Summary

The papers in this book have been divided into two groups: one dealing with analysis and design, and the other dealing with case histories.

Analysis and Design

Eight papers are included in the analysis and design group. A summary for each follows.

The paper by Pyke and Beikae reviews current analytical methods for single piles subjected to lateral loading. Then a new analytical method is described, which takes into account soil fully surrounding the pile but only adhering to it along the part of the circumference where the soil resists pile movement, that is, the front and sides but not the back. A section is included that evaluates methods for determining Young's modulus for soils. A comparison of modulus of subgrade reaction values determined by the new analytical method with those determined by several other methods is presented in tabular form. No attempt is made to compare the various solutions with pile load test results, but the authors believe that the new method for calculating the modulus of subgrade reaction, when used with appropriate Young's modulus values, should provide reasonable results for pile resistance to lateral loading for initial loading and for working loads.

The paper by Habibagahi and Langer presents an extensive review of published methods for determining the coefficient of horizontal subgrade reaction for granular soils and includes a discussion of the factors on which it is dependent. Horizontal subgrade reaction parameters based on eight published methods are presented in tabular form for comparison. They demonstrate the wide range in published values. Another comparison is made in graphical form where the coefficient of subgrade reaction is plotted against relative depth (depth divided by pile diameter) for values given by twelve published methods. The authors suggest that the wide range in values may be due to variations in magnitude of pile deflection, effective overburden pressure, and relative density of the soil. They have proposed an equation for calculating the coefficient of horizontal subgrade reaction, which accounts for these factors. The proposed equation is dependent upon knowing the value of a parameter labeled $A$, which is a function of pile deflection, the soil's angle of internal friction and the pile width, and must be determined from load test data. Recommended values for $A$ are given for a friction angle of 30° and pile deflection.
ranging from 2.54 to 25.4 mm (0.1 to 1.0 in.). Using these values and other parameters given in the previous graph referred to, a similar graph is included that is based on the proposed equation. It demonstrates how sensitive the coefficient of horizontal subgrade reaction is to the pile deflection.

The paper by Sogge describes how a structural analysis computer program may be used for the analysis of a laterally loaded pile. An example is given showing how a pile and the soil in which it is embedded are modeled for the computer solution. The input and output data are given as well. The discussion points out the advantages in making an analysis for the combined superstructure and foundation rather than making independent analyses. The discussion also points out a disadvantage in the type of analysis presented in that any vertical arching arising from horizontal pile movement is not accounted for in the solution.

The paper by Selvadurai presents an approximate solution for the torsional stiffness of a rigid cylindrical pier embedded in an isotropic elastic soil mass. The derivation of the approximate solution is outlined, and the results are compared graphically with exact solutions. The graph shows that the relatively simple approximate solution gives results close to those given by complicated exact solutions.

The paper by Reese, Wright, and Aurora compares three methods of analysis for a laterally loaded pile group founded in stiff clay. The three methods are the Poulos-Focht-Koch method, a modification of that method, and the imaginary large-diameter single-pile method. All three methods utilize P-Y curves to correlate lateral soil resistance with pile deflection. The selection of an appropriate value for soil modulus and relative stiffness factor is discussed in detail. Graphs are included that show the sensitivity of pile group deflection to these two parameters. The results of parameter studies for lower and upper boundary soil stiffness and for lower and upper boundary relative stiffness factors are presented in tabular form. The imaginary large-diameter pile method gave results similar to those where the relative stiffness factors are presented in tabular form. The imaginary large-diameter pile method gave results similar to those where the relative stiffness factor was assumed to be unity. The writers conclude that very careful attention must be given to the selection of the soil modulus that is used in the Poulos analysis of a single pile. They recommend that parameter studies be made for a range of possible soil moduli to determine probable pile foundation behavior since currently available methods for determining the relevant properties of natural soil deposits are imprecise.

The paper by Gleser presents a generalized solution for calculating the lateral movement of a vertical pile and resulting stresses due to lateral loading. The solution is based on finite-difference equations, requiring the use of a digital computer. It includes a solution for a nonlinear soil response by characterizing the $P-Y$ curve as three straight lines, each applicable for specific ranges of deflection. A procedure is given for making iterative solutions and comparing the calculated lateral deflection with range of deflection applicable for the
The authors present the generalized solution for calculating the load-deflection behavior of laterally loaded piles. This solution is based on the $P-Y$ equation used, and making adjustments as necessary. A procedure is also given for using the generalized solution for piles subjected to fluctuating lateral loads. A procedure is given for determining $P-Y$ curves for the soil based on data obtained from lateral pile load tests made in a specific manner. Following the procedures for using the generalized solution, the author applies the solution to the test pile results reported by Alizadeh and Davisson for the Arkansas River Project and makes several observations of the results with respect to the influence of pile shape on lateral deflection characteristics.

The paper by Briaud, Smith, and Meyer presents a discussion of the influence of the depth below the ground surface on soil-pile interaction and how the pressuremeter may be used to determine parameters for predicting load-deflection characteristics for piles. Earlier methods for determining the maximum depth where the soil resistance is reduced because of the proximity of the ground surface, termed the critical depth, are reviewed. Then, seven proposed methods for predicting the load-deflection characteristics for laterally loaded piles using pressuremeter test results are outlined. The first four of these methods are applied to a lateral-load test case history, and the results are compared graphically with the load test data. The authors believe that pressuremeter data provides a sound basis for predicting the behavior of laterally loaded piles.

The paper by Horvath reviews the two principal methods for calculating the load-deflection behavior of laterally loaded piles: one using Winkler's modulus of subgrade reaction concept, and the other using the elastic continuum concept. The advantages and disadvantages of each method are discussed. The author then reviews an elastic continuum solution by Reissner using simplifying assumptions for vertical loads applied to the surface of the elastic continuum. He then refers to his previous paper where he used Reissner's simplified continuum approach to solve the problem for vertical loads assuming that Young's modulus varies either linearly or with the square root of depth to more closely simulate the actual behavior of soil. The author then uses this approach to develop a solution for laterally loaded piles, the derivation of which is included in the Appendix to this paper. He notes that this approach can be readily solved by computer using finite-difference equations and that variations in Young's modulus with depth can be used as well. The author is currently evaluating several lateral-load test case histories using the simplified continuum approach and will publish the results after the study is complete.

**Case Histories**

The papers in this group are, with one exception, case histories. Lateral load testing was carried out on small-scale models (Cox et al and Stephenson et al), drilled piles (Bhushan and Askari, Johnson et al, and Long and Reese), and driven piles (Gle and Woods, and Robertson et al). The soils providing the lat-
eral resistance ranged from very soft clays to very dense sands. Testing was generally at high strains, and deflections and moments correlated reasonably well with existing theories. Bhushan and Askari, however, examined the response at low lateral loads and strains, and found effectively stiffer conditions. Bhushan also examined the effects of cyclic loading and determined that, at the low strains, cyclic loading increased strain only for the first few cycles. This was generally confirmed by Long and Reese at high strains but not by Robertson et al. Gle and Woods dynamically tested the piles and found that the response could be well matched with existing solutions or could be modified to match where necessary. The Oakland and Chameau paper presented a three-dimensional finite-element model for drilled piles as a method to stabilize slopes.

Cox et al investigated the efficiencies of small-scale model pile groups in soft clay under lateral loading conditions. The piles were single-diameter open ended pipe pushed to different depths into the clay in in-line and side-by-side configurations of different numbers and spacings. The authors concluded that there was a remarkably uniform distribution of lateral loads on the side-by-side configuration with group efficiencies in excess of 0.76. For pile groupings in-line, there was considerably more variation both in distribution of loads and the group efficiency with minimum efficiencies of 0.54.

Stephenson et al also carried out lateral load tests on model piles as well as full-scale tests on helical anchor piles to develop a suitable mathematical model of the lateral load versus deflection behavior. The model tests were on ¼-scale helical piles and were carried out in medium sand with an angle of internal friction of 42°. The full-scale load tests, with which they were compared, were in both sands and clays. Stephenson et al concluded that helical anchor piles can develop significant resistance to lateral loads, and that, in most cases, this is controlled by the behavior of the extension shafts. To estimate deflections, they were able to use mathematical models similar to those for slender piles modified to account for the installation procedure used.

Long and Reese presented the results of testing and analysis of two offshore 1.22-m diameter drilled shafts in dense sand subjected to lateral loads of up to 500 kN. The loading was cycled 40 times for each increment. A semi-empirical computer model was used to predict the behavior of the shaft, and the predictions were compared with the measured results. Predicted deflections were found to be 21 to 30% less than measured values but maximum bending moment predictions were within 4 to 14%. It was concluded that, even though there were several differences between the characteristics of the load test and the computer model, there was reasonable agreement of maximum moments and horizontal deflections.

Johnson et al report on a lateral-load test carried out in 1982 on a 0.46-m diameter drilled shaft constructed in 1966 in stiff expansive clay soil. There had been considerable swelling of the soil around the 10.5-m long shaft. Pressure-
meter and laboratory undrained triaxial strength tests were found to be suitable for the analysis of the lateral behavior, although criteria for evaluating the behavior led to less stiff \( p-y \) curves than frequently used. This may have been due to long term field conditions such as wetting and remolding.

Bhushan and Askari carried out low-level cyclic load tests on 0.91-m diameter by 5.5-m long drilled shafts in dense sands and gravelly sands. The testing resulted in a 40% reduction in lengths for the foundation piers, as it was determined that the \( p-y \) curves were much stiffer than would be indicated by conventional procedures with high lateral loadings. Other findings include: a linear load-deflection response; the observation of 20 to 50% increase in deflection during the first few cyclic loads with no increase thereafter; a permanent set of approximately 25% of the deflection under the maximum load; and little increase in deflections caused by soaking of the surrounding ground. Bhushan and Askari proposed a semi-empirical relationship to obtain coefficient of subgrade reaction values from the standard penetration resistance, and this appeared to provide reasonable results.

Robertson et al used a driven pressuremeter to measure soil properties and thereby predict the lateral load behavior of four 30-cm\(^2\) precast concrete piles driven to 7 to 8 m depth through loose gravelly sand fill and very soft peat to bearing in glacial till. It was felt that the driven pressuremeter would fairly accurately model the pile driving. The test results were limited, but the agreement between the calculated and measured deflections was good.

Gle and Woods developed a procedure for dynamic lateral-load testing of single piles to investigate the soil-pile interaction parameters for foundations subjected to fairly high frequency cyclic loadings. This consisted of a steel mass plate, Lazan eccentric-mass oscillator, and vibration monitoring equipment attached to the head of the pile as close as possible to the ground surface. The response of the system was then measured on eleven pipe piles at three sites with both cohesive and cohesionless soils. The frequency of the dynamic loading ranged from 8 to 55 Hz. The results were supplemented by plucking tests on the piles. It was found that the observed lateral response could be matched quite well by the PILAY solution up to and slightly above the lateral translation resonance from stiffness and dampness values obtained from the dynamic field testing. At greater frequencies the design parameters could be modified to approximately model the observed response.

Oakland and Chameau report on preliminary development of a three-dimensional finite-element model to analyse the benefits of drilled piers for stabilizing slopes. It was concluded that there is substantial development required of the model, especially as regards to the boundary conditions. However, the model indicates that drilled piers can be used to stabilize slopes and reduce slope movements, mostly below the piers.

In summary, the case histories presented in this session are a valuable addition to data on lateral loading of piles. They are encouraging in that they gen-
erally indicate that existing mathematical and computer models or modifications thereof can be used to predict lateral deflections. The pressuremeter would appear to be a useful instrument for determining the soils properties to employ in these models.

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