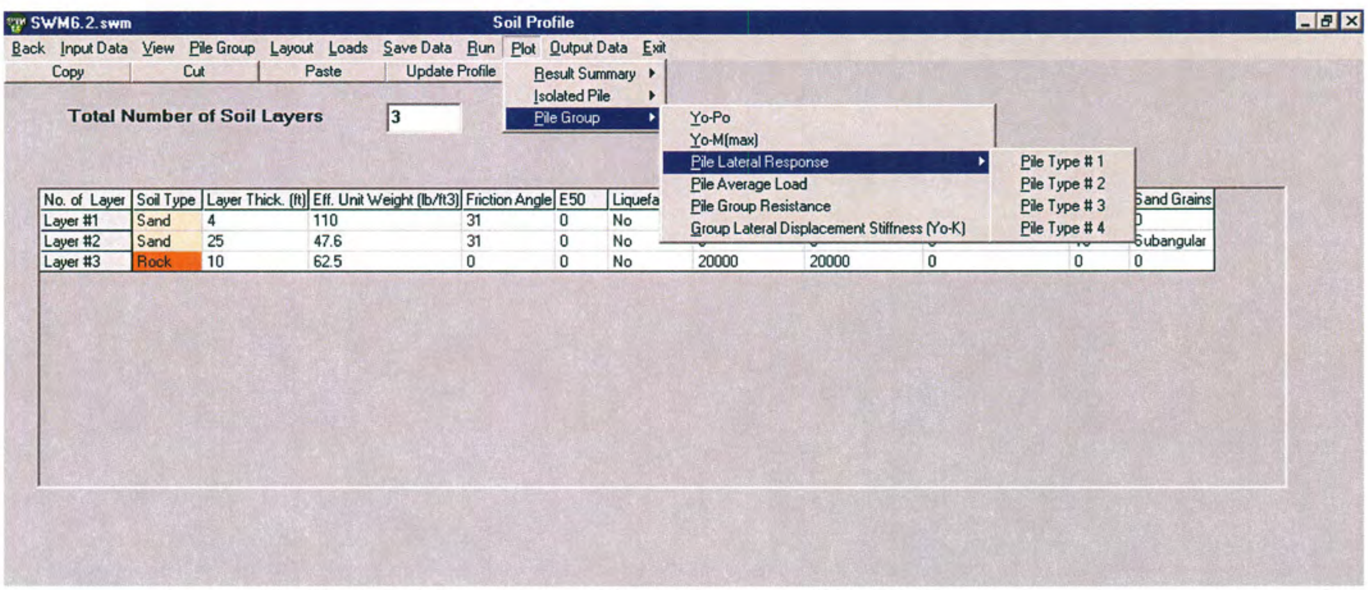


Fig. 28 A Pull-Down Menu to Plot the Response of Pile/Pile Group

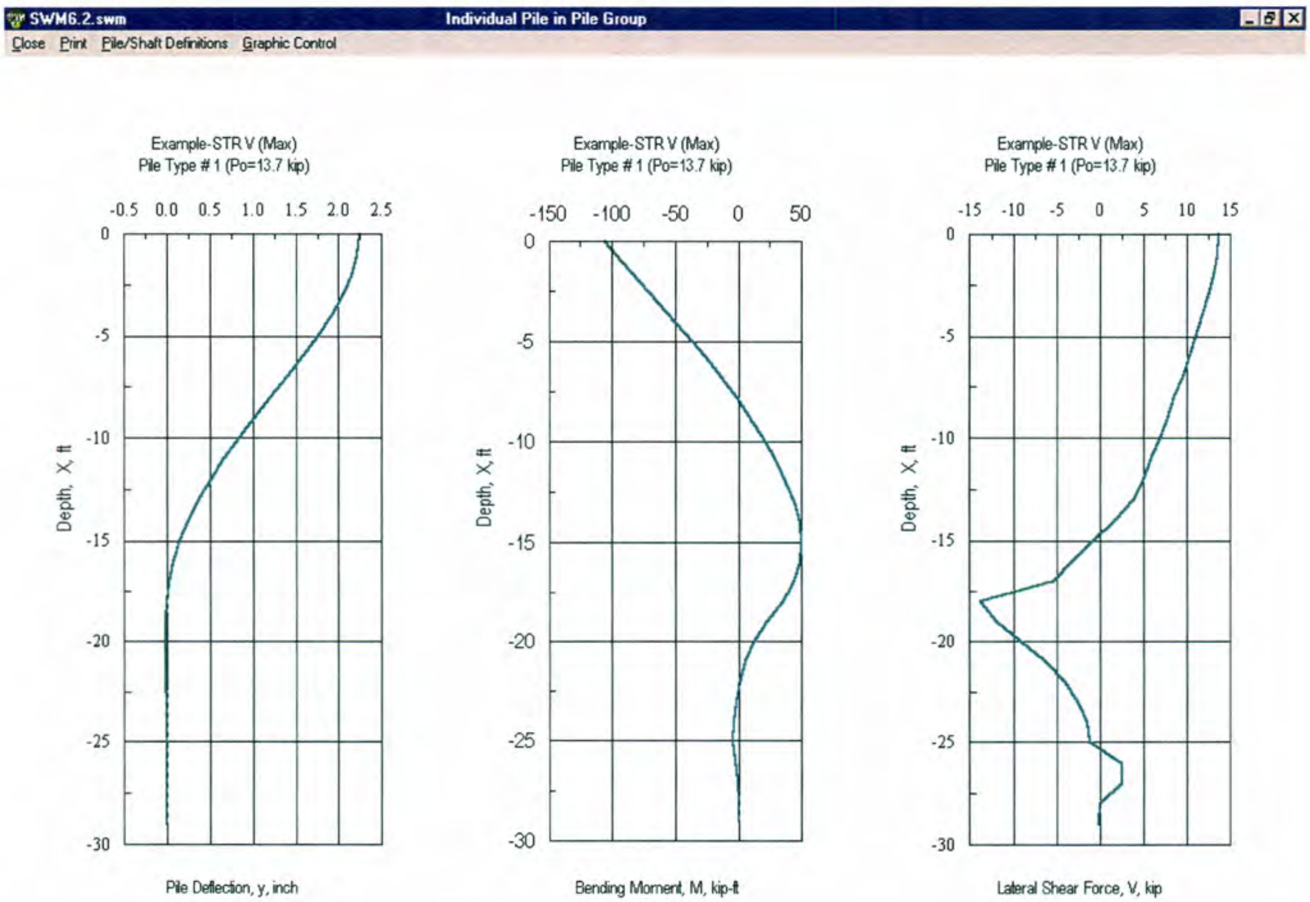


Fig. 29a Lateral Deflection, Moment, and Shear Force along the Length of Pile Type 1 in the Pile Group

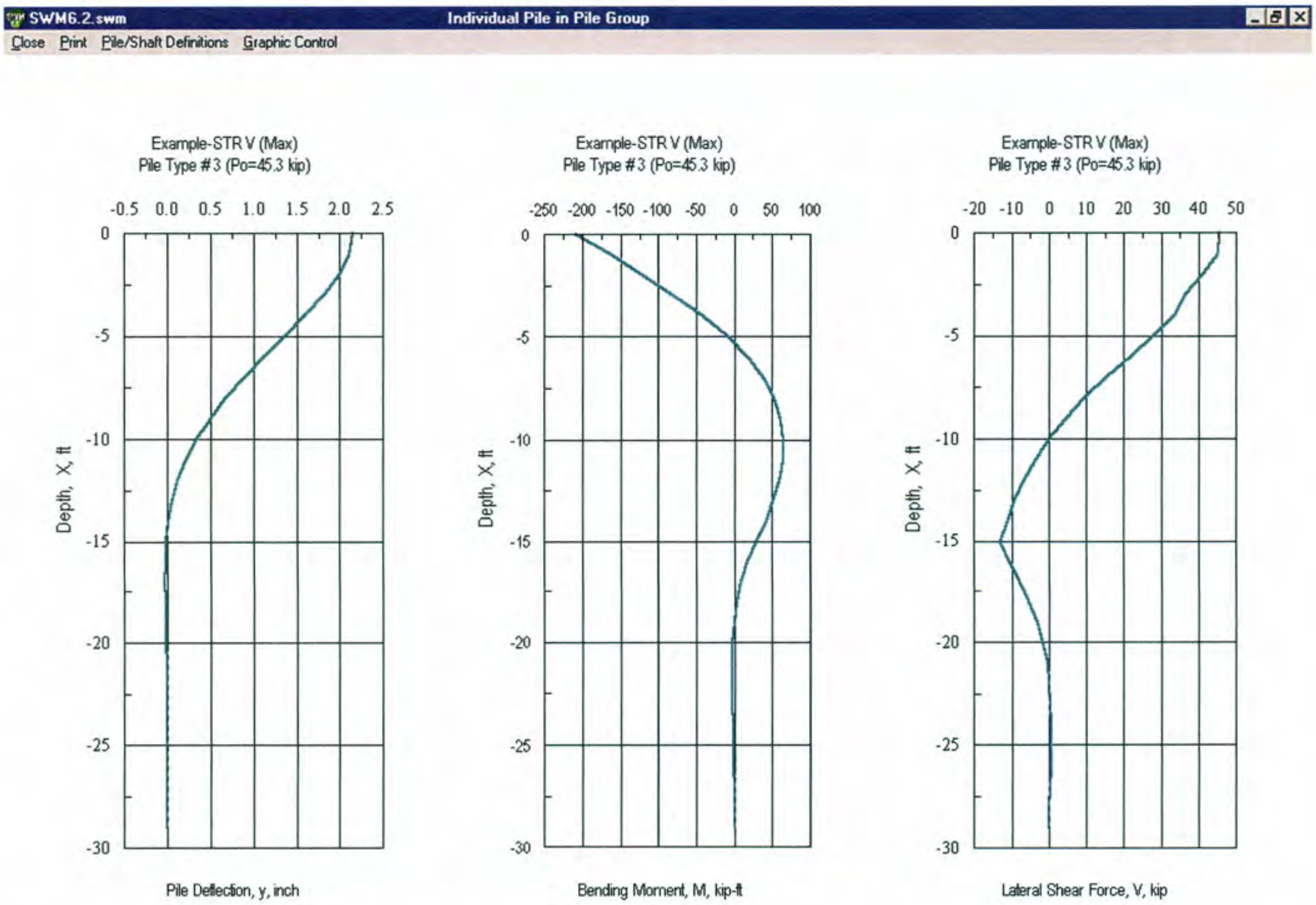


Fig. 29b Lateral Deflection, Moment, and Shear Force along the Length of Pile Type 3 in the Pile Group.

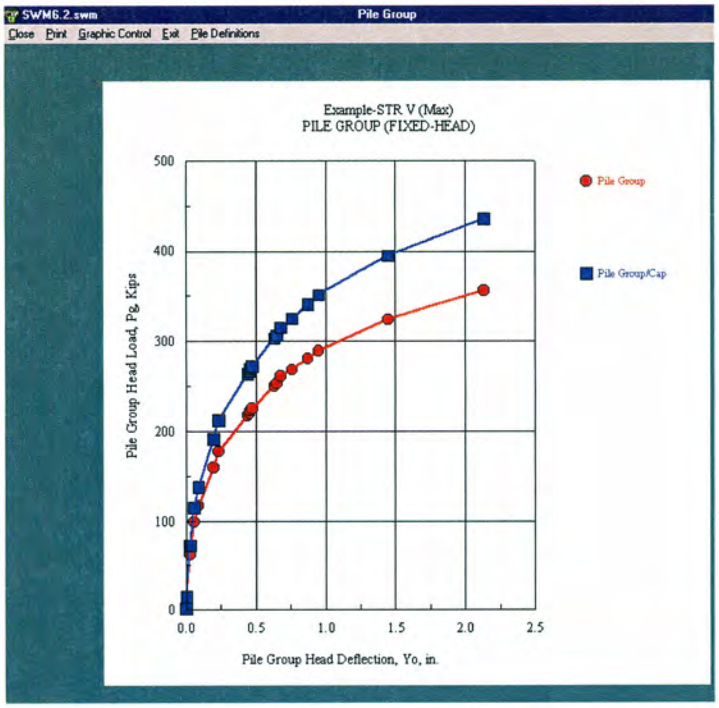


Fig. 30 Pile-Head Lateral Load vs. Deflection for Pile Group with and without Pile Cap

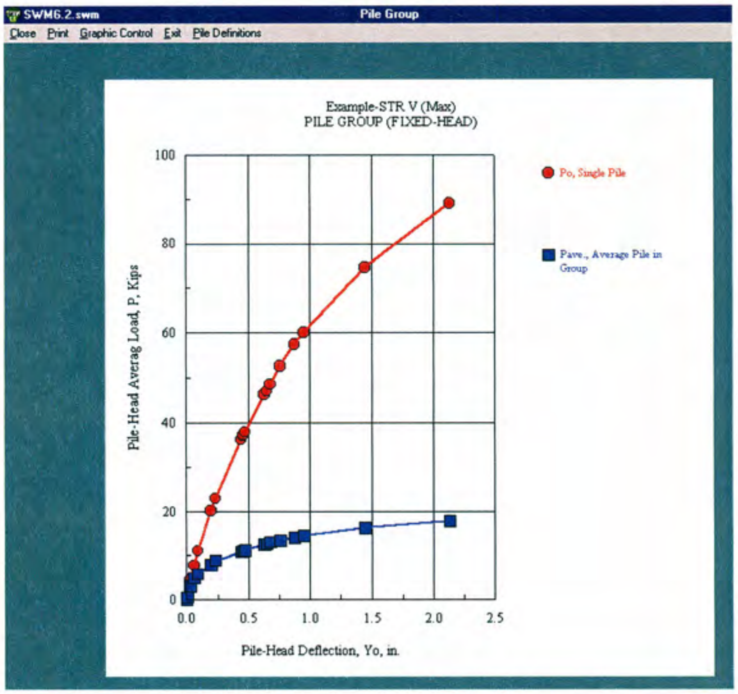


Fig. 31 Lateral Load vs. Deflection for Isolated and Average Pile in a Pile Group
(No Pile Cap Effect is Included)

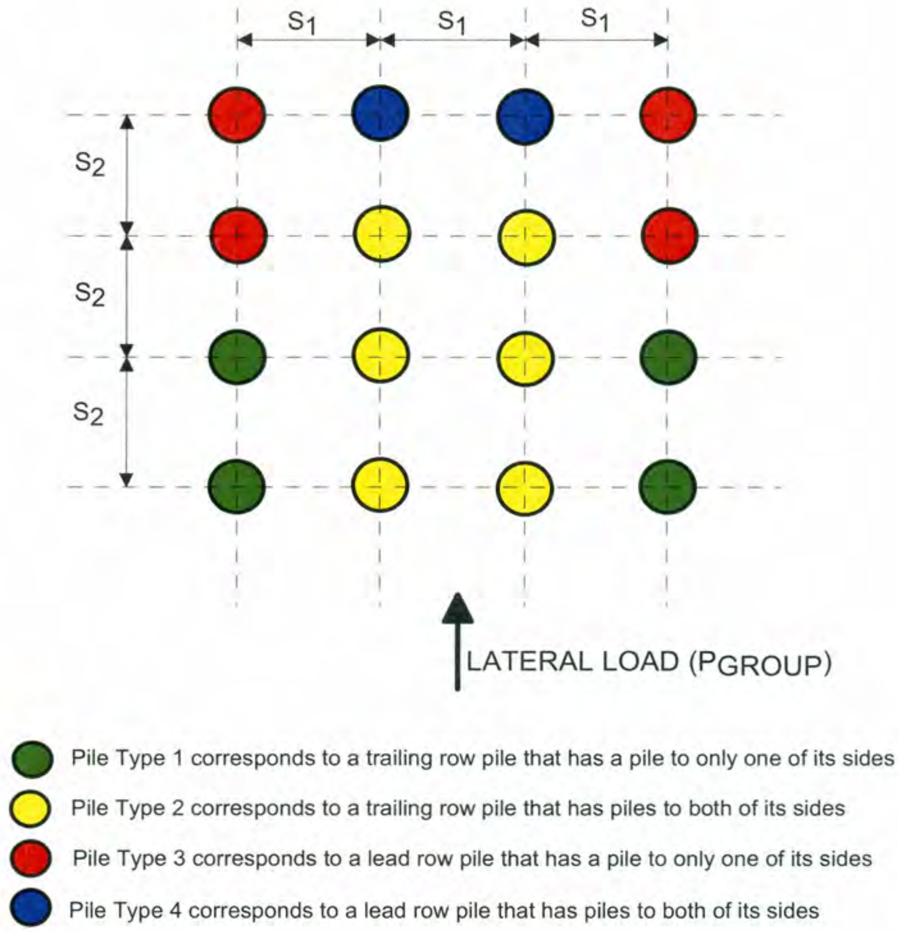


Fig. 32 Description and Distribution of Piles in a Group

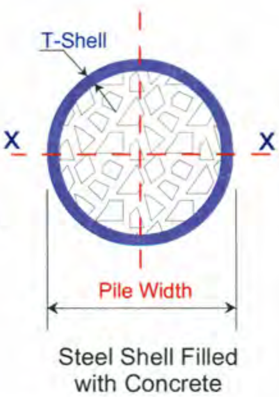
EXAMPLES

The following examples are part of the examples attached to the program software and have the same numbers in software package. The soil and pile properties specified in the following figures represent the exact input data employed with these examples as seen in the examples attached to the program software.

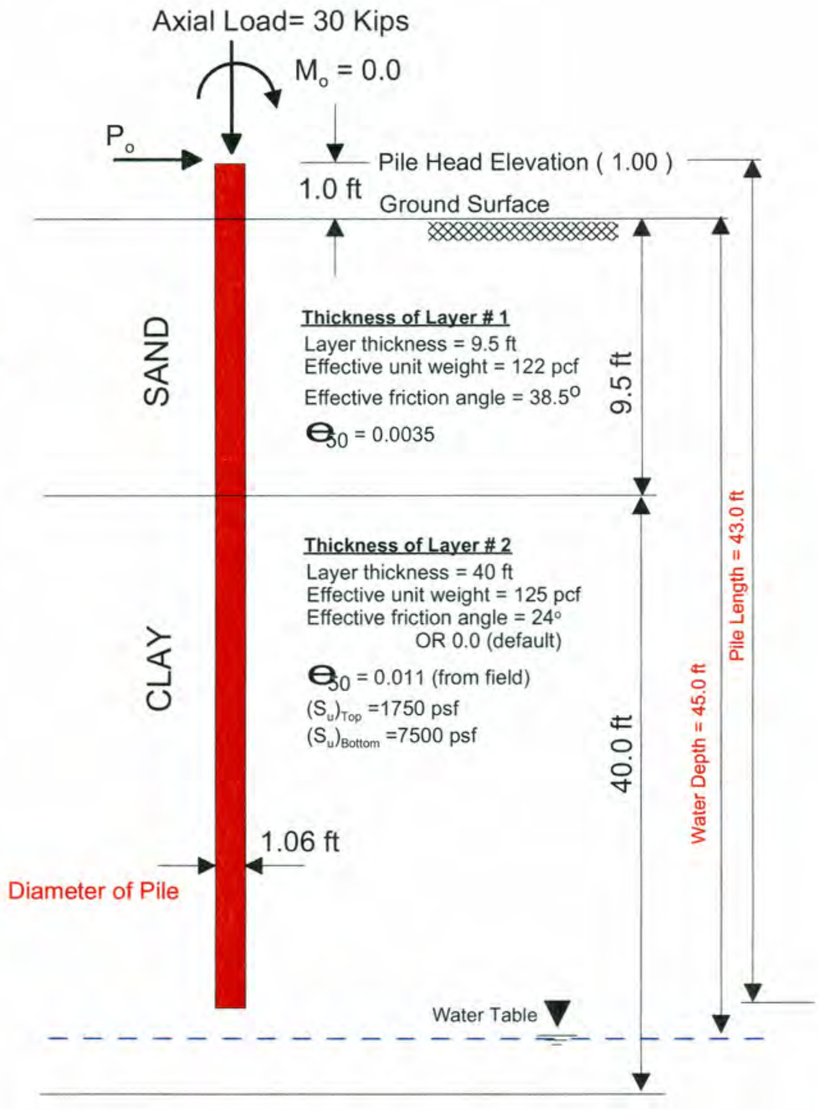
EXAMPLE 1

Isolated Pile and (3 x 3) Pile Group

T-Shell = 0.375 inch
f_c of concrete = 5.0 ksi
f_y of the steel shell = 36 ksi



Pile Cross-Section

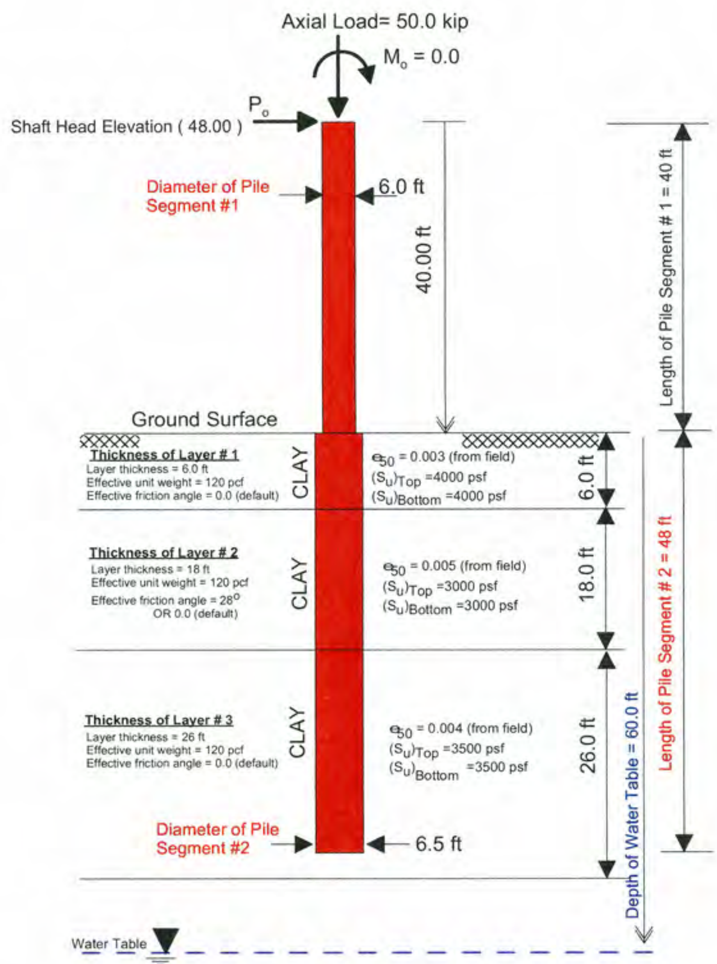


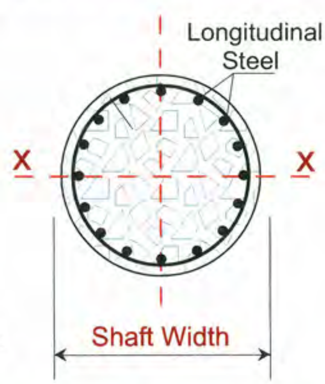
Pile Group

3 pile rows normal to the loading direction
3 pile rows parallel to the loading direction
Pile Spacing in both directions = 3D = 2.7 ft

EXAMPLE 2

University of California Los Angeles (UCLA) Test Drilled Shaft in Stiff Clay



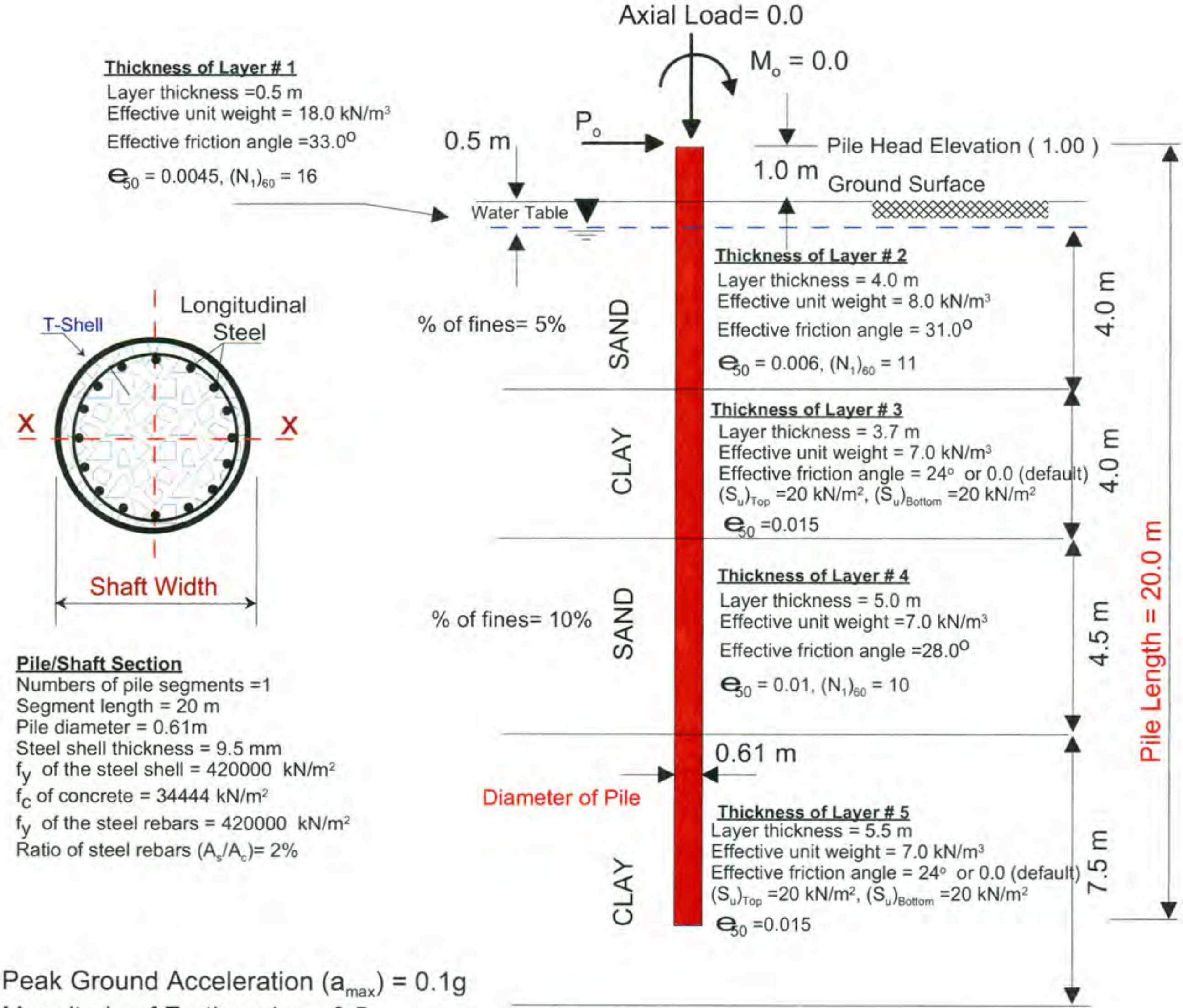


Shaft Section# 1
Segment length = 40 ft
Shaft diameter = 6.0 ft
f_c of concrete = 6100 psi
f_y of the steel rebars = 71 Ksi
Ratio of steel rebars (A_s/A_c)= 2%
Ratio of transverse steel (A'_s/A_c)= 0.5%

Shaft Section# 2
Segment length = 48 ft
Shaft diameter = 6.5 ft
f_c of concrete = 6100 psi
f_y of the steel rebars = 71 Ksi
Ratio of steel rebars (A_s/A_c)= 1.8%
Ratio of transverse steel (A'_s/A_c)= 0.5%

Reinforced Concrete Drilled Shaft

EXAMPLE 3
Treasure Island Test



Pile/Shaft Section
Numbers of pile segments =1
Segment length = 20 m
Pile diameter = 0.61m
Steel shell thickness = 9.5 mm
f_y of the steel shell = 420000 kN/m²
f_c of concrete = 34444 kN/m²
f_y of the steel rebars = 420000 kN/m²
Ratio of steel rebars (A_s/A_c)= 2%

Peak Ground Acceleration (a_{max}) = 0.1g
Magnitude of Earthquake = 6.5
No lateral spreading
Free- and near-field excess porewater pressure effect
Assume sand grains "Subangular"

PUBLICATIONS

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Ashour, M., and Norris, G. M. "**Formulation of Undrained Behavior of Saturated Sands from Drained Rebounded Response.**" Geotechnical Special Publication No. 75, **ASCE**, *Geotechnical Earthquake Engineering and Soil Dynamics Conference,* Seattle, Washington, Vol. 1, August, 1998, pp. 361-372.

Ashour, M., and Norris, G. M. **"Undrained Laterally Loaded Pile Response in Sand."** Special Geotechnical Special Publication No. 75, **ASCE**, *Geotechnical earthquake Engineering and Soil Dynamics Conference*, Seattle, Washington, Vol. 2, August, 1998, pp. 1356-1367.

Ashour, M., Norris, G. M., and Pilling, P. **"Lateral Loading of a Pile in Layered Soil Using the Strain Wedge Model."** *Journal of Geotechnical and Geoenvironmental Engineering*, **ASCE**, Vol. 124, No. 4, April, 1998, pp. 303-315.

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