

Methodology for Design of Piled Raft for Five-Storeys Buildings on Very Soft Clay

Tan, Y.C.¹, Cheah, S.W.¹ and Taha, M.R.²

Abstract

Conventional piled foundation is usually designed for buildings to provide adequate load carrying capacity and to limit the overall settlement and hence control differential settlement within tolerable limits. Piles are often installed into competent stratum or to 'set'. However, this solution generally only addresses the short-term problem associated with soft clay as pile capacity is also significantly reduced due to negative skin friction. This often reduces the cost-effectiveness of such 'conventional solution'. In this paper, design methodologies of a 'floating' piled raft foundation system for medium rise building (5-storey) on soft clay are discussed. The design objective is to control the differential settlement at the onset rather than only limiting the overall settlement. The foundation of medium rise building is designed using skin-friction piles of different length. The design also considers the interaction between piled raft and soil in order to produce an optimum design which satisfies both serviceability and ultimate limit states. The design methodologies and monitoring results of the successfully implemented buildings are also presented in the paper.

1.0 Introduction

The medium rise building is located at a residential and commercial development of about 1200 acres at Bukit Tinggi, Klang, Malaysia which comprises of terrace houses, semi-detached houses, bungalows, apartments, commercial units, and other amenities. This development is constructed over soft silty clay, termed as Klang Clay (Tan et al., 2004a).

The conventional design approach and construction of buildings over deep deposit of highly compressible soft clay is often associated with problems such as

¹ Gue and Partners Sdn Bhd, Kuala Lumpur, Malaysia, 39-5 Jalan 3/146, The Metro Centre, Bandar Tasik Selatan, 57000 Kuala Lumpur, Malaysia. e-mail: gnp@gueandpartners.com.my

² Professor, Dept. of Civil & Structural Eng., University Kebangsaan Malaysia, Bangi, Malaysia, e-mail: dmrt@eng.ukm.my

excessive differential settlement, negative skin friction and bearing capacity failure. Piles are introduced to address the issue of bearing capacity and excessive differential settlement. The piles are often installed into competent stratum or to ‘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. (2004b) have presented a design methodology for low-rise buildings (less than 3-storey high) on very soft clay using settlement reducing piles. In this paper, a design methodology 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.

2.0 Subsoil Condition

The alluvial deposits at the site generally consist of very soft at the top to firm silty CLAY layer up to a depth of 25 to 30m with the 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. The details of Klang Clay are presented in the paper by Tan *et al.* (2004a).

3.0 Design Approach for Platform Earthworks

Design approaches for foundation of the apartments on very soft soils are integrated with ground treatment design for the earthworks so that both designs are technically compatible and efficient. In this 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. Asaoka’s method (Asaoka, 1978) was adopted to determine the degree of consolidation. After the subsoil had consolidated to the required degree of consolidation, the temporary earth fills were removed and followed by the foundation works.

4.0 Design Methodology for Foundation of 5-Storey Apartments

4.1 Design concept and methodology

Differential settlement control approach has been adopted for foundation of 5-storey apartment where the settlement reducing piles are introduced at the concentrated load area or large settlement area to control the differential settlement but not necessarily reducing the average total settlement significantly.

Horikoshi and 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 and Randolph,

2004). However, these recommendations have yet to be explored for medium rise buildings with concentrated column loads on very soft clay.

Poulos (2001) suggested that in order to provide an optimum piled raft foundation design, the following aspects shall be considered and checked: -

- (a) Ultimate load capacity of piled raft for vertical, lateral and moment loadings
- (b) Maximum settlement
- (c) Differential settlement
- (d) Raft moments and shears for the structural design of the raft
- (e) Pile loads and moments for the structural design of the piles

4.2 Structural column loadings

Generally, the column loads 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 inch thick brick wall) and the uniform live load acting on the ground floor raft is 2.7 kN/m² (1.5 kN/m² live load + 1.2 kN/m² 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 differential settlement and relative angular distortion to 1/350 (Skempton and MacDonald, 1956) to prevent cracking in walls and partitions.

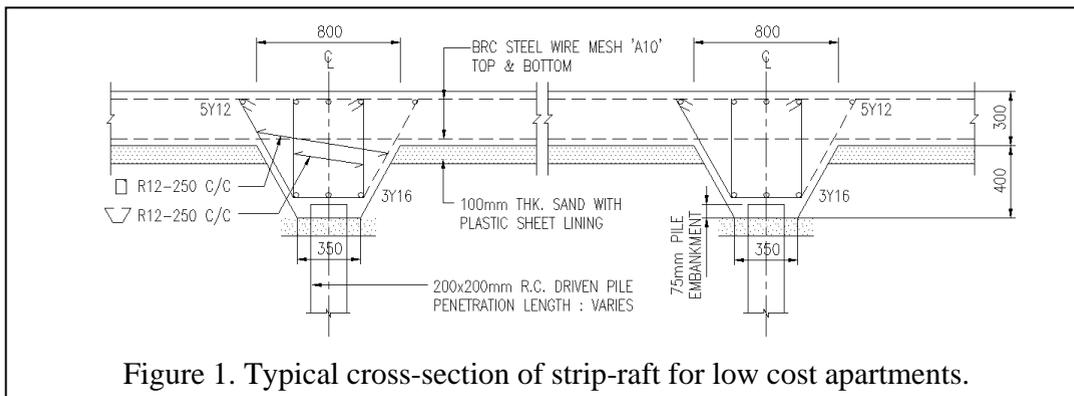


Figure 1. Typical cross-section of strip-raft for low cost apartments.

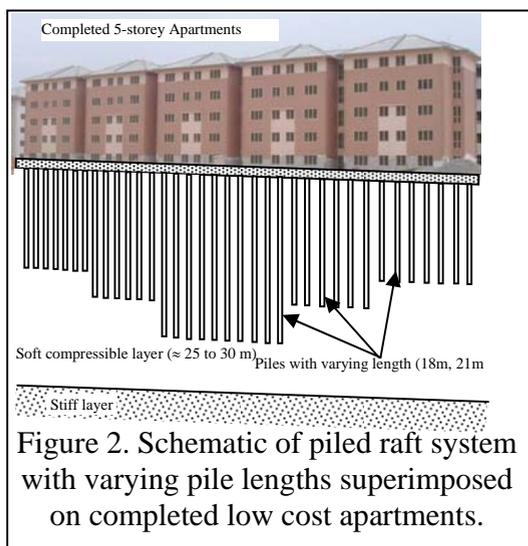


Figure 2. Schematic of piled raft system with varying pile lengths superimposed on completed low cost apartments.

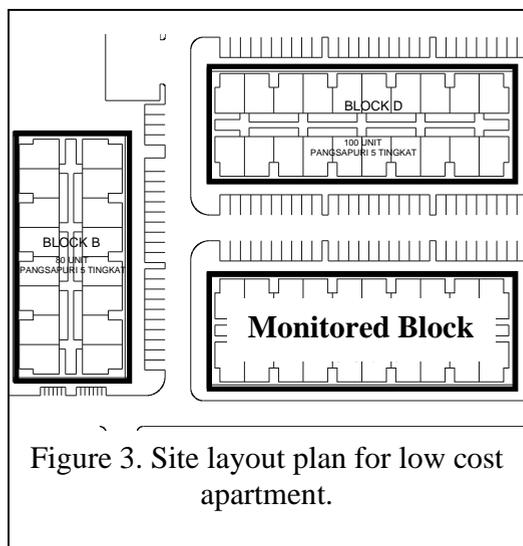


Figure 3. Site layout plan for low cost apartment.

4.3 *Foundation system of 5-Storey apartments*

The foundation system adopted for the low cost apartments consists of 200mm x 200mm reinforced concrete (RC) square piles of lengths varying from 18m to 24m interconnected with 350mm x 700mm strips and 300mm thick raft.

Fig. 1 shows a typical section of the strip-raft foundation system and Fig. 2 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 the strips are available beneath all the columns (i.e. concentrated loads) for optimum structural design.

4.4 *Foundation analysis and design*

Two major cases were considered in the detailed analysis for the foundation of 5-storey apartment, i.e.: -

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

Case 1 takes into consideration of the pile-soil-structure (foundation raft) interaction in order to determine the stresses distribution and deformation and settlement of the piles and raft. The modelling of pile-soil-structure interaction can be carried out using 3-dimensional finite element method (FEM) software (e.g. PLAXIS 3-D Foundation). However, due to the computation limit, the available FEM software for engineering usage at this stage can only account for simple piled raft problems with small numbers of piles at reasonable time and computer resources but not for complicated piled raft problems with irregular loadings pattern and large numbers of piles. Therefore, an iterative approach using combination of 2-dimensional FEM software (e.g. SAFE) to compute the structural stresses induced in the raft foundation and elastic pile interaction software (e.g. PIGLET/PIGEON) to compute the pile-soil-pile interaction has been adopted to reduce the required computation time.

Since the foundation system of the 5-storey apartment consists piles of varying lengths, therefore, the solutions of Randolph and Wroth (1979) which was 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. Hence, the original equation proposed by Randolph and Wroth (1979) is revisited by the Authors 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 and 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 concept has been incorporated in the software, Pile Group Analysis Using Elastic or Non-linear Soil Behaviour, PIGEON (Chow and Cheah, 2003).

Fig. 3 shows the site layout plan for the 5-storey apartments. In this layout, as the apartments are located close to each other, the pile-soil-pile interaction of the adjacent blocks have also been considered in the foundation analysis instead of considering the pile-soil-pile interaction within the individual block only.

As Case 1 only addresses the short term behaviour of the piled raft foundation, therefore, an additional case, namely Case 2 is required to address the long term behaviour of the piled raft foundation which considers the overall settlement behaviour (immediate and consolidation settlement) of the piled raft foundation system in order to predict the settlement profile for structural design. The settlement analysis is carried out based on Terzaghi's 1-dimensional consolidation theory. The stresses in the subsoil induced by adjacent blocks of buildings have been taken into consideration in the settlement analysis. Appropriate adjustments were 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 in the 2-dimensional FEM software to generate the overall stresses on the foundation raft due to the settlement profile.

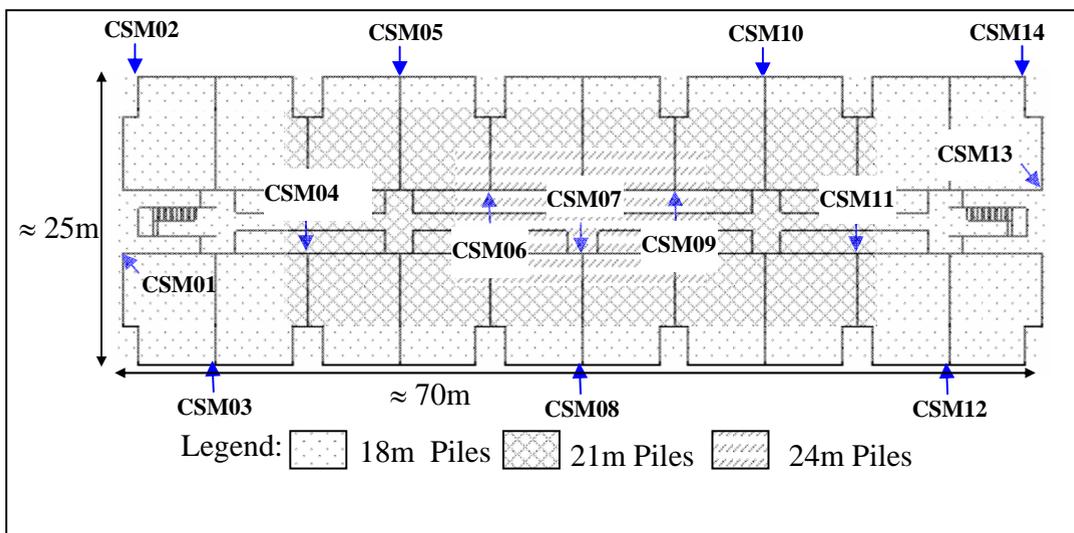


Figure 4. Locations of column settlement markers. (Plan View)

5.0 Settlement Monitoring

A total of 14 precise settlement markers were installed at ground floor columns of the structure as shown in Fig. 4 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 October 2004 when the building has been

completed for more than nine months. Settlement points CSM01, CSM03, CSM04 and CSM08 were damaged and the values were extrapolated from the trend of available earlier readings.

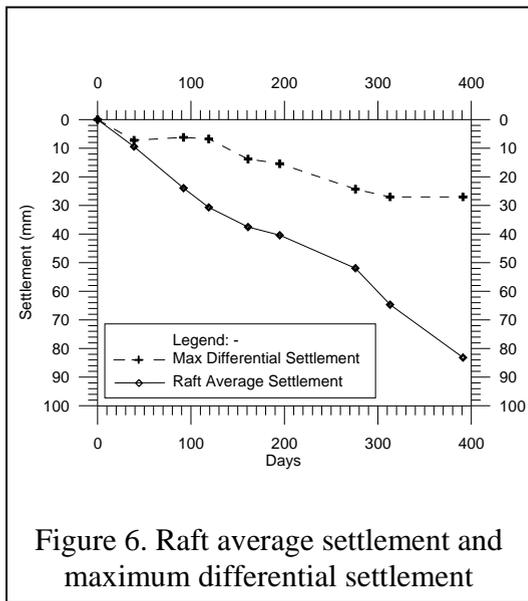
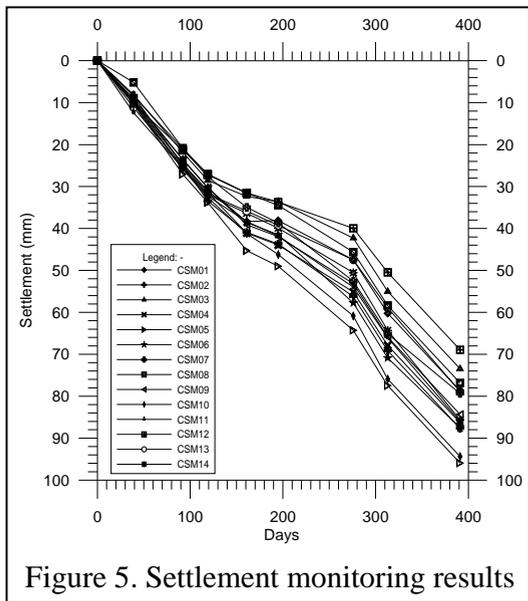


Figure 6. Raft average settlement and maximum differential settlement

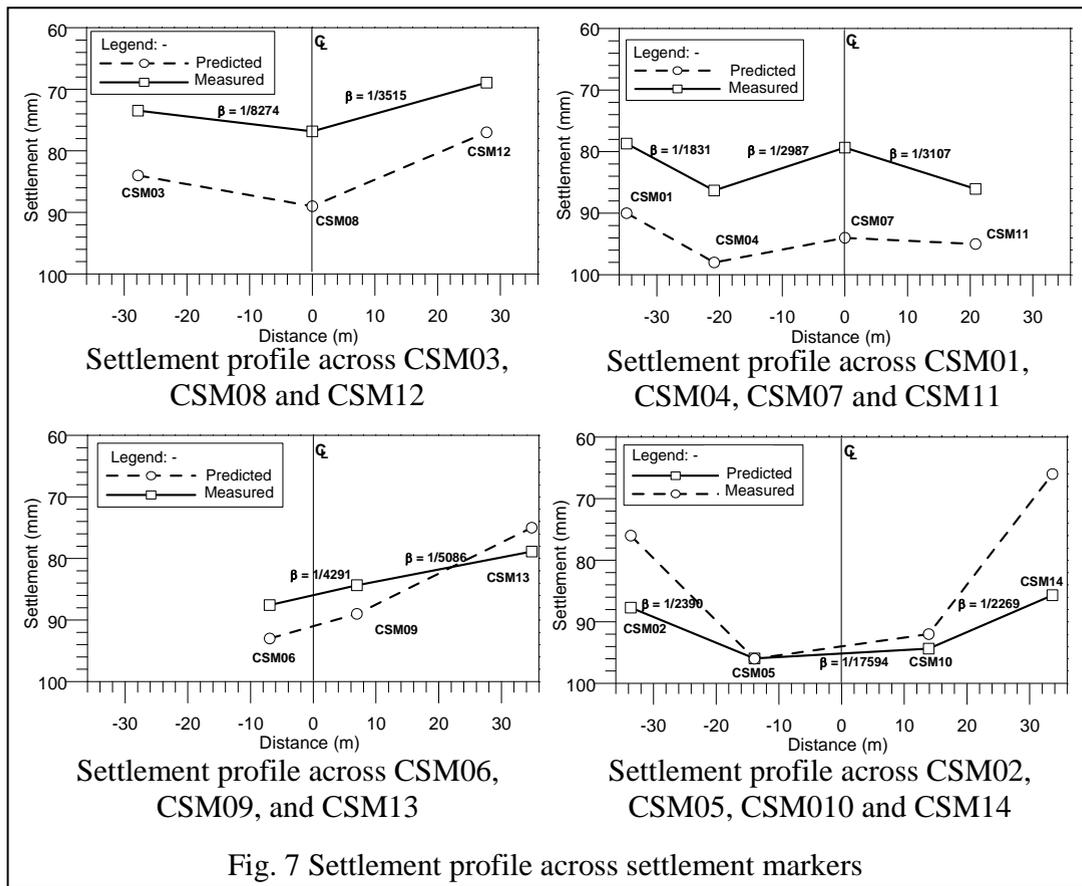


Fig. 7 Settlement profile across settlement markers

The measured settlement monitoring results of the 14 settlement markers are presented in Fig. 5 while the average settlement and maximum differential settlement are shown in Fig.6. The maximum differential settlement stabilised at about 27mm for the last two monitoring measurement while the average building settlement does not stabilised due to consolidation settlement.

Fig. 7 shows both the measured and predicted (from Case1) cross-sectional settlement profile of the apartments at the edge and centre of the apartment. The relative maximum local angular distortion recorded is 1/685 (between CSM11-CSM12). The monitoring results also show that the apartment experiences tilting towards the adjacent blocks (towards left and top side of the apartment) as shown in Fig. 8 due to the stress influence from adjacent blocks.

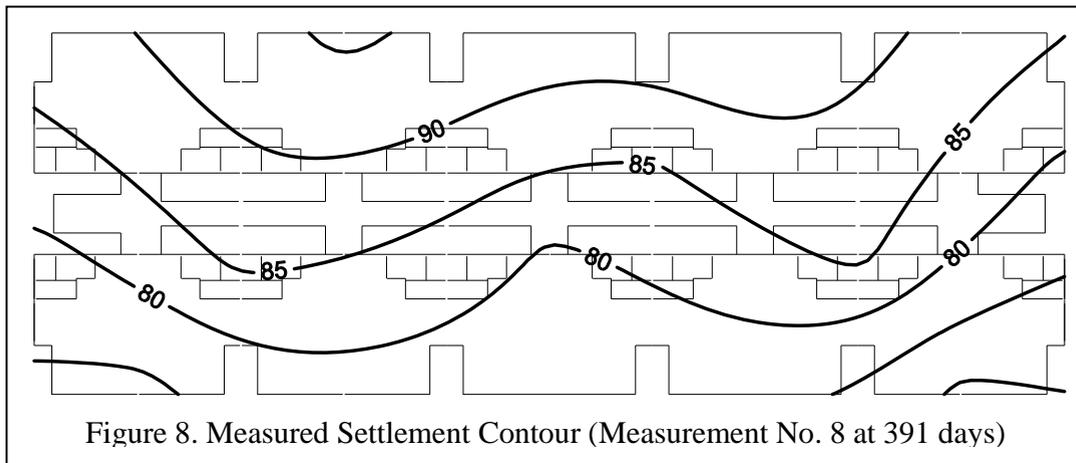


Figure 8. Measured Settlement Contour (Measurement No. 8 at 391 days)

The monitoring results show relatively smaller settlement at the edge of the building also indicate that further improvement and refinement by shortening piles or totally omitting piles at the edge of the apartment can be explored. A reduction of stiffness at the building edge may lead to a more economical design and improved raft performance as differential settlement can be reduced.

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 especially for buildings on very soft ground where bearing capacity is also of major concern.

6.0 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 involved pile-soil-structure interaction analysis of the piled raft foundation (Case 1) in order to determine the

load distribution and local settlement of the piles. The overall settlement behaviour of the piled raft foundation system (Case 2) has also been incorporated in the design. The influence of adjacent blocks has to be taken into consideration in the piled raft foundation design as confirmed by the monitoring results.

References

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

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. and 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. and MacDonald, D.H. 1956. The allowable settlement of buildings. *Proceedings Institution Civil Engineers*, 3(5), 727-784.

Poulos, H. G. 2001. Pile raft foundations: design and applications. *Geotechnique* 51, No. 2, 95-113.

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

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