Practical experience with piled raft design for tall buildings

Expérience pratique de la conception de radiers sur pieux pour les immeubles de grandes hauteurs

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ABSTRACT: For many tall buildings, a practical and cost effective foundation solution is provided by a piled raft. Recent research and field observations have shown that in practically all cases, serviceability conditions control the behaviour of the footings. The design of a piled raft usually requires non-linear analysis in three dimensions, based on detailed knowledge of the ground conditions, the soil and rock properties (especially modulus and its variation with strain), structural loads and raft geometry. Information on ground properties can only reliably be obtained from a detailed ground investigation with a heavy reliance on quality insitu testing. Further information can be obtained from instrumented pile load testing. This paper describes the design of the pile rafts for two tall towers: the 1000 m Nakheel tower in Dubai, which is founded on weak carbonate rocks and a group of tall towers (up to 300 m high) founded in deep alluvial deposits.

RESUME: La construction de radiers sur pieux offre une solution pratique et économique pour les fondations de nombreux immeubles de grande hauteur. Les observations récentes faites sur le terrain et dans le domaine de la recherche ont montré que, dans pratiquement tous les cas, les conditions de service contrôlent le comportement de ces fondations. La conception d'un radier sur pieux nécessite généralement une analyse non linéaire tridimensionnelle, basée sur une connaissance approfondie de l'état du sol en profondeur, des propriétés du sol et de la roche (en particulier le module et sa variation avec la déformation), des charges appliquées par la structure et de la géométrie du radier. Les données sur les propriétés du sol et/ou de la roche ne peuvent être obtenues de manière fiable qu'à partir d'une campagne de reconnaissance géotechnique détaillée et avec des essais de bonne qualité. Des informations complémentaires peuvent être obtenues à partir d'essais de chargement de pieu. Cet article décrit la conception des radiers sur pieux de deux tours de grande hauteur: la tour Nakheel de 1000m de hauteur, à Dubaï, fondée sur des roches carbonatées de faibles caractéristiques et un groupe de tours (jusqu'à 300 m de hauteur), fondées en profondeur dans des dépôts alluvionnaires.

KEYWORDS: piled raft, insitu testing, settlement, pile load testing

1 FACTORS AFFECTING FOOTING PERFORMANCE

For a typical pile-supported footing, it is necessary to consider both individual pile, pile group and raft performance. These require consideration of the behaviour of the ground in critical locations:

- Immediately beneath the surface raft or footing, where the important factors are strength for bearing capacity and stiffness for settlement and interaction effects.
- Along the pile shaft where the factors of most interest are strength for bearing, excavatability and stability; stiffness for settlement and interaction effects; geology and permeability for pile stability and, most importantly, pile shaft resistance.
- At the pile toe where all the factors for the pile shaft are present and in addition the pile end bearing is of interest.
- Beneath the pile where stiffness for pile settlement is important for a depth of at least twice the building width.

Recent research and field observations have shown that in practically all cases, serviceability conditions control the behaviour of the footings. Therefore this paper concentrates on evaluation of ground modulus for the calculation of behaviour at serviceability limit state.

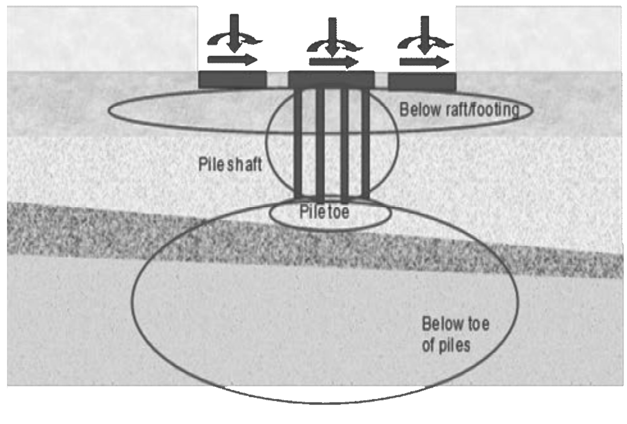

Figure 1 Areas of interest for footing design

2 METHODS OF GROUND INVESTIGATION

For many tall buildings, the ground investigation is required to extend to significant depths (e.g. up to 200 m for the Nakheel tower) due to the heavy loads and relatively large plan area of the building. Where footings do not found on relatively strong rock, a major component of settlement can result from compression of the soil or weak rock below the pile toe. The measurement of representative deformation and strength properties at this depth can be problematic.

2.1 Laboratory testing of core

Core samples subjected to laboratory testing are affected by disturbance and stress relief and can give erroneous results which usually represent a significant underestimate of the insitu stiffness of the material. This leads to over-design of footings, higher costs and in some cases the footings can be impractical to design or construct.

2.2 In situ testing by SPT or cone tests

Two of the insitu tests commonly used in ground investigations; standard penetration tests and cone penetration tests, are either not appropriate for testing at significant depths or cannot penetrate relatively competent founding materials. For example, the results of SPTs at reasonable depth (say 30 m) must be considered to be unreliable due to the rod weight and the resulting ineffectiveness of the impact from the hammer. It is also of very little value to report an 'SPT' value of 50 blows for some nominal (say 50 mm penetration). Such a result cannot be interpreted to give an estimate of ground stiffness.

Cone penetrometer tests are ineffective where they cannot penetrate moderately competent ground. Predrilling to overcome frictional resistance is not a solution since refusal often occurs at the tip.

2.3 Pressuremeter and cross-hole seismic tests

High quality pressuremeter testing and cross-hole seismic testing provide a practical method for obtaining estimates of the deformation parameters of the rock at different strain levels.

The crosshole seismic test provides estimates of small strain modulus which cannot be applied directly to analysis of footings where strains in the ground under dead, live and wind loading are significantly higher than those experienced during seismic testing. As deformation parameters depend on the strain level imposed in the test, this must be taken into account in the test interpretation.

The pressuremeter on the other hand provides deformation properties at strain levels which are commensurate with those of the ground when subjected to service loading from the building. On some sites however, for example in deep alluvial deposits, pressuremeter testing may result in significant disturbance to the ground and hence the results of such testing may not be of benefit. Self-boring pressuremeter tests can overcome this problem, however they may be impractical in relatively hard materials such as discussed in Section 4.

2.4 Instrumented pile load tests

Deformation properties of the ground under load can be obtained from an appropriately designed test on an instrumented pile. The results can be used to supplement those obtained from the tests described in Section 2.3 prior to final design of the footing system.

Load cells (typically Osterberg cells) are located in the pile at chosen depths, while displacement transducers can be located below the tip. By placing one Osterberg cell close to the base of the pile in conjunction with a displacement transducer, the load-displacement performance of the base of the pile can be measured. It is a relatively straight forward process to then back calculate a representative modulus for the material immediately below the pile toe.

By combining the results from pressuremeter and cross-hole seismic tests (adjusted to take into account strain levels), a reasonable level of confidence can generally be obtained to undertake the footing design.

The overall pile load-displacement performance can also be measured and provides a means of back-figuring pile and ground properties for use in a group settlement analysis package such as PLAXIS or FLAC.

2.5 Application of in situ testing to modulus estimates

The methods for estimating ground modulus described in Sections 2.3 and 2.4 are demonstrated for the design of footing systems for two towers. Section 3 describes the application to the design of the proposed 1000 m Nakheel tower in Dubai which is to be founded in a weak calcareous siltstone (UCS of about 2 MPa). Section 4 considers design for a group of tall towers (up to 300 m high) founded in deep alluvial deposits comprising very dense silty sand and hard sandy silt.

3 NAKHEEL TOWER, DUBAI

3.1 The tower and ground conditions

The Nahkeel Tower in Dubai was designed to extend to a height in excess of 1 km. With about 2,000,000 tonnes dead load, the structure would have been one of the heaviest ever built. The project was placed on hold in early 2009 at a stage when about half of the foundations had been constructed.

The high bearing pressures applied to the ground coupled with the soft calcareous rock ground conditions present at the site provided a significant challenge to the design of the footing system.

3.2 Foundation system

Based on prior but limited knowledge of the ground conditions in Dubai, the foundation system concept adopted for the tower was a piled raft. The raft design had a variable thickness, being up to 8 m under the most heavily loaded structural elements. Design founding depth was at about 20 m below ground level, and at the base of a 120 m diameter excavation supported by a circular, embedded diaphragm wall. Approximately 400 barrettes were proposed, for installation to depths of between approximately 60 m and 80 m below ground level. The design of the barrettes had to consider not only the control of ground response to the tower loading, but also various regulatory requirements and constructability issues.

3.3 Ground investigation

The ground investigation (Haberfield and Paul, 2011) comprised an extensive laboratory testing program on core samples together with pressuremeter and crosshole seismic testing. The self-boring pressuremeter tests extended to depths of up to 200 m below ground level. Cross-hole seismic testing was undertaken in arrays of 3 boreholes with 3 m centre-to-centre spacing between the boreholes.

Figure 2 shows the values of initial loading modulus (E_i) calculated from laboratory unconfined compression strength (UCS) tests, pressuremeter tests and cross-hole seismic tests.

The small-strain cross-hole seismic tests gave estimates of modulus which ranged between about 3 to 7 times those measured in the pressuremeter tests at the same depths. This difference is consistent with the effects of strain level on modulus. To obtain a modulus value for engineering design adopting the strain levels appropriate to field behaviour, the cross-hole values were reduced by a factor of five.

The modulus values measured in the UCS tests showed a wide scatter. An upper bound to the results over the depth of interest is around 600 MPa, which is about half the value estimated from the pressuremeter test results.

3.4 Instrumented pile load tests

The preliminary foundation design was based on the results of the in situ tests. However, prior to the detailed design stage, three test barrettes with cross-sectional dimensions of 1.2 m ×

2.8 m were installed to depths of 65 m and 95 m. Load testing of the barrettes comprised two levels of Osterberg cells in each test barrette with each level of cells designed to achieve a bi-directional load of up to 83 MN. The Osterberg cells were positioned to measure performance of the lower 20 m (approximately) of the barrettes .

The remaining instrumentation for each test barrette included strain gauges and tell-tales as well as a displacement transducer located in the rock below the toe in order to directly measure the displacement of the rock at this location. The displacement transducer at the toe of the barrettes was used to make a direct measurement of compression of the ground immediately below the toe.

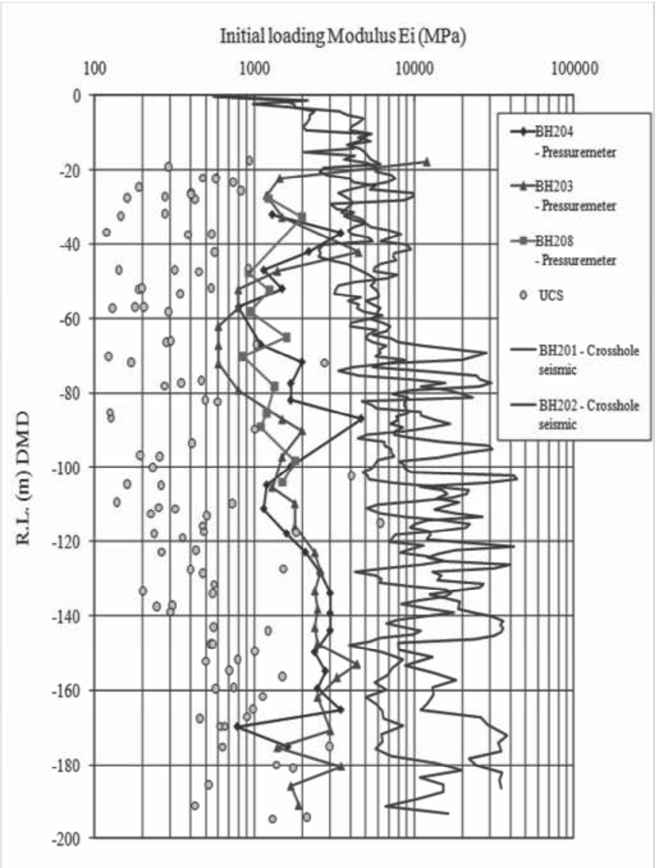

Figure 2 comparison of modulus values form UCS tests, pressuremeter and cross-hole seismic tests

3.5 Comparison of modulus values

The results of the three pressuremeter tests shown in Figure 2 show values of modulus of between about 1200 MPa and 2000 MPa at the depths corresponding to the bases of the barrettes. Reducing the modulus values from the cross-hole seismic tests by a factor of five gives results in the range of 1000 MPa to 4000 MPa (with the highest values being obtained in layers of gypsum).

Back analysis of the test data from the instrumented barrettes indicates a modulus (Ei) of the soft rock below the toe of between 1200 MPa and 1500 MPa.

The most optimistic assessment of the UCS results at the depths considered is about 600 MPa.

There is good agreement between modulus values from the test barrettes, the pressuremeter results and factored-down cross-hole seismic results. This gave confidence in the adoption of a value for final design. Adoption of the laboratory test results would have led to an overly conservative design (and, in fact, would have shown the design of a pile-supported raft to meet the settlement criteria to be impractical).

4 TALL TOWERS ON DEEP ALLUVIAL DEPOSIT

4.1 Ground conditions and original investigation methods

The author has recently been involved in the design of piled rafts for a series of towers from 50 levels to 80 levels. The site is located on a river flood plain and is underlain by very deep alluvial deposits comprising predominantly very dense silty sands and hard sandy silts.

The original ground investigation undertaken by others included SPT tests to about 100 m depth, with SPT refusal (more than 50 blows for less than 150 mm penetration) occurring for all tests below about 30 m depth. It was therefore not possible to make a reliable estimate of ground stiffness from the SPT results.

Menard pressuremeter testing was also performed. The Menard pressuremeter tests gave unrealistically low results, possibly the result of relatively poor drilling methods which caused significant disturbance of the borehole. Cone penetrometer testing was also attempted but the cone refused at relatively shallow depth. Continuation of cone testing beyond refusal depth using predrilling was not successful as cone refusal occurred within 0.5 m of the base of the predrill.

The information from the geotechnical investigation (undertaken by others) was not sufficient to be able to reliably design the foundations for the towers. In addition, preliminary calculations indicated that based on a reasonable interpretation of the ground investigation data, a pile only or pile raft solution of sufficient capacity and dimensions to support the towers could not be practically installed using available piling technology.

4.2 Cross-hole seismic and pile load tests

The author requested cross-hole seismic testing to be undertaken to supplement the original ground investigation data. Two cross-hole seismic tests were carried out to about RL 60 m (CHST1 and CHST2). The two deeper cross-hole seismic tests (CHST3a and CHST4a) were carried out to below RL 10 m. Figure 3 compares estimates of Young's modulus assessed from the various tests. The cross-hole seismic modulus results have been reduced by a factor of five to account for the increased strain levels appropriate to pile performance.

The resulting design line used for the analysis of the pile rafts is also shown in Figure 3.

The author also recommended that pile load testing be undertaken to provided additional information with respect to the properties of ground in the vicinity of the pile shaft and below the toe of the test pile. To maximize the amount of information from the pile testing, Osterberg cell testing using two levels of Osterberg cells was recommended. By using two levels of cells, the shaft resistance between the upper and lower cells could be directly measured without reliance on interpretation of strain gauges which can be problematic. By placing the lower Osterberg cell close to the base of the pile, the direct measurement of the base performance of the pile could also be measured directly. Interpretation of this load versus settlement performance would allow an estimate of the modulus of the ground below the toe of the test pile.

Load testing was carried out on a pile of 1.2 m diameter and about 47 m length, constructed from the basement excavation at about 20 m below surrounding ground level.

The results of the pile load test indicated an unknown but significant thickness of debris at the base of the pile, which made estimation of the modulus of the soil below the toe of the pile more difficult and less certain. An estimate of the modulus of the soil below the toe of the pile was therefore made on the basis of the unload-reload response of the pile load test. This estimate of 250 MPa is reasonably consistent with the results from the factored cross-hole seismic test results shown in Figure 3 at the pile toe elevation (about RL 33 m).

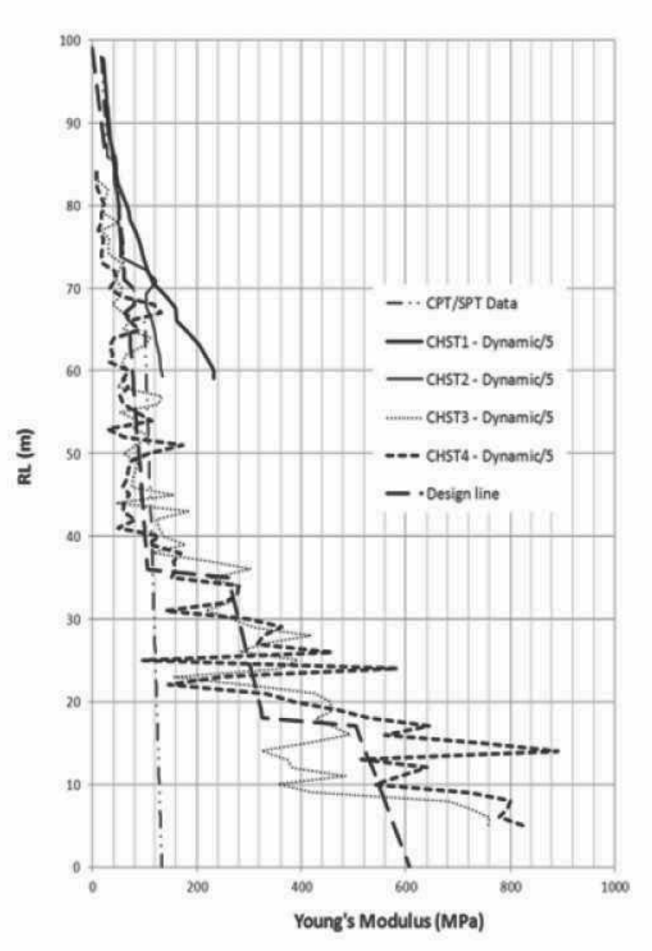

Figure 3 Estimates of modulus assessed from cone tests, SPTs and cross-hole seismic tests

5 CONCLUSION

Piled rafts often form practical solutions for the support of tall buildings on sites comprising weak rock or deep alluvial deposits. The analysis of piled rafts in these ground conditions requires a good understanding of the soil deformation modulus at the appropriate strain level.

Laboratory testing on core samples often underestimates the modulus because of stress relief and sample disturbance. In situ testing by cone penetrometer or by the use of standard penetration testing is often unsatisfactory or impossible in relatively stiff materials such as those encountered at the sites discussed in this paper.

Experience at the sites discussed shows that a careful evaluation of the results of pressuremeter tests, cross-hole seismic tests and instrumented pile load tests can provide a consistent picture of deformation modulus. This consistency provides confidence in the results of the analyses using these values.

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7 REFERENCES

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