A Design Approach for Piled Raft with Short Friction Piles for Low Rise Buildings on Very Soft Clay

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Abstract: Geotechnical works in 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. Piles are often installed into competent stratum or 'set' in order to limit the differential settlement by reducing the overall settlement of a structure. However, this solution generally only addresses 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, a design approach is presented in which a 'floating' piled raft foundation system is adopted for a proposed housing development on soft clay. The 'floating' piled raft foundation is designed to limit differential settlement and it consists of short piles strategically located at areas of concentrated loadings and interconnected with a rigid system of strip-raft to control differential settlement. This foundation system coupled with a properly planned temporary surcharging of the earth platform has shown to be very effective as demonstrated by monitoring results on the completed structures.

1 INTRODUCTION

A residential and commercial development was carefully planned and executed at a site of about 1200 acres at Bukit Tinggi, Klang, Malaysia, which is about 40 km towards south west of Kuala Lumpur. This development was constructed over soft silty clay, termed as Klang Clay (Tan *et al.*, 2004). The proposed and constructed buildings mainly consist of two-storey terrace houses, semi-detached houses, commercial units, five-storey apartments and also other amenities buildings.

Construction and maintaining 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 also significantly reduced due to negative skin friction. This often reduces the cost-effectiveness of such 'conventional solution'. In this paper, a design approach is presented in which a 'floating' piled raft foundation system is adopted for two-storey terrace and semi-detached houses on soft clay. At the time of preparation of this paper, more than 1000 units of two-storey and semi-detached houses supported by the 'floating' piled raft have been constructed and ready for occupancy. Some settlement monitoring results on the buildings are presented and discussed in this paper.

2 SUBSOIL CONDITION

The alluvial deposits at the site generally consist of very soft to firm silty CLAY up to a depth of 25 m to 30 m 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 depth of 15 m. 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 value for the first 3 m 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.* (2004).

3 DESIGN APPROACH FOR PLATFORM EARTHWORKS

The design approaches for foundation 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. In Malaysia, many foundation failures investigated by the Authors (Gue *et al.*, 2004) show that these failures are either caused by settlement of the subsoil not being taken into consideration in the foundation design or lack of geotechnical engineering knowledge on settlement problems.

For the current project, both temporary surcharging and preloading technique is 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 0.5 m to 1.0 m and the average uniform load from the two-storey terrace houses is about 25 kPa. The temporary surcharging heights ranges from 2 m to 5 m depending on the available waiting period.

After the subsoil has 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.

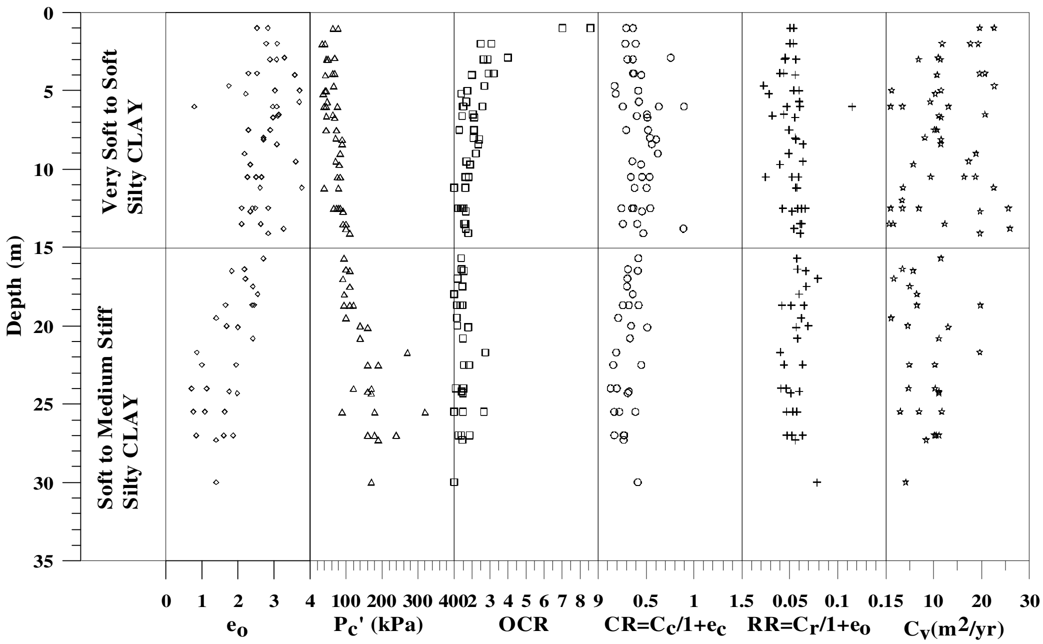

Fig. 1. Compressibility parameters for Klang Clay (from Tan *et al*., 2004).

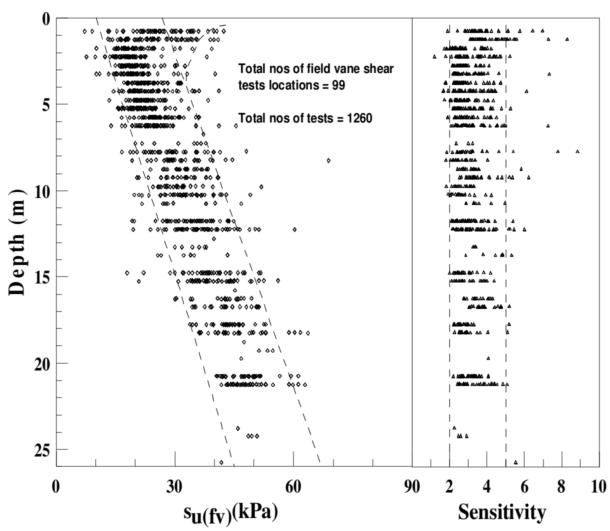

Fig. 2. Undrained shear strength and sensitivity of Klang Clay (from Tan *et al.* 2004).

4 DESIGN APPROACH FOR FOUNDATIONS OF TWO-STOREY TERRACE AND SEMI-DETACHED HOUSES

4.1 *Loadings of two-storey Houses and Design Criteria*

Generally, the loadings of 2-storey houses are highest at the columns and ranges from 10 kN to 360 kN. The line load from the brick walls ranges from 9 kN/m (4.5" brick wall) to 16 kN/m (9" brick wall) and the uniform live load acting on the ground floor raft ranges from 2.5 kN/m^2 to 3.0 kN/m^2 as per recommended values given by BS6399: Part 1: 1996. The main design criterion for the two-storey houses is to limit the relative rotation (angular distortion) to 1/350 (Skempton & MacDonald, 1956) to prevent cracking in walls and partitions. The long-term total settlement (20 years) should not be more than 75 mm after completion of the building. Even when the total settlement is larger than the designed value, the buildings will still not crack as differential settlement is controlled.

4.2 *Design Methodology*

Many cases on the use of settlement reducing piles to support a structure have been reported (e.g. Love, 2003, Yamashita *et al.* 1994 and Burland & Kalra, 1986). Recent understanding and advances in the design and analysis of piled raft foundation (e.g. Poulos, 2001 and Randolph, 1994) have also enabled practicing engineers to adopt the concept of settlement reducing piles with greater confidence.

The approach adopted in this paper generally follows the recommendations of Poulos (2001) where four circumstances in which a pile is provided beneath a concentrated load (i.e. column):

a) Condition 1: if the maximum moment in the structural member below the column exceeds the allowable value for the structural member.
b) Condition 2: if the maximum shear in the structural member below the column exceeds the allowable value for the structural member.
c) Condition 3: if the maximum contact pressure below the foundation exceeds the allowable design value for the soil.
d) Condition 4: if the local settlement below the column exceeds the allowable value.

The only difference between Poulos (2001) recommendations and the proposed approach by the Authors is that Poulos (2001) recommendations are only for stiff/dense soil. The approach described in this paper however, has been extended for very soft soils.

In order to adopt the concept of settlement reducing piles, the foundation raft must be able to provide adequate bearing capacity in the first place and the piles are solely introduced to control differential settlements within allowable values (e.g. 1/350), and also reduces the stresses on the structural member. A simple calculation based on bearing capacity theory would indicate that the raft for one block of 12 units of terrace houses typically measuring 15 m x 80 m and one block of semi-detached houses typically measuring 20 m x 20 m would provide adequate bearing capacity. However, the concentrated column loads would impose large contact pressure below the foundation and would lead to excessive local settlement leading to cracks on buildings. Therefore, Condition 3 and Condition 4 arise which necessitate the introduction of settlement reducing piles. The settlement reducing piles are designed as friction piles and this eliminate the risk of structural failure or inadequacy of piles due to negative skin friction.

The structural member of the foundation system consists of combination of strips and raft. This system is adopted to minimize the thickness of the raft for maximum economic benefits while not sacrificing the required rigidity. Therefore, the strips serve the dual purpose of providing the required rigidity to the foundation system and also as pile caps to distribute the column loads to the piles. With the strips located directly beneath the columns, Conditions 1 and 2, which are governed by structural considerations, are no longer critical.

4.3 *Analysis*

The locations of the settlement reducing piles as determined based on Conditions 3 and 4 mainly concentrates at column locations and along the long span of line loads. With the piling layout confirmed and the framing of the strip-raft completed, detailed analysis of the foundation system to determine the stresses induced on the structural members are carried out for subsequent structural design. This can be carried out using commercially available structural analysis software.

However, due to the limitations of structural analysis software where supports are usually modelled using uncoupled spring constants or Winkler foundations, it is necessary to determine the appropriate spring constants to account for the actual behaviour of the foundation system. The limitations of the Winkler foundations as highlighted by Poulos (2000) must be clearly understood in order to produce meaningful analysis results. The detailed analysis carried out can be broadly divided into two categories:

a) Local stresses at locations of concentrated loads
b) Overall stresses for the whole block of the houses

Analysis to determine local stresses are further divided into three different cases:

a) Case 1: Pile performance as per prediction
b) Case 2: Pile performance is lower than prediction (under-capacity)
c) Case 3: Pile performance is better than prediction (over-capacity)

The three cases are to cater for possible variations in the subsoil properties and pile installation procedures resulting in different values of relative pile stiffness and soil stiffness beneath the raft. The variations of the stiffness would affect the stresses generated in the structural member and needs to be taken into consideration. Similar design approach using settlement reducing piles has also been adopted by Love (2003).

As highlighted by Terzaghi (1955) and Poulos (2000), the Winkler system has its limitations in that it is only able to furnish values of local stresses. Therefore, in order to cater for overall stresses on the whole block of the houses, additional settlement analyses are carried out to determine the settlement profile for subsequent determination of spring stiffness for the piles and soil. The settlement analysis is carried out based on Terzaghi's 1-dimensional consolidation theory and the stress distribution is based on Boussinesq's theory. The raft is assumed to be truly flexible which is on the conservative side for design. The settlement analysis also takes into consideration the effect of adjacent rows of houses as shown in Figs. 3 and 4.

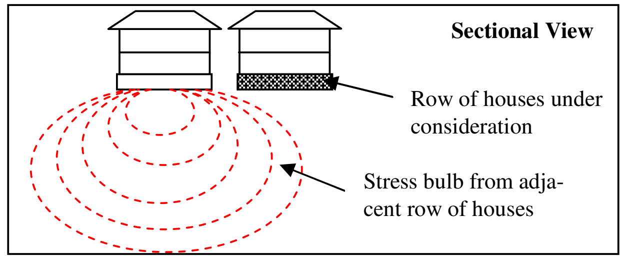

Fig. 3. Effect of adjacent houses on settlement (terrace house).

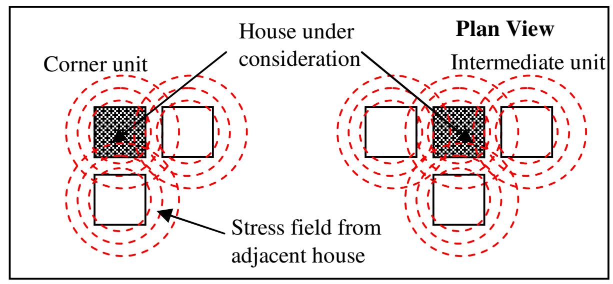

Fig. 4. Effect of adjacent houses on settlement (semi-detached house).

Typical settlement profiles obtained from the settlement analyses are shown in Figs. 5, 6 and 7 respectively. The settlement profile will subsequently be used to determine the spring stiffness (value of load/settlement) for the pile and soil support in order to simulate a similar settlement profile giving the overall stresses on the whole block of houses. The figures show the effect of load from the adjacent blocks of houses in increasing the settlement and hence differential settlement. Therefore, particular care should be given to the design of the foundation system especially at the corner of the blocks and at areas facing another adjacent block of houses, as the differential settlement and hence bending moment are the largest at those areas. The final foundation system adopted consists of 150 mm x 150 mm x 9 m length reinforced concrete (RC) square piles interconnected with 350 mm x 600 mm strips and 150 mm thick raft. Figs. 8 and 9 show typical layout of foundation system adopted for terrace houses and typical cross-section of the strip-raft foundation system respectively.

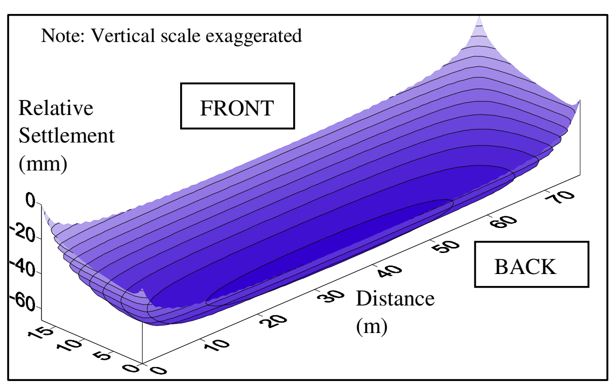

Fig. 5. Settlement profile for terrace house.

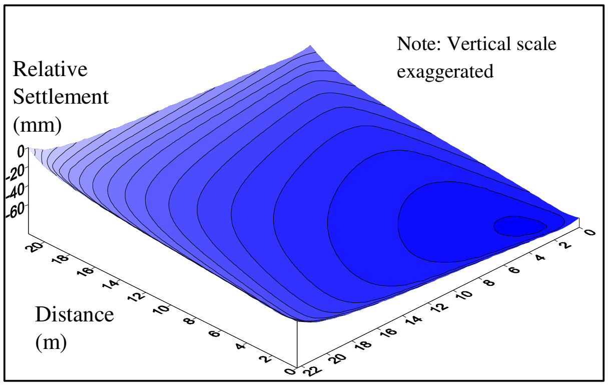

Fig. 6. Settlement profile for semi-detached house (corner unit).

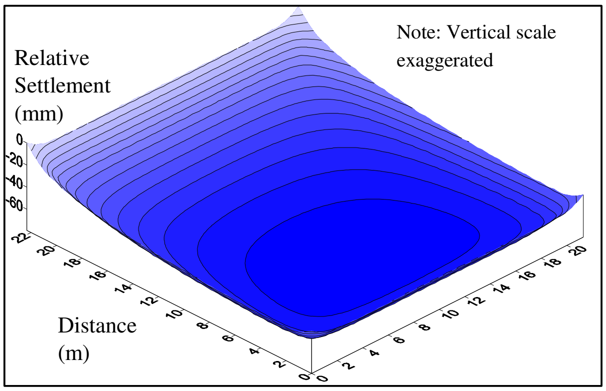

Fig. 7. Settlement profile for semi-detached house (intermediate unit).

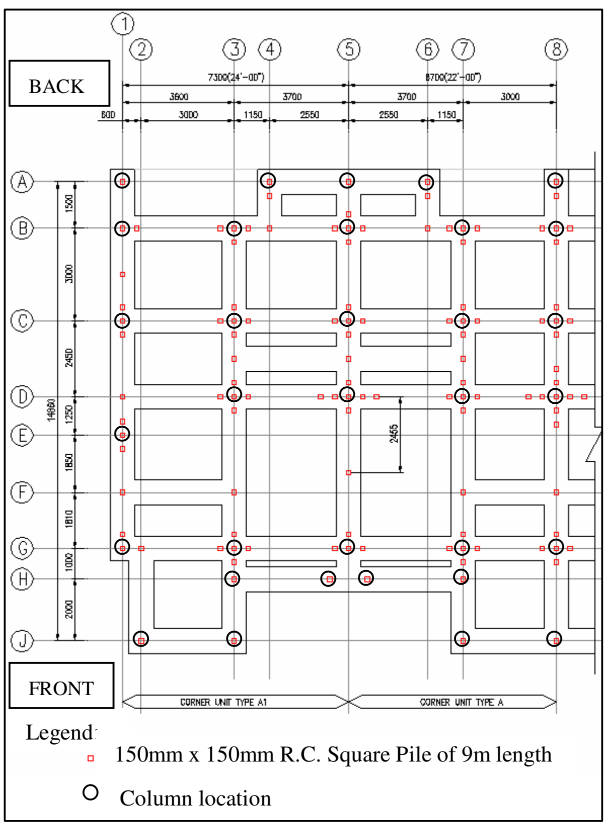

Fig. 8. Typical layout of foundation system for terrace houses.

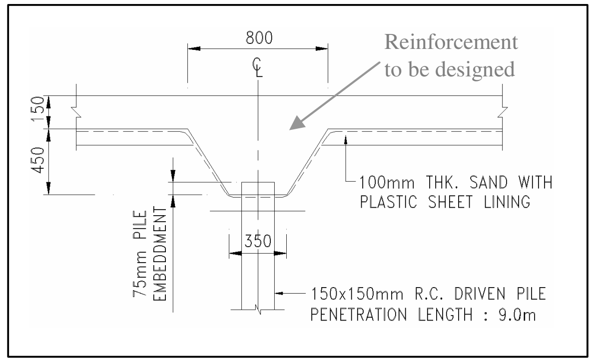

Fig. 9. Typical cross-section of strip raft foundation system.

5 SETTLEMENT MONITORING

A settlement monitoring programme was carried out using precise settlement markers installed on columns of the structure. Fig. 10 shows the locations of the settlement markers for the two blocks of terrace houses where a total of 22 nos. of settlement markers were installed. Monitoring works were carried out starting from November 2002 when the ground floor columns have been constructed to March/April 2003 when it was stopped prematurely to facilitate installation of architectural finishes. Therefore, the monitoring is only carried out during the construction period where additional loads from the first floor were subsequently imposed.

Figures 11 and 12 show the settlement monitoring results for the two blocks of terrace houses. It is worth noting that the settlement increases rather steeply with time. However, this is expected as loads from the first floor (additional loads) were imposed during the monitoring period. The maximum recorded differential settlements are 8.99 mm (between CS07 - CS09) and 13.25 mm (CS17 - CS21) for Blocks 2 and 3 respectively. The maximum angular distortions recorded (end of construction) are 1/2850 and 1/1775 for Blocks 2 and 3 respectively.

The settlement monitoring results also confirm the settlement characteristics of the structure where it can be seen that the settlement at the corners of the structure are the smallest which is characteristics for a flexible foundation where the settlement profile is of a curved or ‘bowl’ shape. In addition, as the back portion of the block of houses is very close (≈ 10 m) to each other as compared to the front where the structure is separated by approximately 20m by a road and the front yard, the settlement at the back is greater due to the influence of loadings from adjacent block of houses as shown in Fig. 3. Such findings agree well with the predicted settlement trend shown in Fig. 5, which has taken into consideration the effect of loadings from adjacent houses. This demonstrates the importance of determining the overall stresses of the foundation based on its settlement profile rather than relying solely on local stresses obtained from conventional Winkler foundation analysis.

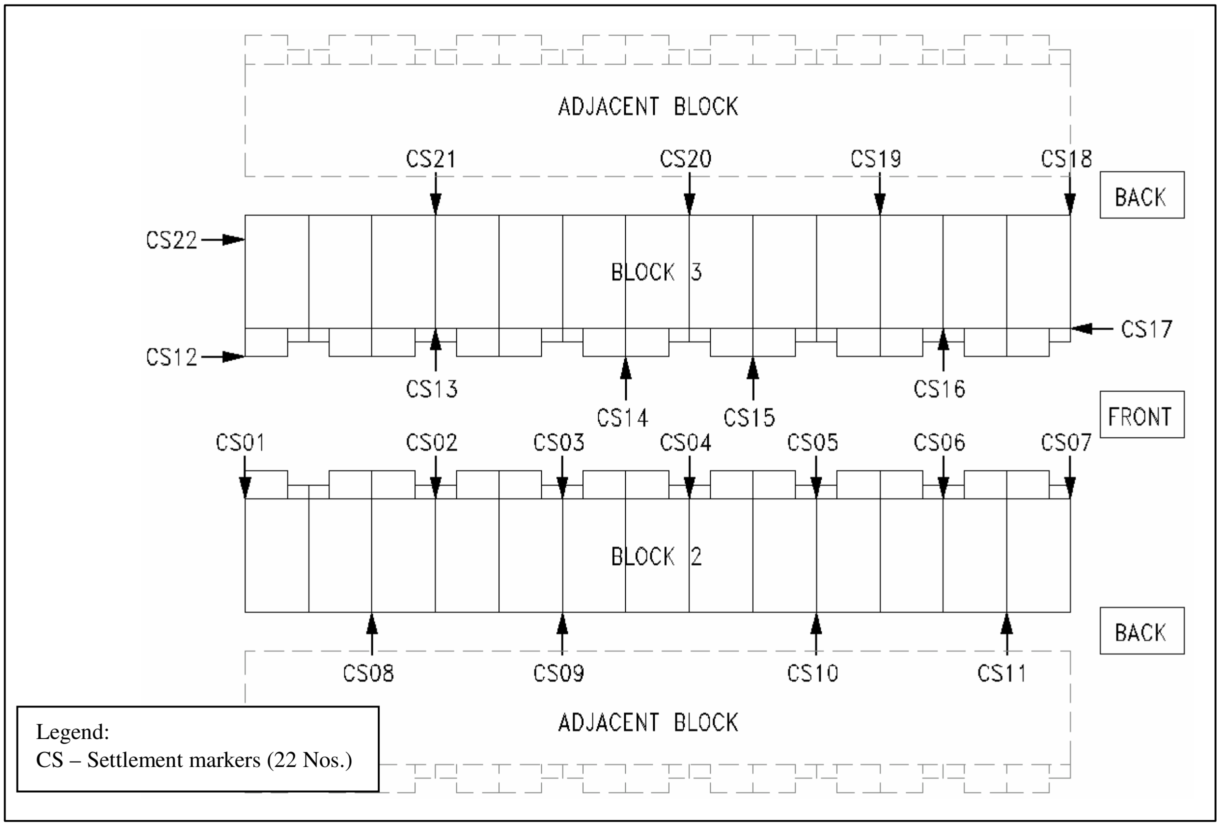

Fig. 10. Locations of settlement markers.

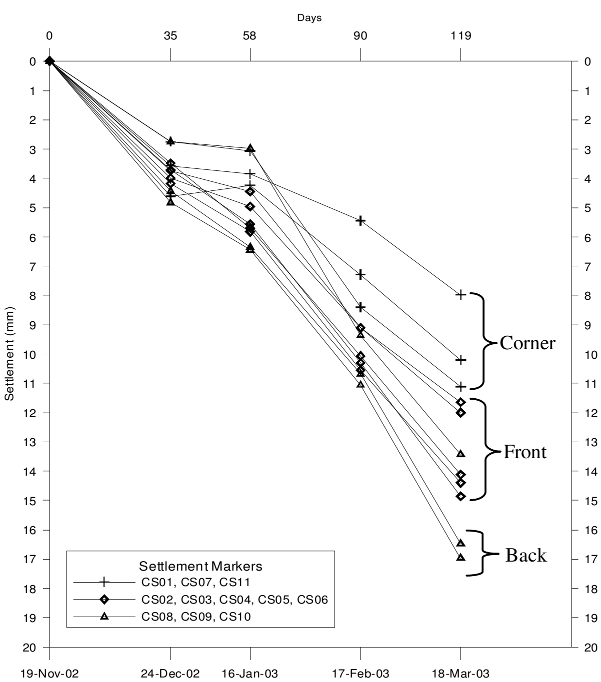

Fig. 11. Settlement monitoring results for Block 2.

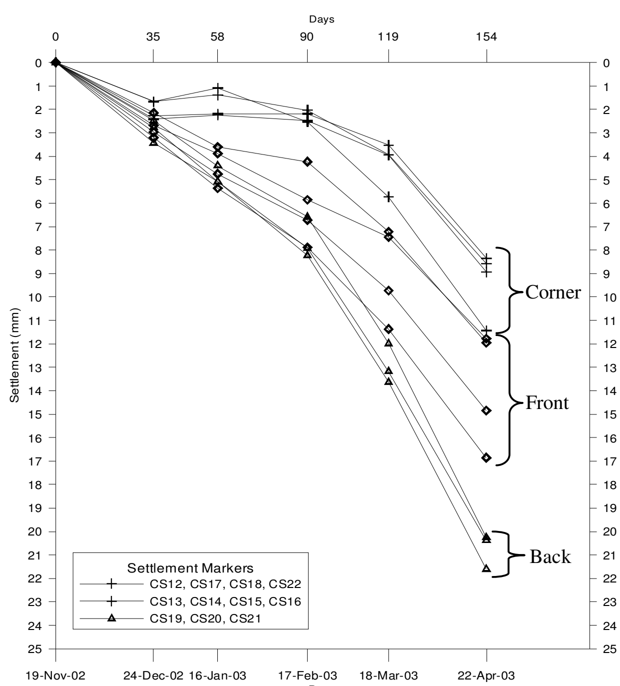

Fig. 12. Settlement monitoring results for Block 3.

6 CONCLUSIONS

A design approach for 'floating' piled raft foundation system for two-storey terrace and semi-detached houses on soft clay are presented. The foundation consists of a system of settlement reducing piles interconnected with a strip-raft foundation system.

The use of settlement reducing piles is solely to control differential settlements within allowable values to prevent cracking in walls and partitions and also to reduce stresses on the structural member. In order to adopt the concept of settlement reducing piles, the foundation raft must first be able to provide adequate bearing capacity.

The detailed analysis of the foundation system to determine the stresses acting on the structural member requires careful consideration of the following cases:

a) Local stresses at locations of concentrated loads
b) Overall stresses for the whole block of houses.

Analysis to determine local stresses are further divided into three different cases:

a) Case 1: Pile performance as per prediction
b) Case 2: Pile performance is lower than prediction (under-capacity)
c) Case 3: Pile performance is better than prediction (over-capacity)

Analysis to determine overall stresses involves the determination of settlement profile for the whole block of houses. This is to facilitate the adjustment of spring stiffness values for the pile in conventional Winkler foundation analysis and to simulate similar settlement profile giving the overall stresses. Influence of adjacent rows of houses on the settlement profile is also important, as it would directly affect the overall stresses.

Settlement monitoring results have demonstrated the effectiveness of the proposed foundation system in controlling differential settlement and the importance of the influence from adjacent nearby houses on the settlement profile and hence stresses on the structural members.

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