DESIGN OF PILED RAFT FOUNDATION ON SOFT GROUND

Y.C. Tan[1] & C.M. Chow[2]

ABSTRACT

Piled raft on soft ground is an economical foundation system where the bearing capacity of the raft is taken into consideration in supporting the loads from superstructure. The friction piles in a piled raft system are located strategically to enhance the bearing capacity of the raft and also to control settlement, especially differential settlement and hence, these piles are commonly known as 'settlement reducing piles'. Therefore, piled raft is a technically competent foundation system and offers significant savings in terms of overall foundation cost as compared to conventional piled foundation. This is because conventional piled foundation usually ignores the contribution of the raft and assumes the loads are supported entirely by the piles. However, the use of piled raft foundation system requires careful design and analysis as it involves complex pile-soil-structure interaction. In this paper, design issues on piled raft foundation system will be discussed with particular reference to buildings on soft ground. However, the approach presented in this paper is also applicable to more competent ground conditions. The design approach is generally divided into two types, i.e. low-rise buildings (less than 3-storeys high) and medium-rise buildings (3 to 5-storeys high). The piled raft foundation system has been successfully designed and constructed on soft ground, and case histories are presented.

Keywords: Piled raft, friction piles, settlement reducing piles, pile-soil-structure interaction, soft clay

1. INTRODUCTION

Design and construction of foundation system on soft ground (undrained shear strength, S_u < 40kPa) have posed various problems to geotechnical engineers, such as excessive settlement (especially differential settlement), negative skin friction on piles 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 total settlement of a structure. The loads from the structure are assumed to be supported entirely by the piles. However, this solution only addresses short-term problem associated with soft ground as pile capacity is also significantly reduced with time due to negative skin friction and associated voids formation and settlement problems beneath the ground floor slab due to long-term settlement. In addition, the solution of driving piles into competent stratum also becomes least attractive as the depth of the compressible layer increases. Therefore, piled raft foundation system using friction piles as settlement reducer is a technically superior foundation system as the bearing capacities of both the raft and piles are taken into consideration. The piles in a piled raft foundation system consist of relatively short friction piles located strategically to enhance the bearing capacity of the raft and also to control differential settlement. The capacity of these piles does not have to be downgraded for negative skin friction. The piles are then interconnected with a rigid system of strip-raft to ensure uniform settlement profile and distribution of loads.

In this paper, design approach for piled raft foundation system on soft ground for low-rise buildings (less than 3-storeys high) and medium-rise buildings (3 to 5-storeys high) are presented. Prior to that, a short discussion on the design criteria of limiting deformation of buildings and design of temporary surcharging

[1] Director, Gue & Partners Sdn Bhd, Kuala Lumpur, Malaysia
[2] Senior Geotechnical Engineer, Gue & Partners Sdn Bhd, Kuala Lumpur, Malaysia

of the earth platform which complements the piled raft foundation system on soft ground will also be presented.

2. LIMITING DEFORMATION OF BUILDINGS

One of the important design criteria to be satisfied by the piled raft foundation system is to limit the deformation of the buildings such that it is safe and stable and satisfies its intended serviceability and function. A simple criterion for limiting deformation commonly adopted is the angular distortion, β and deflection ratio, Δ/L as shown in Figure 1. The angular distortion or deflection ratio must be designed to within acceptable limits and commonly adopted limits are reproduced in Table 1 and Figure 2. It can be seen that in order to control cracking in walls and partitions of framed buildings, the limiting angular distortion ranges from 1/300 to 1/500. Therefore, the design of the piled raft foundation system shall satisfy the above limiting angular distortion to ensure no cracking in walls and partitions.

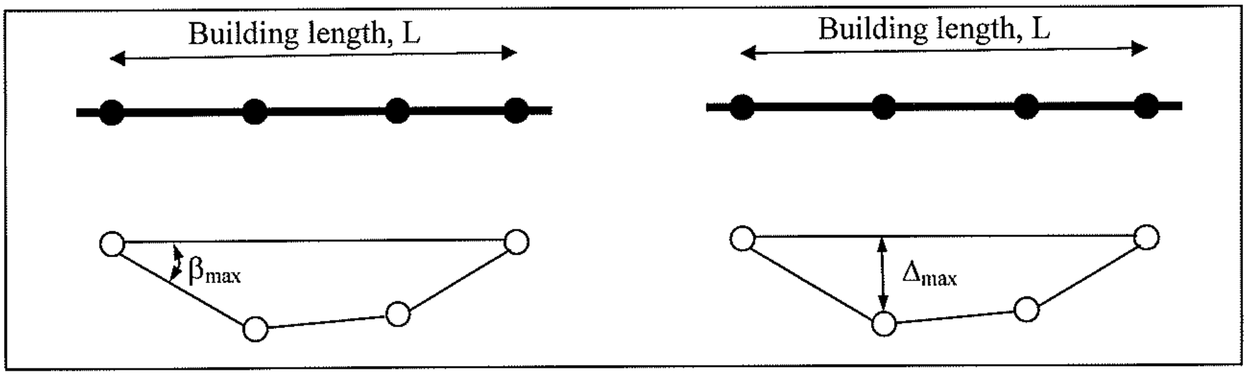

Figure 1: Definitions of foundation movement.

Table 1: Summary of limiting deformations (after Institution of Structural Engineers, 1989).

a) Framed buildings and reinforced loadbearing walls

LIMITING VALUES OF RELATIVE ROTATION (ANGULAR DISTORTION), β				
	Skempton & MacDonald (1956)	Meyerhof (1956)	Polshin & Tokar (1957)	Bjerrum (1963)
Structural damage	1/150	1/250	1/200	1/150
Cracking in walls and partitions	1/300 (but 1/500 recommended)	1/500	1/500 (0.7/1000 to 1/1000 for end bays)	1/500

b) Unreinforced loadbearing walls

LIMITING VALUES OF DEFLECTION RATIO, Δ/L FOR THE ONSET OF VISIBLE CRACKING			
	Meyerhof (1956)	Polshin & Tokar (1957)	Burland & Wroth (1975)
Sagging	1/2500	L/H < 3; 1/3500 to 1/2500 L/H < 5; 1/2000 to 1/1500	1/2500 at L/H = 1 1/1250 at L/H = 5
Hogging (unreinforced)	-	-	1/5000 at L/H = 1 1/2500 at L/H = 5

Note: L/H is ratio of building length to building height.

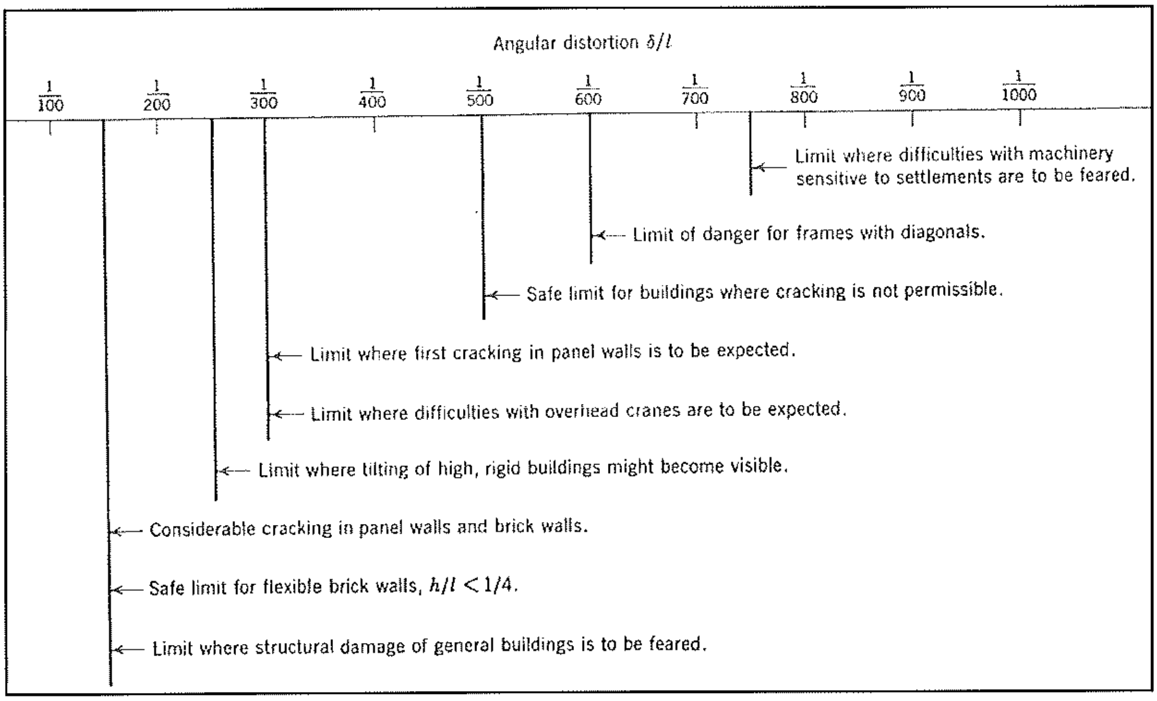

Figure 2: Limiting angular distortion (after Bjerrum, 1963).

3. TEMPORARY SURCHARGING OF EARTH PLATFORM

The design approaches for foundation of buildings on soft ground have to integrate with ground treatment design for the earthworks (if necessary) so that both designs are technically compatible and efficient. In certain projects, temporary surcharging and preloading technique with or without vertical drains 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. The design of the temporary surcharging and preloading technique requires careful determination of subsoil and profile and its properties (especially consolidation parameters) and verification from field monitoring. Tan & Gue (2000) provide some general guidance on the design of preloading and surcharging and the methods of interpreting field measurement of settlement using Hyperbolic Method (Tan, 1971 and Tan, 1995) and Asaoka's Method (Asaoka, 1978).

Preloading is to compress the subsoil prior to placing the permanent load. This method involves the placement and removal of fill (pressure) of similar to or greater than the permanent load. On the other hand, surcharging is to subject the ground to higher pressure than that during the service life in order to achieve a higher initial rate of settlement, thus reducing long-term settlements. Unlike preloading, a large proportion of the fill is left behind after the surcharge has been removed. Several important design criteria for this method are:

a) Stability should be checked with preloading or surcharged load
b) Preloading or surcharging should be designed to the chosen construction period
c) Settlement after construction should be within the range of tolerances (acceptable serviceability limit)
d) The option should be economical
e) Proper planning of construction programme for cost effective use of materials
f) Does not cause damage to any adjoining structures and utilities

The magnitude and duration of the preloading or surcharging will be controlled by the magnitude of total settlement (consolidation and secondary settlements). Usually the extra loading must be imposed on the subsoil until the effective stress in the subsoil is larger than that from the long-term loading from the structures. This method can also reduce the effects of secondary settlement. Figure 3 shows the concept of preloading and surcharging respectively.

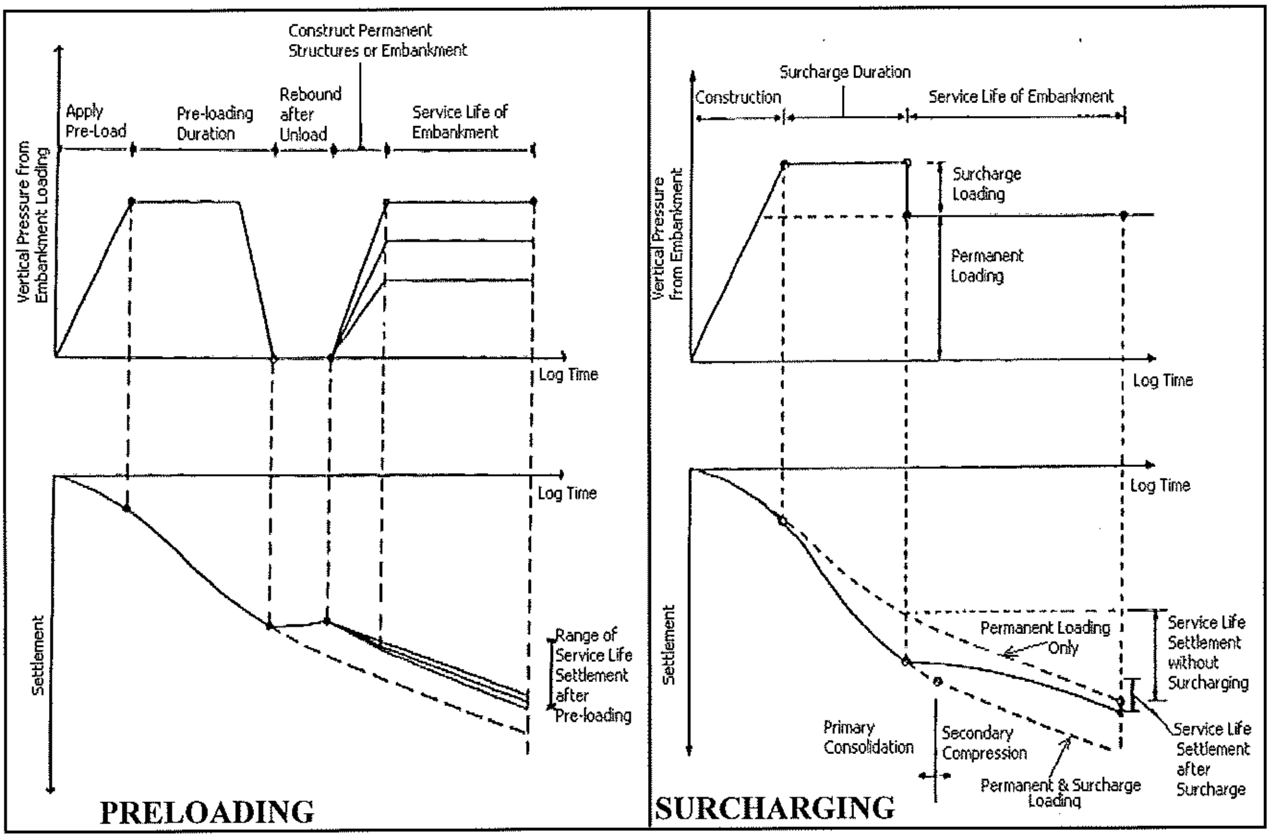

Figure 3: Concept of preloading and surcharging.

4. GENERAL CONCEPTS OF PILED RAFT USING SETTLEMENT REDUCING PILES

The general concept of piled raft using settlement reducing piles is illustrated in Figure 4. The method is first proposed by Burland et al. (1977) and subsequently, various case histories have been reported (e.g. Love, 2003, Yamashita et al., 1994 and Burland & Kalra, 1986). For the idealized condition of uniform loading, the settlement profile of the raft foundation is of 'bowl' shaped where the settlement is the largest in the centre and smallest at the edge. Settlement reducing piles are therefore introduced in the centre of the raft to reduce raft settlement at the centre and thus reduce differential settlement.

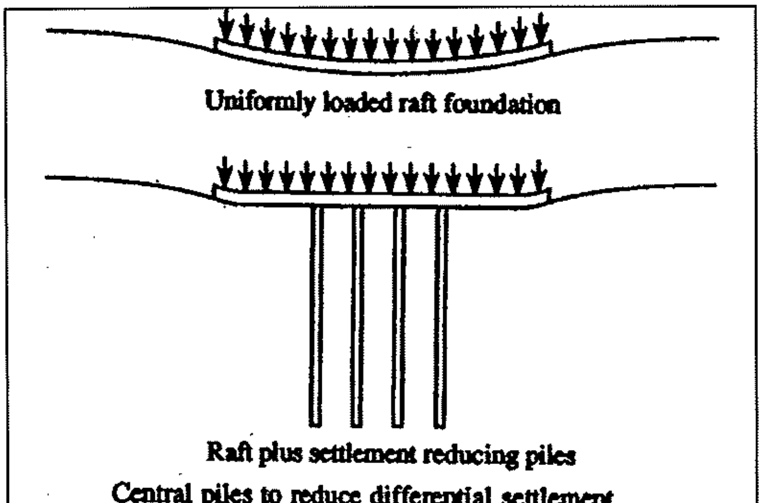

Figure 4: Concept of settlement reducing piles (after Randolph, 1994).

The approach of using settlement reducing piles can be further divided into two categories of application:

a) Local deformation
b) Overall deformation

The use of settlement reducing piles to control local deformation is illustrated in Figure 5 while the control of overall deformation is similar to the concept illustrated in Figure 4 and further demonstrated in Figure 6.

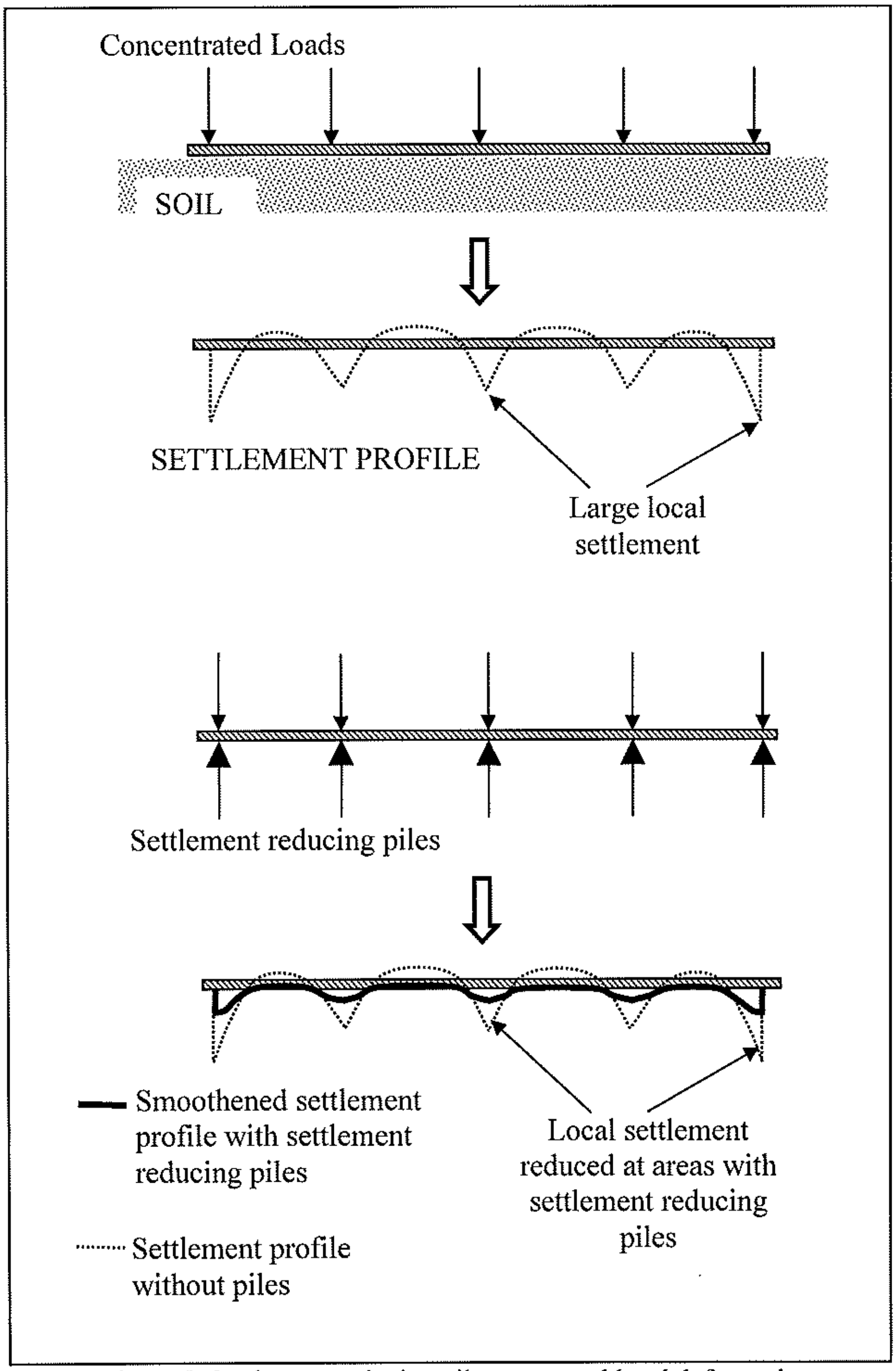

Figure 5: Settlement reducing piles to control local deformation.

It can be seen then that with piles strategically located at areas of concentrated loadings or at areas with the largest settlement, the differential settlement of the foundation can be controlled to prevent serviceability problems such as cracking, etc. In addition, it must be pointed out that the use of settlement reducing piles would also reduce the stresses on the structural raft. The use of piles to reduce stresses on the structural raft can also be referred to as "stress reducing piles" (Burland & Kalra, 1986).

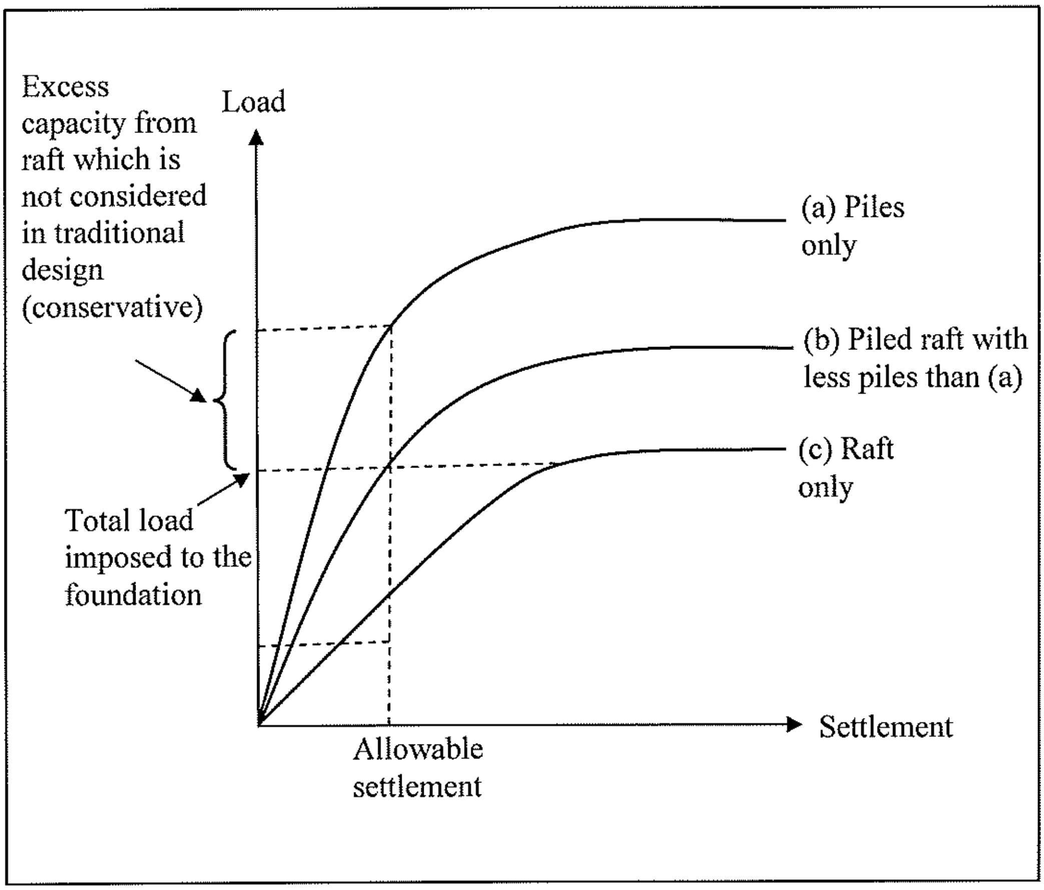

Figure 6: Concept of piled raft.

The benefits of considering both raft and piles in the assessment of the foundation system are clearly illustrated in Figure 6. Traditionally, piles are often introduced when the overall settlement of the raft is unacceptable for the particular usage of a structure. However, by assuming that the loads are resisted entirely by the piles only (raft ignored) would result in unduly conservative design where the settlement is reduced significantly smaller than necessary. In addition, significantly higher numbers/total lengths of piles are required when the load resisting contribution of the raft is ignored. This is significant especially for large pile group with large spacing in soft ground with a filled platform where capacity of pile designed conventionally have to be downgraded for negative skin friction.

As the design approach takes into consideration of both the raft and piles, understanding of the behaviour of pile groups and raft is important and will be briefly discussed in this paper.

4.1 Pile Groups

The use of settlement reducing piles is most efficient for friction piles (i.e. pile capacity is achieved primarily through shaft friction with little or no end bearing) and therefore, the behaviour of 'floating' pile groups is important in the design of piled raft using settlement reducing piles. In this paper, the load-settlement behaviour of pile groups will be discussed as it directly affects the design of the piled raft in terms of differential settlement and also stresses induced on the structural members.

The load-settlement behaviour of pile groups is governed by the interaction between the piles (Figure 7) which depends on the following factors:

a) pile slenderness ratio, L_p/d_p
b) pile stiffness ratio, $\lambda = E_p/G_l$
c) pile spacing ratio, s/d_p
d) homogeneity of soil, characterised by ρ (Figure 8)
e) soil Poisson's ratio, ν

where

L_p = pile length
d_p = pile diameter
E_p = elastic modulus of pile
G_l = soil shear modulus at pile tip
s = pile spacing

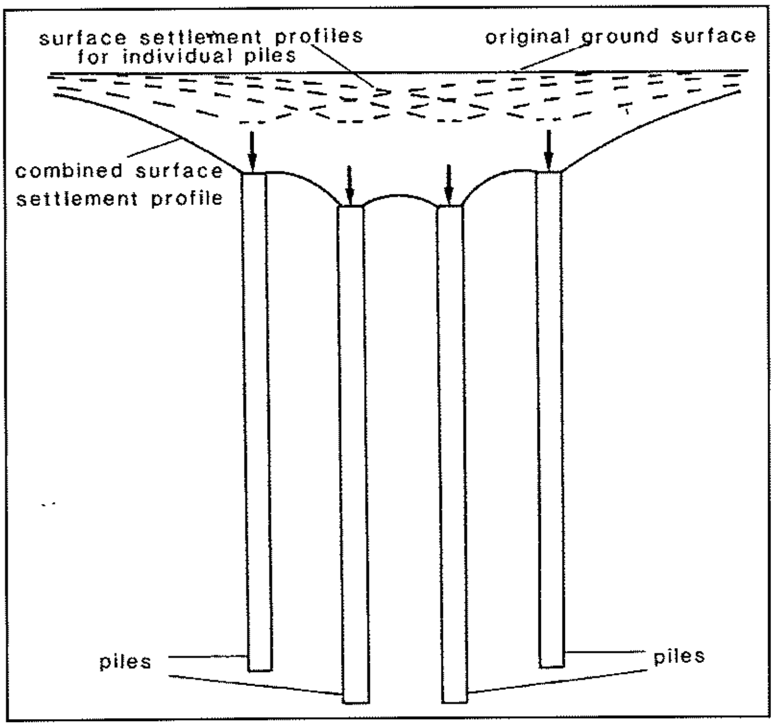

Figure 7: Interaction of piles in pile group (after Fleming et al., 1992).

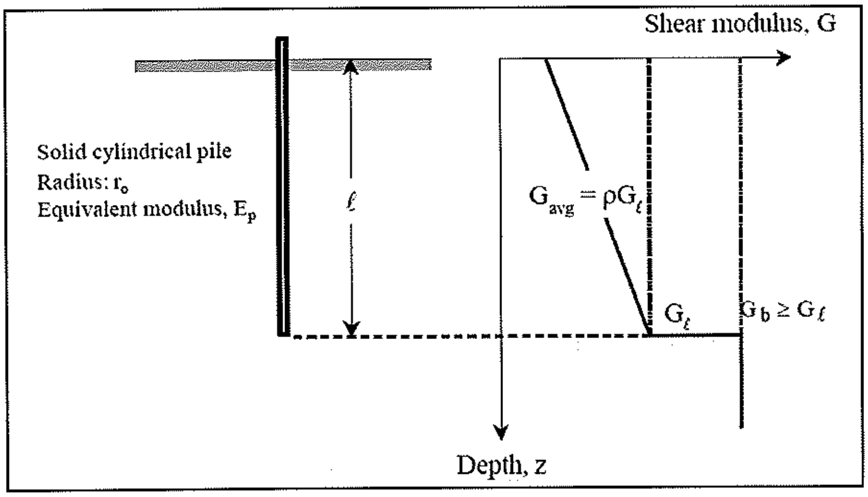

Figure 8: Variation of soil shear modulus with depth (homogeneity) characterised by ρ (after Randolph, 2003).

The solutions for load-settlement behaviour of single piles and pile groups were given by Randolph & Wroth (1978) and Randolph & Wroth (1979) and have been incorporated in the software PIGLET (Randolph, 2003). However, it must be highlighted that the software PIGLET only caters for piles of uniform length.

4.1 Raft

The load-settlement behaviour of raft on soil has been studied by a number of researchers, e.g. Richart et al. (1970) and Poulos & Davis (1974). Generally, the load-settlement or stiffness of raft is governed by:

a) raft dimensions, *c* and *d*
b) soil shear modulus, G_s
c) soil Poisson's ratio, v

Typical solutions for stiffness of raft acting alone have been given by Richart et al. (1970) as follow:

a) $k_r = 4G_s r_o/(1-v_s)$ for rigid circular raft
b) $k_r = [G_s/(1-v_s)]\ \beta_z\ (4cd)^{1/2}$ for rigid rectangular raft

where

r_o = circular raft radius
β_z = coefficient depending on raft dimensions, *c* and *d* (Figure 9)

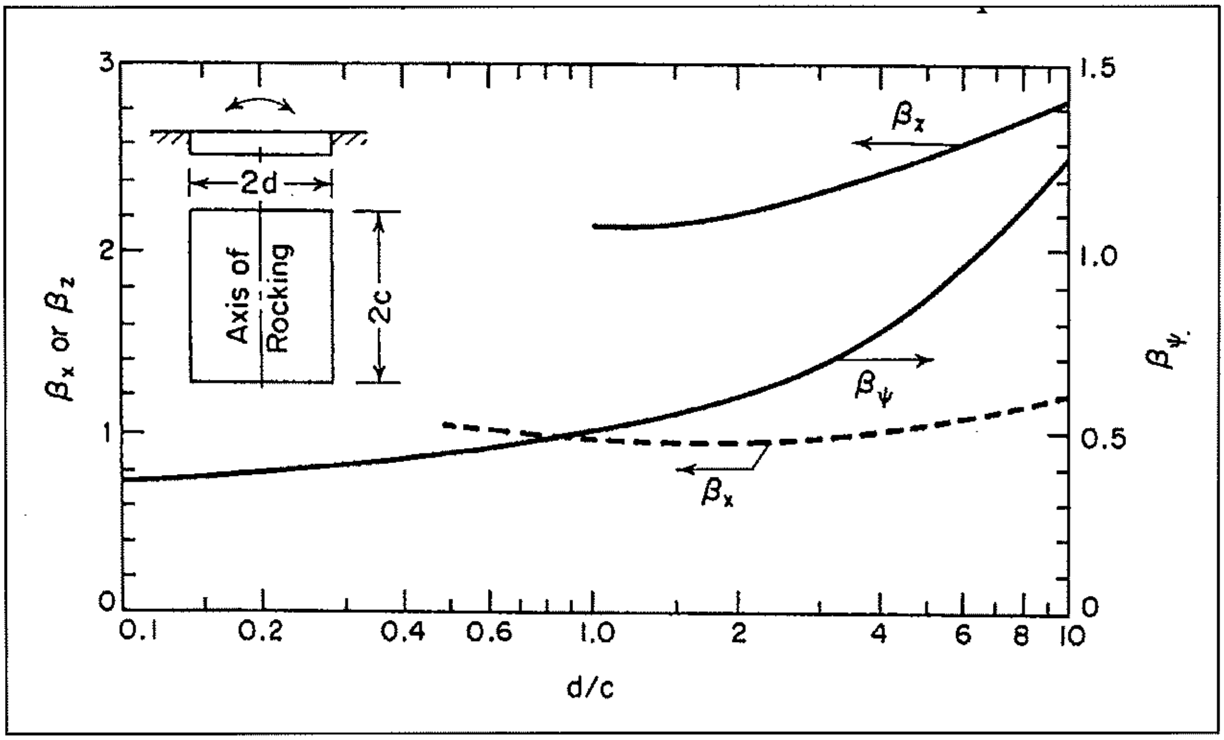

Figure 9: Coefficients of β_z, β_x, β_ψ for rectangular footings (after Richart et al., 1970).

The above serves to illustrate the behaviour of raft foundation only and to explain the fundamental theory behind piled raft foundation system. In actual design, due to the complexity of the system, an iterative design process using suitable computer software to cater for the pile group interaction (e.g. PIGLET, PIGEON) and raft behaviour (e.g. SAFE) is carried out and will be discussed in the following sections.

5. PILED RAFT SYSTEM FOR LOW-RISE BUILDINGS (LESS THAN 3-STOREYS HIGH)

The piled raft system for low-rise buildings is generally based on the concept of settlement reducing piles to control local deformation where piles of single length are strategically located beneath concentrated loads. The design approach adopted in this paper generally follows the recommendation of Poulos (2001) where four circumstances in which a pile is provided beneath a concentrated load (i.e. column or wall):

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.

Poulos (2001) original recommendations as summarised above are derived for stiff/dense soil. However, in this paper, the above approach has been extended for soft ground with some adjustments.

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 limits of angular distortion as discussed in Section 2, and also to reduce the stresses on the structural member. At areas of concentrated column and wall loads, large contact pressure is induced on the soft ground which can cause excessive local settlement leading to cracks on buildings. Therefore, Conditions 3 and 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 is then determined based on factors such as the architectural layout, arrangement of columns and walls, etc in order to provide the required rigidity to distribute the superstructure loads. Usually, for low-rise buildings, 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 'pilecaps' to distribute the column and wall loads to the piles. With the strips located directly beneath the columns and walls and subsequently designed to resist the stresses induced by the column and wall loads with the settlement reducing piles in place, Conditions 1 and 2, which are governed by structural considerations, are no longer critical.

5.1 Analysis

The location of the settlement reducing piles as determined based on Conditions 3 and 4 mainly concentrates at column locations and along the span of line loads (i.e. wall). With the piling layout confirmed and 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 the local stresses are further divided into three different cases:

a) Case 1: Pile performance as per predicition
b) Case 2: Pile performance is lower than prediction (undercapacity)
c) Case 3: Pile performance is better than prediction (overcapacity)

The load-settlement response of the pile given by the three cases above is shown in Figure 10.

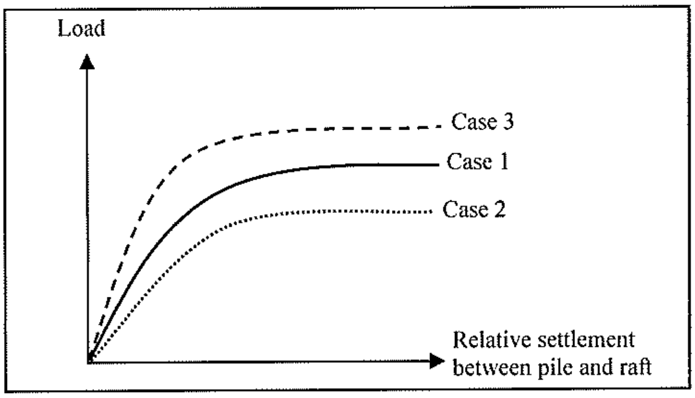

Figure 10: Load-settlement response for Cases 1, 2 and 3.

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. A hypothetical example as illustrated in Figure 11 shows that different magnitudes of hogging and sagging moments are induced in the structural member due to different values of relative pile-soil stiffness of Cases 1, 2 and 3. The design of the structural member to cater for localised stresses, therefore, has to be based on the envelope of stresses (bending moment and shear) for the three cases. Similar design approach using settlement reducing piles has also been adopted by Love (2003) for stiffer materials.

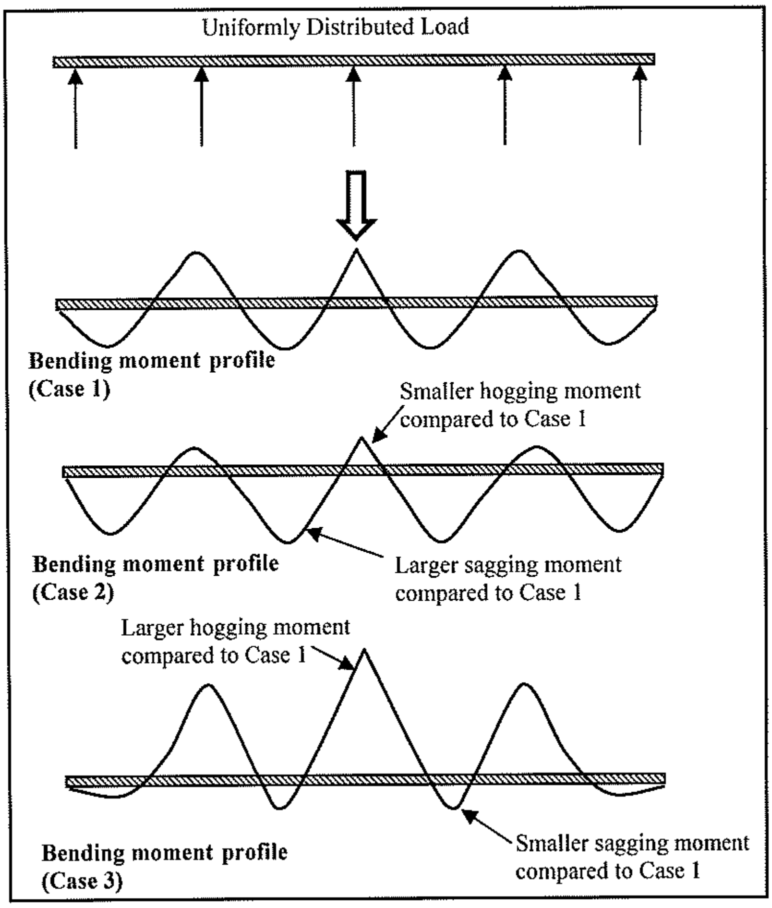

Figure 11: Hypothetical bending moment profile for Cases 1, 2 and 3.

With the local stresses being catered for by the three cases (Cases 1, 2 and 3), the overall stresses for the whole block of the houses needs to be analysed based on the overall settlement profile of the block of houses. 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 can be carried out based on Terzaghi's 1-dimensional consolidation theory and the stress distribution is based on Boussinesq's theory. The raft can be assumed to be truly flexible which is on the conservative side for design. The settlement analysis must also takes into consideration the effect of adjacent rows of houses as shown in Figures 12 and 13.

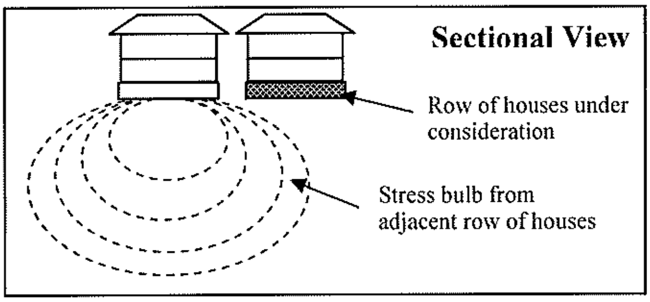

Figure 12: Effect of adjacent houses on settlement (terrace house).

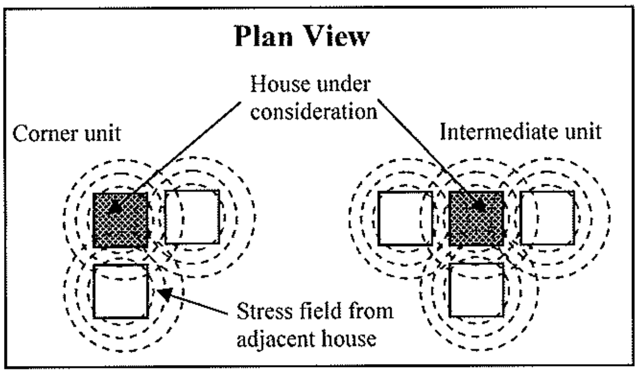

Figure 13: Effect of adjacent houses on settlement (semi-detached house).

Typical settlement profiles obtained from the settlement analyses are shown in Figures 14, 15 and 16 respectively. The settlement profile are subsequently 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 adjacent block 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 block of houses, as the differential settlement and bending moment are the largest at those areas.

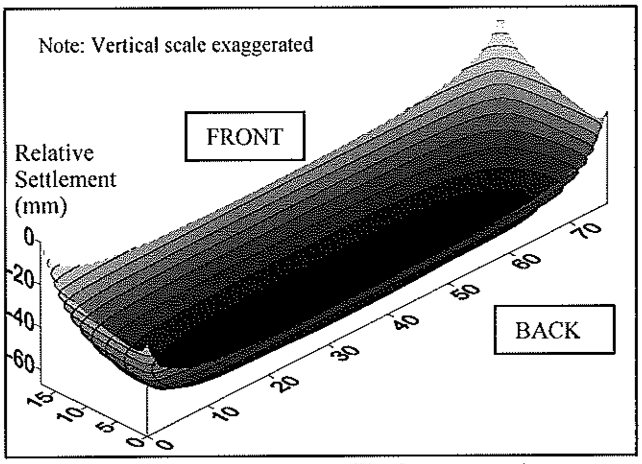

Figure 14: Settlement profile for terrace house.

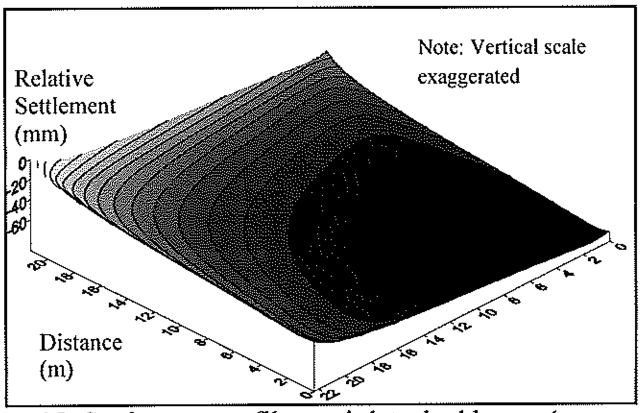

Figure 15: Settlement profile semi-detached house (corner unit).

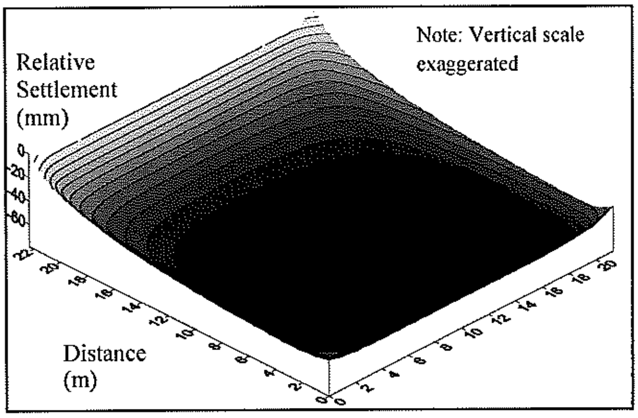

Figure 16: Settlement profile semi-detached house (intermediate unit).

6. PILED RAFT SYSTEM FOR MEDIUM-RISE BUILDINGS (3 to 5-STOREYS HIGH)

For medium-rise buildings, due to relatively higher loads imposed onto the foundation, the piled raft system consists of piles with varying pile length interconnected with a rigid system of strip-raft. This approach is adopted due to the larger overall settlement expected as compared to low-rise buildings. This will result in a more pronounced 'bowl' shaped settlement profile. Therefore, piles of varying length with the longest piles in the middle and progressively shorter piles towards the edge are adopted as shown in Figure 17 to reduce differential settlement.

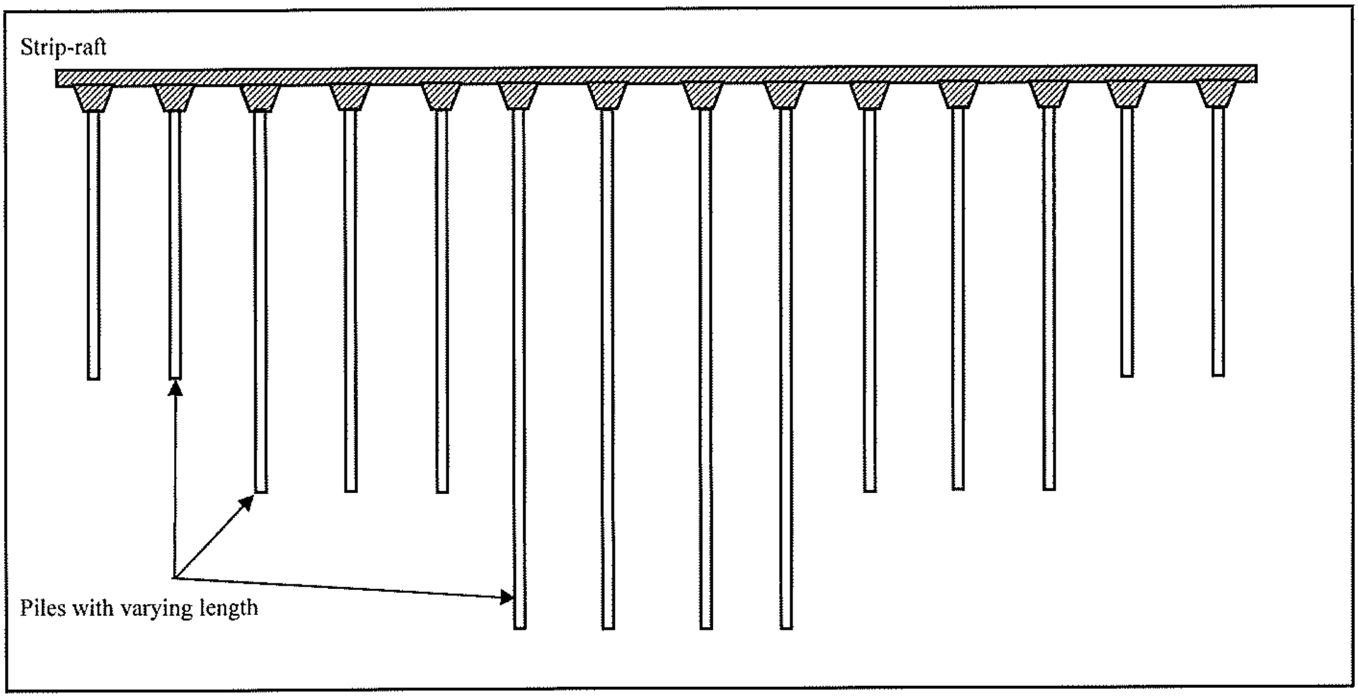

Figure 17: Schematic of piled raft system with varying pile lengths for medium-rise buildings.

The interaction between the pile-soil-structure (strip-raft) is carried out iteratively using pile interaction software (e.g. PIGLET, PIGEON) and structural analysis software (e.g. SAFE). The convergence criteria adopted for the iterative analysis is set at ±10% variation of pile reactions from previous analysis. The proposed approach of using the pile interaction and structural analysis software iteratively arises due to limitations of the respective software in modelling pile-soil-structure interaction as follow:

a) General pile interaction software
   - Limitations:
     i. Unable to model strip-raft.
     ii. Unable to cater for random locations of column and wall loads (only caters for point load at centre of strip-raft, uniformly distributed load over the entire foundation or point load on each pile).
   - Applications:
     i. To model pile-soil interaction which cannot be modelled by general structural analysis software.

b) General structural analysis software
   - Limitations:
     i. General structural analysis software usually adopts Winkler model for soil and uncoupled spring constants for piles where interaction between piles and soil cannot be modelled.
   - Applications:
     i. To model the strip-raft and its effect on the pile-soil interaction.
     ii. To cater for random locations of column and wall loads.
     iii. To determine stresses on the strip-raft for design.

It must be noted that the iterative analysis is proposed to enable pile-soil-structure interaction analysis be carried out using commonly available software within reasonable time and computer resources for practical design purposes. The analysis can also be carried out using Finite Element Method (FEM) software (e.g. PLAXIS 3-D Foundation) that can model 3-dimensional pile-soil-structure interaction. However, the FEM software will have great limitation on the numbers of piles that can be modelled practically.

Results of the analysis, such as pile reactions and settlement, are then checked against design criteria adopted to ensure the pile capacity are not exceeded and the settlement are within allowable limits.

In this paper, the interaction of piles is based on the solutions of Randolph & Wroth (1979) as discussed in Section 4.1. It is also highlighted in Section 4.1 that the original solution of Randolph & Wroth (1979) and subsequently adopted in the software PIGLET is derived for piles of uniform length. Therefore, the original equation proposed by Randolph & Wroth (1979) is revisited by the Authors in order to derive a solution for piles with varying pile length.

The solution for pile interaction by Randolph & Wroth (1979) is based on the solution for single pile (Randolph & Wroth, 1978) and extended for pile groups based on 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. Therefore, for cases with different pile lengths, the interaction of the pile base at different levels is very complicated and its effect to shear stress along 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 & 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 Author's firm internally developed software, Pile Group Analysis Using Elastic or Non-linear Soil Behaviour, PIGEON (Chow, C.M. & Cheah, S.W., 2003).

7. CASE HISTORIES

7.1 Mixed Development Overlying Highly Compressible Soft Clay

This development comprises of residential and commercial units at a site of about 1200 acres at Bukit Tinggi, Klang, Malaysia, which is about 40km towards south west of Kuala Lumpur. This development was constructed over soft silty clay, termed as Klang Clay. The detailed descriptions of the Klang Clay were reported by Tan et al. (2004) and generally consist of alluvial deposits of very soft to firm silty clay up to a depth of 25m to 30m with presence of intermediate sand layers.

The foundation system adopted for the low-rise buildings generally consists of 150mm x 150mm x 9m length reinforced concrete (RC) square piles interconnected with 350mm x 600mm strips and 150mm thick raft. Figures 18 and19 show the cross-section of the strip-raft foundation system and typical layout of foundation system adopted for terrace houses. The view of recently completed houses are shown in Figures 20 and 21.

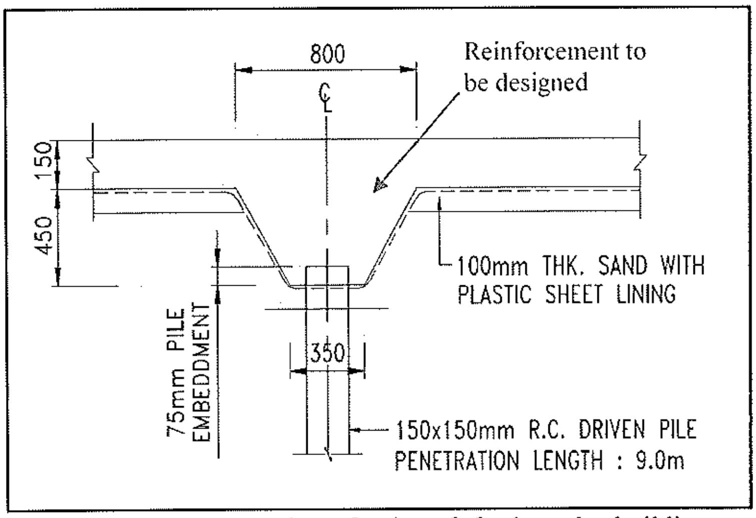

Figure 18: Cross-section of strip-raft for low-rise buildings.

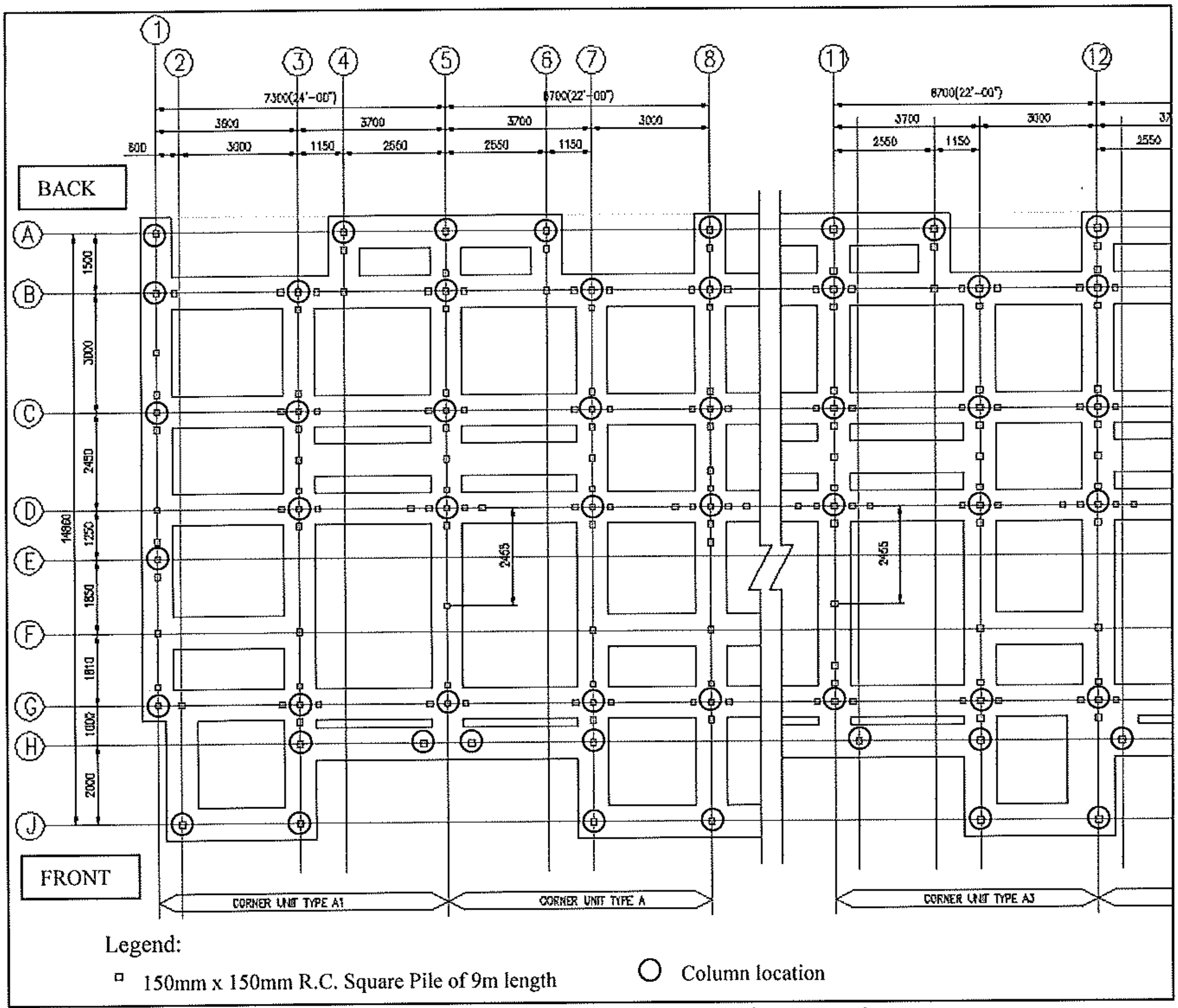

Figure 19: Typical layout of foundation system for terrace houses.

Figure 20: View of recently completed terrace houses.

Figure 21: View of recently completed bungalow houses.

The foundation system adopted for the medium-rise buildings (5-storeys low cost apartment) generally consists of 200mm x 200mm (RC) square piles with pile length varying from 18m to 24m interconnected with 350mm x 700mm strips and 300mm thick raft. Figures 22, 23 and 24 show the cross-section of the strip-raft foundation system, typical piling layout for low cost apartment and view of the recently completed low cost apartment respectively.

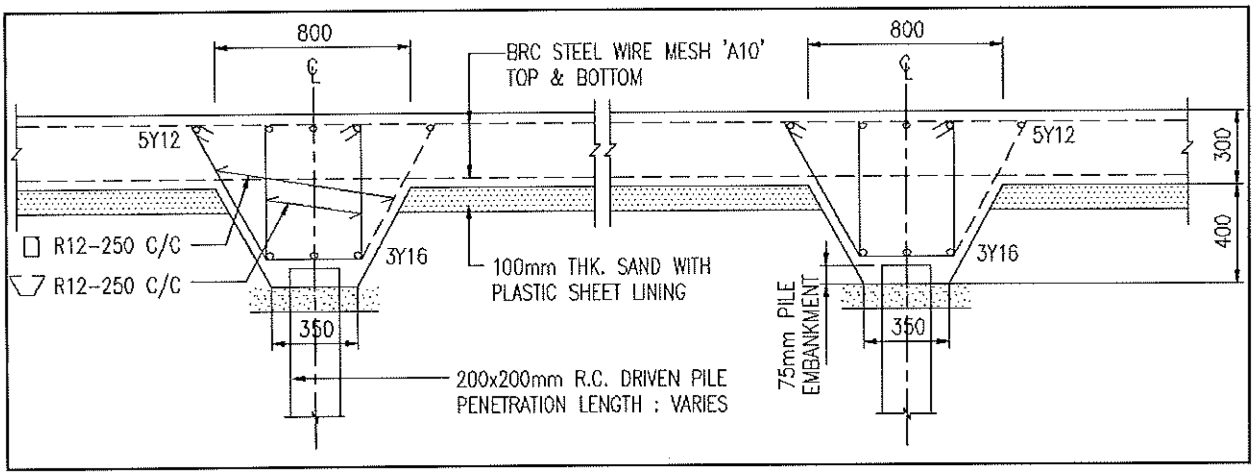

Figure 22: Typical cross-section of strip-raft for low cost apartments.

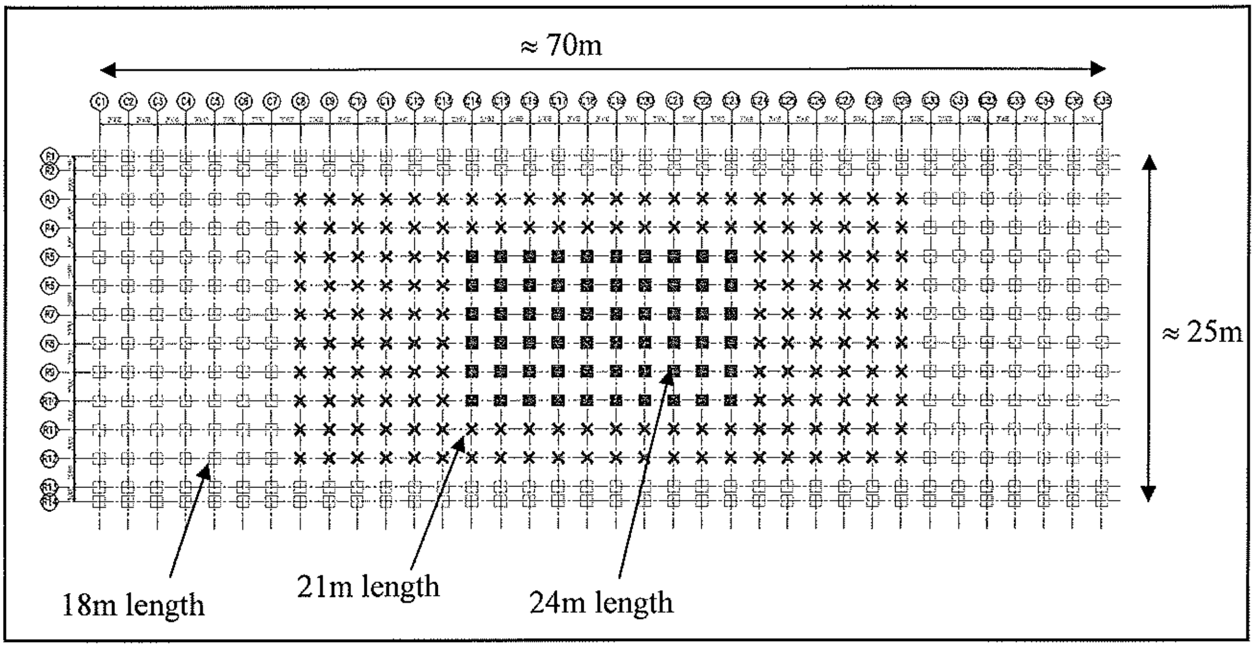

Figure 23: Typical piling layout for low cost apartments.

Figure 24: View of recently completed low cost apartments.

Building settlement monitoring has also been carried out for both the low-rise buildings and medium-rise buildings. The settlement monitoring results have confirmed the validity of the proposed design approach and the performance of the buildings satisfactory. A detailed discussion on the design approach adopted for the low-rise buildings and discussion on the results of monitoring have been presented in Tan, Chow & Gue (2004). The settlement monitoring for the medium-rise low cost apartments is still ongoing at the time this paper is being prepared.

7.2 2500-Ton Oil Storage Tank on Very Soft Alluvium Deposits

A palm oil mill has been constructed over sand filled platform with an area of about 83,000m^2 on soft swampy ground. The proposed site is located about 50km away from Sg. Guntung of Province of Riau, Sumatra, Indonesia. The subsoil conditions of the site generally consist of top one metre of organic materials of peat and decayed tree roots at the surface with no obvious dessicated weathered crust. The top 5m of the subsoil has over-consolidation ratio (OCR) of 1.6 at the top and gradually reduces to 1.0. Underneath the organic materials, the subsoil mainly consists of very soft normally consolidated clayey deposit of 34m thick followed by 12m thick medium stiff clay overlying the white medium dense fine sand and dense clayey sand.

The tank structure consists of a 12.2m high steel tank with external diameter of 17.5m and shell plate thickness of 8mm. All the tanks with coned-down base slope of 1/39 are seated on the 0.5m thick sand bed contained on the 0.5m thick reinforced concrete (RC) raft. There are a total of 137 numbers of 350mm diameter hollow circular prestressed concrete spun piles spaced at 1.5m square grids. Piles with lengths of 24m (68 piles), 30m (48 piles) and 36m (21 piles) respectively have been strategically located with the longer piles at the centre rim and shorter piles at the outer rim of the raft to control the raft distortion under the imposed loading of about 3500 ton. Figures 25 and 26 show the schematic of the piled raft foundation system and view of the completed tank respectively. The design and instrumentation results of the tank foundation have been presented by Liew, Gue & Tan (2002).

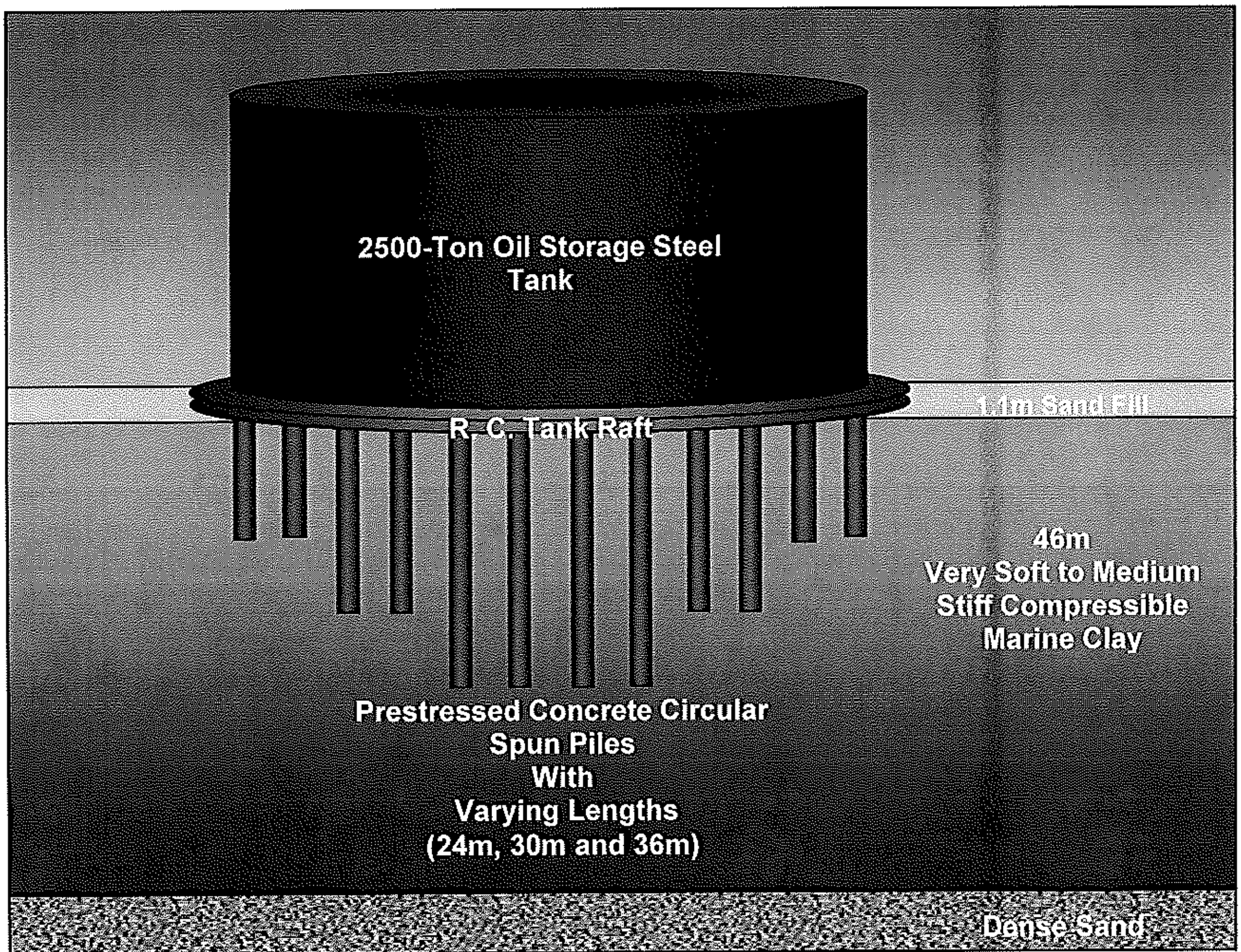

Figure 25: Schematic of piled raft foundation system.

Figure 26: View of completed tanks.

8. SUMMARY

A design approach for piled raft foundation system using settlement reducing piles on soft ground is presented. The design approach is divided into two categories, i.e. for low-rise buildings (less than 3-storeys high) and medium-rise buildings (3 to 5-storeys high). The piled raft system for low-rise buildings is generally based on the concept of settlement reducing piles to control local deformation where piles of short length are strategically located beneath concentrated loads. For medium-rise buildings, piles of varying length with the longest piles in the middle and progressively shorter piles towards the edge are adopted to control differential settlement within allowable limits. Various design cases must be considered for the design of piled raft using settlement reducing piles to ensure adequate provisions of pile and design of the strip-raft (for low-rise buildings) while an iterative analysis to model pile-soil-structure is proposed to analyse the medium-rise buildings.

Various case histories designed by the Author's firm are presented and extensive monitoring results on the completed structures have demonstrated the validity of the proposed design approach.

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