CHAPTER 8

SUMMARY AND CONCLUSIONS

It is clear, from examples in the literature and from the field tests performed on pile groups at Virginia Tech's field test site, that pile caps provide considerable resistance to lateral loads on deep foundation systems. Neglecting this resistance in design results in excessive estimates of pile group deflections and bending moments under load, and underestimates the foundation stiffness. In many situations, neglecting cap resistance introduces inaccuracies of one hundred percent or more. There is a need for rational procedures for including cap resistance in the design of pile groups to resist lateral loads. This research has made it possible to quantify many important aspects of pile group and pile cap behavior under lateral loads due to wind, waves, and thermal expansions and contractions of bridge decks.

The program of work accomplished in this study includes performing a detailed literature review on the state of knowledge of pile group and pile cap resistance to lateral loads, developing a full-scale field test facility, conducting 31 lateral load tests on pile groups and individual piles, performing laboratory tests on natural soils obtained from the site and on imported backfill materials, and developing an analytical method for including the lateral resistance of pile caps in the design of deep foundation systems.

8.1 LITERATURE REVIEW

A comprehensive literature review was conducted to examine the current state of knowledge regarding pile cap resistance and pile group behavior. Over 350 journal articles and other publications pertaining to lateral resistance, testing, and analysis of pile caps, piles, and pile groups were collected and reviewed. Pertinent details from these studies were evaluated and, whenever possible, summarized in tables and charts.

Of the publications reviewed, only four papers were found that described load tests performed to investigate the lateral resistance of pile caps. These studies indicate that the lateral resistance of pile caps can be quite significant, especially when the cap is embedded beneath the ground surface.

A review of the most widely recognized techniques for analyzing laterally loaded single piles was performed. These techniques provide a framework for methods that are used to evaluate the response of closely spaced piles, or pile groups. Modifications of single pile techniques are often in the form of empirically or theoretically derived factors that are applied, in various ways, to account for group interaction effects.

Piles in closely spaced groups behave differently than single isolated piles because of pile-soil-pile interactions that take place in the group. Deflections and bending moments of piles in closely spaced groups are greater than deflections and bending moments of single piles, at the same load per pile, because of these interaction effects.

The most widely used method of adjusting for group interaction effects is the group efficiency factor, G_e, which is defined as the average lateral capacity per pile in a group divided by the lateral capacity of a single pile. The value of G_e is always less than or equal to unity.

The current state of practice regarding pile group behavior was reviewed from an experimental and analytical basis. Thirty-seven experimental studies were reviewed in which the effects of pile group behavior on the group efficiency, G_e, were observed and measured. These included 15 full-scale field tests, 16 1g model tests, and 6 geotechnical centrifuge tests. Thirty analytical studies were reviewed that addressed pile group lateral load behavior. These studies included closed-form analytical approaches, elasticity methods, hybrid methods, and finite element methods. Based on these studies, a number of factors were evaluated to determine the influence that pile group behavior has on the group efficiency, G_e. These factors, listed in order of importance are: pile spacing, group arrangement, group size, pile-head fixity, soil type and density, and pile displacement.

Measurements of pile displacements and stresses during full-scale and model tests indicate that piles in a group carry unequal lateral loads, depending on their location within the group and the spacing between piles. This unequal distribution of load among piles is caused by “shadowing”, which is a term used to describe the overlap of shear zones and consequent reduction of soil resistance.

Shadowing is accounted for in the p-y method of analysis using p-multipliers, which are empirical reduction factors that are experimentally derived from load tests on pile groups. The p-multiplier (f_m) values depend on pile position within the group and pile spacing. The procedure follows the same approach used in the p-y method of analysis for single piles, except a multiplier, with a value less than one, is applied to the p-values of the single pile p-y curve. This reduces the ultimate soil resistance and softens the shape of the p-y curve. Because they are determined experimentally, the multipliers include both elasticity and shadowing effects.

The results from 11 experimental studies were reviewed in which p-multipliers for pile groups of different sizes and spacings were developed. In these studies, which include 29 separate tests, values of f_m were determined through a series of back-calculations using results from instrumented pile-groups and single pile load tests.

Group efficiency factors (G_e) and p-y multipliers (f_m) represent two approaches for quantifying group interaction effects. Because these approaches represent the same phenomenon, the factors listed above for empirically derived G_e values apply equally as well to the empirically derived f_m values. Three additional factors that are more specific to the f_m approach are:

1. **Row position**. The lateral capacity of a pile in a group is significantly affected by its row position (leading row, first trailing row, etc.) and the center to center pile

spacing. The leading row carries more load than subsequent rows; consequently, it has the highest multiplier. Multipliers decrease going from the leading to the trailing row, which has the lowest multiplier.

2. **Corner pile effects**. At spacings less than 3D, the outer corner piles will take a greater share of load than interior piles, and consequently, will experience greater bending moments and stresses. Ignoring this behavior is unconservative, and could results in overstressed corner piles. Recommendations were presented for modifying bending moments computed for the corner piles if the spacing normal to the direction of load (side-by-side spacing) is less than 3D.

3. **Depth**. Although a single value of f_m for all depths is commonly used for the sake of simplicity, it is possible to use values of f_m that vary with depth, to achieve improved agreement between computed and measured group response.

Design lines were developed for estimating pile group efficiency values and p-multipliers as functions of pile arrangement and pile spacing. The design lines are presented in chart form in Chapter 2.

These design lines represent state-of-the-art values for use in analysis and design of laterally loaded pile groups. The writer believes that these lines are suitable for all except the largest projects, where lateral load behavior of pile groups is an extremely critical issue. For projects where the expense can be justified, these lines can be verified or improved by performing on-site full-scale load tests on groups of instrumented piles.

8.2 FIELD LOAD TESTS

A field test facility was developed to perform full-scale lateral load tests on single piles, pile groups, and pile caps embedded in natural soil and backfilled with granular soil. The facility was designed specifically for this project to evaluate the lateral resistance provided by pile caps. The test facility is located at Virginia Tech's Kentland Farms, approximately 10 miles west of Blacksburg, Virginia. Test foundations that were constructed at the facility consisted of three groups of four piles each, one with a cap 18 inches deep and two with 36-inch-deep caps, two individual test piles, and an embedded bulkhead with no piles.

Details of the facility including the in-ground appurtenances, the loading equipment and connections that were used to apply horizontal compressive loads to the foundations, the instrumentation that was used for monitoring displacements and slopes of the single piles, pile caps, and bulkhead, and the data acquisition system are described in Chapter 4.

A total of thirty-one tests were performed at the facility using incremental, cyclic, and sustained loading procedures.

Results from the testing program clearly support the research hypothesis that pile caps provide significant resistance to lateral load. The pile caps that were tested in this study provided approximately 50 % of the overall lateral resistance of the pile group foundations.

The lateral resistance provided by a pile group/pile cap foundation depends on many interacting factors, which were isolated during this study to evaluate their significance. In order of importance, these are:

1. **Stiffness and density of soil in front of the cap**. The passive resistance that can be developed in front of a pile cap is directly related to the backfill strength. As

was demonstrated during the load tests, the lateral resistance increases as the stiffness and density of soil around the cap increases.

2. **Depth of cap embedment**. Increasing cap thickness or depth results in smaller lateral deflections.

3. **Rotational restraint at the pile head**. The rotational restraint available at the pile head can most often be described as a partially restrained condition. This condition results in response that falls between that of a fixed-head and free-head boundary condition. Response curves can be calculated using partially restrained boundary conditions by calculating, measuring, or estimating the rotational restraint, $k_{m\theta}$.

4. **Pile group axial capacity**. Lateral behavior of a pile group is directly related to the vertical or axial capacity of the piles. Pile groups comprised of longer piles (greater axial capacity) have significantly greater lateral resistance than groups with shorter piles. The rotation of the cap and the passive resistance developed in front of the cap are both affected by the axial capacity of the piles.

5. **Stiffness and density of soil around the piles**. Lateral load resistance increases as the stiffness and density of soil around the piles increase. The soil within the top 10 pile diameters has the greatest effect on lateral pile response.

6. **Cyclic and sustained loads**. For the conditions tested in this study, the effects from cyclically applied loads and long-term sustained loads were minor, or secondary, in comparison to the other factors described above. In other situations, such as high groundwater or soft compressible soils, the effect of cyclic loading or long term sustained loading could be more significant.

In conclusion, the load tests performed in this study clearly indicate that pile caps provide considerable resistance to lateral loads. The lateral resistance of a pile group is largely a function of the passive resistance developed by the cap and the rotational restraint of the pile-cap system. The passive resistance of the cap is controlled by the stiffness and density of the backfill soil and the interface friction angle. The rotational restraint is a function of the pile-to-cap connection and the axial capacity of the piles.

8.3 SOIL PARAMETERS

The natural soils encountered at the Kentland Farms field test site consisted of sandy clay, sandy silt, and silty sand with thin layers of gravel. Two soil types were used as backfill in the lateral load tests: a poorly graded fine sand (New Castle sand) and a well graded silty gravel (crusher run gravel). These materials were used because they are representative of the types of backfill materials often used for pile caps, footings, and other buried structures.

Various in situ techniques were used to determine soil stratification, shear strength, soil modulus, state of stress in the ground, and groundwater levels. The subsurface investigation included solid-stem auger borings with standard penetration tests, dilatometer soundings, groundwater piezometer installation, and backhoe test pits. Split spoon samples, Shelby tube samples, and hand-excavated block samples were obtained during the investigation for subsequent laboratory testing.

A comprehensive suite of laboratory tests were conducted on these materials to measure soil properties and to provide a basis for estimating the values of parameters that were used in the analyses. The laboratory testing program included soil classification, unit weight, strength (UU, CU, and CD triaxial tests), and consolidation. Parameters required for the pile group analyses included: ϕ, c, δ, α, ν, E_i, and γ_m. The testing program and the measured values of these parameters are discussed in Chapter 5. Correlation charts and tables from published sources are provided in Chapter 7 for many of these parameters. The correlations are useful as a supplement to laboratory and in situ tests.

8.4 ANALYTICAL METHOD

An analytical method was developed for evaluating the lateral response of pile groups with embedded caps. The approach involves creating p-y curves for single piles, pile groups, and pile caps using the computer spreadsheets *PYPILE* and *PYCAP*.

Single pile p-y curves are developed using Brinch Hansen's (1961) ultimate load theory for soils that possess both cohesion and friction. The approach is programmed in *PYPILE*, which can be used to calculate p-y curves for piles of any size, with soil properties that are constant or that vary with depth.

A method called the "group-equivalent pile" (abbreviated GEP) approach was developed for creating pile group and pile cap p-y curves in a way that is compatible with established approaches for analyzing laterally loaded piles. GEP p-y curves are obtained by multiplying the "p" values of the single pile p-y curves by a modification factor that accounts for reduced capacities caused by group interaction effects, and summing the modified p-values for all the piles in the group. The p-multiplier curves developed in Chapter 2 are used for this purpose. The pile group is modeled in the computer program *LPILE Plus 3.0* using these GEP p-y curves. The flexural resistance of the GEP pile is equal to the sum of the flexural resistances of all the piles in the group.

A rotationally restrained pile-head boundary condition can be modeled in the analysis. The rotational stiffness is estimated from the axial skin friction of the piles, the deflection required to mobilize skin friction, and the corresponding moment on the pile cap.

Pile cap resistance is included in the analysis using cap p-y curves. A method for calculating cap p-y curves was developed during this study, and has been programmed in the spreadsheet *PYCAP*. The approach models the passive earth pressures developed in front of the cap. The relationship between passive pressure and the cap deflection is represented by p-y curves developed using a hyperbolic formulation, which is defined by the ultimate passive force and the initial elastic stiffness of the embedded pile cap. The ultimate passive force is determined using the log spiral earth pressure theory in conjunction with Ovesen's (1964) three-dimensional correction factors.

The commercially available computer program *LPILE Plus 3.0* (Reese et al. 1997) was used in conjunction with the GEP approach to calculate load-deflection curves for the pile groups tested in this study, and for a load test described in the literature. Comparisons between measured and calculated load-deflection responses indicate that the analytical approach developed in this study is conservative, reasonably accurate, and suitable for use in design. Deviations between calculated and measured load-deflection values fall well within the practical range that can be expected for analyses of the lateral response of pile groups. This approach represents a significant improvement over current design practices, which often completely ignore the cap resistance.

The author believes it would be difficult to obtain more accurate estimates of pile group behavior, even with more complex analytical methods, because of the inevitable uncertainties and variations in soil conditions, unknown or uncontrollable construction factors, and the complex structural and material interactions that occur between the piles, pile cap, and soil.

8.5 RECOMMENDATIONS FOR FUTURE RESEARCH

The response of piles to lateral loading has been the focus of numerous analytical and experimental studies over the past 60 years. However, the response of the pile cap, and the interaction between the pile cap and the pile group have received little attention, in these studies. The results of this research project represent a significant initial contribution in the area of pile cap response to lateral loads. In addition, the analytical approach and computer program developed during this study are expected to be a valuable asset to practicing engineers. It is recommended that future research be conducted to support and refine the results of this study.

The following recommendations for future research include additional experimental studies, as well as advanced analytical and numerical studies.

1. Research is needed to investigate further the rotational stiffness concept that was used in this study. Additional experimental studies are needed to explore the relationship between pile skin friction and pile group rotational restraint. These studies should include the effect that the pile cap and the pile cap backfill conditions (soil type, density, and interface shear strength) have on rotational restraint. The geotechnical centrifuge may be a good tool for performing these studies, because it provides a relatively inexpensive means of varying test conditions. The experimental studies would be enhanced by finite element analyses to supplement interpretations based on direct observations.

2. The technique developed in this study for estimating the pile cap initial elastic stiffness could be further explored, and possibly improved, using finite element

analyses. Additional experimental work could be performed to verify the suitability of the analyses.

3. The concept of modifying the plane strain log spiral solution for three-dimensional effects was developed during this study. Three-dimensional modification factors were obtained from Ovesen's (1964) research on embedded anchor blocks. Additional research would be useful to refine the modification factors for different soil types, including cohesive soils and soils that have both cohesion and frictional shear strength components.

4. Little is known about the performance of pile caps during dynamic or vibratory loading. Research, including full-scale experimental studies, is needed in this area to evaluate the effect the pile cap has on the stiffness and lateral response of pile groups subjected to these types of loads.