REPORT ON 2-DAY SHORT COURSE ON ANALYSIS AND DESIGN OF PILE FOUNDATIONS

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Speakers with Organising Committee

One hundred and sixty-four (64) participants attended a 2-day short course on Analysis and Design of Pile Foundations from 14 to 15 July 2003 that was organised by the Geotechnical Engineering Technical Division at the Armada Hotel, Petaling Jaya. The course leader was Prof. Harry Poulos, Emeritus Professor of the University of Sydney and Senior Principal of Coffey Geosciences Pte. Ltd., Australia.

Prof. Poulos began his lecture by outlining the three main objectives of the short course, i.e.:

- To assist in understanding the behaviour of pile foundations and the factors affecting the behaviour,
- To present the results of modern analysis which may be useful in design, and
- To emphasise the importance of ground movements in pile design.

The course materials were presented in eight lectures, covering the following topics:

- Lecture 1: Aspects of pile foundation design and construction and axial load capacity;
- Lecture 2: Analysis of settlement of piles and pile groups;
- Lecture 3: Piles under lateral loading;
- Lecture 4: General analysis of pile groups; piled raft foundations – analysis and design;
- Lecture 5: Piles subjected to lateral and vertical ground movements;
- Lecture 6: Pile response to construction induced ground movements;
- Lecture 7: Pile response to dynamic and earthquake loadings; and
- Lecture 8: Pile testing; code design provisions.

In the first lecture, Prof. Poulos outlined the typical applications of piles in marine and harbour works, roads and bridges, buildings, retaining walls, etc. He went on to describe the different types of piles, differentiated by materials (steel, concrete and timber), by effect of installation (displacement, low displacement and non-displacement), and by method of installation (driven, driven and cast-in-place, bored/drilled, composite and screwed). He discussed the effects of pile installation of bored piles, driven piles in clay and driven piles in sand. Some concerns were raised regarding displacement piles; these concerns include vibrations during installation, generation of excess pore pressures, induced vertical and lateral soil movements, accessibility of pile driving rigs, and limitations of headroom in confined spaces. Problems that could arise from induced vertical soil movements include pile uplift and ground heave. Similarly, problems could also arise from induced lateral soil movements, including shearing of piles or movement and damage to adjacent structures.

Prof. Poulos went on to discuss the design requirements for pile foundations. These include the

Ir. kenny Yee, Chairman of Geotechnical Engineering Technical Division presenting a token of appreciation to Prof. Harry Poulos.

design for ultimate limit state (to ensure adequate capacity to resist ultimate load combinations), serviceability limit state (to ensure that deflections and settlements at normal working loads are within tolerable limits), and durability (to ensure that the piles remain durable within its design life). Some design considerations in the selection of pile type and installation method was discussed. He stressed the importance of adequate ground investigations, and the need to extend exploration to the depth of influence of pile or pile group. Four (4) alternative approaches may be adopted for safety considerations, namely:

- *Use of overall safety factor*
  Pa = Pu /FS
- *Use of partial safety factors*
  – factor up the loads and use factored-down soil parameters to compute design resistance
- *Use of load and resistance factored design*
  – resistance computed using factored-down ultimate shaft and base capacities (=Rd)
  – load factored-up load factors (=Sd) – Rd > Sd
  Probabilistic approach

Three categories of analysis and design methods were described, i.e. empirical methods, analytical method based on sound simplified theory and/or design charts, and site specifics methods. He noted that there can be wide variations in the prediction of ultimate load capacity based on the various design methods. Ultimate load capacity is usually obtained by summing the resistances of pile shaft and base. Several methods are available to compute shaft capacity, including the total stress method, the effective stress method, the hybrid/lamda method, by using SPT data, by using CPT data, and by using PMT data.

For piles socketed in rock, the ultimate shaft friction and end-bearing capacity are usually related to the unconfined compressive strength of the rock.

The load capacity of a pile group is related to the pile group efficiency, h, which is the ratio of the group capacity to the sum of the individual pile capacities. For pile groups in clay, h is usually less than 1. For a pile group driven in sand, h is usually greater than 1, whereas for pile groups bored into sand, h is approximately 0.67. For end-bearing pile group _ is usually close to 1.

In the second lecture, Prof. Poulos discussed the methods of analysis of pile-soil interaction, and the load transfer of friction piles and end-bearing piles. He went on to discuss the elastic analysis solutions to compute the settlement of single piles. Several closed-form solutions were discussed, including the Randolph and Wroth (1978) equations. Chart solutions were also discussed, including the Poulos and Davis (1980) solution for uniform soil profile and Poulos (1979) solution for "Gibson" soil profile.

Some of the main characteristics of pile settlement behaviour were outlined. These included:

- *The major part of pile settlement is immediate settlement (typically > 80%)*
- *The effect of compressibility is important for long slender piles*
- *For long compressible piles, settlement is little influenced by soil stiffness at pile tip. The effects of bearing stratum are more pronounced for shorter and stiffer piles*
- *The effect of finite layer is most pronounced for shorter and stiffer piles. It has relatively little effect for long compressible piles*
- *The effect of Poisson's ratio of soil is generally small, especially for more compressible piles*
- *The effects of enlarged base on pile settlement are only significant for relatively short piles*
- *For piles of normal proportions in clay, the load-settlement behaviour is largely linear at normal working loads. Thus, elastic theory can be used directly.*
- *Non-linear effects are important when piles derive much of their capacity from base resistance, for example piles in sand, piles with enlarged base, and large diameter bored piles.*

In the estimation of soil parameters for use in the analysis of pile settlement, soil modulus is the key parameter. However, results from laboratory testing are usually not very useful because of differences in stress paths in the laboratory models and field conditions, as well as difficulty for accounting of pile installation effects in the laboratory models. The interpretation of pile load tests is usually the most satisfactory method, where results are used to fit theory to the observed behaviour.

The settlement of pile groups may be analysed by various methods (hand calculations), including:

- *Interaction factor method*
- *Settlement ratio method*
- *Equivalent raft method*

- *Equivalent pier method*

Based on the comparisons made of the different methods of analysis, the following lessons may be learned:

- *Assessment of soil modulus values is critical*
- *The method of analysis is less critical (provided it is sound)*
- *Extra care should be afforded when analysing very large groups of piles with the interaction factor method. There is a potential for significant over-estimation of settlements*
- *Equivalent raft and pier methods are useful checks on the order of group settlement and should always be carried out in addition to computer analyses*

In the third lecture, Prof. Poulos discussed the behaviour of piles subjected to lateral loading. In this lecture, he discussed issues relating to analysis of ultimate lateral capacity, analysis of lateral deflection of piles, and the interaction and effects of pile groups. Prof. Poulos mentioned that lateral deflections usually govern pile design for lateral loadings. However, ultimate lateral resistance may be important for short piers, long slender piles, and in the non-linear analysis of deflections.

The general principles of analysis of ultimate lateral capacity of piles are to consider either horizontal load equilibrium or moment equilibrium. However, the failure mode and the distribution of the ultimate lateral pile-soil pressure need to be estimated and prescribed. He went on to present various methods of analysis of lateral load capacity in clays, sands and c-ø soils.

For the case of lateral deflection of piles, Prof. Poulos discussed various methods of analysis, including the sub-grade reaction theory, non-linear p-y analyses and continuum soil model. A comparison of the various methods of analyses indicated all the methods show acceptable agreement.

Prof. Poulos mentioned in his lecture that in reality, the leading pile of a laterally loaded group tend to be stiffer and take a larger proportion of the lateral load than the inner or rear piles.

In the fourth lecture, Prof. Poulos discussed the analysis of pile groups and piled raft foundations. For pile group analysis he outlined, simple analytical methods, the equivalent bent analysis, the hybrid analysis, the elastic-based methods for lateral loading and general loading, and finite element analyses. In comparing these methods of analysis, he concluded that vertical pile loads are not very sensitive to the analysis method employed. However, considerable difference occurs between head moments, and group deflections and rotations from the equivalent bent method and elastic analysis.

On the subject of piled raft foundations, Prof. Poulos discussed the design concepts and critical related issues. Piled raft foundations differ from normal pile foundations in that the piles in a piled raft share loads between the raft and the piles. In essence, a piled raft becomes useful the raft is capable of providing significant capacity and stiffness, e.g. in relatively stiff clay profiles and relatively dense sand. Piled rafts are also favourable where soil movements due to external causes do not occur. The circumstances where piled rafts become unfavourable include situations where soft clay and/or loose sand occur near the surface, where compressible layers occur at depth and where consolidation settlements or swelling movements may occur.

In the case of a pile raft foundation, the design focuses more on stiffness of the foundation than its load capacity. The design is based on controlled stiffness and the piles designed as settlement reducers. Hence, the piles in a piled raft operate at lower safety margins than conventional piles. The typical design issues include the ultimate load capacity (vertical, lateral and moment loading), maximum settlement, different settlement, raft moments and shear forces and the pile loads and moments.

Prof. Poulos went on to discuss the design procedures and the methods of analysis. He discussed simplified methods of analysis, which include the Poulos-Davis-Randolph (PDR) method and the Burland (1995) method, and computer analytical solutions. He illustrated the applications in several case histories, which included piled raft foundations for the Westend Strasse 1 Tower in Frankfurt, a building in Sweden, and the Akasaka Building in Sao Paulo, Brazil.

Prof. Poulos described some general observations with regard to piled rafts. These include:

- *The settlement decreases as the number of piles increases*
- *Major reduction in settlement can occur for relatively small number of piles*
- *Increasing number of piles beyond a certain point is ineffective*
- *Piles may reduce bending moments in raft if carefully located*
- *Raft thickness affects differential settlements much more than total settlements*
- *Foundation performance may be improved by using piles of varying length – shorter piles for lighter loads and longer piles for heavy loads*

In the fifth lecture, Prof. Poulos discussed design issues for pile subjected to ground movements. He described some possible sources of ground movement which include consolidation, expansive soil, piles near tunnelling operations, installation of adjacent piles, slope instability, piles near an embankment, piles near an excavation, and the construction of an adjacent building. He discussed the main effects of negative friction on the piles, i.e. it causes increased axial load in the pile and increased settlement of the pile. He described simple methods to estimate the down-drag forces on end-bearing piles. He discussed methods which may be used to reduce magnitude of negative friction on the piles, including provision of surface coating, use of dummy casing outside the pile, and application of electro-osmosis method.

For piles in swelling or expansive soil, Prof. Poulos highlighted several key concerns in design, which include:

- *How much will the pile move due to soil movement?*
- *What forces (tensile) are induced in the pile?*

The analysis approach for piles in expansive soil is similar to piles subjected to negative friction. Problems arise because expansive soils are usually unsaturated, and soil parameters vary with moisture content or soil suction.

Prof. Poulos described examples of piles in soil undergoing lateral movement. These include piles near retaining structures, piles in unstable slopes, pile near embankments, piles near excavations, piles near tunnels, and piles near newly installed piles. In all these cases, the piles are subjected to additional horizontal movements and additional bending moments and shear forces. Prof. Poulos discussed several theoretical solutions for idealised cases. He also discussed approximate methods for predicting pile response to these soil movements. He presented several examples of the analysis of pile response to soil movements.

In the sixth lecture, Prof. Poulos discussed the response of piles to ground movements from tunnelling and excavation works. He outlined the characteristics of pile response near tunnels and discussed the use and application of design charts for single piles. He also discussed 3-D finite element analyses of the effect of tunnelling on forces and bending moments on piles.

Prof. Poulos also discussed the response of pile groups to tunnelling works. He discussed a typical example of a 4-pile group compared with a single pile at the same distance from the tunnel. In comparison, the settlements and lateral deflections of the pile group and the single pile are similar. However, the axial forces piles in the group are less than in a single pile. Thus, it is conservative to use single pile solutions for a small group.

In the seventh lecture, Prof. Poulos discussed design issues for piles subjected to dynamic and earthquake loadings. He outlined dynamic design criteria and the response of simple dynamic systems. He discussed solutions for dynamic loading on single piles and pile groups. In general, 6 modes of vibration for a foundation are recognisable, i.e. 3 translational and 3 rotational modes. He discussed response curves for dynamically loaded systems for varying degrees of freedom. Basic dynamics equations were discussed and dynamic response curves derived for differing conditions were illustrated.

Prof. Poulos also outlined the response of piles subjected to earthquakes and the effects of soil liquefaction on pile response. He further discussed the effects on pile axial loads due to earthquake-induced settlements.

In the eighth lecture, Prof. Poulos issue relating to pile testing. He outlined the types of pile tests commonly carried out, i.e. static load tests, dynamic load tests, and statnamic tests. The static tests are conventional tests, using either the maintained loading method or the constant rate of penetration method. The dynamic load tests are now widely used, whereby the high-strain tests are used to obtain an estimate of the static load capacity, the load-settlement characteristics and the structural integrity of the pile. The low-strain dynamic tests are principally used to measure the structural integrity of the pile.

Prof. Poulos highlighted the usefulness of instrumented test piles as these enable the distribution of skin friction and base load to be evaluated. Typical instrumentation methods include 'tell-tale' strain rods, strain gauges and load cells.

Prof. Poulos also discussed methods of structural integrity assessment of bored piles. These methods utilise non-destructive testing principles and they include core drillings, shaft compression test, radiometric logging, sonic logging, vibration testing, and sonic integrity testing.

In the concluding part of his lecture, Prof. Poulos discussed pile design practises in accordance with the Australian Piling Code requirements. He highlighted issues relating to the requirements for site investigation, general design requirements and procedures, geotechnical and structural design requirements, the design requirements for durability, material and construction requirements, and pile testing. ■

ERRATA

The talk on Water Cascade Table for Minimum Water and Wastewater Targeting by Ms. Tan Yin Ling on 12 April 2003 was attended by about 15 participants; it started at about 10.15 a.m. and lasted for slightly more than an hour, and not as published in the last issue of the Jurutera. The errors are regretted. ■