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3-D PILE GROUP PROGRAM

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3—D PILE GROUP PROGRAM

1.0 PROGRAM ABSTRACT

The Static Analysis of Piles (PILEGP) will analyze a three-dimensional pile group subjected to static loadings. The direct stiffness approach in conjunction with conventional matrix methods is used to perform the analysis. The pile cap is assumed to be rigid with the remainder of the system demonstrating elastic behavior.

PILEGP will analyze up to 200 randomly placed piles. The piles may have varying section properties, bending stiffnesses, and lengths. Battered or plumb piles are handled by PILEGP and may be fixed or pinned to the rigid cap. Friction or end bearing piles also are considered by the program. When a subgrade modulus is specified, the piles experience lateral interaction with the soil. Loads are transmitted to the piles through the origin of the coordinate axis. Factors for Group Loadings may be specified.

Program output includes shears, moments, and axial forces for each pile for multiple load conditions. Deflections at the centroid of the cap as well as arbitrarily chosen points in space are also printed. An equilibrium check of the vertical forces as well as a summary of maximum and minimum axial loads and the governing load cases are output for each pile. Diagnostic information is displayed if abnormal loading or geometric conditions are encountered.

2.0 DESCRIPTION OF PROGRAM

2.1 GENERAL

This program is intended to accommodate the majority of problems encountered in the design of pile groups. The general direct stiffness method for three-dimensional pile foundations is utilized. This allows for a variety of features and configurations which are described in this section. Also described are the limitations and difficulties which are inherent in the general topic of pile group design and pile-soil interaction.

2.2 PROGRAM CAPABILITIES

- a) Pile Group Configurations —Three pile group configurations are offered as options within the program:
 - 1) Standard pile Formulation where the top portion of the pile extends through a uniform material (with a finite value of the subgrade modulus allowed) to fixity (see Figure 4a). Here, the lower layer is sufficiently dense so that it does not allow any movement of the piles.
 - 2) Cantilever Beam Formulation where the top portion of the pile extends through a uniform material (with a finite value of the subgrade modulus allowed) to fixity (see Figure 4b). Here, the lower layer is sufficiently dense so that it does not allow any movement of the piles.
 - 3) Elevated Platform Formulation such as those used offshore where the piling extends above soil level (see Figure 4c). Here, the piles are cantilevered from a uniform homogeneous soil material. (Note that stability should be checked in this case.)
- b) Boundary Conditions —A general set of conditions may be specified for any individual pile within the group or for the group as a whole.
 - 1) Batter may be specified for any pile to any slope or orientation (including a plumb condition);
 - 2) The pile at the cap may be either hinged or fixed;
 - 3) The type of pile may be either friction or bearing;
 - 4) The interaction of the pile with the subgrade may be considered or neglected through the specification of a subgrade modulus, k_s .
- c) Coordinate System —No restriction is placed upon the location of any pile within the group. The individual pile positions are described by X, Y, and Z coordinates which allow for stepped pile caps. Although the origin of the coordinate system can be located

anywhere, the best results are obtained when it is placed as closely as possible to the centroid of the pile group.

- d) General Description of Method —The pile foundation consists of a group of piles placed into the soil covered with a rigid cap. The general direct stiffness method is related to the system through the global coordinates to obtain stiffness of the entire foundation. This method allows for the analysis of numerous pile group types. The advantages of the method are:
- 1) The method yields forces and moments (including torsion) in the piles which, when summate with the applied loads, are in static equilibrium (this is not the case for many popular methods used for pile group design);
 - 2) As a direct output, the method yields the deflections and rotations of the pile cap about the origin;
 - 3) The method allows for the determination of a pile group itself being unstable (this is not to be confused with pile buckling; see Section 2.4b);
 - 4) Interaction with the subgrade may be considered in the analysis either if the pile group is unstable, or if additional group capacity is required;
 - 5) Pile stresses at the intersection of the pile cap and the pile can be obtained considering axial and shear forces, bending and torsional moments.

2.3 PROGRAM LIMITATIONS

- a) Size Restraints — Certain restraints are imposed upon this program as a result of the capacity of the computer. These can be altered rather quickly, usually by changing the DIMENSION statements and certain constants within the program (both of which are identified in the listing). These are given as follows:
- 1) The maximum number of piles allowed currently is 300, with the capacity to handle 1500 with minor alterations;
 - 2) The maximum number of arbitrary locations in space for which deflections are desired = 10;
 - 3) The maximum number of loading cases or group combinations which can be considered is 40.
- b) Limitations of the Method — Certain limitations are imposed upon this program as a result of the methodology used. These are:
- 1) The pile cap is considered rigid (see Figure 1 for a definition of pile cap);
 - 2) The subgrade is idealized as being composed of uniform, elastic, isotropic

material (see Figures 4a, b, and c). Although two layered subgrades usually can be simulated by the program, general multilayered systems cannot be analyzed;

- 3) All piles are considered to be prismatic;
- 4) The batter direction is assumed to be normal to the major and minor bending axis of the pile (see Figure 1);
- 5) Linear elastic theory is assumed throughout the program.

2.4 RECOMMENDED PRACTICE

The topic of the analysis and design of pile groups is a broad subject area requiring expertise in methods relating to soil mechanics, structural analysis, testing methods, and field procedures. The designer often is confronted with insufficient soil data, complex methodology, and the lack of adequate information on proper analysis techniques. Given here is a brief delineation of the procedures which are recommended when using this program. The following topics are presented categorically:

- a) Subgrade Modulus — The subgrade modulus, k_s , is a measure of the ability of the soil to respond to force. It is, in effect, a spring constant with units pounds/inch³ or pounds per square inch of pile area per inch of soil deformation (extreme care must be used in interpreting this quantity when consulting the literature since the units often are not defined uniformly).

It is recommended that the subgrade modulus NOT be used (i.e., input as zero) unless the design conditions warrant. Such conditions would be as follows:

- 1) The analysis of existing structures where the addition of piles would be extremely costly;
- 2) The analysis of unstable pile groups such as those shown in Example 1 figure. Such pile groups, by nature, are statically unstable unless support is provided by the subgrade;
- 3) The analysis of structures from sites where sufficient soil data exists such that k_s can be defined properly.

It is recommended also that where the subgrade modulus k_s is used, its value be chosen as the low limit of the range for the soil identified. It should be determined from plate bearing tests but, in a broad sense, it is given as follows:

“For highly compressible silt, clay, or organic material, $k_s = 0$ pci to 170 pci; for low to medium silt or clay, $k_s = 150$ pci to 225 pci; for sand, fine or poorly graded, $k_s = 200$ pci to 300 pci and for clayey or well graded sand, fine gravel, $k_s = 250$ pci to 450 pci.”

The following is generally true with respect to the subgrade modulus:

- 1) The use of a subgrade modulus generally stiffens the foundation structure;
- 2) Ignoring any soil restraint on the piling may yield incorrect solutions, since even a minimal soil modulus stiffens the structure considerably;
- 3) An analysis of a pile group ignoring the subgrade modulus yield results is compatible with the Hrennilcoff³, the Elastic Center and other popular methods assuming compatible boundary conditions.

- b) Unstable Pile Group Configurations — An unstable pile configuration occurs when the piles within a group are unable to satisfy equilibrium for a general loading system. Consider Example 1 figure where two rows of piles converge at a point C. This group is unstable for the lateral load P positioned at any $h_1 < h_2$, or and $h_3 < h_2$. The instability is apparent because no lateral support is given, from the soil or from fixity at the base of the piles, to resist the lateral load. Here, the program will fail because no static solution exists which satisfies these loading conditions. The program also will fail for the case where the lateral load is positioned at h_2 where a solution does exist. Therefore, the pile group must be stable for all loading conditions.

In order to make the pile group in Example 1 figure stable, either the subgrade modulus, k_s , should be specified or, if conditions warrant, a point of fixity should be determined. (See Figure 4b — PILE CONFIGURATION TYPE 2.) Here, the necessary lateral restraint is present to resist the load P. Another way to insure stability is either to add another row of battered or plumb piles or to place some plumb piles within the row of batter piles (see Example 2 figures, respectively).

- c) Layered System — Although the program does not allow consideration of various soil strata, it is possible to simulate two limiting layered conditions.

Condition 1 — A subgrade composed of a stratum overlaying a very dense soil can be handled using the Pile Configuration Type 2 (see Figure 4b — CANTILEVER BEAM FORMULATION). Here, the upper stratum may be represented by any subgrade modulus, k_s , and the lower stratum must be considered as having a subgrade modulus as infinity.

Condition 2 — A subgrade composed of a very weak layer overlaying a stratum of soil with some restraint. This can be idealized by using Pile Configuration Type 3 (see Figure 4c — ELEVATED PLATFORM) where the subgrade is assumed to be zero for the upper stratum and any infinite modulus for the lower stratum.

It must be emphasized again that it is recommended that no subgrade modulus be used unless conditions warrant (see Section 2.4a).

3.0 INPUT

All numerical input must have a decimal point except those designated as integers which must be rightly justified.

3.1 SYSTEM DATA

Data Type 01012 — Project Data

DESCRIPTION: A general description of the project or problem given as an alphanumeric.

DATE: The date of the run given as an alphanumeric.

Data Type 01022 — Project Data

CONTRACT NUMBER: The contract number given as an alphanumeric.

STRUCTURE NUMBER: The number of structures given as an alphanumeric.

STRUCTURE UNIT:

DESIGN BY: The engineer responsible for creating the computer input given as an alphanumeric.

CHKD BY: The engineer responsible for checking the computer input given as an alphanumeric.

SPECIFICATION USED: The date and interim (where applicable) of the code used is the analysis given as an alphanumeric.

Data Type 01032 — System Options

UNITS: Use 0 for English Units; use 1 for S.I. Units.

PLOT SCALE (FT/IN): A plot of the pile group may be obtained by specifying the scale of the plot.

SYMMETRY OF PILE GROUP: If the pile group is symmetrical about either the X-X or the Y-Y axis, or both axes (see Figure 1), an integer 1 may be used in either one or both of the assigned places. If this option is used, pile data for only one-half or one-quarter of the group need be input depending upon the type of symmetry.

DESIGN CODE ID: Leave blank if no code is to be used; use 1 if AASHTO code is to be used.

NOTE: This is required if STD GROUP NO. option is used (see Sheet 6 of 7, Data 6012).

3.2 OPTIONS AND MATERIALS

Data Type 02012 — Pile Configuration

CONFIGURATION TYPE: There are 3 possible pile group formulations. These are identified as CONFIGURATION TYPES 1, 2, and 3 and are described as follows:

CONFIGURATION TYPE 1: Standard pile formulation when the pile is modeled as a semi-infinite beam or an elastic foundation (see Figure 4a).

CONFIGURATION TYPE 2: Cantilever beam formulation where the pile is modeled as a cantilever beam fixed at some arbitrary depth L' . Here, information pertaining to the point of fixity must be known beforehand. A pile driven into a layer which would allow little or no lateral movement would qualify as a level of fixity (see Figure 4b).

CONFIGURATION TYPE 3: Elevated platform configuration where the piles are modeled as cantilever beams in two regimes, an upper layer of length L' with no soil restraint and a lower layer where the pile is assumed to react with the soil (see Figure 4c).

PILE END CONDITION: Use integer 1 if piles are hinged at the cap; use integer 2 if the piles are fixed at the cap.

FRICITION OR BRG: Use integer 1 if piles are end-bearing; use integer 2 if piles are of the friction type.

PILE LENGTH (FT or m): The total length of the pile, L .

FIXED LENGTH (FT or m): The distance from the pile cap to the point of fixity for CONFIGURATION TYPE 2* (see Figure 4b). Also, the distance from the pile cap to the ground for CONFIGURATION TYPE 3 (see Figure 4c).

*NOTE: Fixity is defined as that point where the original edge position pile location is maintained (i.e., no deflection and rotation).

Data Type 02022 — Group Properties

E OF PILE (KSI or MPa): The modulus of elasticity, E , of the pile material.

G OF FILE (KSI or MPa): The modulus of rigidity, G , of the pile material (given as $E/2(1+\nu)$ where ν is Poissons Ratio).

SUBGRADE MODULUS (PCI or Kg/mm^3): The subgrade modulus not to be used unless design conditions warrant (see Section 2.4a for a definition of the subgrade modulus).

COMPRESSIVE CAPACITY (kips or KN): The actual compressive capacity of the pile.

UPLIFT CAPACITY (kips or KN): The actual capacity of the pile to resist uplift as defined by the code.

NOTE: The values entered should represent the actual unreduced pile capacities for compression and tension, respectively.

3.3 PILE SECTIONS

If all piles have the same section shape, they may be input under Pile Sections. This negates having to input them individually under columns Ix-x, Iy-y, J, W and H on Sheet 4 of 7. It also allows the stresses for some pile types to be computed and output. Only one PILE SECTION can be input from this sheet.

NOTE: If data for the pile sections are input on both Sheet 3 of 7 and 4 of 7, then the data given on Sheet 4 of 7 will control. This allows the input of a few special piles for a large group. To illustrate this, consider that if 95 out of 100 piles are “H” sections, they may be input using Sheet 3 of 7; the remaining 5 piles of any configuration may be input using Sheet 5 of 7.

Data Type 03012 — General Section

Ix-x (IN⁴ or mm⁴ × 10⁴ (or cm⁴)): The uniform moment of inertia of the pile about the x-x axis (see Figure 3).

Iy-y (IN⁴ or mm⁴ × 10⁴ (or cm⁴)): The uniform moment of inertia of the pile about the y-y axis (see Figure 3).

J (IN⁴ or mm⁴ × 10⁴ (or cm⁴)): The torsional constant of the pile cross section (equal to the polar moment of inertia for closed sections and $\frac{1}{3} \sum bt^3$ for open sections).⁴

AREA (SQ.IN or mm²): The uniform area of the pile.

WIDTH (IN or mm): The uniform width of the pile section.

HEIGHT (IN or mm): The uniform height of the pile section.

Data Type 03022 — “I” Section (see TYPE 1 Section, Sheet 3 of 7)

W (IN or mm): The flange width.

t_f (IN or mm): The flange thickness.

H (IN or mm): The height of pile section (from top of top flange to bottom of bottom flange).

t_w (IN or mm): The web thickness.

Data Type 03032 — Circular Section (see Types 2-6, Sheet 3 of 7)

SECTION TYPE: Input the pile TYPE as an integer value where the SECTION TYPES are defined as follows:

SECTION TYPE 2: Circular wood pile.

SECTION TYPE 3: Circular steel unfilled pipe piles.

NOTE: Monotube sections can be approximated by circular sections where the input parameters are calculated as follows:

$$t \cong \frac{A_m}{\pi D_a} \text{ and } D :$$

where A_m = the exact area of the monotube section, and

D_a = average diameter of monotube.

If exact values of section properties are desired, input the monotube section through Data Types 03012 or 04012. If this is done, however, stresses are not output.

SECTION TYPE 4: Circular concrete-filled pipe piles without reinforcement.

SECTION TYPE 5: Circular concrete-filled pile piles with reinforcement.

SECTION TYPE 6: Circular concrete piles with reinforcement.

D (IN or mm): The diameter of the pile.

t (IN or mm): The thickness of the steel shell or pipe (not to be input for SECTION TYPES 2, 3, and 4).

R (IN or mm): The radius of the reinforcement (not to be input for SECTION TYPES 2, 3, and 4).

AREA BARS (SQ.IN or mm²): The area of the reinforcement (not to be input for SECTION TYPES 2, 3, and 4).

3.4 PILE GROUP DATA

Data Type 04012 — Pile Data

PILE NO: The number of the pile input as an integer.

VERT. SLOPE: The pile batter defined as the horizontal/vertical (e.g., a 1:3 slope is input as .333).

ANGLE α (DEG): Clockwise angle from a line parallel to the X-coordinate axis of the group to the direction of the batter. Since the direction of batter is assumed to be perpendicular to the major or minor bending axis of the pile, this angle also must be input for plumb piles (see Figure 1).

COORDINATES - X, Y, Z (FT or m): The X, Y, and Z coordinates of any given pile, respectively.

NOTE: The origin of the coordinate system may be located anywhere, but, for best results, position it as close as possible to the centroid of the pile group. Also, the bottom of the pile cap (see Figure 1 for definition of pile cap) usually is taken as the origin of the cap-axis.

PILE AREA (FT or m): The area of the pile (ignored if entered on input sheet 3 of 7).

I_{x-x} (IN⁴ or mm⁴ $\times 10^4$ (or cm⁴)): The moment of inertia of the pile about the x-x (major bending) axis of the pile (see Figure 3).

I_{y-y} (IN⁴ or mm⁴ $\times 10^4$ (or cm⁴)): The moment of inertia of the pile about the y-y (minor) axis of the pile (see Figure 3).

J (IN⁴ or mm⁴ $\times 10^4$ (or cm⁴)): The torsional constant of the pile cross section (equal to the polar moment of inertia in the case of closed sections and $\frac{1}{3} \sum bt^3$ for open sections ⁴).

W (IN or mm): The uniform width of the pile section.

H (IN or mm): The uniform height of the pile section from the top to bottom of the flanges.

FIXED L' (FT or m): The distance from the pile cap to the point of fixity for CONFIGURATION TYPE 2 (see Figure 4b); the distance from the pile cap to the ground line for CONFIGURATION TYPE 3 (see Figure 4c).

NON-STANDARD PILE ID: Leave blank if pile batter is in the direction of the I_{x-x} bending axis; use 1 if the pile batter is in the I_{y-y} bending axis; use 2 if the batter is not in a principal (i.e., I_{x-x} or I_{y-y}) axis of bending.

3.5 DEFORMATION DATA

Data Type 05012 — Specification of Arbitrary Points where Movement is Desired

POINT NO: The number specified as an integer.

DESCRIPTION OF POINT: The description of the point input as an alphanumeric.

COORDINATES OF POINT - X, Y, Z (FT or m): The X, Y, and Z coordinates of the point. These can be specified at any point in space where movement is desired.

3.6 LOAD DATA

Data Type 06012 — Load Data

This sheet may be used to input loads in three ways, as follows:

- 1) Individual loads with no group action — Here the three components of force and moment are input and processed as given. Also, the LOAD NUMBER is given, but the STANDARD GROUP NO., the CODE ID, and Sheet 7 of 7 all are ignored.
- 2) Individual loads with standard group combinations — Here, the three components of force and moments are input and processed as given. However, the LOAD NUMBER and the STANDARD GROUP NUMBER (e.g., AASHTO Group Number 2 for D+E+B+SF+W) must be given so that the Percentage of Unit Stress can be applied. The CODE ID and Sheet 7 of 7 are ignored.
- 3) Individual loads with arbitrary group action — Here, the three components of force and moment are input but not processed as given in this sheet. The loads represent specific conditions such as Dead Load (input as D in CODE ID), Wind in Structure (input as W in CODE ID) or Centrifugal Force (input as CF in CODE ID). These then are combined in Sheet 7 of 7 in accordance with this combination and Percentage of Unit Stress that the user desires. In this case, the LOAD NO. is input but this STANDARD GROUP NO. is ignored.

An itemized description of the input follows:

LOAD NO: The sequential number of the load input is an alphanumeric (input for all cases).

STANDARD GROUP LD: The AASHTO Group Number (1 through 9). If this option is chosen, the loads are combined manually and entered on Sheet 6 of 7, and Sheet 7 of 7 is not used. If the loads are combined through the use of Sheet 7 of 7, this item should be left blank.

CODE ID: The alphanumeric abbreviated description of the load (such as W for wind, D for dead load, etc.) to be used if the loads are combined through the use of Sheet 7 of 7.

FORCES X and Y (KIPS or KN): The lateral loads acting in the X and Y directions, respectively, which are positioned at the origin of the coordinate system (see Figure 1).

FORCE Z (KIPS or KN): The vertical load positioned at the origin taken as positive if acting down (see Figure 2).

MOMENTS M_{x-x} (FT-k or m-KN): The concentrated moment about the X-axis taken as positive if a downward force is felt by a pile with positive X and Y coordinates (see Figure 2).

MOMENTS M_{y-y} (FT-k or m-KN): The concentrated moment about the Y-axis taken as positive if a downward force is felt by a pile with positive X and Y coordinates (see Figure 2).

MOMENTS M_{z-z} (FT-k or m-KN): The concentrated torque about the Z-Z axis taken as clockwise if looking downward on the pile cap.

3.7 LOAD COMBINATION DATA

Data Type 07012 — Load Combination

The data input here is used to combine the loads given on Sheet 6 of 7 and to define the Group Combination. No specific code is used and all loads, load combinations, and Group Reductions can be defined by the user.

GROUP LOADING NO: The number of the Group (usually as it appears on the CODE) entered as an integer (e.g., the Group I as defined by AASHTO is entered as 1).

CASE NO: Case number, starting from 1, entered as an integer.

LOADING DESCRIPTION: Any alphanumeric description of the load combinations.

% UNIT STRESS: The percentage of unit stress as given by the user (usually defined in the code).

PROPORTIONED LOADS — FACTOR (%): The percentage by which the individual load (defined on Sheet 6 of 7) will be multiplied such that it can be combined to form a Group Loading (e.g., 30% W).

PROPORTIONED LOADS — LOAD NO: The number of the load appearing on Sheet 6 of 7.

4.0 OUTPUT

All output is given in the form of tables that are identified by number. These can be output selectively by the user by inputting the table numbers desired under — SELECTION OF OUTPUT TABLES (see 01042 on Sheet 1 of 7). Only those tables specified will be given. (If no tables are specified, the system will output a diagnostic and the run will be terminated.) If all the tables are desired, the NON-SELECT option may be used. A description of the output is as follows:

4.1 VERIFICATION OF INPUT

TABLE NO. 1.0 — INPUT VERIFICATION: Input verification yields the output of all input given on Input Sheets 1 of 7 through 7 of 7 as close to the original format as possible. It is suggested that this Table be output for every run.

4.2 DESIGN CODE

TABLE NO. 2.0 — PILE CONFIGURATION AND CODE SCAN

- a) Specification — Output of the specification used along with interims, dates, etc.
- b) Configuration — A narrative output is given as to the pile configuration and materials specified in the input. This allows the user to identify quickly any errors in the input.
- c) Code Scan — Here, the pile group which was input is checked with respect to the specification input on Sheet 1 of 7 (Data Type 01032).

4.3 BASIC OUTPUT

TABLE NO. 3.0 — PILE FORCES, MOMENTS, AND SHEARS

This table is composed of the basic output of the PILE program for each loading case.

PILE NO: The pile number as given in the input.

AXIAL FORCE (K or KN): The axial force in each pile due to the loads specified, compression taken as positive.

AXIAL-CAPACITY (K or KN): The COMPRESSIVE CAPACITY of the pile as input in Sheet 2 of 7 multiplied by the Percentage of Unit Stress specified by the code or as input by the user. If no Percentage of Unit Stress is specified, the COMPRESSIVE CAPACITY is taken as input.

AXIAL — FLAG: A flag indicating that the AXIAL FORCE exceeds the AXIAL COMPRESSIVE CAPACITY.

MOMENTS, X-X, Y-Y, and TORSION (FT-K or m-KN): The moments about the X-X,

Y-Y, and Z-Z axes of the pile, respectively (see Figure 2).

SHEARS, X, Y (K or KN): The shears in the X and Y directions of the pile respectively (see Figure 2).

4.4 STRESSES

The stresses are given in a series of tables specialized for each pile section type (see Sheet 3 of 7). The purpose of these tables is to give basic information pertaining to the elastic (or working) stress level in the pile at the junction of pile and pile cap. The output consists of longitudinal stresses due to the combined effects of axial loads and moments along with shear stresses due to torsion and transverse loading.

Maxima are given within the pile cross-section but not longitudinally along the pile. (For a determination of maximum deflection, moments and shear along the length of a pile, another theory, and program, must be used.)⁵ Generally, in a well designed pile group the axial stresses predominate with the stresses due moment and shear being low. The maximum stresses output by the program allow for the determination of whether bending is important and whether it should be considered in the analysis. In the case where bending (or shear) has been found to be important, the designer must determine the criteria for judging whether a pile section and material is adequate (such as by using an interaction equation). In such cases, further study may also be required on determining the maximum pile stresses throughout the length of the pile.

The following is a description of each pile section type for which stresses are given:

TABLE NO. 4.1 — PILE STRESSES FOR TYPE 1 ("1") SECTION

This table is composed of the axial bending, shear, and torsional stresses in each pile for each loading case. Tension is taken as positive.

PILE NO: The pile number is given in the input.

DIRECT STRESS (KSI or MPa): The axial stress in each pile.

BENDING STRESS, X-X, Y-Y (KSI or MPa): The bending stress in each pile about the X-X and Y-Y axes of the pile, respectively.

DIRECT + BENDING, MAXIMUM and MINIMUM (KSI or MPa): The maximum and minimum combined axial and bending stress in the pile section, respectively.

DIRECT SHEAR, WEB, and FLANGE (KSI or MPa): The maximum shear stresses due to direct shear VQ/It in the center of the web and the flanges adjacent to the web, respectively.

TORSIONAL STRESS (KSI or MPa): The (St. Venant) shear stress due to torsion in the section.⁵

TABLE 4.2 — PILE STRESSES FOR TYPE 2 (CIRCULAR WOOD) SECTION

This table is composed of the axial, bending, shear, and torsional stresses in each pile at the interface with the cap (see Figure 1 for a definition of the pile cap).

PILE NO: The pile number is given in the input.

DIRECT STRESS (KSI or MPa): The axial stress in each pile.

BENDING STRESS, x-x, y-y (KSI or MPa): The bending stress in each pile about the x-x and y-y axes of the pile, respectively.

BENDING STRESS, MAXIMUM, MINIMUM (KSI or MPa): The maximum and minimum bending stress in the circular pie.

DIRECT + BENDING STRESS, MAXIMUM, MINIMUM (KSI or MPa): The maximum and minimum stresses in the pile due to combined axial and bending stresses.

MAXIMUM DIRECT SHEAR (KSI or MPa): The maximum shear stress due to the maximum components of the shear force in the pile.

TORSIONAL STRESS (KSI or MPa): The maximum shear stress in the pile due to torsion.

TABLE NO. 4.3 — PILE STRESSES FOR TYPE 3 (CIRCULAR SHELL) SECTION

This table is composed of the axial, bending, shear, and torsional stresses in each pile.

PILE NO: The pile number given in the input.

DIRECT STRESS, x-x, y-y (KSI or MPa): The maximum and minimum bending stress in the shell.

DIRECT + BENDING, MAXIMUM, MINIMUM (KSI or MPa): The maximum and minimum stresses in the shell due to axial and bending stresses.

MAXIMUM DIRECT SHEAR (KSI or MPa): The maximum shear stress due to the maximum component of the shear force in the pile.

TORSIONAL STRESS (KSI or MPa): The maximum shear stress in the pile due to torsion.

4.5 DEFORMATIONS

TABLE NO. 5.0 — DEFORMATIONS DUE TO PILE GROUP DEFLECTIONS AND ROTATIONS

DEFORMATIONS OF PILE CAP AT ORIGIN: The deformations and rotations of the (rigid) pile cap due to the applied loads.

DEFLECTIONS AT ARBITRARILY SELECTED POINTS:

- a) Coordinates may be specified at any point in space and are defined in the same coordinate system as the pile group.
- b) Deflections are given in inches and are consistent in direction with the X, Y, and Z coordinate system of the pile group.

4.6 SUMMARY OF BASIC OUTPUT

TABLE NO. 6.0 — SUMMARY OF THE GOVERNING AXIAL PILE FORCES

This table is composed of a summary of the basic output consisting of the axial loads, capacities, and governing loading case for each pile and condition. These are given as follows:

PILE NO: The pile number as given in the input.

PILE COORDINATES, X, Y, Z (FT or m): The coordinates of each pile as given in the input.

GOVERNING AXIAL MAXIMA, FORCE, CAPACITY, GROUP, CASE (K or KN): The minimum difference between the pile force and capacity, whichever controls all loading conditions. (In the cases where differences are equal, the one involving the largest pile force will govern.) Also, the corresponding pile capacity, Group, and Case loading numbers are given along with a flag if the force exceeds the capacity.

GOVERNING AXIAL MINIMUM (K), FORCE, CAPACITY, GROUP, CASE: The minimum axial force or the maximum difference between the pile force and capacity, whichever controls all loading conditions. Also, the corresponding pile capacity, Group, and Case loading numbers are given along with a flag if the uplift exceeds the uplift capacity.

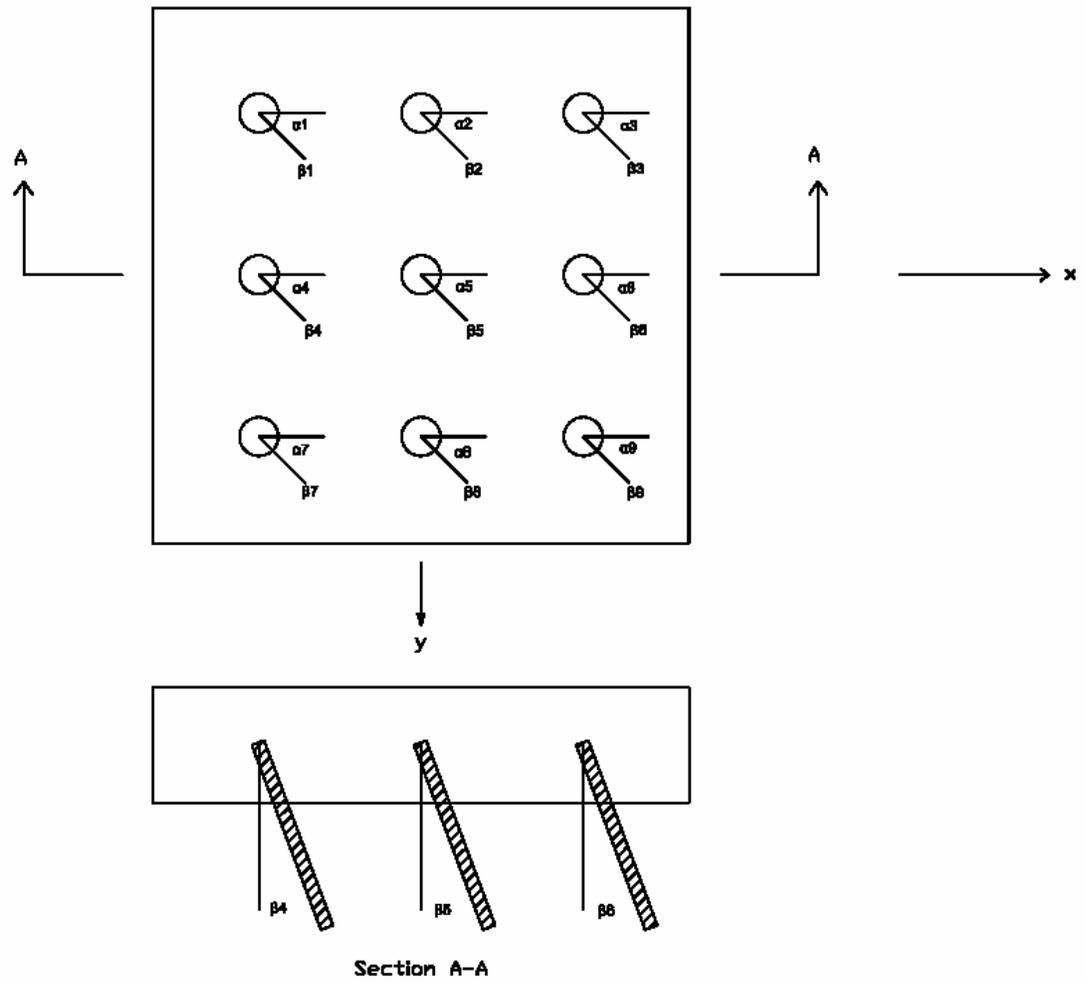


Figure 1 – Definition of the Pile Group Configuration

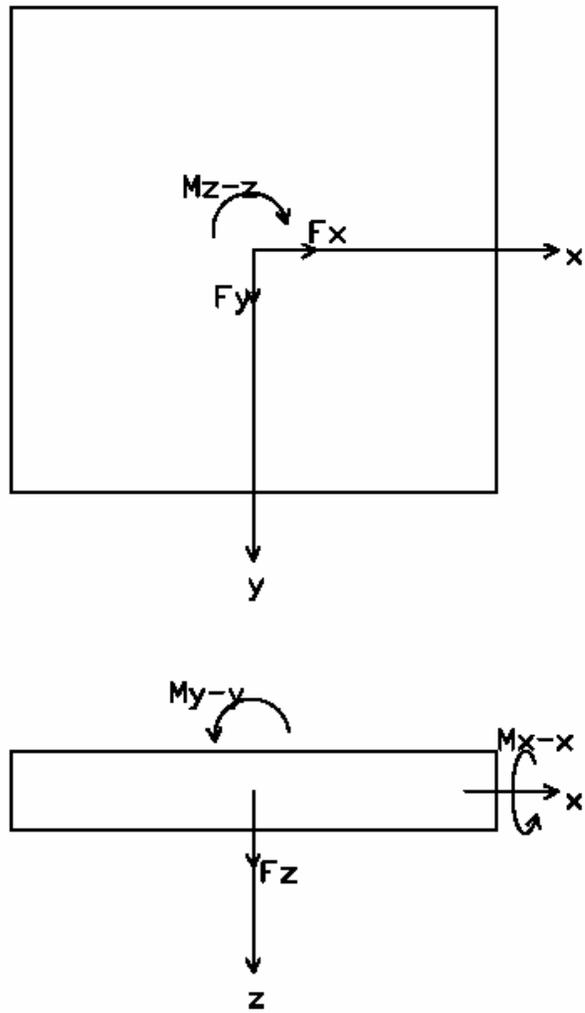


Figure 2 – Force Components and Sign Conventions

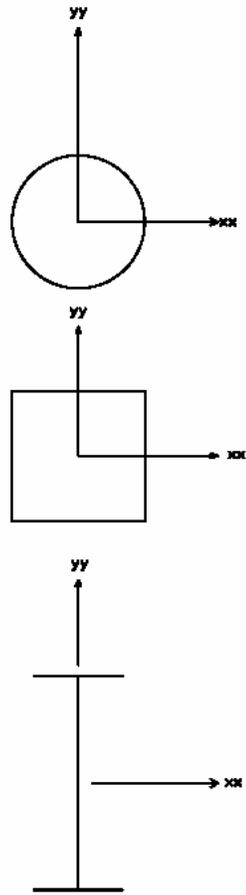
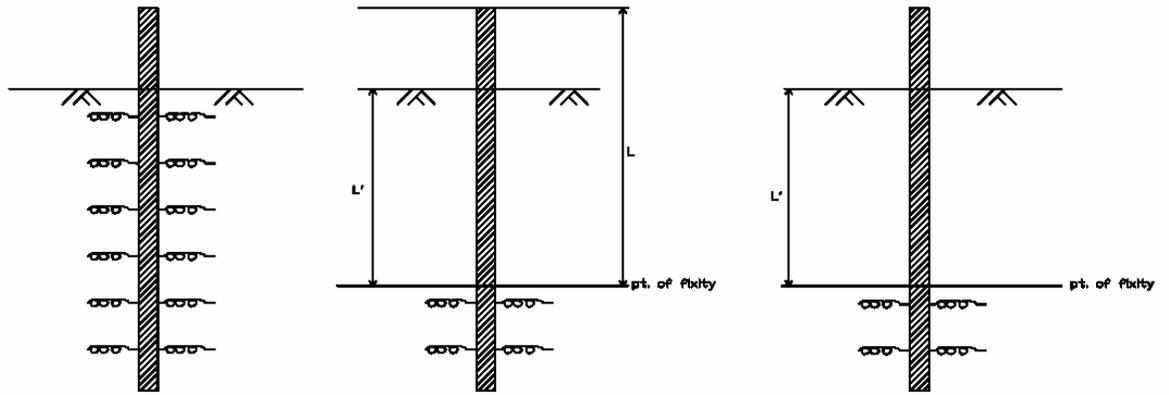


Figure 3 – Axes of Bending Moments of Inertia



(a) Standard Pile Formulation

(b) Type 2: Cantilever
Beam Formulation

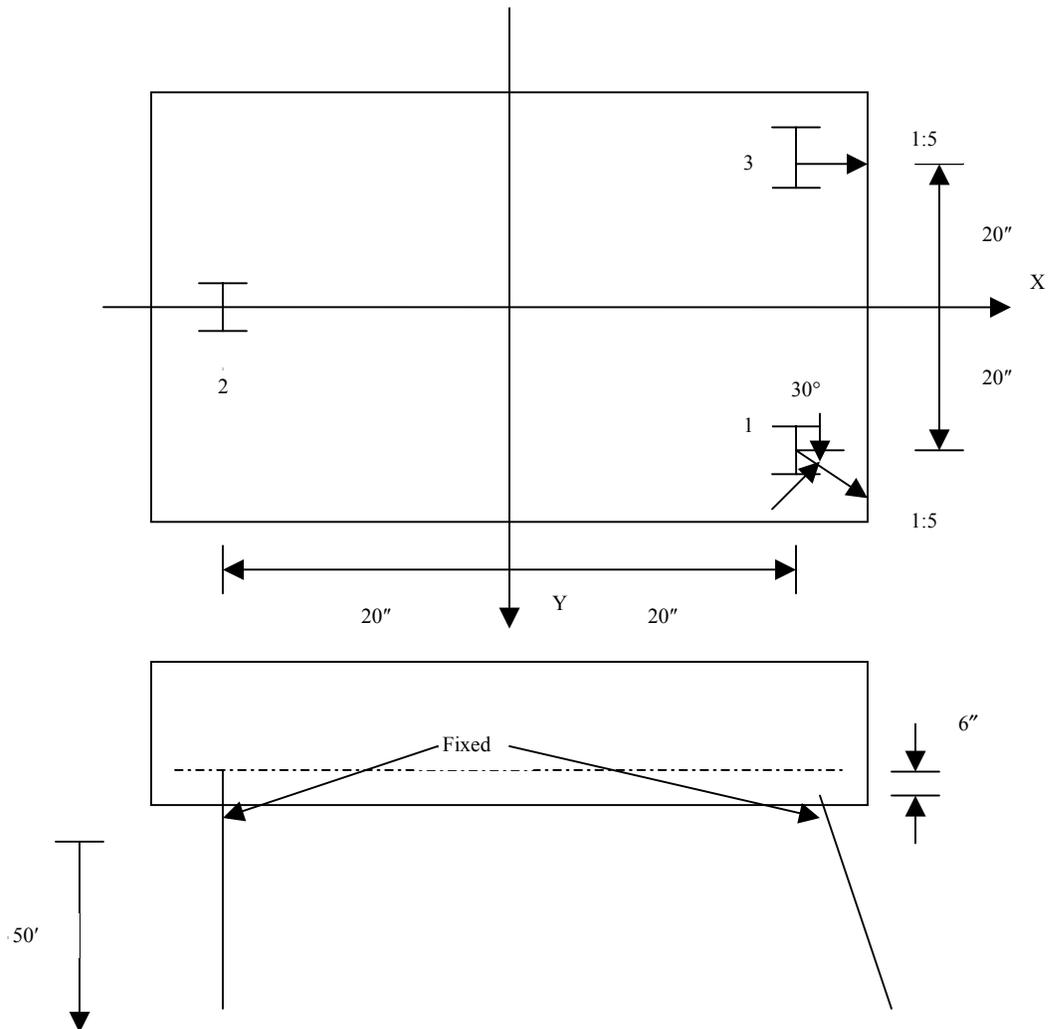
(c) Type 3:
Elevated
Platform
Formulation

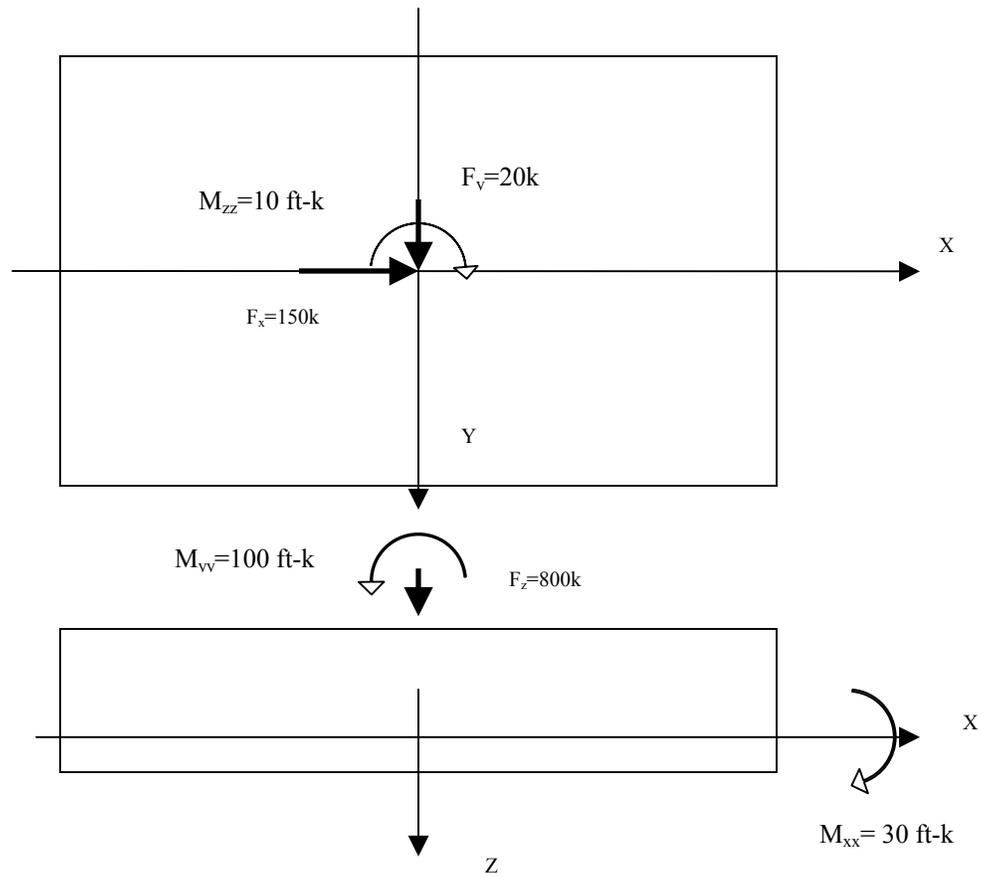
Figure 4 – Pile Configurations

5.0 EXAMPLE PROBLEMS

Example 1.

- a) REFERENCE
Wm E. Saul, "STATIC AND DYNAMIC ANALYSIS OF PILE FOUNDATIONS," Journal of the Structural Div., ASCE, Vol. 94, NO. ST5, May 1968.
- b) CONFIGURATION
Three steel H-Piles, CBP 124 with $E = 30,000$ ksi, $I_x = 566.50$ in.⁴, $D_x = 12.217$ in., $D_y = 12.12$ in., area = 21.76 in.², $G = 12,000$ ksi, length = 50 ft., soil modulus of subgrade = 0.1 kci, $k_T = 2$ and $k_L = 2$. The locations of each pile are shown in the figure below. Considering the end condition is fixed and the cap loads are $Q_1 = 150$ kips, $Q_2 = 30$ kips, $Q_3 = 800$ kips, $Q_4 = 360$ kip-in., $Q_5 = 1200$ kip-in. and $Q_6 = 120$ kip-in. (Configuration – Type 1)





Output Verification

Pile No.	1		2		3	
	Reference	Program	Reference	Program	Reference	Program
Axial	248.7	248.02	341.2	342.24	226.9	226.55
V_x	19.39	19.64	20.72	20.74	19.42	19.10
V_y	-14.06	-14.60	5.75	6.48	2.54	2.22
M_{xx}	72.29	74.14	-17.63	-20.88	-4.18	-3.03
M_{yy}	65.21	65.88	71.49	71.41	67.95	66.92
Torsion	-0.89	-0.01	-1.52	-0.01	-1.40	-0.01

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE PROBLEM # 1 (3 STEEL H-PILES, CBP 124)

12/24/2004

PAGE 1

CONTRACT NUMBER XXXX STRUCTURE# STRUC UNIT DESIG CHECK SPECIFICATION USED X

TABLE 1.1 : INPUT VERIFICATION

0SYSTEM DATA (INPUT SHEET 1)

GENERAL PROGRAM OPTIONS

UNIT (SI=1,EN=0)	SYMMETRY OF PILE GROUP (USE 1 IF X-X)	PILE GROUP (USE 1 IF Y-Y)	CODE (1=AASHTO)
0	0	0	1

TABLE 1.2 : INPUT VERIFICATION

0 PILE OPTIONS (INPUT SHEET 2)

0PILE CONFIGURATION

CONFIG. TYPE (1,2 OR 3)	PILE END COND (1 OR 2)	FRICT OR BRG (1 OR 2)	PILE LENGTHS (FT)	FIXED LENGTHS (FT)
1	2	2	50.00	.00

0GROUP PROPERTIES

E OF PILE (KSI)	G OF PILE (KSI)	SUB MODULUS (PCI)	ALL. AXIAL LOAD (K)	COMP LOAD (K)	UPLIFT CAP (K)
30000.	12000.	100.0000	300.000		-5.000

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE PROBLEM # 1 (3 STEEL H-PILES, CBP 124)

PAGE 2

TABLE 1.3 : INPUT VERIFICATION

0 PILE SECTION DATA (INPUT SHEET 3)

0 GENERAL SECTION

IX-X (IN**4)	IY-Y (IN**4)	J (IN**4)	AREA (SQ IN)	WIDTH (IN)	HEIGHT (IN)
566.50	184.70	2.97	21.76	12.22	12.10

1

TABLE 1.4 : INPUT VERIFICATION

FILE DATA (INPUT SHEET 4)

PILE NO	REQUIRED DATA					RESTRICTED DATA					L		
	VERT ANGLE	COORDINATES			PILE L	PILE AREA	MOMENTS OF INERTIA			PILE WIDTH		PILE H	
	SLOPE ALPHA (DEG)	X (FT)	Y (FT)	Z (FT)	(FT)	(SQ IN)	IX-X IN**4	IY-Y IN**4	IJ IN**4	(IN)		(IN)	
1	.200	30.	1.7	1.7	1.	50.	21.8	567.	185.	3.	12.2	12.1	0.
2	.000	0.	-1.7	.0	0.	50.	21.8	567.	185.	3.	12.2	12.1	0.
3	.200	0.	1.7	-1.7	1.	50.	21.8	567.	185.	3.	12.2	12.1	0.

1

TABLE 1.5 : INPUT VERIFICATION

SPECIFICATION OF ARBITRARY POINTS WHERE MOVEMENT IS DESIRED (INPUT SHEET 5)

POINT NO	DESCRIPTION OF POINT	COORDINATES OF POINTS		
		X	Y	Z
		(FT)	(FT)	(FT)
1	NONE	.000	.000	.000

1

TABLE 1.6 : INPUT VERIFICATION

LOAD DATA (INPUT SHEET 6)

LOAD NO	STD GROUP	CODE ID	FORCES			MOMENTS		
			X	Y	Z	X-X	Y-Y	Z-Z
			(K)	(K)	(K)	(FT K)	(FT K)	(FT K)
1	1		150.00	30.00	800.00	30.00	100.00	10.00

C1 STANDARD GROUP NUMBER AND LOADCOMBINATIONS(INPUT SHEET 7)
 BOTH ARE INPUT;LOAD COMBINATION AUTOMATICALLY ASSUMED.

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE PROBLEM # 1 (3 STEEL H-PILES, CBP 124)

PAGE 6

TABLE 1.7: INPUT VERIFICATION

LOAD COMBINATIONS (INPUT SHEET 7)

NO	CASE	DESCRIPTION	GROUP LOADINGS		PROPORTIONED LOADS								CARD SEQ	
			UNIT	%	FACT	LD	FACT	LD	FACT	LD	FACT	LD		FACT
			STRESS	%	%	%	%	%	%	%	%	%	%	%
1	1		100.00	100.	1	0.	0	0.	0	0.	0	0.	0	0

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE PROBLEM # 1 (3 STEEL H-PILES, CBP 124)

PAGE 7

PILE ANALYSIS

TABLE 2. 1: LOAD CASE NO. 1

LOAD COMBINATION NO 1 - CASE 1

GROUP NO 1 PCT UNIT STRESS=100.0 ()

VERT LOAD AT ORIGIN (KIPS)	HORZ LOAD IN X-DIRECTION (KIPS)	HORZ LOAD IN Y-DIRECTION (KIPS)	MOM ABOUT X-X AXIS (FT-K)	MOM ABOUT Y-Y AXIS (FT-K)	MOM ABOUT Z-Z AXIS (FT-K)
800.00	150.00	30.00	30.00	100.00	10.00

TABLE 3. 1: PILE FORCES, MOMENTS AND SHEARS

PILE NO	AXIAL		MOMENTS			SHEARS	
	FORCE (K)	CAPACITY* FL (K)	X-X (FT K)	Y-Y (FT K)	TORSION (FT K)	X (K)	Y (K)
1	248.02	300.00	74.14	65.88	-.01	19.63703	-14.60334
2	342.24	300.00 *	-20.88	71.41	-.01	20.74364	6.47831
3	226.55	300.00	-3.03	66.92	-.01	19.09569	2.22081

EQUILIBRIUM CHECK OF ALL FORCES AND MOMENTS(PERCENT ERROR)

X-DIRECTION	Y-DIRECTION	VERTICAL	X-X AXIS	Y-Y AXIS	VERT AXIS
.00	.00	.95	.00	.00	.00

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE PROBLEM # 1 (3 STEEL H-PILES, CBP 124)

PAGE 8

TABLE 5.1 : DEFORMATIONS DUE TO PILE GROUP DEFLECTIONS AND ROTATIONS

APPROXIMATE PILE CAP DEFLECTIONS AND ROTATIONS

PILE CAP DEFL AT ORIGIN (IN)		PILE CAP ROTATION AT ORIGIN (RAD)	
-----		-----	
X-DEFLECTION =	.193133	X-X ROTATION =	.0001482
Y-DEFLECTION =	.051395	Y-Y ROTATION =	.0021069
Z-DEFLECTION =	.114301	Z-Z ROTATION =	-.0008033

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE PROBLEM # 1 (3 STEEL H-PILES, CBP 124)

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TABLE 5.2 : DEFLECTION AT ARBITRARY SELECTED POINTS

POINT NO	COORDINATES OF POINTS (FT)			DEFLECTIONS (IN)		
	X	Y	Z	X	Y	Z
1	.00	.00	.00	.19313	.05140	.11430

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE PROBLEM # 1 (3 STEEL H-PILES, CBP 124)

PAGE 10

NORMAL PILE ANALYSIS TERMINATION

1

Example 2.

a) REFERENCE

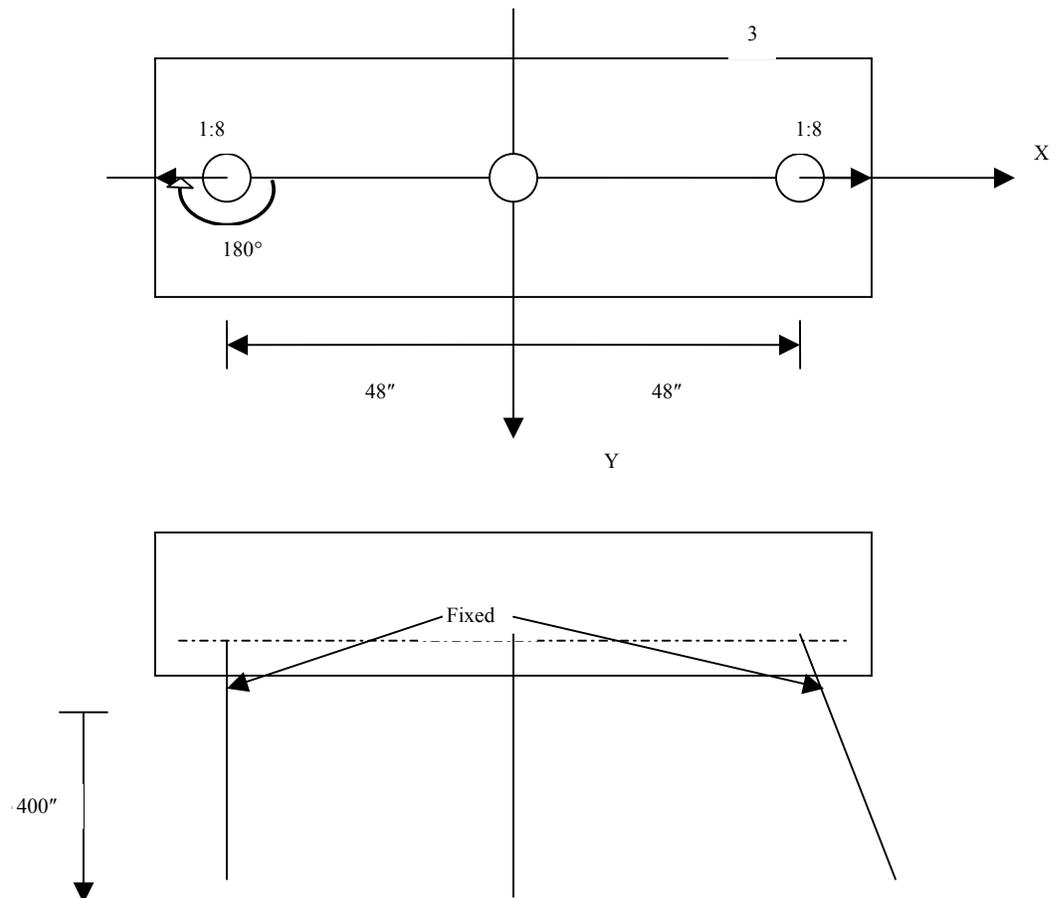
Wm E. Saul, "STATIC AND DYNAMIC ANALYSIS OF PILE FOUNDATIONS," Journal of the Structural Div., ASCE, Vol. 94, NO. ST5, May 1968.

b) CONFIGURATION

Three-pile foundation with the length of cantilever 20 ft., using circular concrete pile with $E = 3600$ ksi, $G = 0.4E$, diameter = 8 in., $L = 400$ in. long, $k_T = 1.0$, $k_L = 1.0$ penetrated into a cohesive soil which $k_s = 0.1$ kci. Using the second model checks the embedded length of pile.

Assume the allowable $\Delta_1 = 1.5$ in., $\Delta_2 = 1.5$ in., $\Delta_3 = 0.5$ in., $\Delta_4 = 0.0001$ rad., $\Delta_5 = 0.0001$ rad., and $\Delta_6 = 0.0001$ rad. The end connection is fixed.

(Configuration – Type 3; $K_s = 0.1$ kci; $D = 8$ in.; $I_x = 201$ in⁴; $I_y = 201$ in⁴; $J = 402$ in⁴; $E = 3600$ ksi; $G = 1440$ ksi)



To determine the depth of fixity.

Circular pile,

$$R_x = R_y = \sqrt[4]{\frac{EL}{k_s D}}$$

$$I_x = I_y = \frac{\Pi D^4}{64} = \frac{\Pi(8)^4}{64} = 201 \text{ in}^4$$

Solving for R_x and R_y ,

$$R_x = R_y = \sqrt[4]{\frac{3600 \times 201}{0.1 \times 8}} = 30.8 \text{ in.}$$

$$\begin{aligned} \ell_x = \ell_y &= 1.4 R_x = 1.4 R_y \\ &= 1.4 \times 30.8 \\ &= 43.12 \text{ in.} \end{aligned}$$

$$\begin{aligned} \text{say } \ell_x = \ell_y &= 44.0 \text{ in.} \\ L_x = L_y &= 20 \times 12 + 44 \\ &= 284 \text{ in.} \end{aligned}$$

Data Input

E	I_x	I_y	D_x	D_y	A	J	G
30,000	766.9	184.7	12.217	12.12	21.76	751.2	12,000.
L	l_x	l_y	l_u	k_s	η	k_L	k_T
600.	0.	0.	0.	0.1	0.	2.	2.

Load No.	F_x	F_y	F_z	M_{xx}	M_{yy}	M_{zz}
1	22.05	1.69	671.7	19.83	630.19	0.06

Output Verification

Pile No.	1		2		3	
	Reference	Program	Reference	Program	Reference	Program
Axial	306.5	306.55	225.2	226.22	142.4	142.4
V_x	.55	.54	.57	.57	-.59	-.59
V_y	.57	.56	.56	.56	-.56	-.57
M_{xx}	-6.68	-6.62	-6.64	-6.64	6.61	6.68
M_{yy}	6.49	6.61	6.81	6.96	-7.04	-7.20
Torsion	-0.89	-0.01	-1.52	-0.01	-1.40	-0.01

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE 2- SAUL'S EXAMPLE (5)

12/30/04
PAGE 1

CCF

TABLE 1.1 : INPUT VERIFICATION

0SYSTEM DATA (INPUT SHEET 1)

GENERAL PROGRAM OPTIONS

UNIT	SYMMETRY OF PILE GROUP	CODE
(SI=1,EN=0)	(USE 1 IF X-X)	(USE 1 IF Y-Y) (1=AASHTO)
0	0	1

TABLE 1.2 : INPUT VERIFICATION

0 PILE OPTIONS (INPUT SHEET 2)

0PILE CONFIGURATION

CONFIG. TYPE	PILE END COND	FRICT OR BRG	PILE LENGTHS (FT)	FIXED LENGTHS (FT)
(1,2 OR 3)	(1 OR 2)	(1 OR 2)	(FT)	(FT)
3	2	1	33.33	20.00

0GROUP PROPERTIES

E OF PILE (KSI)	G OF PILE (KSI)	SUB MODULUS (PCI)	ALL. AXIAL LOAD (K)	COMP UPLIFT CAP (K)
3600.	1440.	100.0000	300.000	-5.000

0CIRCULAR SECTION

SECTION TYPE	D (IN)	T (IN)	R (IN)	AREA BARS (SQ IN)	MODULAR RATIO
6	8.00	.0000	3.25	6.00	9.2950

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE 2- SAUL'S EXAMPLE (5)

PAGE 2

TABLE 1.4 : INPUT VERIFICATION

PILE DATA (INPUT SHEET 4)

PILE NO	REQUIRED DATA				RESTRICTED DATA				-----FIXED				
	VERT ANGLE SLOPE ALPHA (DEG)	COORDINATES (FT)			PILE L (FT)	PILE AREA (SQ IN)	MOMENTS OF INERTIA (IN**4)			PILE WIDTH (IN)	PILE H (IN)	L (FT)	
		X	Y	Z			IX-X	IY-Y	J	(IN)	(IN)	(FT)	
1	.125	0.	4.0	.0	0.	33.	100.0	464.	464.	928.	8.0	8.0	20.
2	.000	0.	.0	.0	0.	33.	100.0	464.	464.	928.	8.0	8.0	20.
3	.125	180.	-4.0	.0	0.	33.	100.0	464.	464.	928.	8.0	8.0	20.

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE 2- SAUL'S EXAMPLE (5)

PAGE 3

TABLE 1.5 : INPUT VERIFICATION

SPECIFICATION OF ARBITRARY POINTS WHERE MOVEMENT IS DESIRED (INPUT SHEET 5)

POINT NO	DESCRIPTION OF POINT	COORDINATES OF POINTS		
		X (FT)	Y (FT)	Z (FT)
1		.000	.000	.000

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE 2- SAUL'S EXAMPLE (5)

PAGE 4

TABLE 1.6 : INPUT VERIFICATION

LOAD DATA (INPUT SHEET 6)

LOAD NO	STD GROUP	CODE ID	FORCES			MOMENTS		
			X (K)	Y (K)	Z (K)	X-X (FT K)	Y-Y (FT K)	Z-Z (FT K)
1	1		22.05	1.69	671.70	-19.83	-630.19	-.06

C1 STANDARD GROUP NUMBER AND LOADCOMBINATIONS(INPUT SHEET 7)
BOTH ARE INPUT;LOAD COMBINATION AUTOMATICALLY ASSUMED.

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

EXAMPLE 2- SAUL'S EXAMPLE (5)

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TABLE 1.7: INPUT VERIFICATION

LOAD COMBINATIONS (INPUT SHEET 7)

NO	CASE	DESCRIPTION	GROUP	LOADINGS STRESS	%	UNIT	PROPORTIONED LOADS												CARD SEQ			
							FACT	LD	FACT	LD	FACT	LD	FACT	LD	FACT	LD	FACT	LD		FACT	LD	
							%	NO	%	NO	%	NO	%	NO	%	NO	%	NO	%	NO		
1	1			100.00	100.	1	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0	0

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

PILE ANALYSIS

TABLE 2. 1: LOAD CASE NO. 1

LOAD COMBINATION NO 1 - CASE 1

GROUP NO 1 PCT UNIT STRESS=100.0 ()

VERT LOAD AT ORIGIN (KIPS)	HORZ LOAD IN X-DIRECTION (KIPS)	HORZ LOAD IN Y-DIRECTION (KIPS)	MOM ABOUT X-X AXIS (FT-K)	MOM ABOUT Y-Y AXIS (FT-K)	MOM ABOUT Z-Z AXIS (FT-K)
671.70	22.05	1.69	-19.83	-630.19	-.06

TABLE 3. 1: PILE FORCES, MOMENTS AND SHEARS

PILE NO	AXIAL		MOMENTS			SHEARS	
	FORCE (K)	CAPACITY* FL (K)	X-X (FT K)	Y-Y (FT K)	TORSION (FT K)	X (K)	Y (K)
1	306.55	300.00 *	-6.62	6.61	.01	.54037	.56129
2	226.22	300.00	-6.64	6.96	-.01	.56917	.56302
3	142.40	300.00	6.68	-7.20	-.03	-.58905	-.56569

EQUILIBRIUM CHECK OF ALL FORCES AND MOMENTS(PERCENT ERROR)

	X-DIRECTION	Y-DIRECTION	VERTICAL	X-X AXIS	Y-Y AXIS	VERT AXIS
1	.00	.00	.00	.00	.00	.00

M E R L I N - 3 D - P I L E

PROGRAM

2.02

TABLE 5.1 : DEFORMATIONS DUE TO PILE GROUP DEFLECTIONS AND ROTATIONS

APPROXIMATE PILE CAP DEFLECTIONS AND ROTATIONS

PILE CAP DEFL AT ORIGIN (IN)	PILE CAP ROTATION AT ORIGIN (RAD)
X-DEFLECTION = .730444	X-X ROTATION = .0005291
Y-DEFLECTION = .798578	Y-Y ROTATION = -.0000116
Z-DEFLECTION = .251239	Z-Z ROTATION = -.0000425

1

M E R L I N - 3 D - P I L E

PROGRAM

2.02

TABLE 5.2 : DEFLECTION AT ARBITRARY SELECTED POINTS

POINT NO	COORDINATES OF POINTS (FT)			DEFLECTIONS (IN)		
	X	Y	Z	X	Y	Z
1	.00	.00	.00	.73044	.79858	.25124

M E R L I N - 3 D - P I L E

PROGRAM

2.02

 NORMAL PILE ANALYSIS TERMINATION

1