PROGRAM CLAP

(VERSION 6.2, Rev. Q4)

(COMBINED LOAD ANALYSIS OF PILES)

USERS MANUAL

COFFEY GEOTECHNICS PTY. LTD.

JANUARY 2009

1.0 INTRODUCTION

CLAP is a development of the program DEFPIG, for the analysis of axially- and laterally-loaded pile groups. It allows for simultaneous application of lateral and moment loadings in two horizontal directions and also the application of a torsional load to the pile group. It is able to handle soil profiles in which there are various layers below the pile tip, and also has a more rational data input sequence. Within the group, different pile types and different soil profiles can be considered. The analysis is non-linear and considers both geotechnical and structural failure of the piles.

The earlier Version 4.3 assumed that all piles within the group are identical. The latest Version (6.2) allows for different pile types and different soil profiles to be considered within the same group.

2.0 PROGRAM DEVELOPMENT

The basic method of analysis followed that used in the DEFPIG program, the basis of which has been set out by Poulos (1980). Some major changes were made to the basic program logic and execution, the key changes being as follows:

- The ability to input a number of vertical loads, lateral loads, moment loadings and torsional loadings on a pile group.
- Lateral and moments loadings in two horizontal directions can be considered.
- Layers of various thickness along the pile shaft can be input, each with different values of Young's modulus and ultimate pile-soil skin friction;
- A number of different layers can be specified below the pile tip, each with different values of Young's modulus, Poisson's ratio and ultimate end bearing capacity;
- Equivalent values of Young's modulus and ultimate base bearing capacity are calculated for the layered system below the pile tip;
- Improved integration techniques are used for the numerical evaluation of elastic influence factors using Mindlin's equations;
- A more logical sequence of data input is used.
- In Version 6.2, different types of piles can be specified, and also different soil profiles can be input.

In carrying out the changes involving layering of the below-tip soil profile, the following assumptions have been made:

- The equivalent Young's modulus has been evaluated by computing the settlement of the pile tip on the actual layered system, and then finding the equivalent value of Young's modulus which gives the same settlement with the Poisson's ratio of the soil layers above the pile tip;
- The equivalent ultimate end bearing capacity of the pile tip has been estimated by computing a weighted average ultimate end bearing capacity. Because of the lack of a proper theoretical analysis for this case, it has been assumed that the weighting factor reduces from unity at pile tip level to zero at a depth of influence (zinf) relative to the pile tip diameter, where zinf is specified by the user. zinf would typically be in the range 2 to 5, depending on the type of layering. The smaller value would be relevant if the layers increase in strength with depth, while the larger value would be relevant where there were softer layers at some depth below the pile tip.

To facilitate data input, the soil profile can be specified via layers above the pile tip, and below the pile tip. The program then computes the values for the relevant nodes along the pile shaft and at the pile tip. In this way, changes in the number of pile elements can be easily made without having to make significant changes in the data file.

The new program has been designated as **CLAP** (**C**ombined **L**oad **A**nalysis of **P**iles).

2.1 Program Limitations

The current version of CLAP (Version 6.2Q4) has the following limitations:

- Maximum total number of axial elements per pile = 51
- Maximum number of lateral elements = 150
- Maximum number of soil layers along and below the pile tip = 40.
- Maximum number of piles = 500
- Maximum number of different pile types = 20
- Maximum number of individual loadings = 480.

3.0 ANALYSIS DETAILS

Appendix A summarizes the details of the analysis procedure used in CLAP. The general assumptions are similar to those employed in the original DEFPIG program.

4.0 DETAILS OF THE INPUT REQUIREMENTS

4.1 Data Input Instructions

Appendix B gives the instructions for the Version 6.2 (Rev. Q4). Some notes relating to input data items are provided below.

4.2 Geotechnical Reduction Factors

The program requires the input of geotechnical reduction factors for ultimate skin friction, ultimate end bearing, ultimate pile cap bearing capacity, and ultimate lateral pile-soil pressure. These factors enable an analysis to be carried out of the stability of the pile group under ultimate limit state conditions. The pile group will be stable if it is able to withstand the ultimate limit state load combinations when the pile resistances are factored (down) by the geotechnical reduction factors.

For estimates of pile group movements under serviceability or working loads, the geotechnical reduction factors should be specified as unity.

4.3 Pile Details

For each pile type specified, the pile details include the pile length, pile shaft and base diameter, the number of elements into which the shaft is to be divided for axial response (all are of equal length), the number of annular elements into which the base is divided, and the number of elements for lateral response. Generally, 20 to 30 shaft elements and 1-3 base elements are adequate for axial response. If a cap is assumed to be in contact with the soil, then the number of cap annular elements is also important; about 5 is usually adequate. However, a greater number of lateral elements is usually required, especially for longer piles, and the maximum number allowed is 150. Solution times increase considerably as the number of elements inresaes.

Other input data includes the Young's modulus of the pile, the bending moment of inertia (assumed the same in all directions), the torsional (polar) moment of inertia, and the area ratio (ratio of pile cross-sectional area to the gross cross-sectional area).

To allow for failure of the pile material itself, the following values are input:

- Ultimate moment capacity (assumed constant);
- Ultimate structural strength in compression;
- Ultimate structural strength in tension.

Finally, if a hyperbolic axial load-settlement response is to be assumed, then two hyperbolic factors, RFP and GFAC must be specified. RFP can usually be taken in the range 0.5 to 0.9, while GFAC = 1.0 gives normal hyperbolic behaviour.

4.4 Soil Profile Details

For each pile type, the soil profile details are required. A series of options are available for input of the soil profile, but the most convenient may often be the option of specifying soil layers above and below the pile tip (UNISOL=3). For each layer above the pile tip, the following information must be supplied:

- Layer thickness;
- Initial tangent Young's modulus for axial loading;
- Initial Young's modulus for lateral loading (usually taken as 0.6-0.75 times the value for axial loading);
- Ultimate skin friction;
- Ultimate lateral pile-soil pressure.

For each layer below the pile tip, the following input is required:

- Layer thickness;
- Young's modulus (for axial loading);
- Poisson's ratio;
- Ultimate end bearing pressure.

The program carries out an averaging procedure over the assumed depth of influence to obtain equivalent Young's modulus and end bearing pressures for the pile tip.

The modulus of the base layer underlying the specified soil layers, and reduction factors for the limiting stresses in uplift (as a fraction of the values for compression) are also input.

4.5 Pile Group Specification

The pile group may be specified either as a rectangular group with constant spacings in the x- and y-directions, or by specifying the pile type, the x- and y-coordinates of each pile, and the batter angles in the x- and y-directions.

To allow for some piles being damaged or defective, the number of each affected pile, and the ratio of its properties to that of the undamaged pile, can be input.

4.6 Loading Details

There are various options for the input of the applied loads, and also an option for inputting the pile head deflections and rotations of each pile within the group. For many cases however, the option of using input loads and moments may be most convenient. The number and location of individual loads can be specified. It is also possible to input various components of load (dead, live, wind, earthquake, and other) and then load factors to be applied to each component. In this way, a variety of load combinations can be analysed by simply changing the load factors, rather than by re-computing the resulting loads manually.

5.0 OUTPUT

The output includes the following:

- An echo of the input data;
- Computed interaction factors and pile stiffness values for each pile type;
- The computed deflections and rotations of the pile group;
- The computed pile loads, moments and torsional loads for each pile within the group;
- Detailed axial and lateral response of specified piles within the group.

6.0 PROGRAM TESTING

To check that the program is giving results consistent with existing software, a series of check problems have been analysed by various methods. These problems are discussed below.

6.1 Test Problem 1 – Settlement of a Single Pile in Layered Soil

This problem was first published by Poulos (1979), and is illustrated in Figure 1. Three cases are considered:

- Soil modulus of layers increasing with depth;
- Soil modulus of layers decreasing with depth;
- Soil modulus decreases and then increases.

Table 1 shows the solutions for pile head settlement obtained by CLAP, together with the values from a finite element analysis using the program PLAXIS, and the two programs used by Poulos (1979), one of which was a finite element program (ISOPE). Table 1 shows that the results from CLAP are in good agreement with the program AXPIL5 (which forms the basis of the axial response analysis in DEFPIG). The minor differences between these two programs are due to changes in the numerical integration procedures used in CLAP. The solutions from ISOPE and PLAXIS are very close, and agree well with the CLAP and AXPIL5 solutions for Cases 1 and 3. However, for Case 2, as was pointed out by Poulos (1979), the AXPIL5 analysis tends to underestimate the pile head settlement when the stiffness of the soil profile decreases with depth. In contrast, the CLAP analysis over-estimates the settlement. Overall, the comparisons in Table 1 indicate that the CLAP program gives results comparable with the existing software.

TABLE 1

COMPARISON OF SOLUTIONS FOR PILE HEAD SETTLEMENT – TEST PROBLEM 1

Case	***Pile Head Settlement Influence Factor I_p***			
	CLAP	***AXPIL5***	***ISOPE***	***PLAXIS***
1	.0390	.0386	.0377	.0380
2	.0473	.0330	.0430	.0426
3	.0375	.0366	.0382	.0387

Pile Head Settlement = $P.I_p / (d.E_{ref})$

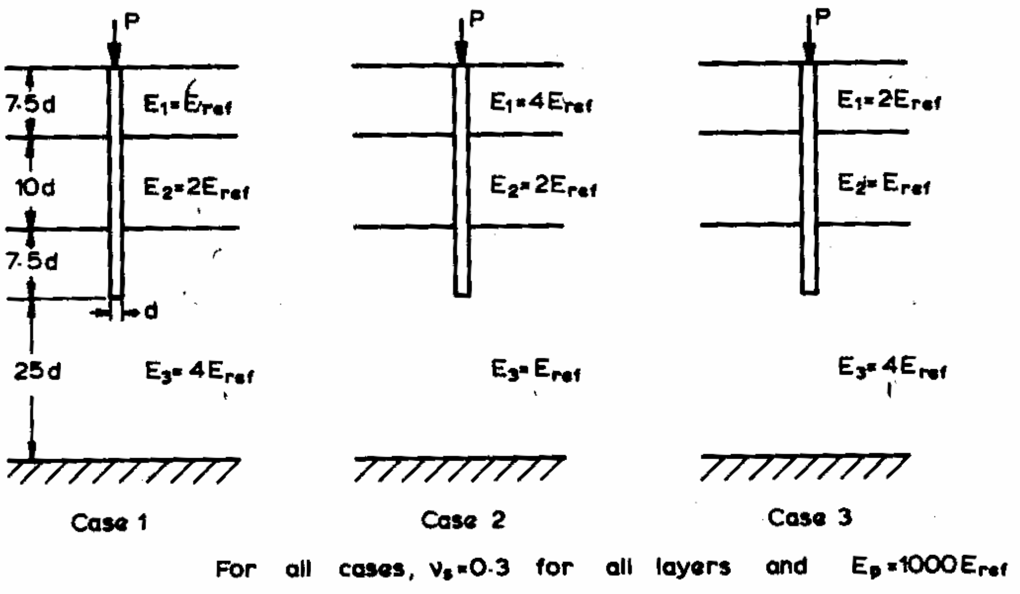


Figure 1 Test Problem 1 (after Poulos, 1979).

6.2 Test Problem 2 – Single Pile in Soil with Layering below Pile Tip

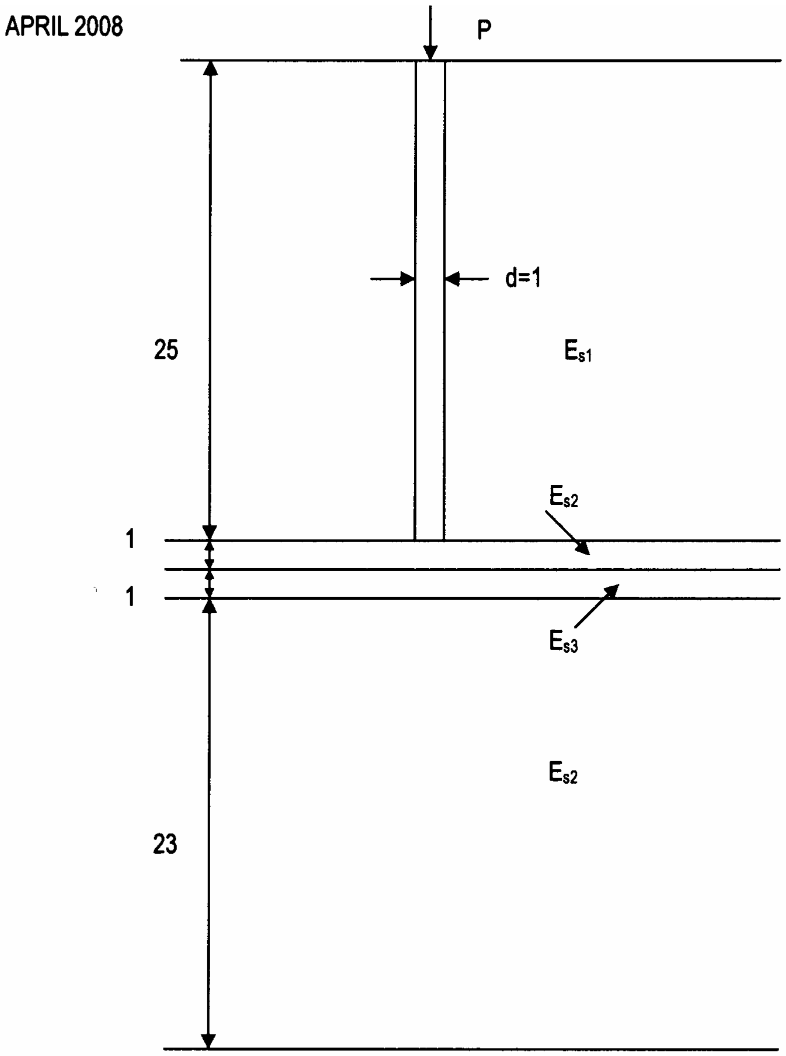
This problem is illustrated in Figure 2. Four cases are considered, involving a uniform soil layer above and below the tip, a uniform (but stiffer) bearing stratum below the tip, a bearing stratum with a softer inclusion, and a uniform soil with a "hard" inclusion below the tip. All soil layers are assumed to be linear elastic continua.

Table 2 compares solutions from four sources: CLAP, DEFPIG, the approximate closed-from solutions of Randolph and Wroth (1978), and the finite element program PLAXIS. In obtaining the DEFPIG results, and in utilizing the Randolph and Wroth solutions, the equivalent modulus of the bearing stratum (as computed by CLAP) has been used. It has been found that this equivalent value of Young's modulus agrees well with the value that would be computed from the method described by Poulos (1994).

Table 3 shows the settlement of the pile head, relative to the settlement for Case 1.

The following observations can be made from Tables 2 and 3:

- There is generally reasonable agreement between the solutions for pile head settlement from CLAP, DEFPIG, PLAXIS, and the Randolph and Wroth method; the latter tends to over-estimate the settlement because it does not allow for the presence of the underlying rigid layer;
- The settlements *relative to Case 1* from the various methods are generally similar to those from CLAP, with the exception of Case 3 (where there is a soft layer within the bearing stratum). In this case, the settlement via PIGAP is a little larger than that from PLAXIS, suggesting that the approach adopted may be a little conservative;
- There is some variability among the solutions for the proportion of load on the pile base. The PLAXIS solutions are approximate only as they have been derived from the computed vertical stresses within the elements near the base, and are liable to some inaccuracy as a result.



Case	Es1	Es2	Es3
1	10	10	10
2	10	100	100
3	10	100	10
4	10	10	100

Figure 2 Test Problem No. 2

TABLE 2

COMPARISON OF SOLUTIONS FOR PILE HEAD SETTLEMENT AND PILE BASE LOAD – TEST PROBLEM 2

Case	***Pile Head Settlement mm***				***Proportion of Load on Pile Base %***			
	CLAP	***DEFPIG***	***Randolph & Wroth***	***PLAXIS***	***CLAP***	***DEFPIG***	***Randolph & Wroth***	***PLAXIS***
1	6.34	6.31	7.22	6.4	3.7	5.2	7.4	4
2	3.65	3.28	3.72	3.8	53.0	59.1	36.8	20
3	5.15	4.83	4.98	4.5	30.1	36.1	20.1	13
4	6.29	6.24	6.95	6.2	6.0	8.2	8.4	4

TABLE 3

SOLUTIONS FOR PILE SETTLEMENT, RELATIVE TO CASE 1

Case	***Settlement Relative to Case 1***			
	CLAP	***DEFPIG***	***Randolph & Wroth***	***PLAXIS***
1	1.0	1.0	1.0	1.0
2	0.58	0.52	0.52	0.59
3	0.81	0.77	0.69	0.70
4	0.99	0.99	0.96	0.97

6.3 Test Problem 3 – Settlement of Pile Group with Rigid Cap in Layered Soil

The soil profile for the pile group problem analysed is the same as that shown in Figure 2. The pile group consists of nine 25 m long piles, 1 m in diameter, arranged in a square pattern at a centre-to-centre spacing of 3 m. Four soil profiles are considered, being the same as those for Test Problem 2. Three methods have been used to compute the pile group settlement: CLAP, DEFPIG, and the program PIGLET developed by Prof. Mark Randolph.

In using the latter two programs, the value of Young's modulus of the bearing stratum has been obtained from the equivalent value computed by CLAP.

Table 4 shows the computed settlement and load distribution for the group of 9 piles. The following points can be noted from Table 4:

- The settlements from the three programs are similar, although the PIGLET program tends to give slightly higher settlements because it assumes that the thickness of the bearing stratum is infinite;
- The maximum and minimum pile loads from the three programs are similar, with the PIGLET solutions tending to be slightly less non-uniform because of the approximations employed in deriving the interaction factors;
- There are minor differences only between the DEFPIG and CLAP solutions, again due to the changes in the numerical integration schemes employed in CLAP. These differences are more apparent when the bearing stratum below the pile tips is stiff.

In summary, the three programs employed all give answers which agree adequately for practical purposes.

TABLE 4

COMPARISON OF SOLUTIONS FOR TEST PROBLEM 3

Case	***Group Settlement mm***			***Maximum Pile Load MN***			***Minimum Pile Load MN***		
	CLAP	***DEFPIG***	***PIGLET***	***CLAP***	***DEFPIG***	***PIGLET***	***CLAP***	***DEFPIG***	***PIGLET***
1	24.4	24.3	30.3	1.41	1.41	1.37	0.19	0.19	0.25
2	8.8	7.1	8.9	1.14	1.11	1.22	0.71	0.76	0.56
3	16.4	14.2	15.1	1.25	1.21	1.29	0.49	0.57	0.41
4	24.1	23.8	28.4	1.41	1.40	1.37	0.20	0.21	0.27

6.4 Test Problem 4 – Pile Group with Equally Loaded Piles

Chow (2007) has carried out a finite element analysis of a 9-pile group with each pile subjected to equal loading. The soil is assumed to be elastic with a modulus that is constant with depth and equal to 1/200 times the Young's modulus of the piles. The piles are 15m long, 0.5 m diameter, and are spaced 4m centre-to-centre.

Figure 3 shows the computed distributions of settlement with depth, for a total applied of 1.0MN (0.111MN per pile), while Figure 4 shows the corresponding distributions of load with depth. The CLAP and DEFPIG solutions agree very closely with each other and also agree reasonably well with those computed by Chow using a three-dimensional finite element analysis for the group.

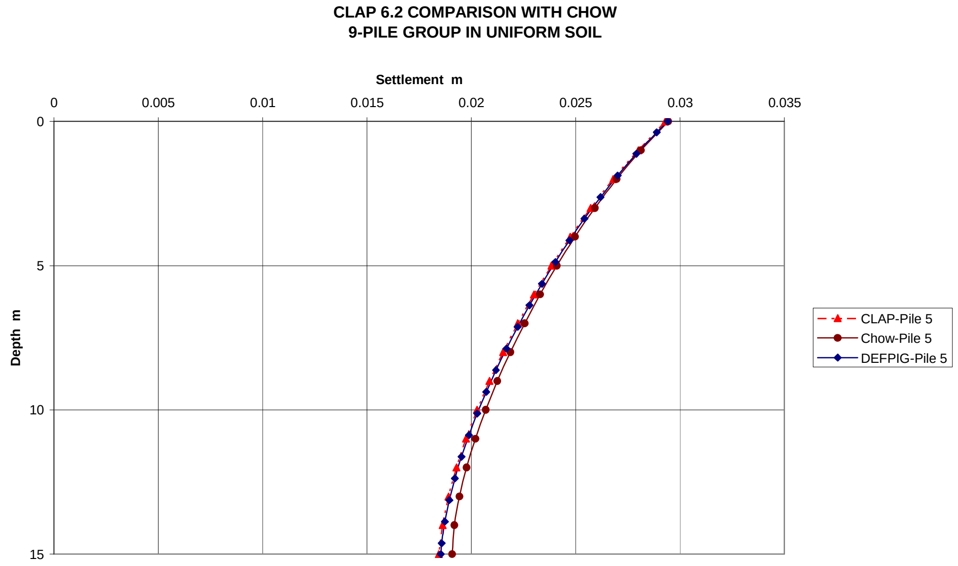


Figure 3 Comparison of Solutions for Settlement – Test Problem 4

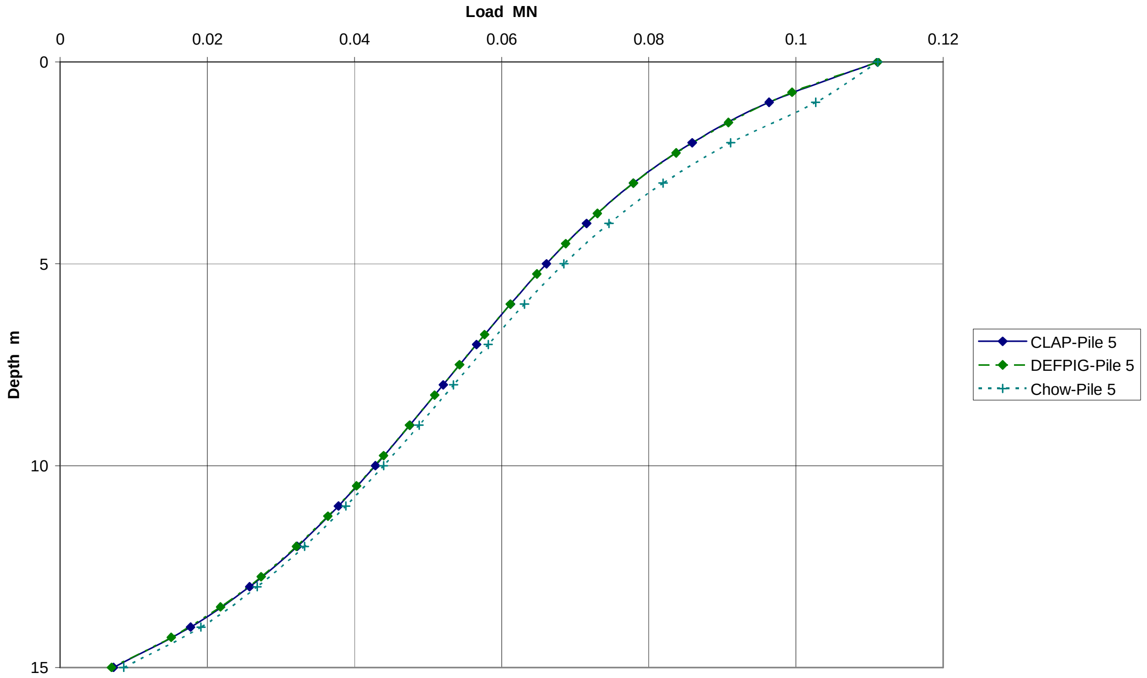


Figure 4 Comparison of Solutions for Load versus Depth – Test Problem 4

6.5 Test Problem 5 – Pile Group Subjected to Combined Loading in One Lateral Direction

This case involves a group of 9 identical piles joined by a rigid cap, and spaced 1.2m centre-to-centre in both directions. The piles have a length of 10m, a diameter of 0.4m and a Young's modulus of 21000 MPa. The soil is assumed to be a deep uniform elastic layer with a constant Young's modulus (both vertical and horizontal) of 7 MPa and a Poisson's ratio of 0.3. The loading consists of a vertical load of 0.6MN, and a lateral load of 0.2MN in the x-direction, a moment of 0.3MNm in the x-direction.

The group has been analysed with CLAP and the results have compared with those obtained from four other programs: DEFPIG, PIGLET, GEPAN (Xu, 2000) and REPUTE (commercially available via GeoCentrix). Table 4 compares the computed responses from the five programs, and reveals generally reasonable agreement for all of the computed responses.

TABLE 4

COMPARISON OF SOLUTIONS FOR TEST PROBLEM 5

Quantity	***CLAP***	***DEFPIG***	***PIGLET***	***GEPAN***	***REPUTE***
Maximum Vertical Pile Load kN	**398**	**389**	**389**	**390**	**397**
Maximum Lateral Pile Load kN	**72**	**72**	**80**	**75**	**78**
Maximum Pile Moment kNm	**42**	**36**	**42**	**39**	**44**
Maximum Settlement mm	**13.2**	**13.4**	**9.9**	**10.8**	**14.1**

Lateral Deflection mm	**11.3**	**11.6**	**11.4**	**10.5**	**11.5**
Rotation rad	**.0023**	**.0024**	**.0024**	**.0024**	**.0026**

6.6 Test Problem 6 – Non-Linear Analysis of a Pile Group for Railway Viaduct

This problem has been used as a benchmark problem by the developers of the REPUTE program, and involves a group of 9 piles (3x3) subjected to combined vertical, lateral and moment loading (in one direction), and embedded in stiff London Clay. The piles are bored reinforced concrete piles 17m long, 0.9m in diameter, with a centre-to-centre spacing of 3 pile diameters in each direction. The assumed loads were: vertical 14200 kN, horizontal 470 kN, and moment 3200 kNm. Both linear and non-linear analyses were carried out in the REPUTE analyses, assuming a Young's modulus for the clay for axial response of 400 c_u for the linear analysis and 1500 c_u for the non-linear analysis, where c_u = undrained shear strength, taken to be given by $c_u = 50 + 9.4z$ kPa, where z= depth below surface (m). For lateral response, Young's modulus was assumed to increase linearly with depth at a rate of 4.14 MPa/m for the linear analysis and 6.15 MPa/m for the non-linear analysis.

CLAP analyses were carried out, also using linear and non-linear analyses and the same parameters as set out above. In addition, assumptions were made about the values of ultimate skin friction, end bearing and lateral pile-soil pressure. Table 5 compares the computed responses from CLAP and REPUTE, and also those computed by DEFPIG and the commercially available program MPILE. It can be seen that there is a reasonable level of agreement between the results of linear analyses, but those from the non-linear CLAP and REPUTE analyses are somewhat smaller because of the larger initial values of soil Young's modulus employed.

TABLE 5

COMPARISON OF SOLUTIONS FOR TEST PROBLEM 6

Quantity	***CLAP (linear)***	***CLAP (non-linear)***	***REPUTE (linear)***	***REPUTE (non-linear)***	***DEFPIG***	***MPILE***
Central Settlement mm	10.8	3.9	11.6	4.0	11.3	9.0
Lateral Deflection mm	3.8	2.7	3.9	2.7	4.3	3.2
Maximum Axial Load kN	2200	2070	2230	2100	2210	2220
Maximum Lateral Load kN	59	58	94	76	62	66
Max. Moment kNm	165	160	225	179	177	120

6.7 Test Problem 7 – Non-Linear Analysis of Laterally Loaded Pile Group

This problem has been used as another benchmark by the developers of REPUTE, and involves a 6-pile group that is part of the design of the high speed rail system in Taiwan. The piles are bored cast-in-situ reinforced concrete piles 34.9m long, 1.5m in diameter, with a Young's modulus of 27.6 GPa. They are in a 3x2 configuration with a centre-to-centre spacing of 4.5m, and connected by a rigid pile cap. A lateral load of 11 MN is applied at the ground surface in the direction of the two rows of 3 piles. The soil is a silty sand or silt and has been idealised as a single cohesionless layer with a friction angle of 30 degrees, and a soil Young's modulus for lateral loading that increases linearly with depth from 77 MPa at the level of the underside of the pile cap at a rate of 9.5 MPa/m. The assumptions made with respect to the limiting lateral pile-soil pressures in REPUTE are not stated, but in the CLAP analyses, it has been assumed that the ultimate lateral pressure is 3 times the Rankine passive pressure, and a submerged unit weight of 7 kN/m^3 has been adopted.

The results of non-linear CLAP and REPUTE analyses are shown in Figure 5, together with the measured lateral load-deflection behaviour. Both analyses agree reasonably well, and the measurements generally lie between the two computed curves.

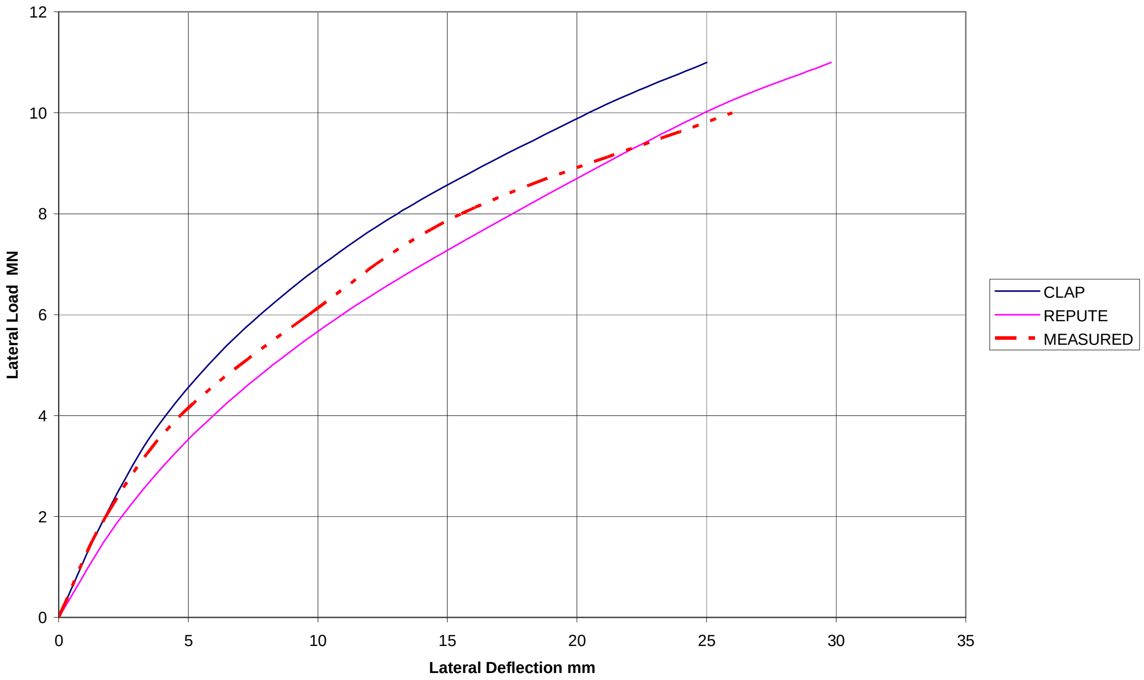


Figure 5 Comparison of Lateral Load – Deflection Curves – Test Problem 7

6.8 Test Problem 8 – Pile Group Subjected to Multi-Directional Loading

For this case, a group of 9 piles (3x3 configuration at a centre-to-centre spacing of 2m in each direction), subjected to all 6 components of loading, has been analysed with CLAP and with PIGLET. The piles are 15m long, 0.5m diameter, with a Young's modulus of 30 GPa, and are located in a15m layer of soil that is underlain by a stiffer bearing stratum. The Young's modulus of the soil is taken to be 50 MPa for both vertical and lateral response, while the Young's modulus of the bearing stratum is 100 MPa. Elastic ground behaviour is assumed for this case. The following loadings are applied:

Vertical = 9.0 MN

Lateral (x-direction) = 0.9 MN

Moment (x-direction) = 3 MNm

Lateral (y-direction) = 0.9 MN

Moment (y-direction) = 4.5 MNm

Torsion = 1.5 MNm.

Table 6 summarizes the results of the CLAP and PIGLET analyses for the group and the computes forces and moments for the most heavily loaded corner pile. This table reveals a reasonable measure of agreement, given the different underlying assumptions of the two analysis programs.

TABLE 6

COMPARISON OF SOLUTIONS FOR TEST PROBLEM 8

Quantity	***CLAP***	***PIGLET***
Central Settlement mm	10.3	9.1
Lateral Deflection (x) mm	3.4	3.1
Lateral Deflection (y) mm	3.4	3.1
Rotation (x) rad	.000584	.000582
Rotation (y) rad	.000584	.000582
Torsional Rotation rad	.000417	.000359
Maximum Axial Load MN	2.05	2.07
Maximum Lateral Load (x) MN	.18	.19
Maximum Lateral Load (y) MN	.19	.18
Maximum Moment (x) MNm	.113	.104
Maximum Moment (x) MNm	.113	.104
Maximum Torsion MNm	.014	.012

6.9 Test Problem 9 – Pile Group with Different Piles

In this case, a group of 6 piles in a 3x2 configuration is analysed. Figure 6 shows the group and all piles have a diameter of 1.0m except Pile 5, whose diameter is 0.5m. The soil profile consists of a 20m deep layer of clay underlain by a stiffer stratum. Young's modulus of the clay is assumed to be 20 MPa (for both axial and lateral loading) while that of the stiffer stratum is 100 MPa. Poisson's ratio of both strata is 0.3. A vertical load of 9.0 MN is assumed to act at the centroid of the group.

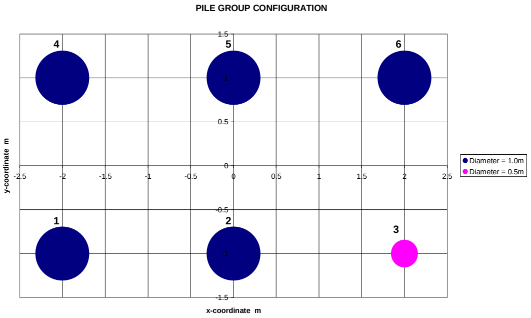


Figure 6 Location of Piles for Test Problem 9

Figures 7 and 8 compare the results of the CLAP analysis with those from an analysis using the program PIGLET. The computed maximum settlements from CLAP and PIGLET 12.3 mm and 11.5 mm respectively, while the lateral deflections in the x-direction are 0.55 mm and 0.57 mm.

Figure 7 compares the computed axial pile head loads and reveals reasonable agreement. The lower load carried by the smaller-diameter pile (Pile 3) can clearly be seen. Figure 8 shows the corresponding comparisons for the pile head moments (Mx) in the x-direction. In this case, the CLAP values are slightly smaller than those from PIGLET, but overall, the agreement is reasonable.

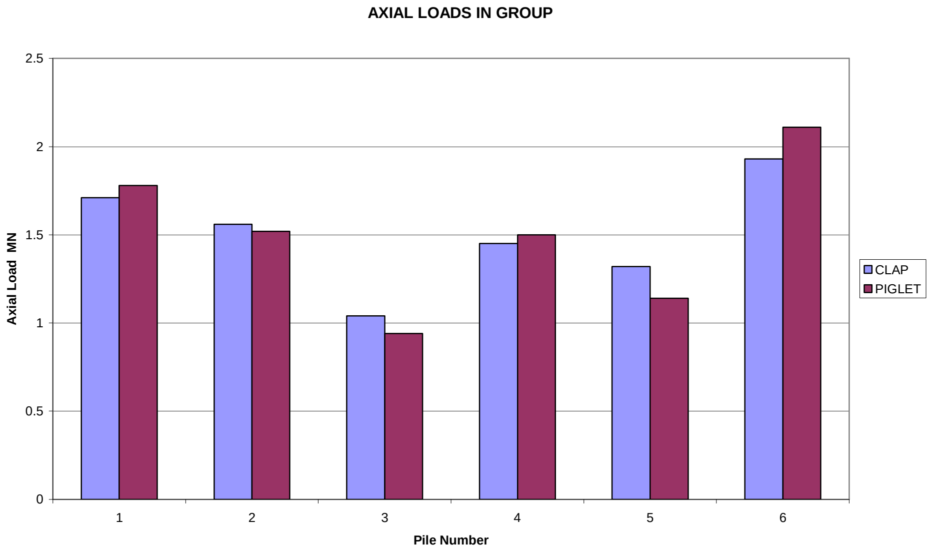


Figure 7 Comparison of Computed Axial Loads for Test Problem 9.

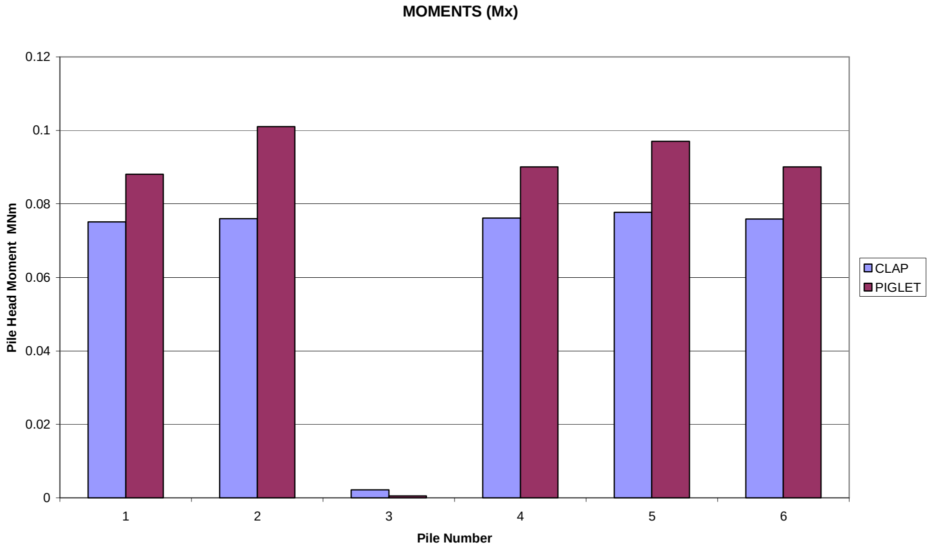


Figure 8 Comparison of Computed Pile Head Moments (Mx) for Test Problem 9

7.0 SAMPLE INPUT AND OUTPUT FILES

Appendices C and D reproduce typical input and output files (these are for Test Problem 9, discussed above).

8.0 SUMMARY

The program CLAP has been developed to allow for consideration of general loading of a pile group in which non-linear pile-soil behaviour can be considered. The program inevitably involves a number of assumptions, in order to allow for practical problems to be specified and solved. It has been tested against some other existing programs and against a commercially available finite element program (PLAXIS). CLAP is found to give comparable results, and it is reasonable to assume that it can be used with a similar measure of confidence to comparable programs such as DEFPIG and PIGLET.

REFERENCES

Chow, H. (2007). “Analysis of piled rafts with piles of different lengths and diameters”. PhD thesis, Dept. Civil Engineering, University of Sydney, Australia.

Poulos, H.G. (1979). “Settlement of single piles in non-homogeneous soil”. J. Geot. Eng. Divn., ASCE, 105(GT5): 627-641.

Poulos, H.G. (1980). “An approach for the analysis of offshore pile groups”. Proc. Int. Conf. On Numerical Methods in Offshore Piling, ICE, London, 119-126.

Poulos, H.G. (1994). “Settlement prediction for driven piles and pile groups”. Geot. Spec. Pub. No. 40, ASCE, Vol. 2: 1629-1649.

Randolph, M.F. and Wroth, C.P. (1978). “Analyses of deformation of vertically loaded piles”. J. Geot. Eng. Divn., ASCE, 104(GT12): 1465-1488.

APPENDIX A

ANALYSIS DETAILS FOR PROGRAM
CLAP Version 6.2(Q4)

BASIS OF CLAP ANALYSIS

1.0 INTRODUCTION

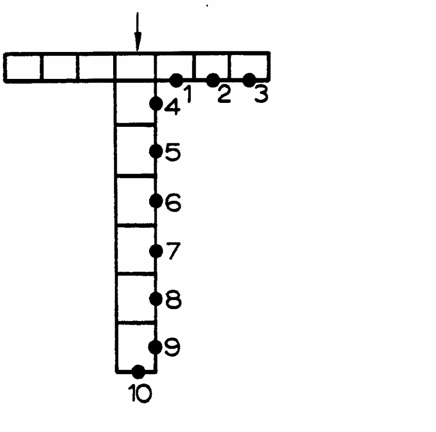
The CLAP program uses an extension of the analysis developed for the program DEFPIG and described in the DEFPIG User's Manual (Poulos, 1990). CLAP computes the distributions of axial and lateral deflections, rotations, axial and lateral loads, and moments at the top of a group of piles subjected to a combination of vertical load, lateral loads in both horizontal directions, moment in both horizontal directions, and torsion. The piles can be attached to a rigid pile cap, or else to be subjected to specified loadings. Raking piles can be present in the group, and the rake can be in both horizontal directions. The program can take into account the effects of the pile cap being in contact with the ground, but only on axial response. The effects on lateral response are ignored. Different pile types can be considered, and different soil profiles can also be specified for the various pile types, so that a pile group within a variable soil profile can be analysed. A number of approximations are made in the analysis to allow for these facilities to be implemented.

Using a simplified boundary element approach, CLAP computes the single pile flexibility values and the two-pile interaction factors for each pile type specified. When calculating the pile flexibilities, it allows for non-linear pile-soil behaviour by limiting the axial and lateral pile-soil pressures to the ultimate values specified by the user. Interaction factors are computed using a purely elastic analysis. Following the suggestions of Mandolini and Viggiani (1997), interaction effects of one pile on another pile are based on the elastic flexibility of the influencing pile, with non-linearity only being introduced for the effect of the influenced pile on itself.

2.0 IDEALIZATION OF PILES

As with DEFPIG, each pile type is divided into a series of equal elements, and a different number of elements can be used for axial and lateral response (the latter usually requires more elements than the former). Figures A1(a) and (b) show typical representations of a pile for axial and lateral response analyses respectively.

Each pile is assumed to have a constant diameter and to be divided equally into the number of elements specified. Allowance is made in the program for structural failure of the pile by specifying the limiting axial pile stress in compression and in tension, and the limiting bending moment capacity. These values are imposed as upper limits within CLAP, and when a pile reaches the structural limit, it is assumed to be able to sustain no further increase in load.



(a) Typical pile-cap unit analyzed for axial response for NC=3, NS=6, NB=1

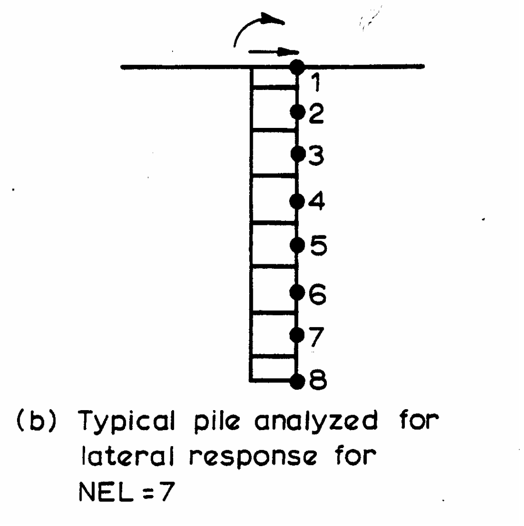


Figure A1 Division of pile into elements

3.0 IDEALIZATION OF SOIL

The soil is assumed to be an elastic continuum so that the classical Mindlin equations can be employed in the axial and lateral response analyses. The soil along the pile shaft can be specified in one of four ways:

- As a uniform material;
- As a "Gibson" soil whose modulus varies linearly with depth;
- As a layered material;
- As a soil mass whose properties vary from element to element along the shaft.

The soil below the pile base can be specified either as a uniform material or as a series of layers. In the latter case, the program computes an equivalent Young's modulus within the depth of influence of the pile base (as specified by the user).

More realistic estimation of the two-pile interaction factors can be made by allowing for the fact that the soil modulus depends on the strain level within the soil, so that the soil modulus between two piles will generally be greater than that at the pile-soil interface because of the lower strain level existing between the piles. A simplified representation of the distribution of soil Young's modulus between the piles is shown in Figure A2, and in this representation, it is necessary to specify the following parameters:

- The ratio of the mass (small strain) modulus to near-pile soil modulus for vertical loading;
- The ratio of the mass modulus to near-pile soil modulus for vertical loading;
- The "transition distance" (s_t /d) (in terms of pile diameter)over which the soil modulus changes from the "near-pile" value to the "mass" value.

3.1 Treatment of Layered Soil Profiles

In DEFPIG and earlier versions of CLAP, when the effect of a loaded element j on an element i was considered, a simple average value of Young's modulus, Es_{av}, was used in the Mindlin elastic equations, whereby:

$$Es_{av} = 0.5(Es_i + Es_j)$$

where Es_i = Young's modulus for element I and Es_j = Young's modulus at element j.

In the current version of CLAP, a more refined approach developed by Yamashita et al (1987) has been implemented. In this approach,

$$Es_{av} = 0.5(Es_i' + Es_j')$$

where Es_i' and Es_j' = weighted average modulus values around elements i and j.

For element i, $Es_i' = \Sigma\, W_{i,k}.Es_k / \Sigma\, W_{i,k}$

where $W_{i,k}$ = weighting factor = $2^{-\mathrm{abs}(i-k)}$

k is taken from i-4 to i+4, i.e. a weighted average is taken for 4 elements above and 4 elements below the element i. Near the top and toe of the pile, the averaging process is curtailed so as not to include non-existent elements.

The above approach has been used for both the axial and lateral response analyses. It has been found to reduce the incidence of oscillating stresses that can occur when the previous scheme is applied near a boundary between two layers of considerably different stiffness.

4.0 REPRESENTATION OF PILE GROUP

The pile group can be specified in two ways:

- As a symmetric configuration of piles, by specifying the number of rows in each direction and the relevant spacings, together with the pile type and the rake angles (if appropriate) for each pile.
- As a general configuration of piles, by specifying the pile type, the x- and y-coordinates, and the rake angle in each direction.

For the symmetrical configuration, the program assigns pile numbers, starting from the lower left-hand corner. An example is shown in Figure A2. For the general configuration, the piles are numbered in the order of input.

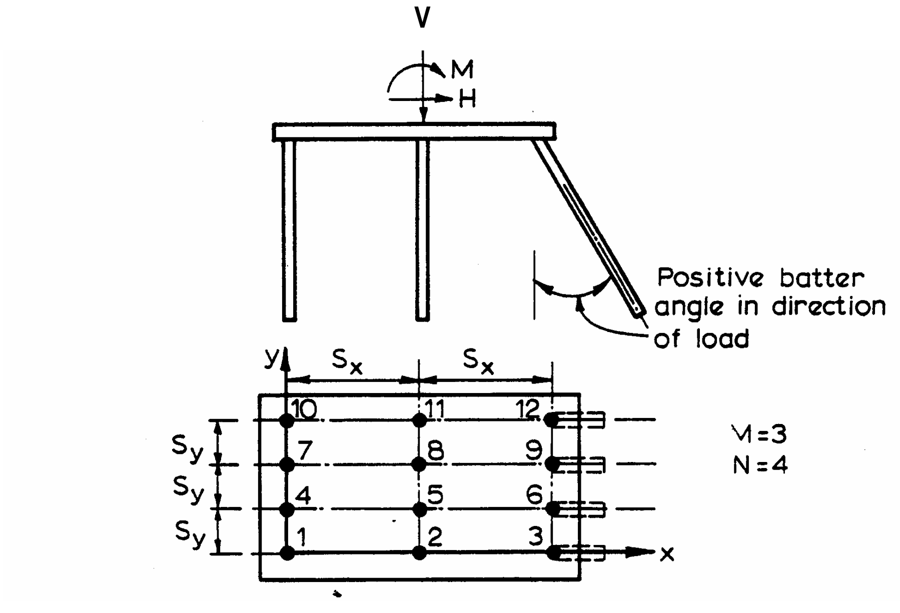


Figure A2 Numbering scheme for piles in a rectangular group

5.0 REPRESENTATION OF LOADS

All six components of load need to be specified in CLAP. The applied loads on the group may be input in a number of different ways, including the following:

- As single resultant loads applied at specified x- and y-coordinates (these can be different for each load component);
- As a series of loads applied at specified x- and y-coordinates (these can be different for each component);
- As a series of column loads, in which case the user specifies:
    - The x- and y-coordinates of the column;
    - The six load components at that column due to dead load, live load, wind load, earthquake load, and other loads;
    - The load factors for each load source.
- As loads applied to each pile within the group (6 values for each pile, one for each load component);
- As displacements applied to each pile within the group (6 values for each pile, one for each displacement or rotation component).

6.0 METHOD OF ANALYSIS

The CLAP program combines the following analyses:

- The settlement of a single pile;
- The settlement of a pile group, based on the superposition of two-pile axial interaction factors;
- The lateral response of a single pile;
- The lateral response of a pile group, based on the superposition of two-pile lateral interaction factors;
- The analysis of a group of piles containing raked piles and subjected to combined axial, lateral and moment loading.
- The analysis of a single pile due to torsion, using the simplified analysis developed by Randolph (1981). For this loading component, it is assumed that there is no interaction between two piles within a group, as assumed in the PIGLET program.

For the specified group configuration, the program computes the spacings between all piles and interpolates the computed (or input) interaction factors to evaluate the axial and lateral interaction factors for all piles. For raked piles, the interaction factors are computed for two vertical piles at a spacing corresponding to the distance between the piles at a depth of one-third of the pile length below the surface. The axial, lateral, rotational and torsional flexibilites (and hence stiffnesses) are computed by the program. Elastic values are computed for use when considering interaction effects among the piles, and non-linear values (dependent on the magnitude of loading) being computed for the previous load level acting on each pile. These latter values are used when computing the contribution of the load acting on a pile to the deflection or rotation of that pile. For axial loading, an option is available whereby the non-linearity is introduced via a hyperbolic function. In this case, the secant axial stiffness, Kvs, is expressed as follows:

$$Kvs = Kvo.(1-R_{fp}.\ P/P_u) \qquad (A1)$$

where Kvo = initial axial stiffness

R_{fp} = hyperbolic factor for pile axial response (typically 0.5 to 0.9)

P = axial load acting on pile

P_u = ultimate axial load (in direction of acting load P).

The <u>tangent</u> axial stiffness, Kvt, (which is used in an incremental analysis) is then given by:

$$Kvt = Kvo.(1-R_{fp}.\ P/P_u)^2 \qquad (A2)$$

A similar formulation is used for the torsional stiffness.

Allowance can be made for group effects in reducing (or even increasing) the limiting values of skin friction, end bearing resistance, pile cap bearing pressure and lateral resistance, via the input of relevant efficiency factors.

Using the approach described by Poulos (1980), the program then assembles the various equations relating the various components of displacement and rotation to the pile loads, moments and torsion loads. The original equations are extended to allow for consideration of both horizontal directions of loading, and also of torsional loading. In so doing, the analyses are simplified by making the following assumptions:

- Lateral loading in the “x” horizontal direction does not affect displacements and rotations in the “y” horizontal direction, and vice-versa;
- Torsional loads give rise only to torsional rotations, and only on the pile on which they act, i.e. there is no torsional interaction among the piles in the group;
- Lateral loads give rise to torsional loading if applied eccentrically to the centroid of the group, in the same way that eccentric vertical loadings give rise to moment loadings.

Equations are assembled for the following responses of each pile within the group:

- Vertical displacement;
- Lateral displacement min the x-direction;
- Rotation in the x-direction;
- Lateral displacement in the y-direction;
- Rotation in the y-direction;
- Torsional rotation.

All 6 components of load may contribute to each of these responses, although the torsional rotation depends only on the torsional load on the pile being considered.

In addition, there will be six equilibrium equations, one for each component of loading. There are then a total of 6N+6 equations, where N = number of piles within the group. These equations can be represented in matrix form as follows:

$$[A].\ \{\Delta P\} = \{\Delta X\} \qquad (A3)$$

where [A] = group stiffness matrix

$\{\Delta P\}$ = incremental pile loading and reference deflection vector

$\{\Delta X\}$ = incremental applied load vector.

The matrix [A] can be subdivided into a series of sub-matrices, as shown in Table A1. The first 6 sets of sub-matrices labelled A, B, C, D, E and Q are of order NxN, where N is the number of piles in the group. They represent the displacement and rotation equations for each of the piles within the group. The remainder of the submatrices A, B, C, D, E and Q are of order 1xN. The sub-matrices labelled F, G, H, I, J and K represent the 6 equilibrium equations. The first 6 sets of these are of order 1xN, while the remainder are 1x1 elements.

6.1 Case of Rigid Pile Cap

Table A2 defines the coefficients of [A], and Table A3 defines the parameters in Table A2 and $\{\Delta P\}$ and $\{\Delta X\}$.

The incremental pile loading and reference deflection vector $\{\Delta P\}$ is defined as follows:

$$\{\Delta P\} = \begin{array}{|c|}\hline \Delta V \\ \hline \Delta Hx \\ \hline \Delta Mx \\ \hline \Delta Hy \\ \hline \Delta My \\ \hline \Delta T \\ \hline \Delta \rho_{vr} \\ \hline \Delta \rho_{hxr} \\ \hline \Delta \theta_{xr} \\ \hline \Delta \rho_{hyr} \\ \hline \Delta \theta_{yr} \\ \hline \Delta \theta_{tr} \\ \hline \end{array}$$

where ΔV=incremental pile axial loads, ΔHx = incremental pile lateral loads in x-direction, ΔMx = incremental pile head moments in x-directions, ΔHy = incremental pile lateral loads in y-direction, ΔHy = incremental pile head moments in y-direction, ΔT = incremental pile head torsional load, $\Delta \rho_{vr}$ = incremental reference vertical deflection, $\Delta \rho_{hxr}$ = incremental reference lateral deflection in x-direction, $\Delta \theta_{xr}$ = incremental reference rotation in x-direction, $\Delta \rho_{hyr}$ = incremental reference lateral deflection in y-direction, $\Delta \theta_{yr}$ = incremental reference rotation in y-direction, $\Delta \theta_{tr}$ = incremental reference torsional rotation.

The incremental applied load vector is defined as follows:

$$\{\Delta X\} = \begin{array}{|l|}\hline 0 \\ \hline 0 \\ \hline 0 \\ \hline 0 \\ \hline 0 \\ \hline 0 \\ \hline \Delta V_G \\ \hline \Delta H_{xG} \\ \hline \Delta V_G.XAPv+\Delta M_{xG} \\ \hline \Delta H_{yG} \\ \hline \Delta V_G.YAPv+\Delta M_{yG} \\ \hline \Delta T_G+\Delta H_{xG}.YAPh-\Delta H_{yG}.XAPh \\ \hline \end{array}$$

where ΔV_G = incremental applied vertical load on group, ΔH_{xG} = incremental applied lateral load in x-direction, ΔM_{xG}= incremental applied moment in x-direction, ΔH_{yG} = incremental applied lateral load in y-direction, ΔM_{yG} = incremental applied moment in y-direction, ΔT_G = incremental applied torsion on group, XAPv = distance in x-direction of resultant vertical applied load from origin (x=0, y=0), YAPv = distance in y-direction of resultant of vertical load from origin, XAPh = distance in x-direction of resultant load H_{yG} from origin, YAPh = distance in y-direction of resultant load H_{xG} from origin.

TABLE A1

Sub-Matrices for Matrix [A]

Avv	Avhx	Avmx	Avhy	Avmy	Avt	A7	A8	A9	A10	A11	A12
Bxv	Bxhx	Bxmx	Bxhy	Bxmy	Bxt	B7	B8	B9	B10	B11	B12
Ctxv	Ctxhx	Ctxmx	Ctxhy	Ctxmy	Ctxt	C7	C8	C9	C10	C11	C12
Dyv	Dyhx	Dymx	Dyhy	Dymy	Dyt	D7	D8	D9	D10	D11	D12
Etyv	Etyhx	Etymx	Etyhy	Etymy	Etyt	E7	E8	E9	E10	E11	E12
Qttz	Qtthx	Qttmx	Qtthy	Qttmy	Qttt	Q7	Q8	Q9	Q10	Q11	Q12
Fv	Fx	Fmx	Fy	Fmy	Ft	F7	F8	F9	F10	F11	F12
Gv	Gx	Gmx	Gy	Gmy	Gt	G7	G8	G9	G10	G11	G12
Hv	Hx	Hmx	Hy	Hmy	Ht	H7	H8	H9	H10	H11	H12
Iv	Ix	Imx	Iy	Imy	It	I7	I8	I9	I10	I11	I12
Jv	Jx	Jmx	Jy	Jmy	Jt	J7	J8	J9	J10	J11	J12
Kv	Kx	Kmx	Ky	Kmy	Kt	K7	K8	K9	K10	K11	K12

6.1.1 Pile Failure

Equation A3 is valid when the pile loads and moments remain less than the ultimate geotechnical or structural values. At each increment, CLAP computes the incremental pile loads and moments, and adds them to the existing values. It then checks each value against the corresponding ultimate geotechnical and structural value. If the computed load or moment exceeds the lower of the geotechnical or structural values, the equation for displacement and rotation for that pile in equation A3 are replaced by an equation stating that the total load is equal to the ultimate value, and that subsequent incremental loads (or moments) on that pile will be zero. No allowance is made for cases where there is post-peak reduction in either geotechnical or structural capacity.

6.2 Case of Specified Loads on Each Pile

In this case, the various deflections and rotations can be computed from the first 6N equations represented by equation A3. Again, an incremental analysis can be carried out, checking at each increment that each applied load component does not exceed the relevant ultimate capacity.

TABLE A2

Definition of Components of Matrix [A]

Component of Sub-Matrix	Equation
$Avv_{i,j}$	$\alpha_{i,j}\ \rho_{v1j} \cos\psi_{ai} \cos\psi_{aj} + \alpha_{\rho hxi,j}\ \rho_{hH1j} \sin\psi_{xi} \sin\psi_{xj} + \alpha_{\rho hyi,j}\ \rho_{hH1j} \sin\psi_{yj} \sin\psi_{yi}$
$Avh_{i,j}$	$\alpha_{i,j}\ \rho_{v1j} \sin\psi_{xj} \cos\psi_{ai} - \alpha_{\rho hxi,j}\ \rho_{hH1j} \cos\psi_{xj} \sin\psi_{xi}$
$Avmx_{i,j}$	$- \alpha_{\rho mxi,j}\ \rho_{hm1j} \sin\psi_{xi}$
$Avhy_{i,j}$	$- \alpha_{\rho hyi,j}\ \rho_{hH1j} \cos\psi_{yj} \sin\psi_{yi} + \alpha_{i,j}\ \rho_{v1j} \sin\psi_{yj} \cos\psi_{ai}$
$Avmy_{i,j}$	$- \alpha_{\rho myi,j}\ \rho_{hm1j} \sin\psi_{yi}$
Avt	0
$Bxv_{i,j}$	$\alpha_{i,j}\ \rho_{vi,j} \cos\psi_{aj} \sin\psi_{xi} - \alpha_{\rho hxi,j}\ \rho_{hH1j} \sin\psi_{xj} \cos\psi_{xi}$
$Bxhx_{i,j}$	$\alpha_{i,j}\ \rho_{v1j} \sin\psi_{xi} \sin\psi_{xj} + \alpha_{\rho hxi,j}\ \rho_{hH1j} \cos\psi_{xj} \cos\psi_{xi}$
$Bxmx_{i,j}$	$\alpha_{\rho mxi,j}\ \rho_{hm1j} \cos\psi_{xi}$
$Bxhy_{i,j}$	$\alpha_{i,j}\ \rho_{v1j} \sin\psi_{yj} \sin\psi_{xi}$
$Bxmy_{i,j}$	0
$Bxt_{i,j}$	0
$Ctxv_{i,j}$	$-\alpha_{\theta hxi,j}\ \theta_{h1j} \sin\psi_{xj}$
$Ctxhx_{i,j}$	$\alpha_{\theta hxi,j}\ \theta_{h1j} \cos\psi_{xj}$
$Ctxmx_{i,j}$	$\alpha_{\theta mxi,j}\ \theta_{m1j}$
$Ctxhy_{i,j}$	0
$Ctxmy_{i,j}$	0
$Ctxt_{i,j}$	0
$Dyv_{i,j}$	$\alpha_{i,j}\ \rho_{v1j} \cos\psi_{aj} \sin\psi_{yj} - \alpha_{\rho hyi,j}\ \rho_{hH1j} \sin\psi_{yj} \cos\psi_{yi}$
$Dyhx_{i,j}$	$\alpha_{i,j}\ \rho_{v1j} \sin\psi_{xj} \sin\psi_{yi}$
$Dymx_{i,j}$	0
$Dyhy_{i,j}$	$\alpha_{i,j}\ \rho_{v1j} \sin\psi_{yj} \sin\psi_{yi} + \alpha_{\rho hyi,j}\ \rho_{hH1j} \cos\psi_{yj} \cos\psi_{yi}$
Dymyi,j	$\alpha_{\rho myi,j}\ \rho_{hm1j} \cos\psi_{yi}$
$Dyt_{i,j}$	0
$Etyv_{i,j}$	$-\alpha_{\theta hyi,j}\ \theta_{h1j} \sin\psi_{yj}$
$Etyhx_{i,j}$	0
$Etymx_{i,j}$	0
$Etyhy_{i,j}$	$\alpha_{\theta hyi,j}\ \theta_{h1j} \cos\psi_{yj}$

$Etymy_{i,j}$	$\alpha_{\theta hyi,j}\ \theta_{m1j}$
$Etyt_{i,j}$	0
$Qttv_{i,j}$	0
$Qtthx_{i,i}$	0
$Qttmx_{i,j}$	0
$Qtthy_{i,j}$	0
$Qttmy_{i,j}$	0
$Qttt_{i,j}$	$\theta_{t1} / [1.0 - R_{fp}(T_j/Tu_j)]^2$ for i=j, otherwise 0
Fv_j	1.0
Fh_j	0
Fmx_j	0
Fy_j	0
Fmy_j	0
Ft_j	0
Gv_j	0
Gx_j	1.0
Gmx_j	0
Gy_j	0
Gmy_j	0
Gt_j	0
Hv_j	$(x_j - XAP)$
Hx_j	0
Hmx_j	1.0
Hy_j	0
Hmy_j	0
Ht_j	0
Iv_j	0
Ixj	0
Imxj	0
Iyj	1.0
Imyj	0
Itj	0
Jvj	$(y_j - YAP)$
Jxj	0

Jmxj	0
Jyj	0
Jmyj	1.0
Jtj	0
Kvj	0
Kxj	(yi – YHYL)
Kmxj	0
Kyj	$-(x_i – XHXL)$
Kmyj	0
Ktj	-1.0
A7	-1.0
A8	0
A9	0
A10	0
A11	0
A12	0
B7	0
B8	-1.0
B9	0
B10	0
B11	0
B12	$-R_i \sin\psi_{ai}$
C7	0
C8	0
C9	-1.0
C10	0
C11	0
C12	0
D7	0
D8	0
D9	0
D10	-1.0
D11	0
D12	$R_i \cos\psi_{ai}$

E7	0
E8	0
E9	0
E10	0
E11	-1.0
E12	0
Q7	0
Q8	0
Q9	0
Q10	0
Q11	0
Q12	-1.0
F7	0
F8	0
F9	0
F10	0
F11	0
F12	0
G7	0
G8	0
G9	0
G10	0
G11	0
G12	0
H7	0
H8	0
H9	0
H10	0
H11	0
H12	0
I7	0
I8	0
I9	0
I10	0

I11	0
I12	0
J7	0
J8	0
J9	0
J10	0
J11	0
J12	0
K7	0
K8	0
K9	0
K10	0
K11	0
K12	1.0

TABLE A3

Definition of Parameters in Governing Matrix and Vectors

Parameter	Definition
$\alpha_{i,j}$	Axial interaction factor for effect of pile j on pile i
$\alpha_{phx\,i,j}$	Lateral interaction factor for horizontal deflection due to x-load-effect of pile j on pile i
$\alpha_{phy\,i,j}$	Lateral interaction factor for horizontal deflection due to y-load-effect of pile j on pile i
$\alpha_{pmx\,i,j}$	Lateral interaction factor for horizontal deflection due to x-moment-effect of pile j on pile i
$\alpha_{pmy\,i,j}$	Lateral interaction factor for horizontal deflection due to y-moment-effect of pile j on pile i
$\alpha_{\theta hx\,i,j}$	Lateral interaction factor for rotation due to x-load-effect of pile j on pile i
$\alpha_{\theta hy\,i,j}$	Lateral interaction factor for rotation due to y-load-effect of pile j on pile i
$\alpha_{\theta mx\,i,j}$	Lateral interaction factor for rotation due to x-moment-effect of pile j on pile i
$\alpha_{\theta my\,i,j}$	Lateral interaction factor for rotation due to y-moment-effect of pile j on pile i
ρ_{v1j}	Vertical deflection under unit vertical load for pile j
ρ_{hH1j}	Lateral deflection under unit horizontal load for pile j (assumed same in both directions)
ρ_{hm1j}	Lateral deflection under unit moment for pile j (assumed same in both directions)
θ_{h1j}	Rotation under unit horizontal load for pile j (assumed same in both directions)
θ_{m1j}	Rotation under unit horizontal moment for pile j (assumed same in both directions)
ψ_{xi}	Rake angle (to vertical) in x-direction for pile i

ψ_{yi}	Rake angle (to vertical) in y-direction for pile i
ψ_{ai}	Real rake angle (to vertical) for pile i
x_i	x-coordinate of pile i
y_i	y-coordinate of pile i
R_i	Radial distance of head of pile i from origin = $(x_i^2+y_i^2)^{0.5}$
XAP	x-coordinate of vertical load
YAP	y-coordinate of vertical load
XHXL	x-coordinate of x-horizontal load
YHXL	y-coordinate of x-horizontal load
XHYL	x-coordinate of y-horizontal load
YHYL	y-coordinate of y-horizontal load
ΔV	Incremental pile head vertical load
ΔHx	Incremental pile head x-horizontal load
ΔMx	Incremental pile head x-moment
ΔHy	Incremental pile head y-horizontal load
ΔMy	Incremental pile head y-moment
ΔT	Incremental pile head torsion
$\Delta\rho_{vr}$	Incremental pile head vertical deflection
$\Delta\rho_{hxr}$	Incremental pile head x-horizontal deflection
$\Delta\theta_{xr}$	Incremental pile head x-rotation
$\Delta\rho_{hyr}$	Incremental pile head y-horizontal deflection
$\Delta\theta_{yr}$	Incremental pile head y-rotation
$\Delta\theta_{tr}$	Incremental pile head torsional rotation
ΔV_G	Increment of applied vertical load on group
ΔH_{xG}	Increment of applied x-horizontal load on group
ΔM_{xG}	Increment of applied x-moment on group
ΔH_{yG}	Increment of applied y-horizontal load on group
ΔM_{yG}	Increment of applied y-moment on group
ΔT_G	Increment of applied torsion on group
T_j	Torsional load on pile j
Tu_j	Ultimate torsional capacity of pile j

7.0 LOAD AND MOMENT DISTRIBUTION IN INDIVIDUAL PILES

The approach adopted in older versions of CLAP for computing distributions of load and moment in specified piles within a group is similar to that used in the program DEFPIG and described in the DEFPIG Users Manual (Poulos, 1990). In the current version of CLAP, a different approach has been taken in which the pile being analysed is treated as a single pile but the soil modulus vales along and below the pile shaft are reduced or "softened" to reflect the effects of pile-soil-pile interaction.

For a pile k within a group of n piles, the soil modulus at an element i, $Esg_{k,I}$, is obtained as follows:

$$Esg_{k,i} = Es_{k,i} / Fg_{k,i}$$

where $Es_{k,i}$ = soil modulus at element i of pile k

$Fg_{k,i}$ **=** group modulus reduction factor.

For cap and shaft elements under axial loading, $Fg_{k,i}$ has been obtained as follows:

$$Fg_{k,i} = \sum \alpha_{k,j}$$

where $\alpha_{k,j}$ = axial interaction factor for effect of pile j on the analysed pile k.

The summation is carried out for all n piles within the group.

For base elements under axial loading, it has been assumed that:

$$Fg_{k,i} = \sum \alpha b_{k,j}$$

where $ab_{k,j}$ = axial base interaction factor

$= 1/(\pi\, r_{k,j})$

$r_{k,j}$ = distance between centres of piles k and j.

For elements subjected to lateral loading, the same expression for $Fg_{k,i}$ as used for shaft elements under axial loading has been used, except that the relevant interaction factor for the effect of lateral loading on lateral deflection has been used instead of the axial interaction factor.

The settlement and lateral deflection of the pile within the group is scaled to give the same value as the group analysis. With lateral loading in particular, this may lead to some inconsistency between deflections and curvatures (and hence moments) along the pile.

The above procedure is approximate only, in view of the assumptions involved in the analysis and the implicit ignoring of the effects of intervening piles on the interaction between the elements of interacting piles.

It does however facilitate greatly the analysis process. For groups under axial loading, it also results in a greater reduction of modulus values along the shaft than at the base. This in turn leads to more load being carried by the base of a pile within a group than is the case for a single pile, and this is a characteristic of group behaviour that is now well-recognised.

As with DEFPIG, the effects of pile-soil slip and soil yielding under lateral loading are taken into account. In evaluating lateral response, CLAP considers and outputs separately the responses in the x- and y-directions.

There are some important limitations in the procedure used in CLAP, including the following:

1. In evaluating individual pile responses, it is assumed that the piles remain elastic and do not fail structurally.
2. If a pile is specified to have "defects" such that its stiffness and capacity is reduced, such defects are not able to be taken into account.

REFERENCES

Mandolini, A. and Viggiani, C. (1997). “Settlement of piled foundations”. Geotechnique, 47(3): 791-816.

Poulos, H.G. (1980). “An approach for the analysis of offshore pile groups”. Numerical Methods in Offshore Piling, ICE, London, 117-126.

Poulos, H.G. (1990). DEFPIG Users Manual. Centre for Geotechnical Research, University of Sydney, Australia.

Randolph, M.F. (1981). “Piles subjected to torsion”. Jnl. Geot. Eng. Divn., ASCE, 107(GT8): 1095-1111.

Yamashita, K., Tomono, M. and Kakurai, M. (1987). “A method for estimating immediate settlement of piles and pile groups”. Soils and Foundations, Vol. 27, No. 1: 61-76.

INPUT DATA DETAILS

PROGRAM CLAP-6.2Q4 - DATED 29/01/2009

RECORD	*SYMBOL*	*DESCRIPTION*
1	KAS	NUMBER OF CASES TO BE ANALYSED
2	ITITLE	TITLE OF RUN
3	IPLRAF	CODE FOR PILE CAP CONTACT CONDITION 0 FOR CAP NOT IN CONTACT (FREE-STANDING GROUP) 1 FOR CAP IN CONTACT WITH SOIL
	NPIL	NO. OF PILES IN GROUP (ONLY NECESSARY IF IPLRAF=1; OTHERWISE, SPECIFY AS 0)
	AR	TOTAL AREA OF PILE CAP (ONLY IF IPLRAF=1; OTHERWISE SPECIFY AS 0)
4	NTOP	CODE FOR PILE HEAD CONDITION 0 FOR HEAD FIXED AGAINST ROTATION 1 FOR FREE HEAD PILE ***NOTE:*** *NTOP SHOULD NORMALLY BE SPECIFIED AS 1*
	NBOT	CODE FOR PILE TIP CONDITION 0 FOR TIP FIXED AGAINST ROTATION 1 FOR TIP FREE TO ROTATE
5	FIGFS	GEOTECHNICAL REDN. FACTOR FOR SKIN FRICTION
	FIGFB	GEOTECHNICAL REDN. FACTOR FOR END BEARING
	FIGPC	GEOTECHNICAL REDN. FACTOR FOR PILE CAP CAPACITY
	FIGPY	GEOTECHNICAL REDN. FACTOR FOR ULT. LATERAL PRESSURE
6	FIS	STRUCTURAL STRENGTH REDUCTION FACTOR (ASSUMED SAME FOR MOMENT, COMPRESSIVE AND TENSILE STRENGTHS)
7	NSPS	NO. OF SPACING/DIAMETER VALUES AT WHICH INTERACTION FACTORS ARE TO BE COMPUTED OR INPUT
8	SPAC(I)	VALUE OF (SPACING/SHAFT DIAMETER) AT WHICH INTERACTION FACTORS ARE TO BE COMPUTED OR INPUT ***NOTE:*** *THESE CAN BE CHOSEN ARBITRARILY, BUT TYPICALLY VALUES OF 2,4,7,10,15,20,AND 30 ARE USEFUL.* *FOR SPACINGS GREATER THAN THE LAST-INPUT VALUE, THE INTERACTION FACTORS ARE ASSUMED TO BE ZERO.*
9	INPAL	CODE FOR INTERACTION FACTOR CALCULATION 0 IF VALUES ARE TO BE COMPUTED BY PROGRAM 1 IF VALUES ARE TO BE INPUT 2 IF VALUES ARE TO BE COMPUTED VIA RANDOLPHS APPROX. EQUATIONS 3 IF VALUES ARE TO BE CALCULATED BY PROGRAM, MAKING ALLOWANCES FOR DIFFERENCES IN THE NEAR-PILE AND MASS SOIL MODULI (FOR BOTH AXIAL & LATERAL RESPONSE).

NOTE: *THE USE OF INPAL=2 IS ONLY APPROPRIATE FOR A A UNIFORM OR LINEARLY VARYING SOIL PROFILE*

RECORD 10 ONLY FOR INPAL = 3 IN RECORD 9

10	UMU	RATIO OF MASS MODULUS TO NEAR-PILE SOIL MODULUS, FOR AXIAL LOADING
	UMUL	RATIO OF MASS MODULUS TO NEAR-PILE SOIL MODULUS, FOR LATERAL LOADING
	STRANS	TRANSITION DISTANCE st, DIVIDED BY DIAMETER, OVER WHICH THE MODULUS CHANGES FROM THE NEAR-PILE TO THE MASS VALUE

NOTE: *TYPICALLY, STRANS IS BETWEEN 3 AND 5.*

11	INLAL	CODE FOR LATERAL INTERACTION FACTORS 0 IF FACTORS CALCULATED BY PROGRAM 1 IF FACTORS ARE TO BE INPUT 2 IF FACTORS ARE COMPUTED FROM RANDOLPHS EQUATIONS

12	NPTYPS	NO. OF DIFFERENT PILE TYPES (MAXIMUM = 20)

13	PLEN	LENGTH OF PILE SHAFT
	DA	PILE SHAFT DIAMETER
	DB	PILE BASE DIAMETER
	NC	NO. OF ANNULAR ELEMENTS FOR PILE CAP (SPECIFY 0 IF IPLRAF = 0 IN RECORD 3
	NS	NO. OF SHAFT ELEMENTS FOR AXIAL RESPONSE ANALYSIS
	NB	NO. OF BASE ELEMENTS
	NEL	NO. OF SHAFT ELEMENTS FOR LATERAL RESPONSE

NOTE: *NS+NC+NB CANNOT EXCEED 51;*
NEL = 150 MAXIMUM

14	EP	YOUNGS MODULUS OF PILE MATERIAL
	PMI	MOMENT OF INERTIA OF PILE SECTION
	TMI	TORSIONAL MOMENT OF INERTIA OF PILE SECTION
	RA	AREA RATIO OF PILE SECTION (RATIO OF X-SECTIONAL AREA TO GROSS X-SECTIONAL AREA

15	ULTMOM	ULTIMATE MOMENT CAPACITY OF PILE SECTION
	CSS	STRUCTURAL STRENGTH OF PILE MATERIAL IN COMPRESSION
	TSS	STRUCTURAL STRENGTH OF PILE MATERIAL IN TENSION

16	IHYP	CODE FOR HYPERBOLIC AXIAL RESPONSE 1 IF HYPERBOLIC MODEL TO BE USEDTO BE USED 0 IF CONVENTIONAL APPROACH TO BE USED

RECORD 17 ONLY OF IHYP=1 IN RECORD 16

17	RFP	HYPERBOLIC FACTOR FOR PILE LOAD-SETTLEMENT CURVE
	GFAC	g FACTOR FOR HYPERBOLIC LOAD-SETTLEMENT CURVE ***NOTE:*** USUALLY, CAN ADOPT RFP=0.5-0.9, GFAC=0.3-1.0 CLASSIC HYPERBOLA REQUIRES GFAC=1.0

18	UNISOL	CODE FOR SOIL DATA INPUT TYPE 0 FOR GENERAL NON-HOMOGENEOUS SOIL - PROPERTIES

		INPUT ELEMENT BY ELEMENT 1 FOR SOIL HOMOGENEOUS WITH DEPTH 2 FOR SOIL WHOSE MODULUS AND STRENGTH VARY LINEARLY WITH DEPTH 3 FOR LAYERED SOIL INPUT

19	PR	POISSONS RATIO OF SOIL (ASSUMED CONSTANT)
	PRPILE	POISSONS RATIO OF PILE (ASSUMED CONSTANT)

RECORDS 20 TO 23 ONLY FOR UNISOL =0 (NON-HOMOGS. SOIL)

20	ES(I)	(NC+NS+NB) VALUES OF SOIL MODULUS, FOR AXIAL RESPONSE. START WITH CAP ELEMENTS, THEN SHAFT ELEMENTS, THEN BASE ELEMENTS

21	ESH(I)	(NEL+1) VALUES OF SOIL MODULUS FOR LATERAL RESPONSE

22	TA(I)	LIMITING PILE-SOIL PRESSURE FOR AXIAL RESPONSE (COMPRN). START WITH CAP ELEMNTS, THEN SHAFT, THEN BASE. A TOTAL OF NC+NS+NB VALUES

23	PY(I)	LIMITING LATERAL PILE-SOIL PRESSURES. BEGIN WITH TOP ELEMENT. A TOTAL OF NEL+1 VALUES

RECORDS 24 & 25 ONLY FOR UNISOL =1 (UNIFORM SOIL)

24	ESR	UNIFORM YOUNGS MODULUS FOR AXIAL RESPONSE
	ESH	UNIFORM YOUNGS MODULUS FOR LATERAL RESPONSE

25	TAUN	UNIFORM VALUE OF LIMITING VERTICAL PILE-SOIL STRESS FOR SHAFT ELEMENTS
	TAB	UNIFORM VALUE OF LIMITING VERTICAL PILE-SOIL STRESS FOR BASE ELEMENTS
	TAUC	UNIFORM VALUE OF LIMITING VERTICAL PILE-SOIL STRESS FOR CAP ELEMENTS
	PYUN	UNIFORM VALUE OF LIMITING LATERAL PILE-SOIL STRESS FOR LATERAL SHAFT ELEMENTS

RECORDS 26 & 27 ONLY FOR UNISOL =2 (LINEARLY VAR. SOIL)

26	ESO	YOUNGS MODULUS AT SOIL SURFACE, FOR AXIAL RESPONSE
	ESL	YOUNGS MODULUS AT PILE TIP LEVEL, FOR AXIAL RESPONSE
	EHO	YOUNGS MODULUS AT SOIL SURFACE, FOR LATERAL RESPONSE
	EHL	YOUNGS MODULUS AT PILE TIP LEVEL, FOR LATERAL RESPONSE

27	TAO	LIMITING AXIAL PILE SHAFT-SOIL STRESS AT SOIL SURFACE
	TAL	LIMITING AXIAL PILE SHAFT-SOIL STRESS AT LEVEL OF PILE TIP
	TAB	LIMITING AXIAL PILE-SOIL STRESS FOR BASE ELEMENTS
	TAUC	LIMITING AXIAL PILE-SOIL STRESS FOR CAP ELEMENTS
	PYO	LIMITING LATERAL PILE-SOIL STRESS AT SOIL SURFACE
	PYL	LIMITING LATERAL PILE-SOIL STRESS AT LEVEL OF PILE TIP

RECORD 28 ONLY FOR UNISOL = 0,1, OR 2

28	EBASE	YOUNGS MODULUS OF MATERIAL UNDERLYING SOIL LAYER(S)
	H	TOTAL THICKNESS OF SOIL LAYER(S)

RECORDS 29 TO 33 ONLY FOR UNISOL =3 (LAYERED PROFILE)

29	NLAY	NO. OF SOIL LAYERS ALONG PILE SHAFT
	NLB	NO. OF SOIL LAYERS BELOW PILE TIP
	RZINF	DEPTH OF INFLUENCE OF PILE TIP, RELATIVE TO TIP DIAMETER

NOTE: *TYPICALLY, A VALUE OF RZINF OF BETWEEN 2 AND 4 IS REASONABLE, DEPENDING ON THE LAYERING OF THE SOIL*

RECORD 30 ONLY IF NC >0

30	ESCAP	YOUNGS MODULUS FOR PILE CAP ELEMS, FOR AXIAL RESPONSE
	TACAP	ULTIMATE BEARING CAPACITY FOR PILE CAP ELEMENTS

31	HLS(NL)	THICKNESS OF LAYER NL ALONG PILE SHAFT
	ESAX(NL)	YOUNGS MODULUS OF LAYER NL, FOR AXIAL RESPONSE
	ESLAT(NL)	YOUNGS MODULUS OF LAYER NL, FOR LATERAL RESPONSE
	SF(NL)	ULTIMATE SKIN FRICTION FOR LAYER NL
	ULP(NL)	ULT. LATERAL PILE-SOIL PRESSURE FOR LAYER NL

REPEAT RECORD 31 TO GIVE TOTAL OF NLAY SETS

32	HL(LB)	THICKNESS OF LAYER LB, BELOW PILE TIP
	EBL(LB)	YOUINGS MODULUS OF LAYER LB (AXIAL RESPONSE)
	PRL(LB)	POISSONS RATIO OF LAYER LB
	FBL(LB)	ULTIMATE PILE TIP BEARING CAPACITY FOR LAYER LB
		REPEAT RECORD 32 TO GIVE TOTAL OF NLB SETS

RECORD 33 ONLY FOR UNISOL=3

33	EBASE	YOUNGS MODULUS OF MATERIAL UNDERLYING SOIL PROFILE

34	FSUP	RATIO OF LIMITING SKIN FRICTION FOR TENSION TO VALUE FOR COMPRESSION (SAME FOR ALL ELEMENTS)
	FBUP	RATIO OF LIMITING END BEARING FOR TENSION TO VALUE FOR COMPRESSION (SAME FOR ALL ELEMENTS)
	FCUP	RATIO OF CAP BEARING CAPACITY FOR TENSION TO VALUE FOR COMPRESSION (SAME FOR ALL ELEMENTS)

RECORD 35 ONLY FOR INPAL = 1 IN RECORD 9

35	AAP(I)	AXIAL INTERACTION FACTORS AT THE RELATIVE SPACINGS IN RECORD 8. *A TOTAL OF NSPS VALUES.*

RECORD 36 ONLY FOR INLAL=1 IN RECORD 9

36	ARH(1,I)	LATERAL INTERACTION FACTOR FOR DEFLECTION DUE TO LATERAL LOAD, FOR A DEPARTURE ANGLE OF 0 DEGREES
	ARH(2,1)	LATERAL INTERACTION FACTOR FOR DEFLECTION DUE TO LATERAL LOAD, FOR A DEPARTURE ANGLE OF 90 DEGREES
	ARM(1,I)	LATERAL INTERACTION FACTOR FOR DEFLECTION DUE TO MOMENT, FOR A DEPARTURE ANGLE OF 0 DEGREES
	ARM(2,I)	LATERAL INTERACTION FACTOR FOR DEFLECTION DUE TO MOMENT, FOR A DEPARTURE ANGLE OF 90 DEGREES
	ATHM(1,I)	LATERAL INTERACTION FACTOR FOR ROTATION DUE TO MOMENT, FOR A DEPARTURE ANGLE OF 0 DEGREES
	ATHM(2,I)	LATERAL INTERACTION FACTOR FOR ROTATION DUE TO MOMENT, FOR A DEPARTURE ANGLE OF 90 DEGREES
		REPEAT RECORD 36 TO GIVE A TOTAL OF NSPS SETS, ONE FOR

		EACH RELATIVE SPACING SPECIFIED IN RECORD 8
		REPEAT RECORDS 13-36 TO GIVE A TOTAL OF NPTYP SETS
37	KONFS	NO. OF PILE GROUP CONFIGURATIONS TO BE ANALYZED
38	JTYPE	CODE FOR TYPE OF GROUP 1 FOR SYMMETRICAL RECTANGULAR CONFIGURATION 2 FOR ANY OTHER TYPE OF CONFIGURATION
		RECORDS 39-43 ONLY FOR JTYPE = 1 IN RECORD 38
39	M	NO. OF ROWS OF PILES IN X-DIRECTION
	N	NO. OF ROWS OF PILES IN Y-DIRECTION
	SX	PILE SPACING (C/C) IN X-DIRECTION
	SY	PILE SPACING (C/C) IN Y-DIRECTION
	IBATT	CODE FOR BATTERED PILES 0 FOR ALL VERTICAL PILES 1 IF GROUP CONTAINS BATTERED PILES
	IBOPT	CODE FOR BATTERED PILE FORMULATION 0 FOR POULOS & MADHAV (1971) 1 FOR POULOS (1974)
	ISAME	1 IF ALL PILES IN GROUP ARE SAME TYPE 0 IF HAVE VARIOUS PILE TYPES IN GROUP
		NOTE 1: *IT IS USUALLY PREFERABLE TO ADOPT IBOPT=0, BUT THIS MAY BE CONSERVATIVE FOR GROUPS WITH PILES BATTERED IN OPPOSITE DIRECTIONS* ***NOTE 2:*** *MAXIMUM VALUE OF M*N IS 200*
		RECORDS 40 & 41 ONLY FOR IBATT=1 IN RECORD 39
40	PSID(I)	BATTER ANGLE OF EACH PILE IN THE GROUP (WITH RESPECT TO THE VERTICAL) - BATTER IS POSITIVE IN THE DIRECTION OF APPLIED LATERAL LOAD (X-DIRECTION) ***A TOTAL OF (M*N) VALUES TO BE INPUT.***
41	PSIDY(I)	BATTER ANGLE OF EACH PILE IN THE GROUP (WITH RESPECT TO THE VERTICAL) - BATTER IS POSITIVE IN THE DIRECTION OF APPLIED LATERAL LOAD (Y-DIRECTION) ***A TOTAL OF (M*N) VALUES TO BE INPUT.***
		RECORD 41 ONLY FOR ISAME=1 IN RECORD 39
42	LPT	PILE TYPE FOR ALL PILES IN GROUP
		RECORD 42 ONLY FOR ISAME=0 IN RECORD 39
43	KPT(I)	PILE TYPE FOR EACH PILE IN GROUP, IN TURN - A TOTAL OF M*N INTEGER VALUES
		RECORDS 44 TO 46 ONLY FOR JTYPE=2 IN RECORD 38
44	NOP	NO. OF PILES IN GROUP (MAXIMUM 200)
45	EX(I)	X-COORDINATE OF PILE I (STARTING WITH PILE 1)
	Y(I)	Y-COORDINATE OF PILE I
	PSID(I)	BATTER ANGLE OF PILE I IN X-DIRECTION (SEE RECORD 35 FOR SIGN CONVENTION)

	PSID(I)	BATTER ANGLE OF PILE I IN Y-DIRECTION (SEE RECORD 36 FOR SIGN CONVENTION)
		A TOTAL OF NOP SETS OF DATA, ONE FOR EACH PILE IN TURN

46	XAP	X-COORDINATE OF APPLIED VERTICAL LOAD (IF A SINGLE LOAD IS TO BE INPUT)
	YAP	Y-COORDINATE OF APPLIED VERTICAL LOAD (IF A SINGLE LOAD IS TO BE INPUT)
	IBOPT	OPTION FOR BATTERED PILE FORMULATION (SEE RECORD 33)

47	EFFAX	GROUP EFFICIENCY FACTOR FOR ULTIMATE AXIAL CAPACITY
	EFFLAT	GROUP EFFICIENCY FACTOR FOR ULTIMATE LATERAL CAPACITY

48	NDAMP	NO. OF DAMAGED OR DEFECTIVE PILES IN GROUP

RECORD 49 ONLY IF NDAMP>0 IN RECORD 48

49	K	NUMBER OF THE DEFECTIVE PILE
	PCC(K)	RATIO OF COMPRESSIVE AXIAL CAPACITY OF DEFECTIVE PILE TO NORMAL PILE
	PTC(K)	RATIO OF UPLIFT AXIAL CAPACITY OF DEFECTIVE PILE TO NORMAL PILE
	POF(K)	RATIO OF AXIAL PILE HEAD STIFFNESS OF DEFECTIVE PILE TO NORMAL PILE
	POFL(K)	RATIO OF LATERAL PILE HEAD STIFFNESS OF DEFECTIVE PILE TO NORMAL PILE
	POFT(K)	RATIO OF TORSIONAL PILE HEAD STIFFNESS OF DEFECTIVE PILE TO NORMAL PILE
	PUM(K)	RATIO OF ULTIMATE MOMENT OF DEFECTIVE PILE TO NORMAL PILE
	PUL(K)	RATIO OF ULTIMATE LATERAL LOAD OF DEFECTIVE PILE TO NORMAL PILE
	CSRED(K)	RATIO OF STRUCTURAL COMPRESSIVE STRENGTH OF DEFECTIVE PILE TO NORMAL PILE
	TSRED(K)	RATIO OF STRUCTURAL TENSILE STRENGTH OF DEFECTIVE PILE TO NORMAL PILE
		REPEAT RECORD 49 FOR ALL NDAMP DEFECTIVE PILES

50	LDGS	NUMBER OF APPLIED LOAD SETS TO BE ANALYSED

51	JPIN	CODE FOR PILE HEAD CONDITION AND LOADING TYPE 0 IF PILES ARE RIGIDLY ATTACHED TO CAP, BUT CAP IS FREE TO ROTATE. LOADS APPLIED TO PILE CAP. 1 IF PILES PINNED TO CAP, AND LOADS APPLIED TO CAP 2 IF PILES FIXED IN MASIVE CAP WHICH CANNOT ROTATE, AND LOADS APPLIED TO CAP. 3 IF INDIVIDUAL PILE HEAD DEFLECTIONS AND ROTATIONS ARE TO BE INPUT, AND THE LOADS AND MOMENTS CALCULATED 4 IF INDIVIDUAL PILE HEAD LOADS AND MOMENTS ARE INPUT, AND DEFLECTIONS AND ROTATIONS ARE TO BE COMPUTED.
	JMULT	CODE FOR MULTIPLE APPLIED LOADINGS 0 IF ONLY SINGLE LOADS TO BE APPLIED

		1 IF MULTIPLE LOADINGS ARE TO BE INPUT 2 IF LOAD COMPONENTS ARE TO BE INPUT AT VARIOUS LOCATIONS & LOAD FACTORS ARE TO BE INPUT
	NITS	NO. OF INCREMENTS IN WHICH LOAD SET TO BE APPLIED NOTE: SINCE THE ANALYSIS IS NON-LINEAR, NITS SHOULD BE RELATIVELY LARGE, eg 10 MINIMUM
52	LDTITLE	DESCRIPTION OF LOAD CASE BEING ANALYSED
		RECORDS 53A-E FOR JPIN = 0, 1 OR 2 & JMULT=O IN RECORD 51
53A	V	APPLIIED VERTICAL LOAD ON GROUP
	HLOAD	APPLIED HORIZONTAL LOAD ON GROUP (IN X-DIRECTION)
	AMOM	APPLIED MOMENT ON GROUP (IN X-DIRECTION)
	HLOADY	APPLIED HORIZONTAL LOAD ON GROUP (IN Y-DIRECTION)
	AMOMY	APPLIED MOMENT ON GROUP (IN Y-DIRECTION)
	TORSLD	APPLIED TORSIONAL MOMENT ON GROUP
53B	XAP	X-COORDINATE OF APPLIED VERTICAL LOAD
	YAP	Y-COORDINATE OF APPLIED VERTICAL LOAD
53C	XHXL	X-COORDINATE OF APPLIED HORIZL. X- LOAD
	YHXL	Y-COORDINATE OF APPLIED HORIZL. X- LOAD
53D	XHYL	X-COORDINATE OF APPLIED HORIZL. Y- LOAD
	YHYL	Y-COORDINATE OF APPLIED HORIZL. Y- LOAD
53E	XAT	X-COORDINATE OF APPLIED TORSION
	YAT	Y-COORDINATE OF APPLIED TORSION
		RECORDS 54 TO 59 FOR JPIN =3 ONLY
54	ROV(I)	VERTICAL DISPLACEMENT AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
55	ROH(I)	X-HORIZONTAL DISPLACEMENT AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
56	THET(I)	X-ROTATION AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
57	ROHY(I)	Y-HORIZONTAL DISPLACEMENT AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
58	THETY(I)	Y-ROTATION AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
59	TORSTH(I)	TORSIONAL ROTATION AT EACH PILE HEAD (IN TURN) ***ONE VALUE FOR EACH PILE.***
		RECORDS 60 TO 65 FOR JPIN =4 ONLY
60	VLD(I)	VERTICAL LOAD AT HEAD OF EACH PILE (IN TURN).

		ONE VALUE FOR EACH PILE.
61	HORLD(I)	X-HORIZONTAL LOAD AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
62	AMLOAD(I)	X-MOMENT AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
63	HORLDY(I)	Y-HORIZONTAL LOAD AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
64	AMLOADY(I)	Y-MOMENT AT HEAD OF EACH PILE (IN TURN). ***ONE VALUE FOR EACH PILE.***
65	TORS(I)	TORSIONAL MOMENT AT HEAD OF EACH PILE (IN TURN) ***ONE VALUE FOR EACH PILE.***

RECORDS 66-72 ONLY FOR JPIN=0,1,OR 2 & JMULT=1 IN REC. 51

66	NGV	NUMBER OF VERTICAL LOADS TO BE INPUT
	NHX	NUMBER OF HORIZONTAL LOADS IN X-DIRECTION
	NMX	NUMBER OF APPLIED MOMENTS IN X-DIRECTION
	NHY	NUMBER OF APPLIED LOADINGS IN X-DIRECTION
	NMY	NUMBER OF APPLIED MOMENTS IN Y-DIRECTION
	NTORS	NUMBER OF TORSIONAL LOADS

RECORD 67 ONLY IF NGV>0 IN RECORD 66

67	GLD(NLS)	MAGNITUDE OF VERTICAL LOAD
	XLD(NLS)	X-COORD OF VERTICAL LOAD
	YLD(NLS)	Y-COORD OF VERTICAL LOAD
		REPEAT RECORD 67 TO GIVE NGV SETS

RECORD 68 ONLY IF NHX>0 IN RECORD 66

68	GHX(NLS)	MAGNITUDE OF HORIZONTAL LOAD IN X-DIRECTION (INPUT NHX VALUES)
	XHX(NLS)	X-COORD OF HORIZL. X-LOAD
	YHX(NLS)	Y-COORD OF HORIZL. X-LOAD

RECORD 69 ONLY IF NMX>0 IN RECORD 66

69	GMX(NLS)	MAGNITUDE OF HORIZONTAL LOAD IN Y-DIRECTION (INPUT NMX VALUES)

RECORD 70 ONLY IF NHY>0 IN RECORD 66

70	GHY(NLS)	MAGNITUDE OF APPLIED MOMENT IN X-DIRECTION (INPUT NHY VALUES)
	XHY(NLS)	X-COORD OF HORIZL. Y-LOAD
	YHY(NLS)	Y-COORD OF HORIZL. Y-LOAD

RECORD 71 ONLY IF NMY>0 IN RECORD 66

71	GMY(NLS)	MAGNITUDE OF APPLIED MOMENT IN Y-DIRECTION (INPUT NMY VALUES)

RECORDS 72 & 72A ONLY IF NTORS>0 IN RECORD 66

72	GTORS(NLS)	MAGNITUDE OF APPLIED TORSIONAL LOADINGS (INPUT NTORS VALUES)

72A	XAT	X-COORD OF CENTRE OF TORSION
	YAT	Y-COORD OF CENTRE OF TORSION
		NOTE: THE CHOICE OF THESE COORDINATES IS ARBITRARY

RECORDS 73-81 ONLY IF JPIN=0,1 OR 2 AND JMULT=2 IN REC 51

73	NCOLS	NO. OF LOAD LOCATIONS
	NLF	NO. OF SETS OF LOAD FACTORS

74	IDCOL(I)	IDENTIFICATION FOR LOAD LOCATION OR COLUMN (MAXIMUM 10 CHARACTERS)

75	XLD(I)	X-COORDINATE OF LOAD OR COLUMN
	YLD(I)	XY-COORDINATE OF LOAD OR COLUMN

76	VDL(I)	VERTICAL LOAD AT LOCATION DUE TO DEAD LOAD
	HXDL(I)	X-HORIZL. LOAD AT LOCATION DUE TO DEAD LOAD
	AMXDL(I)	X-MOMENT AT LOCATION DUE TO DEAD LOAD
	HYDL(I)	Y-HORIZONTAL LOAD AT LOCATION DUE TO DEAD LOAD
	AMYDL(I)	Y-MOMENT AT LOCATION DUE TO DEAD LOAD
	TORDL(I)	TORSION AT LOCATION DUE TO DEAD LOAD

77	VLL(I)	VERTICAL LOAD AT LOCATION DUE TO LIVE LOAD
	HXLL(I)	X-HORIZL. LOAD AT LOCATION DUE TO LIVE LOAD
	AMXLL(I)	X-MOMENT AT LOCATION DUE TO LIVE LOAD
	HYLL(I)	Y-HORIZONTAL LOAD AT LOCATION DUE TO LIVE LOAD
	AMYLL(I)	Y-MOMENT AT LOCATION DUE TO LIVE LOAD
	TORLL(I)	TORSION AT LOCATION DUE TO LIVE LOAD

78	VWL(I)	VERTICAL LOAD AT LOCATION DUE TO WIND LOAD
	HXWL(I)	X-HORIZL. LOAD AT LOCATION DUE TO WIND LOAD
	AMXWL(I)	X-MOMENT AT LOCATION DUE TO WIND LOAD
	HYWL(I)	Y-HORIZONTAL LOAD AT LOCATION DUE TO WIND LOAD
	AMYWL(I)	Y-MOMENT AT LOCATION DUE TO WIND LOAD
	TORWL(I)	TORSION AT LOCATION DUE TO WIND LOAD

79	VEQ(I)	VERTICAL LOAD AT LOCATION DUE TO E-Q LOAD
	HXEQ(I)	X-HORIZL. LOAD AT LOCATION DUE TO E-Q LOAD
	AMXEQ(I)	X-MOMENT AT LOCATION DUE TO E-Q LOAD
	HYEQ(I)	Y-HORIZONTAL LOAD AT LOCATION DUE TO E-Q LOAD
	AMYEQ(I)	Y-MOMENT AT LOCATION DUE TO E-Q LOAD

	TOREQ(I)	TORSION AT LOCATION DUE TO E-Q LOAD

80	VOTH(I)	VERTICAL LOAD AT LOCATION DUE TO OTHER LOADS
	HXOTH(I)	X-HORIZL. LOAD AT LOCATION DUE TO OTHER LOADS
	AMXOTH(I)	X-MOMENT AT LOCATION DUE TO OTHER LOADS
	HYOTH(I)	Y-HORIZONTAL LOAD AT LOCATION DUE TO OTHER LOADS
	AMYOTH(I)	Y-MOMENT AT LOCATION DUE TO OTHER LOADS
	TOROTH(I)	TORSION AT LOCATION DUE TO OTHER LOADS

REPEAT RECORDS 73-80 TO GIVE TOTAL OF NCOLS SETS (REC 73)

81	LFC	LOAD COMBINATION NUMBER
	FACDL	LOAD FACTOR FOR DEAD LOADS
	FACLL	LOAD FACTOR FOR LIVE LOADS
	FACWL	LOAD FACTOR FOR WIND LOADS
	FACEQ	LOAD FACTOR FOR E-Q LOADS
	FACOTH	LOAD FACTOR FOR OTHER LOADS

82	INDEFS	CODE FOR INPUT OF SINGLE PILE UNIT RESPONSES 0 FOR VALUES TO BE CALC, OR =1 FOR INPUT VALUES *NOTE: USE INDEFS = 0*
	NAXPRT	CODE FOR AXIAL RESPONSE DETAILS REQUIRED, = 1 IF DETAILS REQUIRED TO BE PRINTED, OTHERWISE 0
	NLATPR	CODE FOR LATERALAL RESPONSE DETAILS REQUIRED, = 1 IF DETAILS REQUIRED TO BE PRINTED, OTHERWISE 0

RECORD 83 ONLY IF NAXPRT>0 IN RECORD 82

83	NPLS	NUMBER OF PILES FOR WHICH AXIAL RESPONSE DETAILS ARE TO BE COMPUTED AND OUTPUT.

RECORD 84 ONLY IF NAXPRT>0 IN RECORD 82

84	MP(I)	PILE NUMBERS FOR WHICH AXIAL RESPONSE DETAILS ARE TO BE COMPUTED AND OUTPUT. ***A TOTAL OF NPLS VALUES.***

RECORD 85 ONLY IF NLATPR>0 IN RECORD 82

85	NPLS	NUMBER OF PILES FOR WHICH LATERAL RESPONSE DETAILS ARE BE COMPUTED AND OUTPUT.

RECORD 86 ONLY IF NLATPR>0 IN RECORD 82

86	MP(I)	PILE NUMBERS FOR WHICH LATERAL RESPONSE DETAILS ARE TO COMPUTED AND OUTPUT. ***A TOTAL OF NLATPR VALUES.***

**REPEAT RECORDS 74-86 TO GIVE A TOTAL OF NLF SETS (REC. 73)
(ONLY 1 SET IF JMULT = 0 OR 1)**

**REPEAT RECORDS 51-86 TO GIVE A TOTAL OF LDGS SETS
(LDGS IN RECORD 50)**

**REPEAT RECORDS 38-86 TO GIVE A TOTAL OF KONFS SETS
(KONFS IN RECORD 37)**

REPEAT RECORDS 2-86 TO GIVE KAS SETS (KAS IN RECORD 1)

APPENDIX C

TYPICAL INPUT FILE FOR CLAP (Version 6.2Q4)

```
1
TEST CASE 9. CLAP6.2Q4. PIGLET COMPN. DIFF PILES. BASE CASE-PILE 3 d=0.5. 28/1/09
0,0,0.0
1,1
1.0,1.0,1.0,1.0
1.0
6
2.0,4.0,7.0,10.0,15.0,20.0
0
0
2
20.0,1.0,1.0,0,20,1,40
30000.0,0.04909,0.09818,1.0
100.0,100.0,100.0
0
3
0.3,0.3
1,1,5.0
20.0,20.0,20.0,10.0,10.0
100.0,100.0,0.3,100.0
100.0
1.0,1.0,1.0
20.0,0.5,0.5,0,20,1,40
30000.0,0.00307,0.00614,1.0
100.0,100.0,100.0
0
3
0.3,0.3
1,1,5.0
20.0,20.0,20.0,10.0,10.0
100.0,100.0,0.3,100.0
100.0
1.0,1.0,1.0
1
1
3,2,2.0,2.0,0,0,0
1,1,2,1,1,1
1.0,1.0
0
1
0,0,1
VERTICAL LOADING
9.0,0.0,0.0,0.0,0.0,0.0
2.0,1.0
2.0,1.0
2.0,1.0
2.0,1.0
0,0,2
2
3,6
```

APPENDIX D

TYPICAL OUTPUT FILE FOR
CLAP (Version 6.2Q4)

```
================================================================================


                       Coffey Geotechnics Australia

                             500 pile version
                   151 axial elements  150 lateral elements


                           P R O G R A M    C L A P

                       COMBINED LOADING ANALYSIS OF PILES

                           REV:6.2Q4     DATE 28/01/2009




================================================================================

                              FILE INFORMATION


                         Input file name is CASE9-Q.TXT


                         Output file name is CASE9-Q.OUT


================================================================================


  TEST CASE 9. CLAP6.2Q4. PIGLET COMPN. DIFF PILES. BASE CASE-PILE 3 d=0.5. 28/1/0


================================================================================


                     FREE STANDING PILE GROUP


 FREE HEAD

 PINNED TIP

--------------------------------------------------------------------------------
                    GEOTECHNICAL REDUCTION FACTORS ARE :

                     SHAFT   =      1.000
                     BASE    =      1.000
                     CAP     =      1.000
                     LATERAL =      1.000

          STRUCTURAL REDUCTION FACTOR  =      1.000
================================================================================



================================================================================
                    DETAILS FOR PILE TYPE    1
================================================================================



 LENGTH         =   20.000
 DIAMETER       =    1.000
```

```
 CAP DIAMETER   =    0.000
 BASE DIAMETER  =    1.000
 POISSONS RATIO =    0.300


 NO. OF SIDE ELS =   20
 NO. OF CAP ELS  =    0
 NO. OF BASE ELS =    1

 NO. OF ELS FOR LATERAL RESPONSE =   40


 PILE MODULUS =    30000.00000

 AREA RATIO =  1.0000

 EI OF PILE = 1.472700E+03



================================================================================
                              SOIL DETAILS
================================================================================



          DETAILS OF SOIL LAYERS ALONG PILE SHAFT
          ---------------------------------------

  NO       THICKNESS     ESAXIAL        ESLATL      ULT fs         ULT LAT PRESS

    1      20.00000      20.00000      20.00000      10.00000      10.00000

          DETAILS OF LAYERS BELOW PILE TIP
          --------------------------------

LAYER NO.  THICKNESS      MODULUS       POISS.RAT   ULT.PRESS.

   1      100.00000      100.00000       0.300     100.00000
               DEPTH OF INFL FOR END BRG =     5.0000

               EQUIVALENT END BEARING FOR BASE =    100.00000



 BASE MODULUS =      100.00000

 DEPTH OF SOIL =       120.0000



                    ORIGINAL DEFPIG AXIAL FORMULATION



                DESIGN VALUES OF GEOTECH. ULTIMATE PILE LOADS:

                     COMPRESSION =   706.85837
                     UPLIFT      =  -706.85837
                     TORSION     =   628.31855
                     LATERAL     =    45.00000


                DESIGN VALUES OF STRUCTL. ULTIMATE PILE LOADS:


                     MOMENT       =    100.00000
                     COMPRESSIVE  =     78.53982
                     TENSILE      =    -78.53982



                       UPLIFT REDUCTION FACTORS
```

```
                    SHAFT =      1.00000
                     BASE =      1.00000
                      CAP =      1.00000


================================================================================


        SOIL PROPERTY DETAILS, FOR SINGLE PILE


--------------------------------------------------------------------------------


                         AXIAL RESPONSE



  ELEMENT     SOIL MODULUS    LIMITING STRESS

     1          20.0000000        10.000000
     2          20.0000000        10.000000
     3          20.0000000        10.000000
     4          20.0000000        10.000000
     5          20.0000000        10.000000
     6          20.0000000        10.000000
     7          20.0000000        10.000000
     8          20.0000000        10.000000
     9          20.0000000        10.000000
    10          20.0000000        10.000000
    11          20.0000000        10.000000
    12          20.0000000        10.000000
    13          20.0000000        10.000000
    14          20.0000000        10.000000
    15          20.0000000        10.000000
    16          20.0000000        10.000000
    17          20.0000000        10.000000
    18          20.0000000        10.000000
    19          20.0000000        10.000000
    20          20.0000000        10.000000
    21         100.0000000       100.000000

          ++++++++++++++++++++++++++++++++++++++++++++++++++

                         LATERAL RESPONSE



  ELEMENT     SOIL MODULUS    LIMITING STRESS

     1          20.0000000        10.000000
     2          20.0000000        10.000000
     3          20.0000000        10.000000
     4          20.0000000        10.000000
     5          20.0000000        10.000000
     6          20.0000000        10.000000
     7          20.0000000        10.000000
     8          20.0000000        10.000000
     9          20.0000000        10.000000
    10          20.0000000        10.000000
    11          20.0000000        10.000000
    12          20.0000000        10.000000
    13          20.0000000        10.000000
    14          20.0000000        10.000000
    15          20.0000000        10.000000
    16          20.0000000        10.000000
    17          20.0000000        10.000000
    18          20.0000000        10.000000
    19          20.0000000        10.000000
    20          20.0000000        10.000000
    21          20.0000000        10.000000
    22          20.0000000        10.000000
    23          20.0000000        10.000000
    24          20.0000000        10.000000
    25          20.0000000        10.000000
    26          20.0000000        10.000000
    27          20.0000000        10.000000
    28          20.0000000        10.000000
    29          20.0000000        10.000000
    30          20.0000000        10.000000
    31          20.0000000        10.000000
    32          20.0000000        10.000000
    33          20.0000000        10.000000
    34          20.0000000        10.000000
```

```
    35          20.0000000        10.000000
    36          20.0000000        10.000000
    37          20.0000000        10.000000
    38          20.0000000        10.000000
    39          20.0000000        10.000000
    40          20.0000000        10.000000
    41          20.0000000        10.000000


================================================================================



          SCALED VERTICAL SOIL MODULUS VALUES

   ELEMENT      MODULUS

      1       20.00000
      2       20.00000
      3       20.00000
      4       20.00000
      5       20.00000
      6       20.00000
      7       20.00000
      8       20.00000
      9       20.00000
     10       20.00000
     11       20.00000
     12       20.00000
     13       20.00000
     14       20.00000
     15       20.00000
     16       20.00000
     17       21.73913
     18       25.21739
     19       32.17391
     20       46.08696
     21      100.00000

          SCALED LATERAL SOIL MODULUS VALUES

   ELEMENT      MODULUS

      1       20.00000
      2       20.00000
      3       20.00000
      4       20.00000
      5       20.00000
      6       20.00000
      7       20.00000
      8       20.00000
      9       20.00000
     10       20.00000
     11       20.00000
     12       20.00000
     13       20.00000
     14       20.00000
     15       20.00000
     16       20.00000
     17       20.00000
     18       20.00000
     19       20.00000
     20       20.00000
     21       20.00000
     22       20.00000
     23       20.00000
     24       20.00000
     25       20.00000
     26       20.00000
     27       20.00000
     28       20.00000
     29       20.00000
     30       20.00000
     31       20.00000
     32       20.00000
     33       20.00000
     34       20.00000
     35       20.00000
     36       20.00000
     37       20.00000
     38       20.00000
     39       20.00000
     40       20.00000
     41       20.00000

================================================================================
```

```
                            INTERACTION FACTORS



                ****************************************

                 CALCULATED AXIAL   INTERACTION FACTORS

                 CALCULATED LATERAL INTERACTION FACTORS

                ****************************************

     S/D      AA   ARH(B=0) ARH(B=90) ARM(B=0) ARM(B=90) ATHM(B=0) ATHM(B=90)

    2.000    0.360    0.355    0.264    0.181    0.120    0.077    0.050
    4.000    0.269    0.225    0.153    0.091    0.052    0.034    0.019
    7.000    0.203    0.139    0.090    0.040    0.021    0.012    0.007
   10.000    0.164    0.097    0.062    0.020    0.011    0.005    0.003
   15.000    0.121    0.062    0.040    0.007    0.005    0.001    0.001
   20.000    0.093    0.045    0.029    0.003    0.003    0.000    0.001

               ELASTIC UNIT RESPONSES FOR PILE TYPE     1

RN1 =     0.002789  ROHH     0.022659  THH =    0.004972  ROM =     0.004985  THM =     0.002543



================================================================================
                    DETAILS FOR PILE TYPE    2
================================================================================



 LENGTH         =   20.000
 DIAMETER       =    0.500
 CAP DIAMETER   =    0.000
 BASE DIAMETER  =    0.500
 POISSONS RATIO =    0.300


 NO. OF SIDE ELS =   20
 NO. OF CAP ELS  =    0
 NO. OF BASE ELS =    1

 NO. OF ELS FOR LATERAL RESPONSE =   40


 PILE MODULUS =    30000.00000

 AREA RATIO =  1.0000

 EI OF PILE = 9.210000E+01




================================================================================
                              SOIL DETAILS
================================================================================



          DETAILS OF SOIL LAYERS ALONG PILE SHAFT
          ---------------------------------------

  NO       THICKNESS     ESAXIAL        ESLATL      ULT fs          ULT LAT PRESS

    1      20.00000      20.00000      20.00000      10.00000       10.00000

          DETAILS OF LAYERS BELOW PILE TIP
          --------------------------------
```

```
LAYER NO.  THICKNESS      MODULUS       POISS.RAT   ULT.PRESS.

   1      100.00000      100.00000       0.300     100.00000
               DEPTH OF INFL FOR END BRG =     2.5000


               EQUIVALENT END BEARING FOR BASE =    100.00000



 BASE MODULUS =      100.00000

 DEPTH OF SOIL =       120.0000



                    ORIGINAL DEFPIG AXIAL FORMULATION


                DESIGN VALUES OF GEOTECH. ULTIMATE PILE LOADS:

                     COMPRESSION =   333.79423
                     UPLIFT      =  -333.79423
                     TORSION     =   314.15927
                     LATERAL     =    12.50000



                DESIGN VALUES OF STRUCTL. ULTIMATE PILE LOADS:


                     MOMENT       =    100.00000
                     COMPRESSIVE  =     19.63495
                     TENSILE      =    -19.63495



                       UPLIFT REDUCTION FACTORS


                    SHAFT =      1.00000
                     BASE =      1.00000
                      CAP =      1.00000


================================================================================


        SOIL PROPERTY DETAILS, FOR SINGLE PILE


--------------------------------------------------------------------------------


                         AXIAL RESPONSE



  ELEMENT     SOIL MODULUS    LIMITING STRESS

     1          20.0000000        10.000000
     2          20.0000000        10.000000
     3          20.0000000        10.000000
     4          20.0000000        10.000000
     5          20.0000000        10.000000
     6          20.0000000        10.000000
     7          20.0000000        10.000000
     8          20.0000000        10.000000
     9          20.0000000        10.000000
    10          20.0000000        10.000000
    11          20.0000000        10.000000
    12          20.0000000        10.000000
    13          20.0000000        10.000000
    14          20.0000000        10.000000
    15          20.0000000        10.000000
    16          20.0000000        10.000000
    17          20.0000000        10.000000
    18          20.0000000        10.000000
    19          20.0000000        10.000000
```

```
    20          20.0000000        10.000000
    21         100.0000000       100.000000

          ++++++++++++++++++++++++++++++++++++++++++++++++++


                         LATERAL RESPONSE



  ELEMENT     SOIL MODULUS    LIMITING STRESS

     1          20.0000000        10.000000
     2          20.0000000        10.000000
     3          20.0000000        10.000000
     4          20.0000000        10.000000
     5          20.0000000        10.000000
     6          20.0000000        10.000000
     7          20.0000000        10.000000
     8          20.0000000        10.000000
     9          20.0000000        10.000000
    10          20.0000000        10.000000
    11          20.0000000        10.000000
    12          20.0000000        10.000000
    13          20.0000000        10.000000
    14          20.0000000        10.000000
    15          20.0000000        10.000000
    16          20.0000000        10.000000
    17          20.0000000        10.000000
    18          20.0000000        10.000000
    19          20.0000000        10.000000
    20          20.0000000        10.000000
    21          20.0000000        10.000000
    22          20.0000000        10.000000
    23          20.0000000        10.000000
    24          20.0000000        10.000000
    25          20.0000000        10.000000
    26          20.0000000        10.000000
    27          20.0000000        10.000000
    28          20.0000000        10.000000
    29          20.0000000        10.000000
    30          20.0000000        10.000000
    31          20.0000000        10.000000
    32          20.0000000        10.000000
    33          20.0000000        10.000000
    34          20.0000000        10.000000
    35          20.0000000        10.000000
    36          20.0000000        10.000000
    37          20.0000000        10.000000
    38          20.0000000        10.000000
    39          20.0000000        10.000000
    40          20.0000000        10.000000
    41          20.0000000        10.000000

================================================================================


          SCALED VERTICAL SOIL MODULUS VALUES

   ELEMENT      MODULUS

       1       20.00000
       2       20.00000
       3       20.00000
       4       20.00000
       5       20.00000
       6       20.00000
       7       20.00000
       8       20.00000
       9       20.00000
      10       20.00000
      11       20.00000
      12       20.00000
      13       20.00000
      14       20.00000
      15       20.00000
      16       20.00000
      17       21.73913
      18       25.21739
      19       32.17391
      20       46.08696
      21      100.00000

          SCALED LATERAL SOIL MODULUS VALUES
```

```
   ELEMENT      MODULUS

       1       20.00000
       2       20.00000
       3       20.00000
       4       20.00000
       5       20.00000
       6       20.00000
       7       20.00000
       8       20.00000
       9       20.00000
      10       20.00000
      11       20.00000
      12       20.00000
      13       20.00000
      14       20.00000
      15       20.00000
      16       20.00000
      17       20.00000
      18       20.00000
      19       20.00000
      20       20.00000
      21       20.00000
      22       20.00000
      23       20.00000
      24       20.00000
      25       20.00000
      26       20.00000
      27       20.00000
      28       20.00000
      29       20.00000
      30       20.00000
      31       20.00000
      32       20.00000
      33       20.00000
      34       20.00000
      35       20.00000
      36       20.00000
      37       20.00000
      38       20.00000
      39       20.00000
      40       20.00000
      41       20.00000

================================================================================


                            INTERACTION FACTORS



                ****************************************

                 CALCULATED AXIAL   INTERACTION FACTORS

                 CALCULATED LATERAL INTERACTION FACTORS

                ****************************************

     S/D      AA   ARH(B=0) ARH(B=90) ARM(B=0) ARM(B=90) ATHM(B=0) ATHM(B=90)

    2.000    0.383    0.357    0.265    0.184    0.122    0.077    0.049
    4.000    0.304    0.227    0.155    0.092    0.052    0.034    0.019
    7.000    0.243    0.141    0.092    0.040    0.021    0.012    0.007
   10.000    0.206    0.099    0.064    0.020    0.011    0.004    0.003
   15.000    0.164    0.065    0.042    0.007    0.005    0.001    0.001
   20.000    0.135    0.047    0.031    0.003    0.003    0.000    0.001

               ELASTIC UNIT RESPONSES FOR PILE TYPE     2

RN1 =     0.004789  ROHH     0.044905  THH =    0.019134  ROM =     0.019238  THM =     0.019977



                    SCALING FACTORS FOR INDIVIDUAL PILES

   PILE    SHAFT Es    BASE Esb    LATL.Es
```

```
     1    2.4971       1.5418       2.1756
     2    2.6402       1.6230       2.3500
     3    2.6322       1.5816       2.2832
     4    2.5009       1.5460       2.1930
     5    2.6380       1.6463       2.3593
     6    2.4847       1.5020       2.1692
================================================================================

                      DETAILS OF GROUP NUMBER  1


                ****************************************

                RECTANGULAR GROUP

                    3 BY    2

                SX =     2.000000

                SY =     2.000000



    PILE  TYPE    X(I)        Y(I)     X-RAKE ANGLE   Y-RAKE ANGLE  REAL RAKE

    1      1      0.000000     0.000000     0.000000     0.000000     0.000000
    2      1      2.000000     0.000000     0.000000     0.000000     0.000000
    3      2      4.000000     0.000000     0.000000     0.000000     0.000000
    4      1      0.000000     2.000000     0.000000     0.000000     0.000000
    5      1      2.000000     2.000000     0.000000     0.000000     0.000000
    6      1      4.000000     2.000000     0.000000     0.000000     0.000000

          X & Y COORDS OF VERTICAL LOAD =        2.000000          1.000000



          POULOS & MADHAV 1971 FORMULATION





********************************************************************************

                         LOAD SET NUMBER      1




********************************************************************************
               VERTICAL LOADING
--------------------------------------------------------------------------------


                    GENERAL CASE OF RIGID ROTATING CAP


                 VERTICAL LOAD     =        9.000000
                 X-HORIZONTAL LOAD =        0.000000
                 X-MOMENT          =        0.000000
                 Y-HORIZONTAL LOAD =        0.000000
                 Y-MOMENT          =        0.000000
                 TORSIONAL LOAD    =        0.000000


  X & Y COORDS OF VERT LOAD =         2.0000        1.0000

  X & Y COORDS OF HX LOAD   =         2.0000        1.0000

  X & Y COORDS OF HY LOAD   =         2.0000        1.0000
```

```
  X & Y COORDS OF TOR LOAD  =         2.0000        1.0000



--------------------------------------------------------------------------------



********************************************************************************
********************************************************************************

               RESULTS FOR TOTAL LOADING SET

********************************************************************************
********************************************************************************



    PILE    P        HX        MX        HY        MY        TORS     VERT DISP


     1 0.171E+01 0.374E-03 0.751E-01 -.165E-03 -.764E-01 -.541E-03 0.113E-01
     2 0.156E+01 -.365E-02 0.760E-01 0.327E-02 -.784E-01 -.541E-03 0.118E-01
     3 0.104E+01 0.773E-02 0.216E-02 -.729E-02 -.274E-02 -.679E-04 0.123E-01
     4 0.145E+01 -.308E-03 0.761E-01 -.562E-04 -.765E-01 -.541E-03 0.109E-01
     5 0.132E+01 -.386E-02 0.777E-01 0.301E-02 -.787E-01 -.541E-03 0.113E-01
     6 0.193E+01 -.276E-03 0.759E-01 0.124E-02 -.786E-01 -.541E-03 0.118E-01

                      X- HORIZ DEFLN =      0.00055114

                      X- ROTATION    =      0.00022981


                      Y- HORIZ DEFLN =     -0.00054376

                      Y- ROTATION    =     -0.00023107


                      TORSIONAL ROTATION =     -0.00000328


--------------------------------------------------------------------------------




                    AXIAL LOADS IN PILES

     1.70721       1.56081       1.03636       1.45057
     1.31507       1.92997


                    X-NORMAL LOADS IN PILES

     0.00037      -0.00365       0.00773      -0.00031
    -0.00386      -0.00028


                    Y-NORMAL LOADS IN PILES

    -0.00017       0.00327      -0.00729      -0.00006
     0.00301       0.00124

--------------------------------------------------------------------------------

                    SUMMARY OF STATUS OF PILES


  PILE        AXIAL    LATERAL-X   LATERAL-Y   MOMENT-X   MOMENT-Y

     1          0          0          0          0          0
     2          0          0          0          0          0
     3          0          0          0          0          0
     4          0          0          0          0          0
     5          0          0          0          0          0
     6          0          0          0          0          0

================================================================================
```

```
                    SUMMARY OF MAX & MIN VALUES FOR GROUP


                    MAX VERT LOAD =      1.92997
                    MIN VERT LOAD =      1.03636

                    MAX   HX LOAD =      0.00773
                    MIN   HX LOAD =     -0.00386

                    MAX  X MOMENT =      0.07768
                    MIN  X MOMENT =      0.00216

                    MAX   HY LOAD =      0.00327
                    MIN   HY LOAD =     -0.00729

                    MAX  Y MOMENT =     -0.00274
                    MIN  Y MOMENT =     -0.07866

                    MAX TORS LOAD =     -0.00007
                    MIN TORS LOAD =     -0.00054

                    MAX    SETTL. =      0.01226
                    MIN   SETTL.T =      0.01087


================================================================================




--------------------------------------------------------------------------------




                    INDIVIDUAL PILE LATERAL RESPONSES




********************************************************************************
                    LATERAL LOADING IN X-DIRECTION FOR PILE    3



     NORMAL LOAD =      0.00773          MOMENT =      0.00216



 DEPTH     DISPL        ROTATION        MOMENT        PRESSURE        STATUS


      0.00    0.000554       0.000455       0.002163       0.002195            0.
      0.50    0.000351       0.000361       0.002026       0.000734            0.
      1.00    0.000194       0.000275       0.001798       0.000351            0.
      1.50    0.000077       0.000200       0.001526       0.000069            0.
      2.00   -0.000006       0.000137       0.001246      -0.000111            0.
      2.50   -0.000061       0.000087       0.000979      -0.000217            0.
      3.00   -0.000093       0.000048       0.000739      -0.000270            0.
      3.50   -0.000109       0.000020       0.000534      -0.000286            0.
      4.00   -0.000113       0.000000       0.000364      -0.000277            0.
      4.50   -0.000109      -0.000014       0.000228      -0.000253            0.
      5.00   -0.000099      -0.000022       0.000124      -0.000220            0.
      5.50   -0.000087      -0.000026       0.000048      -0.000184            0.
      6.00   -0.000074      -0.000027      -0.000005      -0.000148            0.
      6.50   -0.000061      -0.000026      -0.000040      -0.000115            0.
      7.00   -0.000048      -0.000023      -0.000060      -0.000086            0.
      7.50   -0.000037      -0.000020      -0.000070      -0.000062            0.
      8.00   -0.000028      -0.000017      -0.000072      -0.000041            0.
      8.50   -0.000020      -0.000014      -0.000068      -0.000026            0.
      9.00   -0.000014      -0.000011      -0.000062      -0.000013            0.
      9.50   -0.000009      -0.000008      -0.000054      -0.000005            0.
     10.00   -0.000006      -0.000006      -0.000045       0.000001            0.
     10.50   -0.000003      -0.000004      -0.000036       0.000005            0.
     11.00   -0.000001      -0.000003      -0.000028       0.000008            0.
     11.50    0.000000      -0.000002      -0.000022       0.000009            0.
     12.00    0.000001      -0.000001      -0.000016       0.000009            0.
     12.50    0.000001       0.000000      -0.000011       0.000008            0.
     13.00    0.000001       0.000000      -0.000007       0.000007            0.
     13.50    0.000001       0.000000      -0.000004       0.000006            0.
     14.00    0.000001       0.000000      -0.000002       0.000005            0.
     14.50    0.000000       0.000000      -0.000001       0.000004            0.
     15.00    0.000000       0.000001       0.000000       0.000003            0.
```

```
     15.50    0.000000      0.000000      0.000001      0.000003            0.
     16.00    0.000000      0.000000      0.000001      0.000002            0.
     16.50   -0.000001      0.000000      0.000001      0.000001            0.
     17.00   -0.000001      0.000000      0.000000      0.000001            0.
     17.50   -0.000001      0.000000      0.000000      0.000000            0.
     18.00   -0.000001      0.000000      0.000000     -0.000001            0.
     18.50   -0.000001      0.000000      0.000000     -0.000001            0.
     19.00   -0.000002      0.000000     -0.000001     -0.000002            0.
     19.50   -0.000002      0.000000      0.000000     -0.000002            0.
     20.00   -0.000002      0.000000      0.000000     -0.000007            0.

********************************************************************************

                  LATERAL LOADING IN Y-DIRECTION FOR PILE    3


     NORMAL LOAD =     -0.00729          MOMENT =     -0.00274


 DEPTH     DISPL        ROTATION        MOMENT        PRESSURE        STATUS


      0.00   -0.000537     -0.000441     -0.002741     -0.002782            0.
      0.50   -0.000340     -0.000350     -0.002568     -0.000930            0.
      1.00   -0.000188     -0.000266     -0.002279     -0.000444            0.
      1.50   -0.000074     -0.000194     -0.001934     -0.000088            0.
      2.00    0.000006     -0.000133     -0.001579      0.000140            0.
      2.50    0.000059     -0.000084     -0.001241      0.000275            0.
      3.00    0.000090     -0.000047     -0.000937      0.000343            0.
      3.50    0.000106     -0.000019     -0.000676      0.000363            0.
      4.00    0.000110      0.000000     -0.000461      0.000351            0.
      4.50    0.000105      0.000013     -0.000289      0.000320            0.
      5.00    0.000096      0.000021     -0.000158      0.000279            0.
      5.50    0.000084      0.000025     -0.000061      0.000233            0.
      6.00    0.000072      0.000026      0.000007      0.000188            0.
      6.50    0.000059      0.000025      0.000051      0.000146            0.
      7.00    0.000047      0.000023      0.000076      0.000109            0.
      7.50    0.000036      0.000020      0.000089      0.000078            0.
      8.00    0.000027      0.000017      0.000091      0.000053            0.
      8.50    0.000020      0.000014      0.000087      0.000032            0.
      9.00    0.000014      0.000011      0.000079      0.000017            0.
      9.50    0.000009      0.000008      0.000068      0.000006            0.
     10.00    0.000005      0.000006      0.000057     -0.000002            0.
     10.50    0.000003      0.000004      0.000046     -0.000007            0.
     11.00    0.000001      0.000003      0.000036     -0.000010            0.
     11.50    0.000000      0.000002      0.000027     -0.000011            0.
     12.00   -0.000001      0.000001      0.000020     -0.000011            0.
     12.50   -0.000001      0.000000      0.000014     -0.000010            0.
     13.00   -0.000001      0.000000      0.000009     -0.000009            0.
     13.50   -0.000001      0.000000      0.000005     -0.000008            0.
     14.00   -0.000001      0.000000      0.000003     -0.000007            0.
     14.50    0.000000      0.000000      0.000001     -0.000005            0.
     15.00    0.000000      0.000000      0.000000     -0.000004            0.
     15.50    0.000000      0.000000     -0.000001     -0.000003            0.
     16.00    0.000000      0.000000     -0.000001     -0.000002            0.
     16.50    0.000001      0.000000     -0.000001     -0.000001            0.
     17.00    0.000001      0.000000     -0.000001     -0.000001            0.
     17.50    0.000001      0.000000      0.000000      0.000000            0.
     18.00    0.000001      0.000000      0.000000      0.000001            0.
     18.50    0.000001      0.000000      0.000001      0.000001            0.
     19.00    0.000002      0.000000      0.000001      0.000002            0.
     19.50    0.000002      0.000000      0.000001      0.000003            0.
     20.00    0.000002      0.000000      0.000000      0.000009            0.

********************************************************************************

                  LATERAL LOADING IN X-DIRECTION FOR PILE    6


     NORMAL LOAD =     -0.00028          MOMENT =      0.07593


 DEPTH     DISPL        ROTATION        MOMENT        PRESSURE        STATUS


      0.00    0.000548      0.000226      0.075934      0.011578            0.
      0.50    0.000441      0.000202      0.074495      0.005118            0.
      1.00    0.000346      0.000179      0.071777      0.003849            0.
      1.50    0.000262      0.000156      0.068097      0.002661            0.
      2.00    0.000190      0.000135      0.063751      0.001712            0.
```

```
      2.50    0.000127       0.000116       0.058977       0.000947             0.
      3.00    0.000074       0.000098       0.053967       0.000333             0.
      3.50    0.000030       0.000081       0.048873      -0.000155             0.
      4.00   -0.000007       0.000066       0.043818      -0.000536             0.
      4.50   -0.000037       0.000053       0.038898      -0.000826             0.
      5.00   -0.000060       0.000041       0.034184      -0.001040             0.
      5.50   -0.000078       0.000031       0.029730      -0.001189             0.
      6.00   -0.000091       0.000022       0.025573      -0.001285             0.
      6.50   -0.000101       0.000015       0.021737      -0.001336             0.
      7.00   -0.000106       0.000009       0.018235      -0.001350             0.
      7.50   -0.000109       0.000003       0.015071      -0.001336             0.
      8.00   -0.000109      -0.000001       0.012241      -0.001299             0.
      8.50   -0.000108      -0.000005       0.009736      -0.001245             0.
      9.00   -0.000105      -0.000007       0.007542      -0.001178             0.
      9.50   -0.000100      -0.000010       0.005642      -0.001101             0.
     10.00   -0.000095      -0.000011       0.004018      -0.001020             0.
     10.50   -0.000089      -0.000012       0.002649      -0.000935             0.
     11.00   -0.000083      -0.000013       0.001513      -0.000849             0.
     11.50   -0.000077      -0.000013       0.000590      -0.000764             0.
     12.00   -0.000070      -0.000013      -0.000143      -0.000681             0.
     12.50   -0.000063      -0.000013      -0.000705      -0.000602             0.
     13.00   -0.000057      -0.000013      -0.001116      -0.000526             0.
     13.50   -0.000051      -0.000012      -0.001397      -0.000454             0.
     14.00   -0.000044      -0.000012      -0.001563      -0.000387             0.
     14.50   -0.000039      -0.000011      -0.001633      -0.000324             0.
     15.00   -0.000033      -0.000011      -0.001622      -0.000264             0.
     15.50   -0.000028      -0.000010      -0.001545      -0.000209             0.
     16.00   -0.000023      -0.000010      -0.001416      -0.000157             0.
     16.50   -0.000018      -0.000009      -0.001247      -0.000107             0.
     17.00   -0.000013      -0.000009      -0.001052      -0.000059             0.
     17.50   -0.000009      -0.000009      -0.000842      -0.000011             0.
     18.00   -0.000004      -0.000009      -0.000630       0.000037             0.
     18.50    0.000000      -0.000008      -0.000426       0.000087             0.
     19.00    0.000004      -0.000008      -0.000244       0.000143             0.
     19.50    0.000008      -0.000008      -0.000098       0.000192             0.
     20.00    0.000012      -0.000008       0.000000       0.000717             0.

********************************************************************************

                  LATERAL LOADING IN Y-DIRECTION FOR PILE    6


     NORMAL LOAD =      0.00124          MOMENT =     -0.07861



 DEPTH     DISPL         ROTATION        MOMENT        PRESSURE        STATUS


      0.00   -0.000537      -0.000222      -0.078609      -0.011985             0.
      0.50   -0.000432      -0.000198      -0.077119      -0.005298             0.
      1.00   -0.000339      -0.000175      -0.074305      -0.003985             0.
      1.50   -0.000257      -0.000153      -0.070495      -0.002755             0.
      2.00   -0.000186      -0.000133      -0.065996      -0.001772             0.
      2.50   -0.000125      -0.000113      -0.061055      -0.000980             0.
      3.00   -0.000073      -0.000096      -0.055868      -0.000344             0.
      3.50   -0.000029      -0.000080      -0.050595       0.000161             0.
      4.00    0.000007      -0.000065      -0.045362       0.000555             0.
      4.50    0.000036      -0.000052      -0.040268       0.000856             0.
      5.00    0.000059      -0.000041      -0.035388       0.001077             0.
      5.50    0.000077      -0.000031      -0.030777       0.001231             0.
      6.00    0.000090      -0.000022      -0.026474       0.001330             0.
      6.50    0.000099      -0.000015      -0.022503       0.001383             0.
      7.00    0.000104      -0.000008      -0.018878       0.001398             0.
      7.50    0.000107      -0.000003      -0.015602       0.001383             0.
      8.00    0.000107       0.000001      -0.012672       0.001345             0.
      8.50    0.000106       0.000005      -0.010079       0.001289             0.
      9.00    0.000103       0.000007      -0.007808       0.001219             0.
      9.50    0.000099       0.000009      -0.005841       0.001140             0.
     10.00    0.000093       0.000011      -0.004160       0.001056             0.
     10.50    0.000088       0.000012      -0.002742       0.000968             0.
     11.00    0.000081       0.000013      -0.001566       0.000879             0.
     11.50    0.000075       0.000013      -0.000610       0.000791             0.
     12.00    0.000069       0.000013       0.000148       0.000705             0.
     12.50    0.000062       0.000013       0.000730       0.000623             0.
     13.00    0.000056       0.000013       0.001156       0.000544             0.
     13.50    0.000050       0.000012       0.001446       0.000470             0.
     14.00    0.000044       0.000012       0.001618       0.000400             0.
     14.50    0.000038       0.000011       0.001691       0.000335             0.
     15.00    0.000032       0.000011       0.001679       0.000274             0.
     15.50    0.000027       0.000010       0.001599       0.000216             0.
     16.00    0.000022       0.000010       0.001465       0.000162             0.
     16.50    0.000017       0.000009       0.001291       0.000110             0.
     17.00    0.000013       0.000009       0.001089       0.000061             0.
```

```
     17.50    0.000009       0.000009       0.000872       0.000012            0.
     18.00    0.000004       0.000008       0.000652      -0.000038            0.
     18.50    0.000000       0.000008       0.000441      -0.000090            0.
     19.00   -0.000004       0.000008       0.000253      -0.000148            0.
     19.50   -0.000008       0.000008       0.000102      -0.000199            0.
     20.00   -0.000012       0.000008       0.000000      -0.000743            0.

********************************************************************************

                    DURATION OF RUN =        15.38  SECONDS

********************************************************************************
```