Piled raft with different pile length for medium-rise buildings on very soft clay

Y.C. Tan, C.M. Chow & S.S. Gue
Gue & Partners Sdn Bhd, Kuala Lumpur, Malaysia

ABSTRACT: Conventional piled foundation is usually designed to provide adequate load carrying capacity and to limit the overall settlement (and hence controlling differential settlement) within tolerable limit. As such, the piles are often of the same length and size. In this paper, a design approach is presented in which the foundation of a medium rise building (5-storeys) is designed using skin-friction piles of different length. The design objective is to control the differential settlement at the onset rather than limiting the overall settlement. The design utilises the interaction between piled raft and soil in order to produce an optimum design which satisfies both the serviceability and ultimate limit states. The presence of the deep deposit of highly compressible soft clay also poses major challenge in the design as negative skin friction, excessive differential settlement and bearing capacity failure associated with such soft materials need to be addressed. A monitoring scheme on the structures has been successfully implemented and the monitoring results have demonstrated that the foundation system coupled with a properly planned temporary surcharging of the earth platform is very effective. The monitoring results will also allow for further improvement and refinement of design.

1 INTRODUCTION

A residential and commercial development at a site of about 1200 acres at Bukit Tinggi, Klang, Malaysia comprises of two-storey terrace houses, semi-detached houses, commercial units, five-storeys apartments and other amenities buildings. This development is constructed over soft silty clay, termed as Klang Clay (Tan *et al.*, 2004b).

The design and construction of buildings over deep deposit of highly compressible soft clay is often associated with problems such as excessive differential settlement, negative skin friction and bearing capacity failure. Traditionally, piles are introduced to address the issue of bearing capacity and excessive differential settlement. The piles are often installed into competent stratum or 'set' in order to limit the differential settlement by reducing the overall settlement of the structure. However, this solution only addresses short-term problem associated with soft clay as pile capacity is significantly reduced due to negative skin friction. This often reduces the cost-effectiveness of such 'conventional solutions' especially if the depth of the compressible layer is significant. Tan *et al.* (2004a) have presented a design approach for low-rise buildings (less than 3-storeys high) on very soft clay using settlement reducing piles. In this paper, a design approach for 'floating' piled raft foundations for 5-storey apartments is presented together with a discussion on the results of settlement monitoring on the completed buildings.

2 SUBSOIL CONDITION

The alluvial deposits at the site generally consist of very soft to firm silty CLAY up to a depth of 25 to 30m with presence of intermediate sandy layers. The silty CLAY stratum is generally underlain by silty SAND. Klang Clay can be divided into two distinct layers at a depth of 15m. Some of the compressibility parameters of Klang Clay are presented in Fig. 1 and these parameters play a vital role in settlement analyses for the foundation design. The undrained shear strength profile and sensitivity of the Klang Clay as obtained from in-situ field vane shear tests are shown in Fig. 2.

The undrained shear strength of Klang Clay increases almost linearly with depth and shows relatively high values for the first 3m with the existence of overconsolidated crust. The $s_{u(fv)}/P'_c$ ratio of Klang Clay is relatively high with ratio of $s_{u(fv)}/P'_c = 0.4$ and is independent of plasticity index (PI). Engineering properties of the Klang Clay and related correlations are reported in the paper by Tan *et al.* (2004b).

3 DESIGN APPROACH FOR PLATFORM EARTHWORKS

Design approaches for foundations of the buildings on very soft soils have to integrate with ground treatment design for the earthworks so that both designs are technically compatible and efficient. For the current project, both temporary surcharging and preloading techniques are adopted to control long-term settlement of the subsoil under the loads from the fill and buildings to be placed on top of it. Generally, the net fill height at the site is about 0.5m to 1.0m . The temporary surcharging heights ranges from 2 m to 5 m depending on the available waiting period.

After the subsoil had achieved the required percentage of settlement and verified using Asaoka's method (Asaoka, 1978), the temporary earth fills are removed and the construction of the foundation begins.

4 DESIGN APPROACH FOR FOUNDATIONS OF 5-STOREY APARTMENTS

Generally, the loadings of the 5-storey apartments are highest at the columns and ranges from about 100kN to 750kN. The line load from the brick wall is 9 kN/m (4.5" brick wall) and the uniform live load acting on the ground floor raft is 2.7 kN/m^2 (1.5 kN/m^2 live load + 1.2 kN/m^2 floor finishing) as per recommended values given by BS6399: Part 1: 1996. The main design criterion for the 5-storey apartments is to limit the relative rotation (angular distortion) to 1/350 (Skempton & MacDonald, 1956) to prevent cracking in walls and partitions.

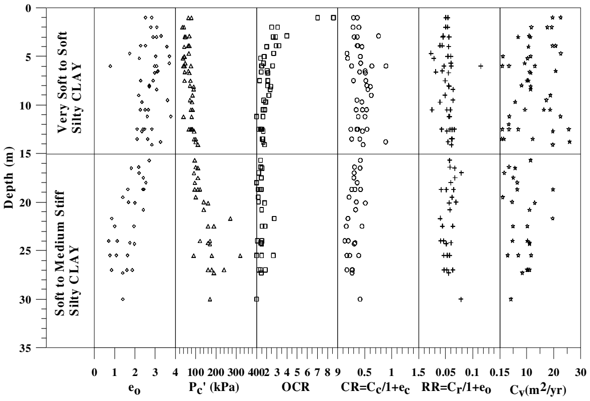


Figure 1. Compressibility parameters for Klang Clay (from Tan *et al.*, 2004b).

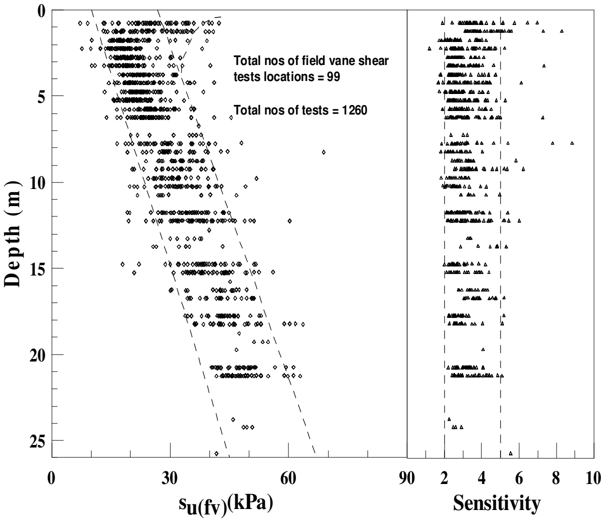


Figure 2. Undrained shear strength and sensitivity of Klang Clay (from Tan *et al.* 2004b).

4.1 *Design methodology*

The objective of the design is to provide an optimum piled raft foundation system that takes into consideration the bearing capacity contribution of the raft and the piles introduced mainly to limit differential settlement. The general approach is to increase the stiffnesses of areas where the settlement is expected to be the largest by introducing settlement reducing piles. Horikoshi & Randolph (1998) suggested that for uniformly loaded raft, piles distributed over the central 16-25% of the raft area is sufficient to produce an optimum design and for piled raft subjected to non-uniform vertical loads, the use of piles with varying length would give the most optimum design (Reul & Randolph, 2004).

The foundation system adopted for the low cost apartments consists of 200mm x 200mm reinforced concrete (RC) square piles with pile length varying from 18m to 24m interconnected with 350mm x 700mm strips and 300mm thick raft. Figure 3 shows typical section of the strip-raft foundation system and Fig. 4 shows schematic view of the foundation system superimposed onto the completed low cost apartments. A total of 504 piles consisting of 284 piles of 18m length, 160 piles of 21m length and 60 piles of 24m length spread over the whole building layout is adopted. This represents pile spacing/pile size, s/d_p ratio of approximately 10 and total pile length (nL_p) of 9912m. The locations of the strips are adjusted during detailed design to ensure they pass beneath all the columns (i.e. concentrated loads) for optimum structural design.

Two cases were considered in the detailed analysis of the foundation system, i.e.:

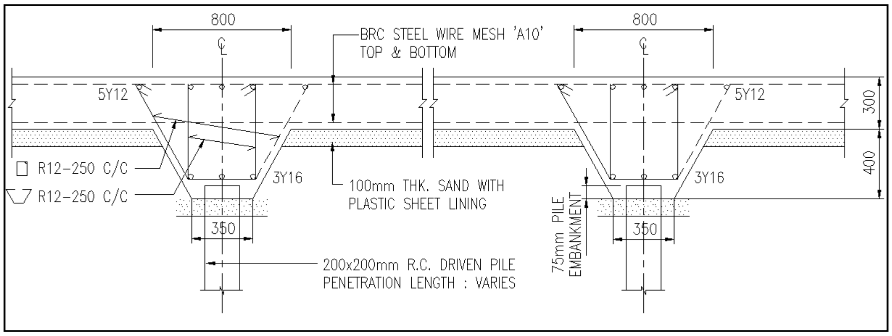
a) Case 1: Overall settlement behaviour
b) Case 2: Pile-soil-structure interaction

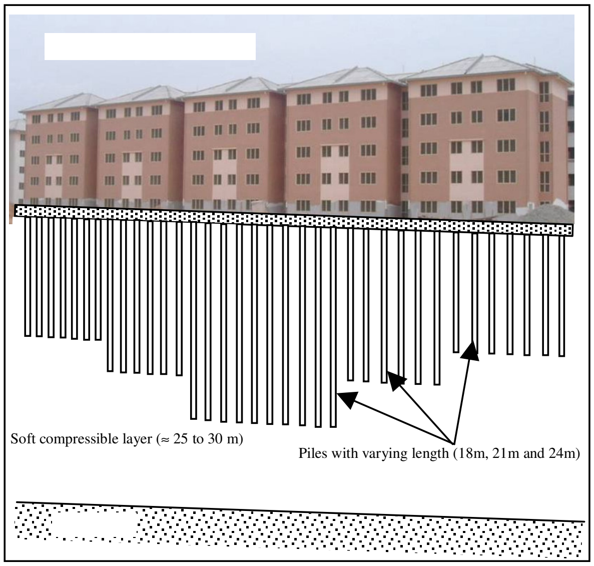
Case 1 considers the overall settlement behaviour of the piled raft foundation system in order to predict the settlement profile for structural design. This is due to limitations of conventional Winkler foundation in modelling actual soil behaviour. The settlement analysis is carried out based on Terzaghi's 1-dimensional consolidation theory. Appropriate adjustments are made to the pressure imposed on the subsoil due to distribution of the superstructure load by the piles using the concept of equivalent raft. The settlement profiles obtained are then used to determine the spring stiffness or Winkler's modulus to generate the overall stresses on the foundation raft due to the settlement profile.

Case 2 considers the interaction between the pile-soil-structure (foundation raft) of the foundation system in order to determine the load distribution and local settlement of the piles. Results from this analysis will also be used for the structural design of the foundation raft to complement Case 1. The pile-soil-structure interaction can be carried out iteratively using elastic pile interaction software (e.g. PIGLET/PIGEON) together with finite element structural analysis software (e.g. SAFE) until convergence of results is achieved (typically ±10%). The iterative approach is proposed due to limitations of available software in modelling pile-soil-structure interaction. It must be noted that the analysis can also be carried out using 3-dimensional finite element method (FEM) software (e.g. PLAXIS 3-D Foundation) that can model 3-dimensional pile-soil-structure interaction. However, the FEM software at this stage places a great limitation on the numbers of piles that can be modelled practically within reasonable time and computer resources. Some of the limitations of existing pile interaction and structural analysis software in modelling pile-soil-structure interaction have been discussed by Tan and Chow (2004).

As the foundation system consists of varying pile length, the solutions of Randolph and Wroth (1979) which is derived for piles of uniform length and adopted in the software PIGLET (which only allows single pile length as input) is no longer applicable for the current design. Therefore, the original equation proposed by Randolph and Wroth (1979) is revisited by the Authors in order to derive a solution for piles with varying pile length.

The solution for pile interaction proposed by Randolph and Wroth (1979) is based on the solution for single pile (Randolph & Wroth, 1978) and extended for pile groups based on the principle of superposition. A stiffness matrix relating load, P_t and settlement, w_t is then obtained with the pile length incorporated into the matrix as a constant. The method is based on the superposition of individual pile displacement fields, considering the average behaviour down the pile shafts separately from that beneath the level of the pile bases. For cases with different pile lengths, the interaction of the pile bases at different levels is very complicated and its effect to shear stress along the pile shaft unknown. However, for the current application in soft ground, the pile capacity is derived primarily from shaft/skin friction with very little end-bearing contribution. Therefore, the original equation proposed by Randolph and Wroth (1979) can be rewritten with pile length as variable where every single pile in the group can be assigned different values of pile length. This has been incorporated in the Authors' firm's internally developed software, Pile Group Analysis Using Elastic or Non-linear Soil Behaviour, PIGEON (Chow & Cheah, 2003).



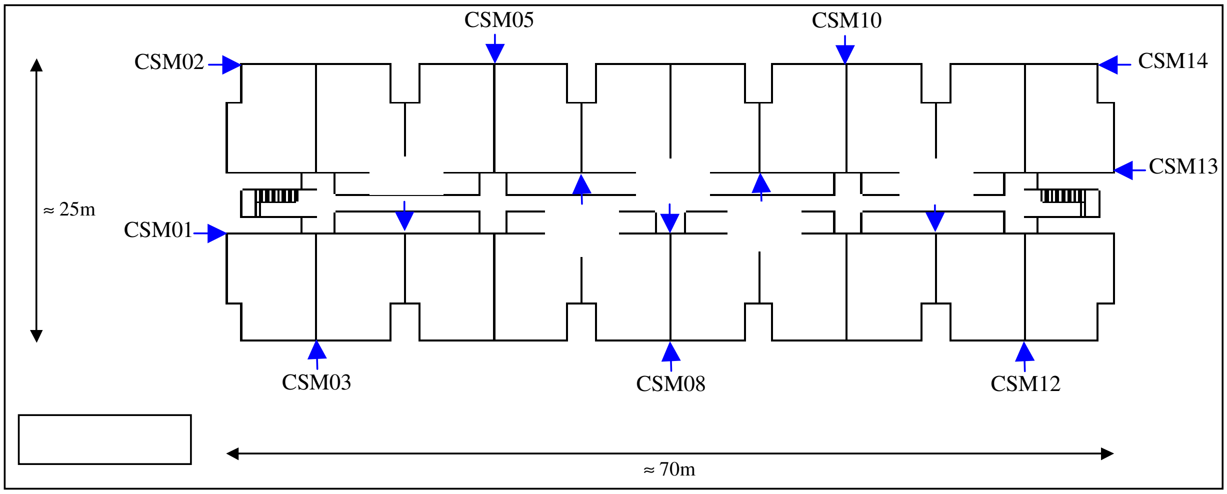


5 SETTLEMENT MONITORING

A total of 14 precise settlement markers were installed at ground floor columns of the structure as shown in Fig. 5 to monitor the performance of the foundation system. Monitoring works were carried out starting from September 2003 when construction works had reached the 3rd floor to July 2004 when the building has been completed for more than six months. Only CSM02, 05, 06, 07, 10, 11, 12, 13 & 14 were recorded until July 2004 as the other instruments were damaged during the monitoring period.

The monitoring results (Fig. 6) showed that the maximum differential settlement recorded is 27.02mm (between CSM05-CSM12). Figures 7 and 8 show the settlement profile across the length of the apartments (≈ 70m) at the edge and at the centre of the building. The relative maximum local angular distortion recorded is 1/1215 (between CSM07-CSM09). The monitoring results also show the building experiences marginal tilt of approximately 1/1000 (Fig. 9). This is probably due to the presence of another block of apartment adjacent to the current block being monitored. However, the value is well within the limits of 1/250 to 1/500 (Charles & Skinner, 2004) for it to be noticeable.

The monitoring results showing relatively smaller settlement at the edge of the building also indicate that improvement and refinement of design by further shortening piles at the edge (or totally omitting piles at the edge) can be explored. By reducing the stiffness at the edge, it may lead to a more economical design and better performance of the building due to smaller differential settlement. This is consistent with the findings of Reul and Randolph (2004) who suggested that for a raft under uniform loading or core-edge loading, the differential settlements can be most efficiently reduced by installation of piles only under the central area of the raft. However, careful considerations of structural and total settlement requirements shall be evaluated before further optimization are carried out.



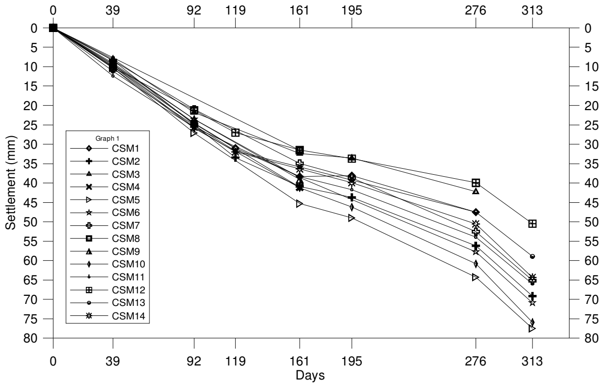


Figure 6. Settlement monitoring results.

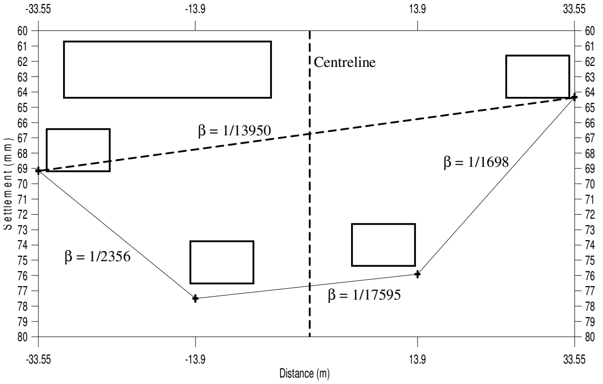


Figure 7. Settlement profile across CSM02, CSM05, CSM10 and CSM14.

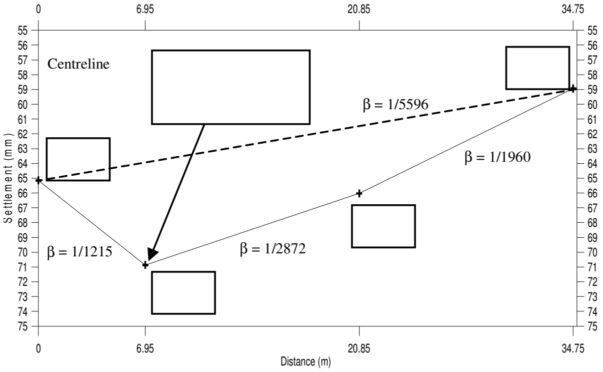


Figure 8. Settlement profile across CSM07, CSM09, CSM11 and CSM13.

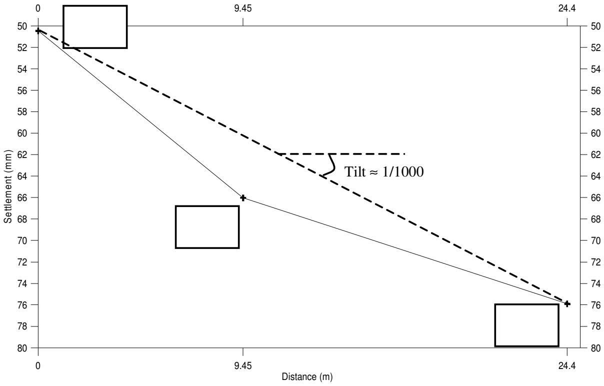


Figure 9. Settlement profile across CSM10, CSM11 and CSM12.

6 CONCLUSION

An iterative design approach for piled raft foundation for 5-storey apartments using settlement reducing piles of varying length in soft ground is presented. The foundation system consists of piled raft with varying pile lengths with longer piles in the central portion of the building and progressively shorter piles toward the edge. The detailed design of the foundation system requires the following cases to be considered:

a) Case 1: Overall settlement behaviour
b) Case 2: Pile-soil-structure interaction

Case 1 considers the overall settlement behaviour of the piled raft foundation system in order to predict the settlement profile for structural design. Meanwhile, Case 2 considers the interaction between the pile-soil-structure (foundation raft) of the foundation system in order to determine the load distribution and local settlement of the piles and also for structural design of the foundation raft to complement Case 1.

A monitoring programme was succesfully carried out and the results show that the foundation system adopted performs satisfactorily.

ACKNOWLEDGEMENTS

The various discussions between the Authors and Mr. Cheah Siew Wai on the development of the design approach presented in this paper are gratefully acknowledged.

REFERENCES

Asaoka, A. 1978. Observational procedure of settlement prediction. *Soils and Foundations,* 28(4), 87-101.

British Standard Institution. 1996. *BS6399: Part 1: 1996: Code of practice for dead and imposed loads.*

Charles, J.A. and Skinner, H.D. 2004. Settlement and tilt of low-rise buildings. *Proceedings of the Institution Civil Engineers-Geotechnical Engineering,* 157 (2), 65-75.

Chow, C.M. and Cheah, S.W. 2003. *PIGEON (Scientific Manual). Gue & Partners In-House Publication.*

Horikoshi, K. and Randolph, M.F. 1998. A contribution to optimum design of piled rafts. *Geotechnique,* 48(3), 301-317.

Randolph, M.F. and Wroth, C.P. 1978. Analysis of deformation of vertically loaded piles. *Journal of the Geotechnical Engineering Division*. Proc. of the ASCE, 104, GT12, 1465-1488.

Randolph, M.F. and Wroth, C.P. 1979. An analysis of the vertical deformation of pile groups. *Geotechnique,* 29(4), 423-439.

Reul, O. & Randolph, M.F. 2004. Design Strategies for Piled Rafts Subjected to Nonuniform Vertical Loading. *Journal of Geotechnical and Geoenvironmental Engineering,* 130(1), 1-13.

Skempton, A.W. & MacDonald, D.H. 1956. The allowable set-tlement of buildings. *Proceedings Institution Civil Engineers,* 3(5), 727-784.

Tan, Y. C., Chow, C. M. & Gue, S. S. 2004a. Piled raft with short piles for low-rise buildings on very soft clay. *Proceedings 15th SEAGC*, Bangkok, Thailand, 171-176.

Tan, Y.C., Gue, S.S., Ng, H.B. & Lee, P.T. 2004b. Some geotech-nical properties of Klang Clay. *Proceedings Malaysian Geotechnical Conference*, 179-185, Kuala Lumpur.

Tan, Y. C. & Chow, C. M. 2004. Design of piled raft foundation on soft ground. *GSM-IEM Forum: The roles of engineering geology & geotechnical engineering in construction works*, Kuala Lumpur.