MALAYSIAN GEOTECHNICAL SOCIETY (PERTUBUHAN GEOTEKNICAL MALAYSIA)

PERFORMANCE OF FLOATING PILED RAFT WITH VARYING LENGTHS IN SOFT COMPRESSIBLE SUBSOIL

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Contents

Introduction

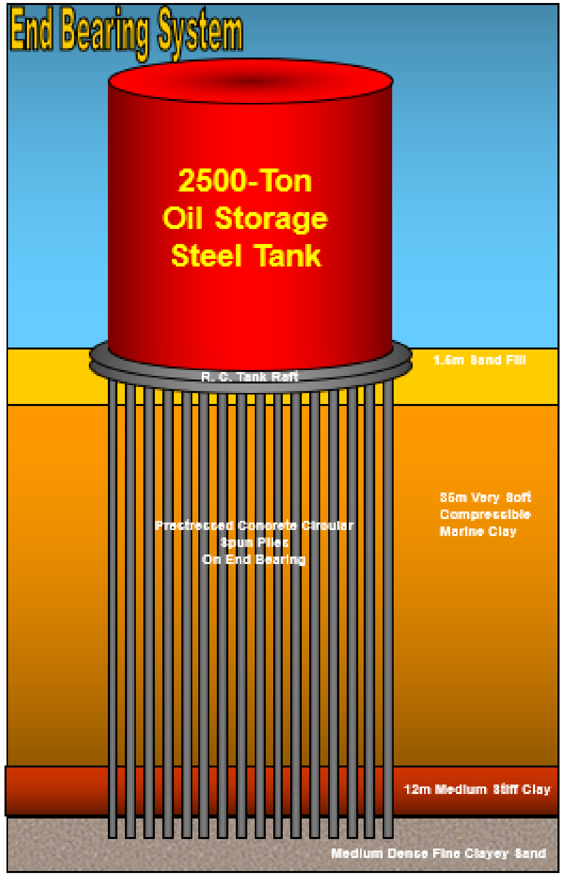
Introduction

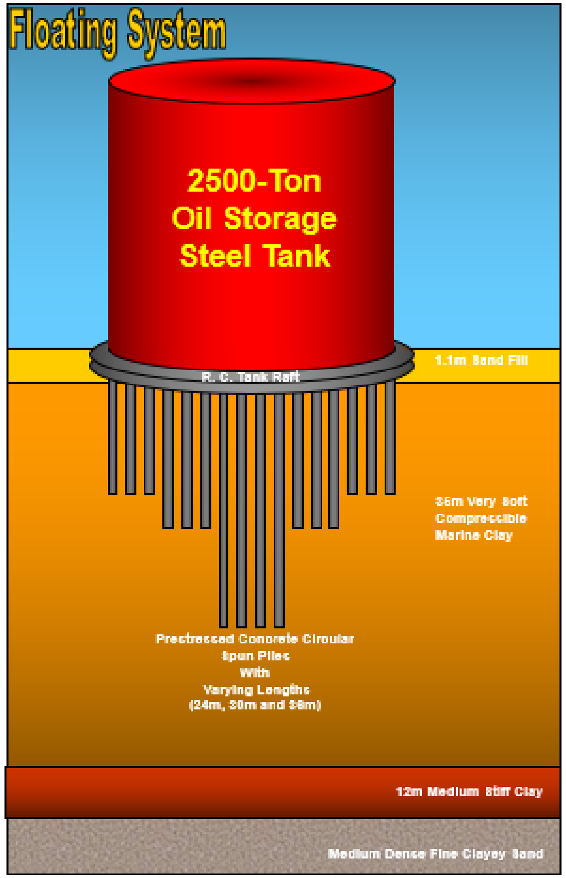
- For Low Rise Buildings on deep and very soft compressible subsoil, pile foundation is used due to low bearing capacity and large differential settlement.
- Current practice of **Conventional Piling System** is not economical for Low Rise Buildings on deep compressible subsoil with ***settling platform***.

RESEARCH AIMS to resolve these issues :-

- To propose an Alternative Pile Foundation system via **'Floating' Piled Raft (FPR)** that is both technically suitable and economical for Low Rise Buildings on deep compressible subsoil with *settling platform*.
- To develop **a practical design methodology** for the Alternative Pile Foundation System which *can be used by practicing engineers for their design works.*

Concept first used for 2500 Ton Oil Storage Steel Tank (1999)





Completed Tank Structure

Adopted

DESIGN AND INSTRUMENTATION RESULTS OF A REINFORCEMENT CONCRETE PILED RAFT SUPPORTING 2500 TON OIL STORAGE TANK ON VERY SOFT ALLUVIUM DEPOSITS

Shaw-Shong Liew, See-Sew Gue and Yean-Chin Tan, Gue & Partners Sdn Bhd, Kuala Lumpur, Malaysia

Note : A technical paper published in the Ninth International Conference on Piling and Deep Foundation, Nice, France, 3rd – 5th June, 2002

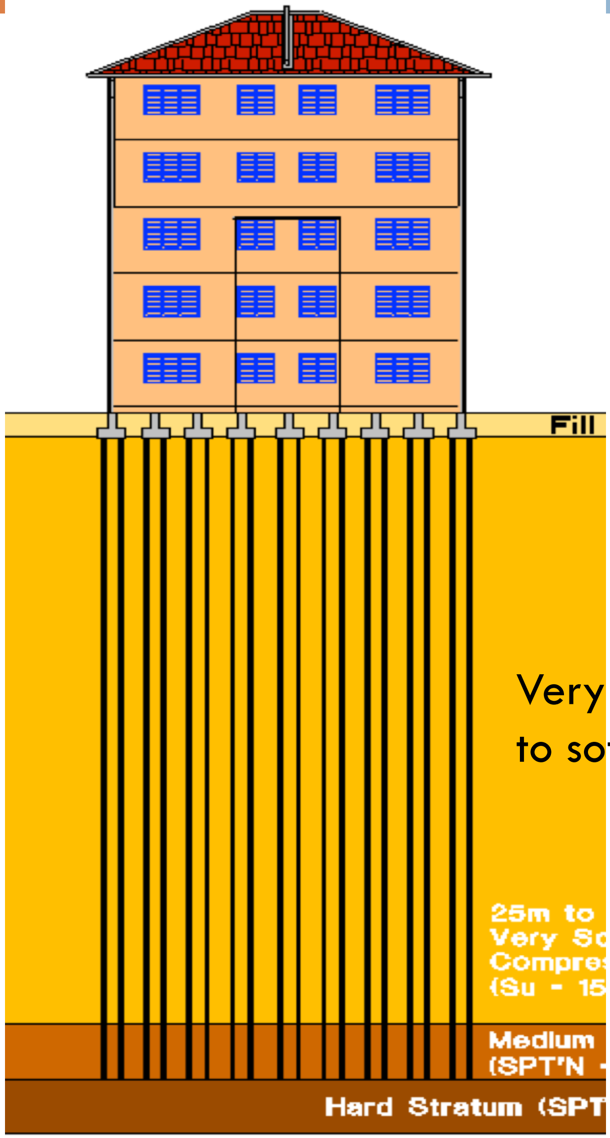
Problem Statements

Problem Statement

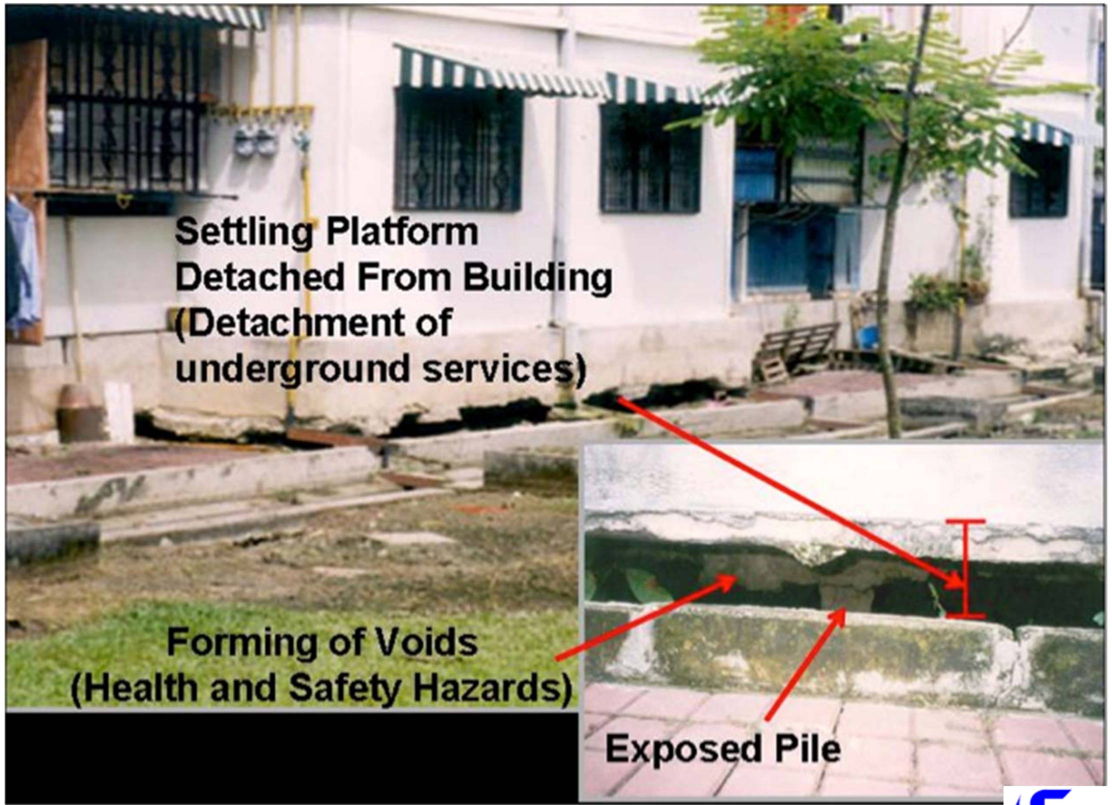
- Conventional Piling system is to installed into competent stratum or to 'set' (terminate) in hard layer. Therefore, if the hard layer is very deep then the piles are very long = *Not economical*
- Conventional Piling **causing Gaps between piled structures and the earth platform** = Health hazard & Problems to Services (e.g. Water, sewerage piping,etc.) = *Not Suitable*.
- Conventional Piling System will also subject to Downdrag Force (Negative Skin Friction) = *Lower working capacity of the Piles*

Problem Statement

Conventional Pile System



Conventional Piling System is Soft Soil will cause Problem



Objectives of the Research

- To look into the possibility of using 'Floating' Piled Raft (FPR) Foundation System and it's design methodology that :

  - Uses shorter piles as do not require to piled to 'set' into deep hard stratum = economical

  - Piled Raft and Platform settled together in a controlled manner = No Gap beneath the buildings thus no problem to services and no health hazard

  - Can be used by Practicing Engineers for day to day design works for projects. (do not required complicated and time consuming 3-D FEM analysis). = Practical usage

Analysis Of Vertically Loaded Single Pile

- Methods of estimating the settlement of single pile generally can be divided into three main categories:-
  - Load transfer (t-z) methods (Colye & Reese (1966); Vijayvergiya (1977) ; Tan et al. (1998) , etc)
  - Elasticity-based methods (Poulos & Davis (1980) ;Randolph & Wroth (1989) ; Randolph (1994) , etc)
  - Numerical methods such as the finite element (FEM) or finite difference methods

Vertically Loaded Pile Group

- the methods to analyse the behaviour of a pile group generally fall into following major categories namely:
  - Simplified Analytical Methods (Randolph and Wroth 1979; Chow 1986; Guo and Randolph 1999). Involving the consideration of vertical displacement of the surrounding soil influenced by the shear stress at shaft and base, and with the influence reduces with distance away from the pile
  - Boundary-Element Methods (Colye & Reese, 1966; O'Neill et al., 1979; Kraft et al., 1981) employing either load-transfer functions to represent the pile-soil interface deformation behaviour
  - Iterative 'hybrid' method (O'Neill et al. (1977); Chow (1986b) and Chow (1987).) Piles are represented as beam-column elements. The soil response at individual piles modelled using load transfer curves (t-z curves).
  - Finite Element Method (Desai, 1974; Ottaviani, 1975; Jardine et al., 1986; Katzenbach, et al., 1998) Considered the most powerful of all other methods in view that FEM can adopt variety of constitutive soil models to simulate soil inhomogeneity and non-linearity in a more consistent manner. However, the three-dimensional nature of the problem makes the method unlikely to be readily applicable to large pile group because of the complexity of the problem, considerable number of geotechnical parameters and high computational requirements. Due to its complexity and high requirements, this method is not commonly used by practising engineers.

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All the methods stated above have not incorporate long term consolidation settlement of the soft compressible subsoil due to loading from the raft.

→ ***To be covered in this Presentation***

Vertically Loaded Pile Group

Fleming *et al*. (1992) proposed the use of pile group only in the central area of a flexible raft. Randolph (1994) suggested that even a relatively flexible raft could undergo minimal differential settlement, provided that an optimum design was achieved. This design concept is shown schematically in Fig. 2.1.

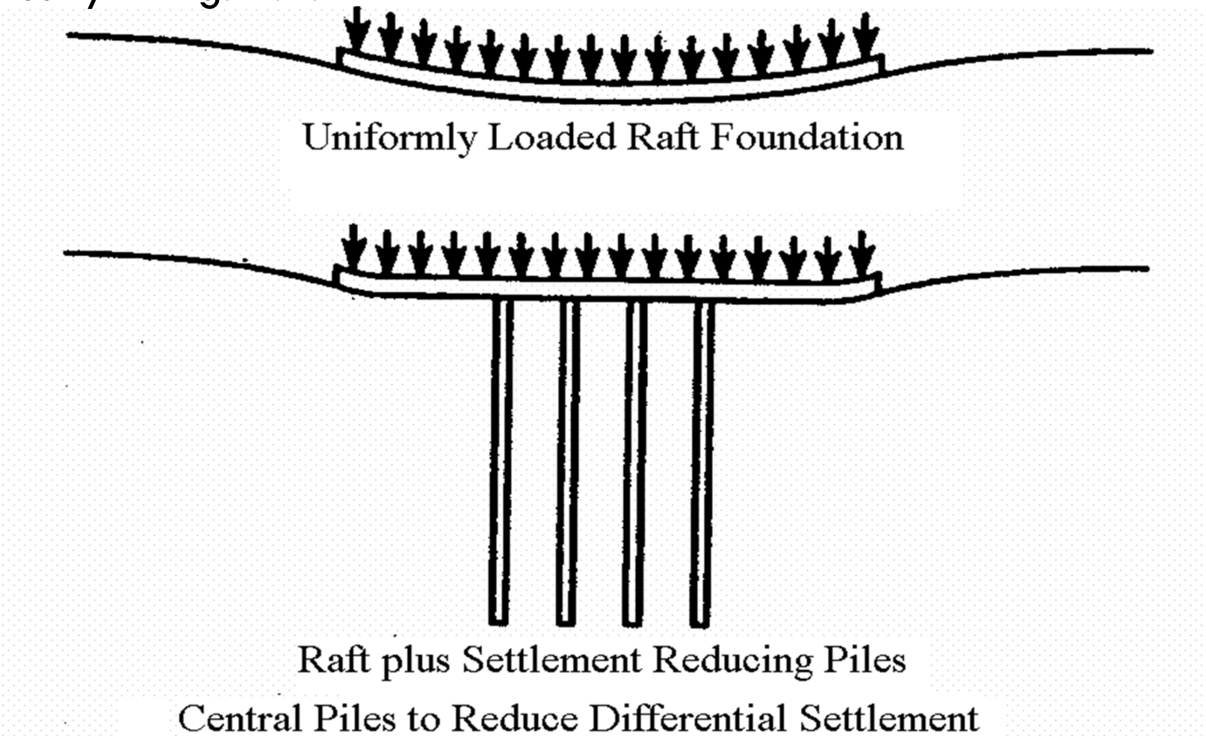


FIGURE 2.1 Central piles to reduce differential settlement (from Randolph, 1994)

Time-Dependent Settlement in Pile Group Analysis

- Time-dependent settlement usually arises from three main sources :
  - ***Consolidation settlement*** of highly compressible clayey and silty soils due to the load from the raft. The magnitude is significant and critical for piled raft on soft compressible subsoil.
  - Creep settlement of the soil under constant loading which is insignificant compared to consolidation settlement.

Time-Dependent Settlement in Pile Group Analysis

- **de Sanctis & Mandolini (2006)** based on 3-D finite element analyses via finite element code ABAQUS version 6.2 **(3-D FEM)** and experimental evidences by others, has proposed a simple criterion to evaluate the ultimate vertical load of a piled raft on soft clay soils with consideration of consolidation effect as a function of its component capacities.
- **Small & Liu (2008)** presented a full three-dimensional **(3-D FEM)** finite element analysis to estimate the rate consolidation settlement of piled raft, magnitude of differential deflections and moments in the raft. However this method cannot be commonly used by engineers doing piled raft design as it required 3-D finite element program.

Time-Dependent Settlement in Pile Group Analysis

- **de Sanctis & Mandolini (2006)** based on 3-D finite element analyses via finite element code ABAQUS version 6.2 and

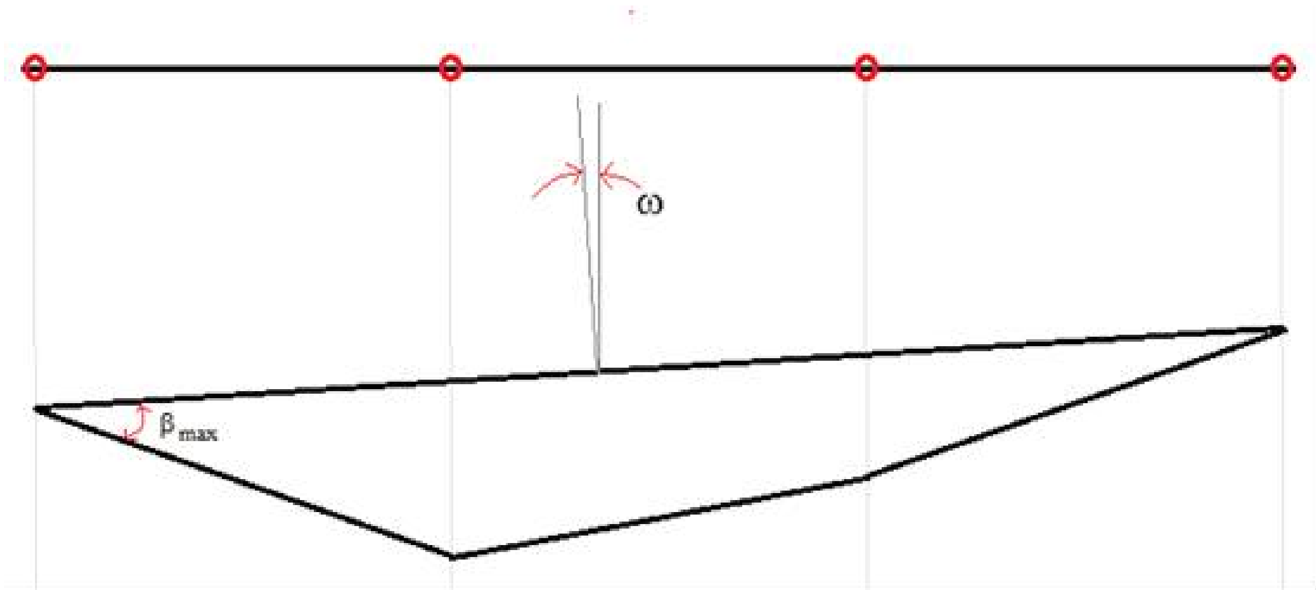
Time-Dependent Settlement normally required 3-D FEM (not easily available to practicing engineers)

→ This research will incorporate the time-dependent settlement in a simplified method that is suitable for practicing engineers.

- and moments in the raft. However this method cannot be commonly used by engineers doing piled raft design as it required 3-D finite element program.

Limiting Deformation For Framed Buildings and Reinforced Load Bearing Wall

- Skempton & MacDonald (1956) studies cover steel-framed industrial buildings, reinforced concrete framed buildings with traditional cladding (e.g. brick wall), and some load bearing masonry wall buildings,
- The criterion for limiting deformation was the "angular distortion' which is same as "relative rotation" (β). Figure below shows the schematic of relative rotation and tilt (ω)



Concluding Comment on Literature Review

- The challenges of analysing and designing piled raft in soft ground are as follows :
  1. The effects of consolidation settlement of the soft compressible subsoil due to the load from the raft. The magnitude of consolidation settlement will have significant effect on the overall performance of the piled raft.
  2. For soft compressible subsoil, piles of varying length will be used in some condition to even out the differential settlement of the relatively flexible raft.
  3. The angular distortion (β) of the piled raft shall be controlled within the acceptable range of 1/500.

- There is a need to **develop a practical analysis and design methodology** for piled raft with piles of varying lengths in deep layer of very soft compressible subsoil that can be used by design engineers in day to day design work.

Bridging Research Gap

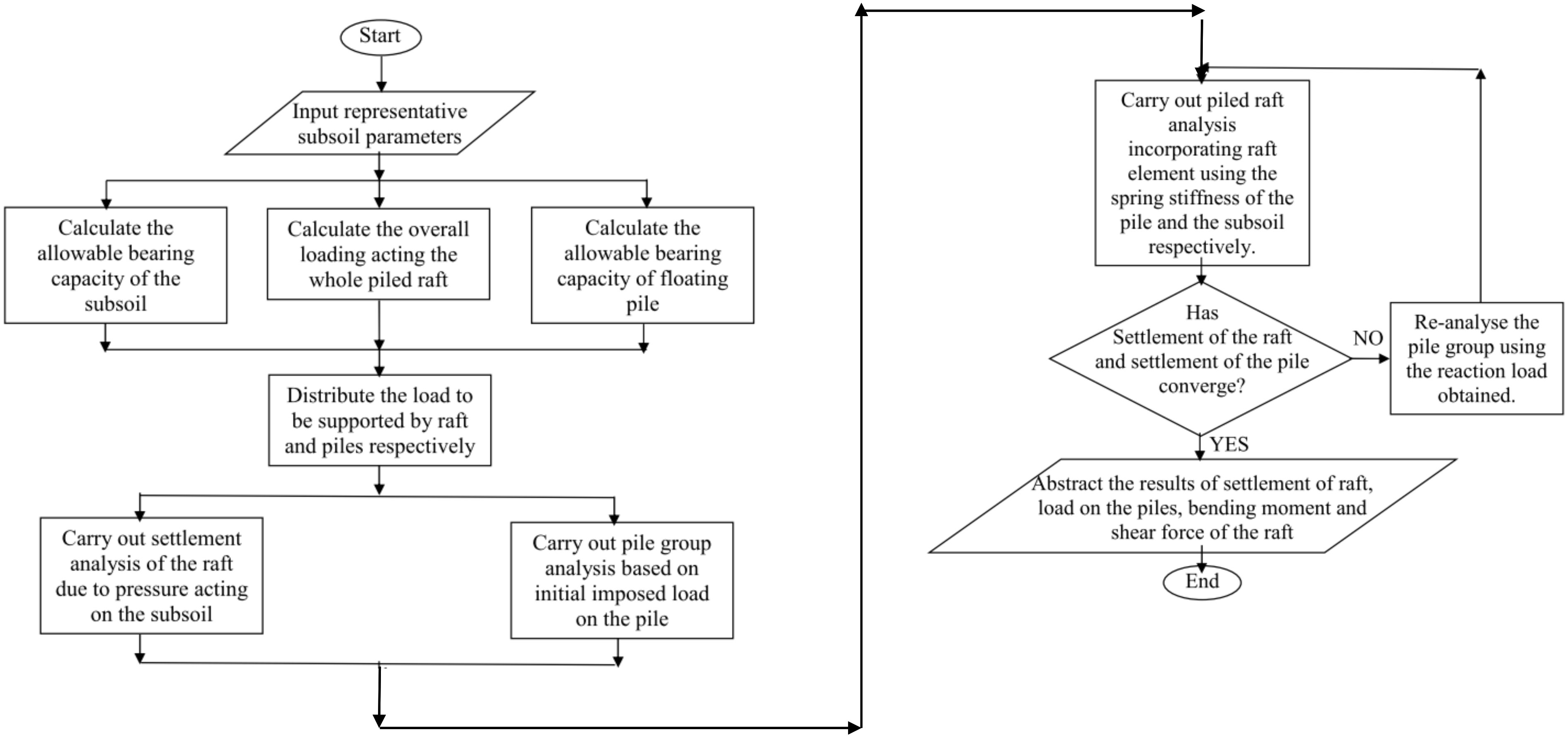
Bridging Research Gap

Literature Review / Works by others	Current Research
1. Piled Raft generally for strong competent subsoil (Not soft compressible subsoil)	1. To use Piled Raft for *soft compressible subsoil*
2. Commonly do not include TIME DEPENDENT settlement.	2. Incorporated *TIME DEPENDENT Settlement* which is main challenges for Piled Raft on soft compressible subsoil
3. Commonly do not include Piles of varying length.	3. Incorporated Piles of *varying length* in the design methodology developed.
4. Required sophisticated 3-D Finite Element method software (FEM).	4. Develop *practical* analysis and design methodology for practicing engineers for design.

Research Methodology

Note : Chapter 3 (Pg. 44)

Flow Chart of Methodology



Note : Detailed Procedures presented in Section 4.4 (Pg. 58 to 60)

Piled Raft Analysis

Note : Chapter 4 (Pg. 53)

Research Analysis

The scope of works for this research are as follows :-

- Only **vertically loaded pile groups** in **soft compressible subsoil** only.
- Piled Raft of 3x3, 6x6 and 9x9 piles with same and varying pile length (e.g. 6m to 24m deep) = **108 Cases in total.**
- One typical and representative soft clay subsoil = using Klang Clay (Tan et. al., 2004)
- Case study on actual projects :-

  a) 2-storey terrace houses @ Bandar Botanic , Klang

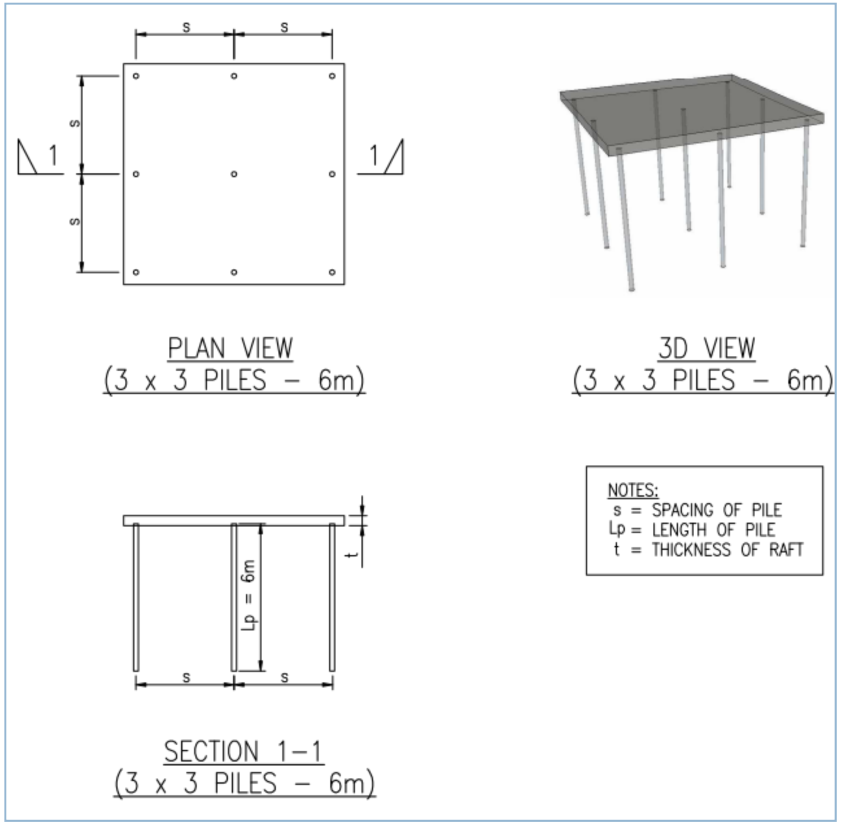
  b) 5-storey medium rise apartment @ Bandar Botanic, Klang

Scope of Works

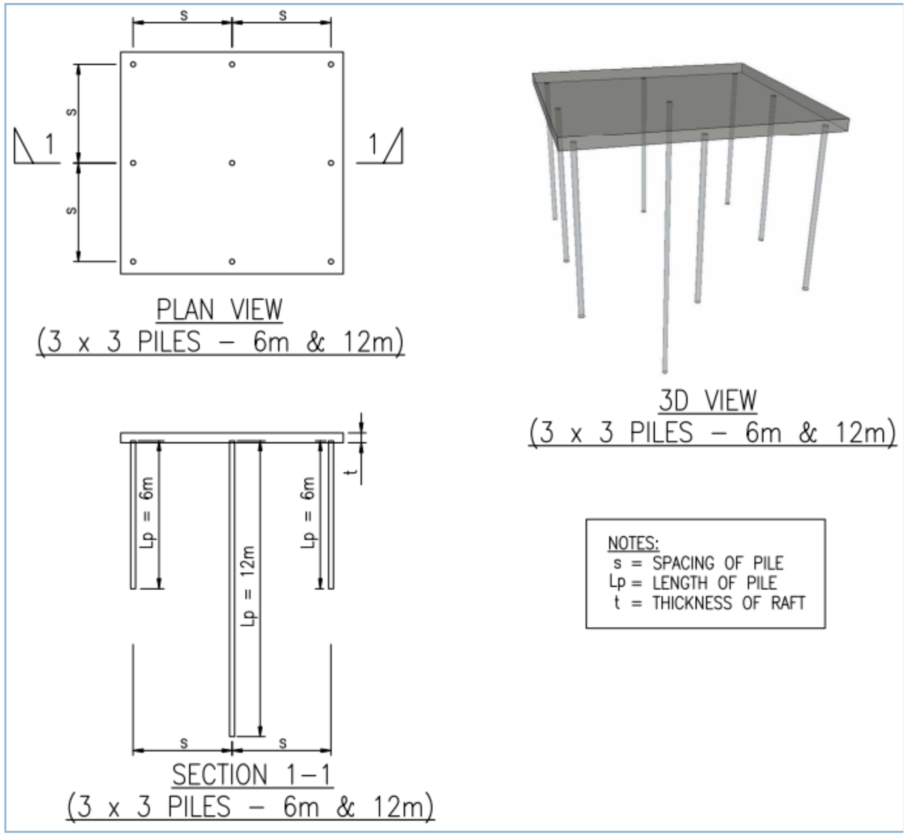
- Matrix showing the cases of analyses for 3x3, 6x6 and 9x9 piled raft = 108 Cases in total.

Pile Spacing, S (m)		2	2	2	4	4	4	6	6	6
Raft Thickness, t (m) =		0.2	0.4	0.8	0.2	0.4	0.8	0.2	0.4	0.8
Piles Numbers	Pile Lengths (m)									
3 x 3 piles	6m	X	X	X	X	X	X	X	X	X
3 x 3 piles	12m	X	X	X	X	X	X	X	X	X
3 x 3 piles	6m & 12m	X	X	X	X	X	X	X	X	X
6 x 6 piles	6m	X	X	X	X	X	X	X	X	X
6 x 6 piles	12m	X	X	X	X	X	X	X	X	X
6 x 6 piles	18m	X	X	X	X	X	X	X	X	X
6 x 6 piles	6m, 12m & 18m	X	X	X	X	X	X	X	X	X
9 x 9 piles	6m	X	X	X	X	X	X	X	X	X
9 x 9 piles	12m	X	X	X	X	X	X	X	X	X
9 x 9 piles	18m	X	X	X	X	X	X	X	X	X
9 x 9 piles	24m	X	X	X	X	X	X	X	X	X
9 x 9 piles	6m, 12m, 18m & 24m	X	X	X	X	X	X	X	X	X
Note : A total of 108 cases are being analysed. One "X" indicate one set of analysis.										

Scope of Works (Typical 3x3 Piled Raft)

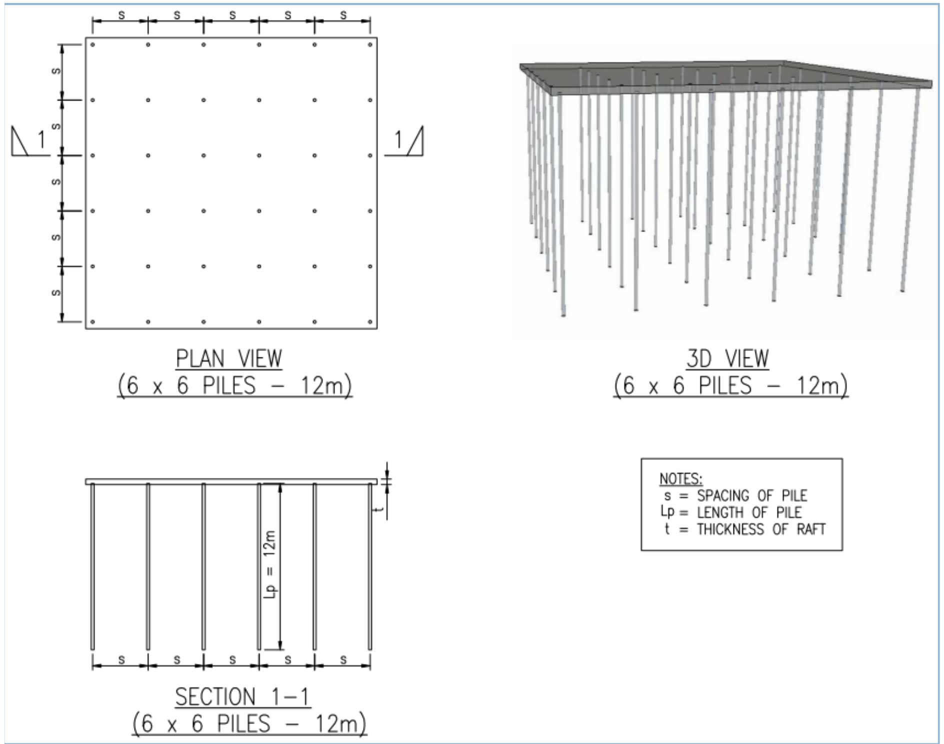


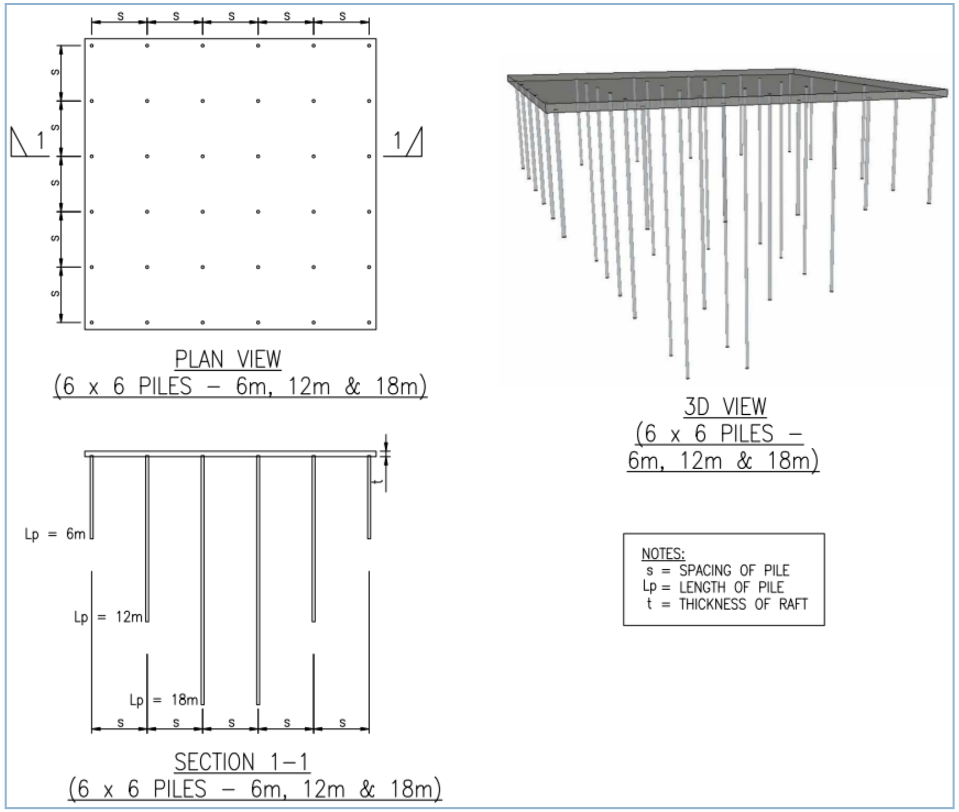
Typical 3x3 piled raft with same pile length (6m)



Typical 3x3 piled raft with varying pile length (6m & 12m)

Scope of Works (Typical 6x6 Piled Raft)

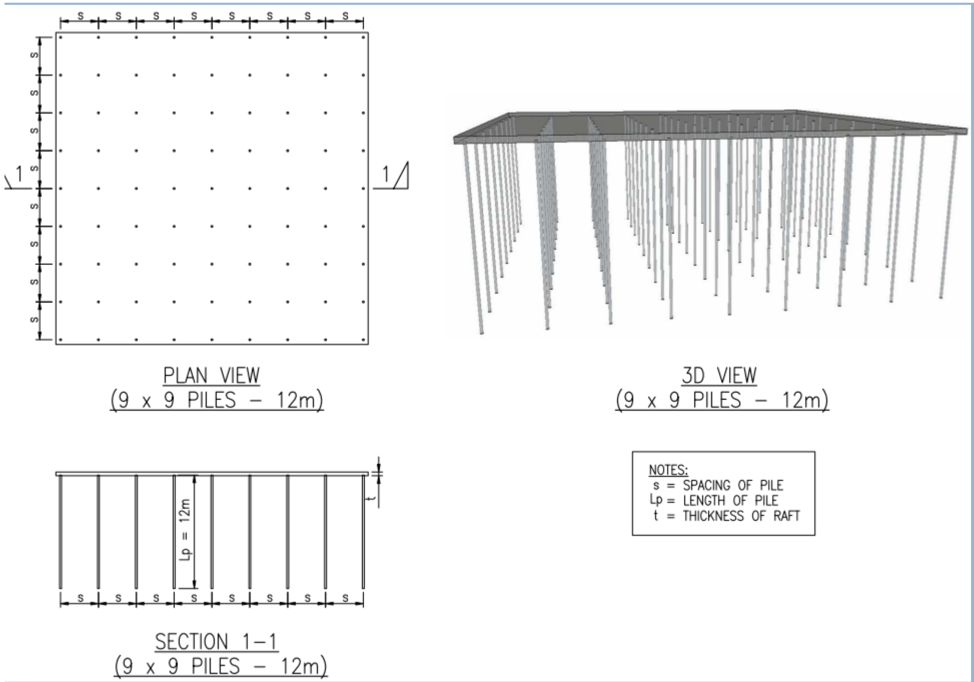


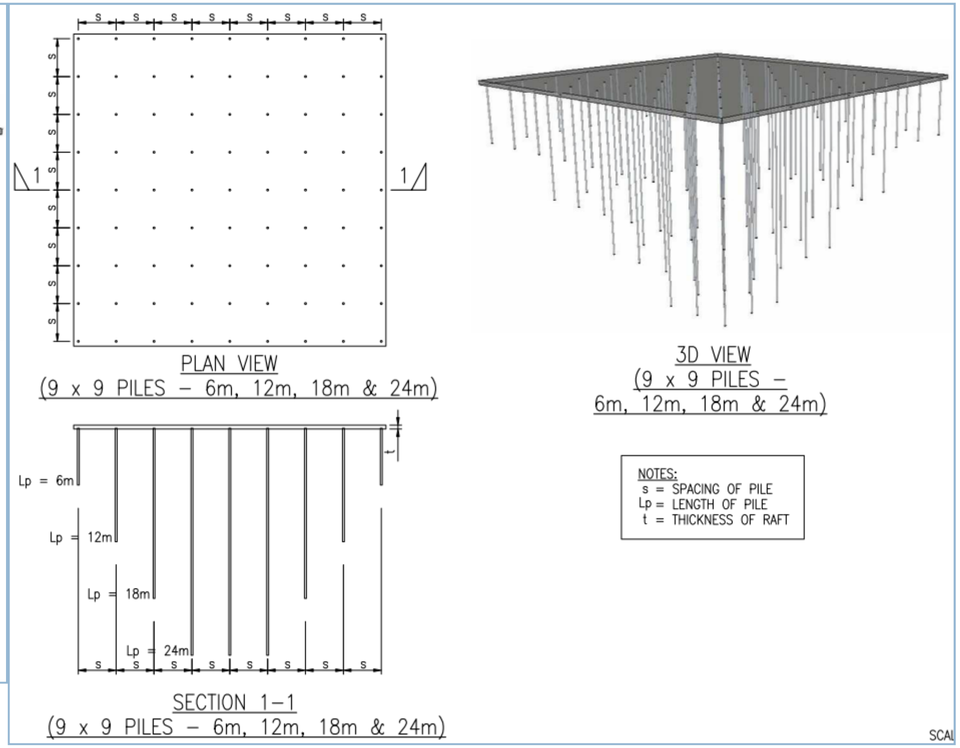


Typical 6x6 piled raft with same pile length (12m)

Typical 6x6 piled raft with varying pile length (6m,12m & 18m)

Scope of Works (Typical 9x9 Piled Raft)

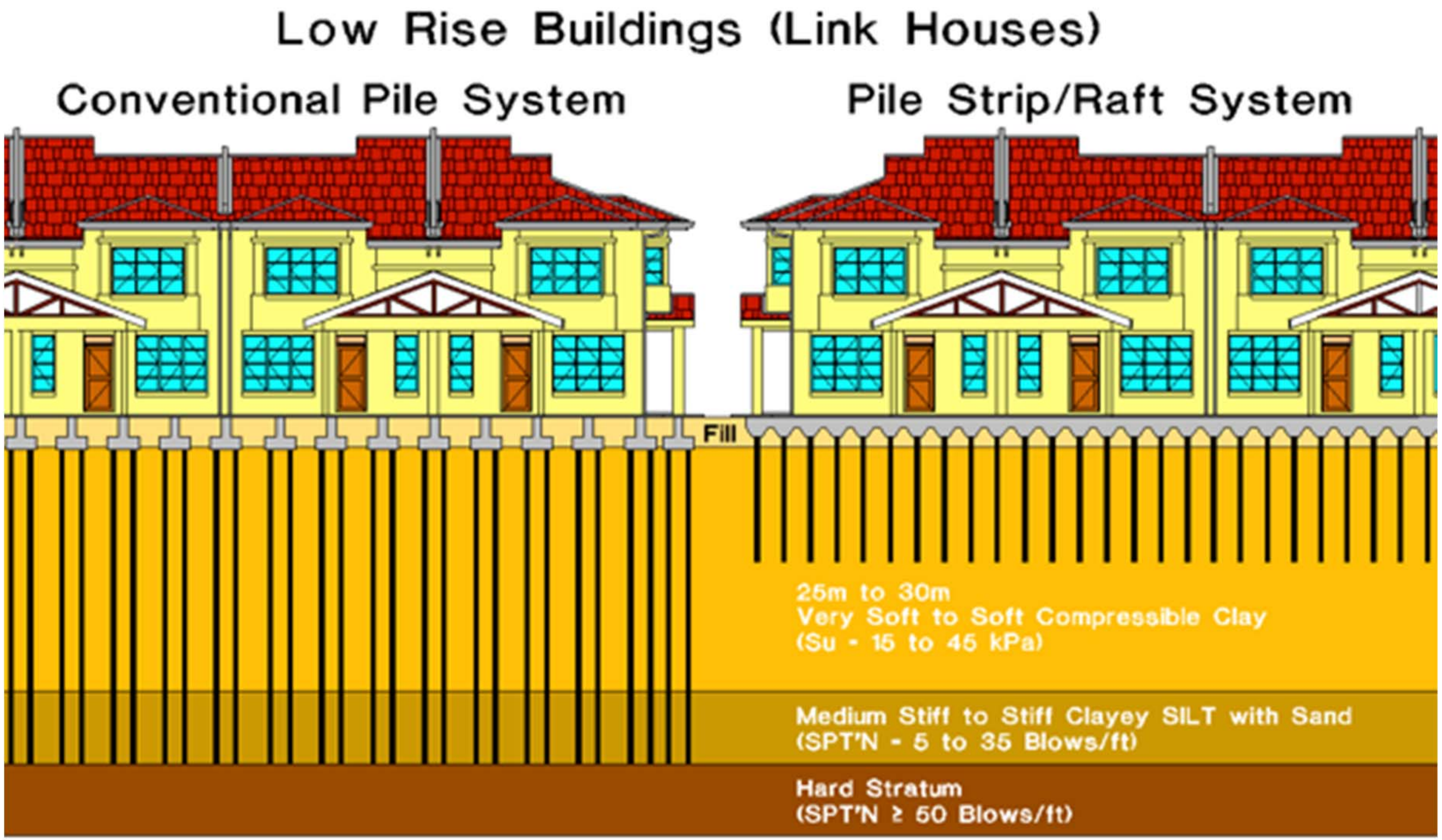




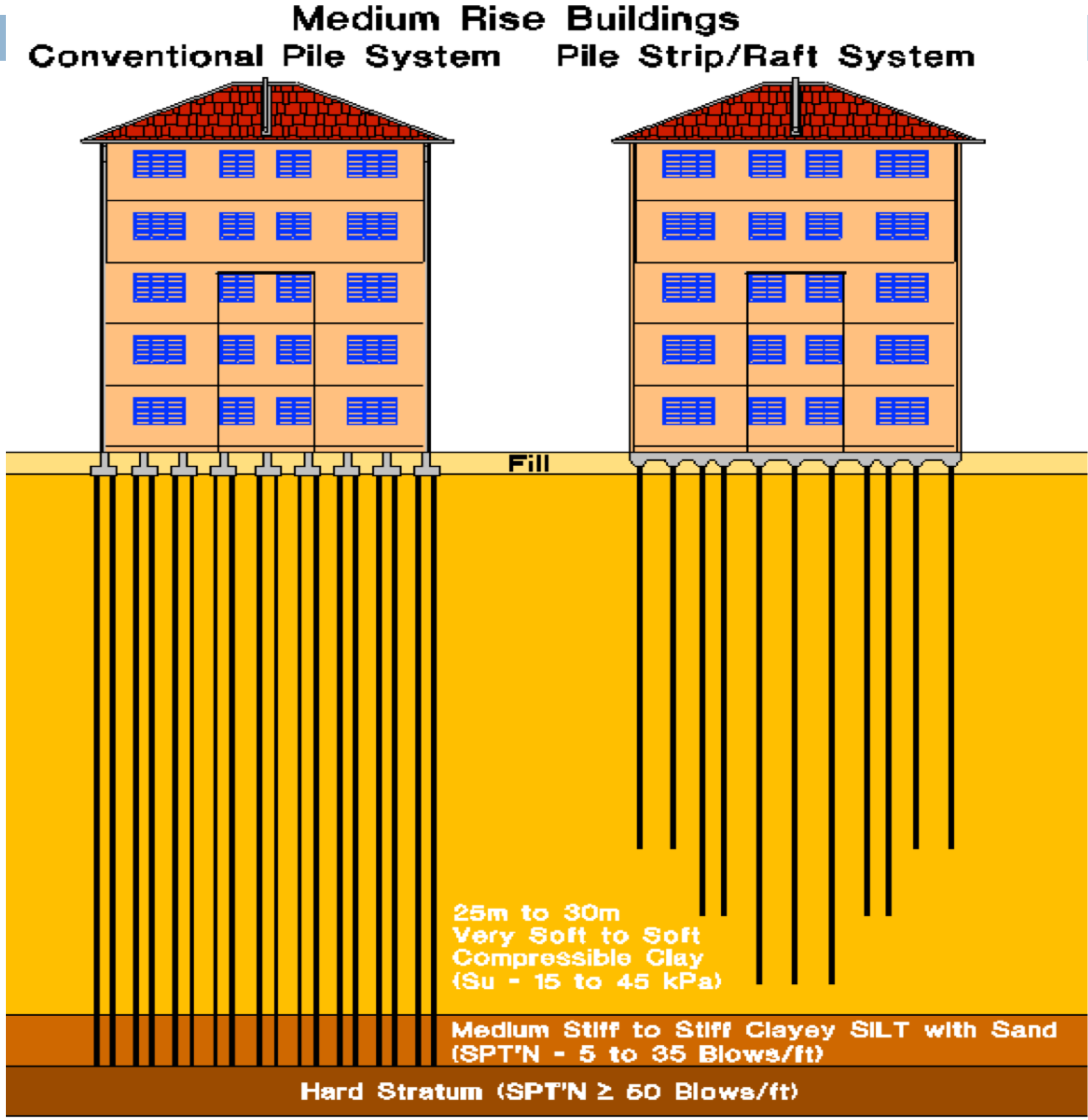
Typical 9x9 piled raft with same pile length (12m)

Typical 9x9 piled raft with varying pile length (6m,12m, 18m & 24m)

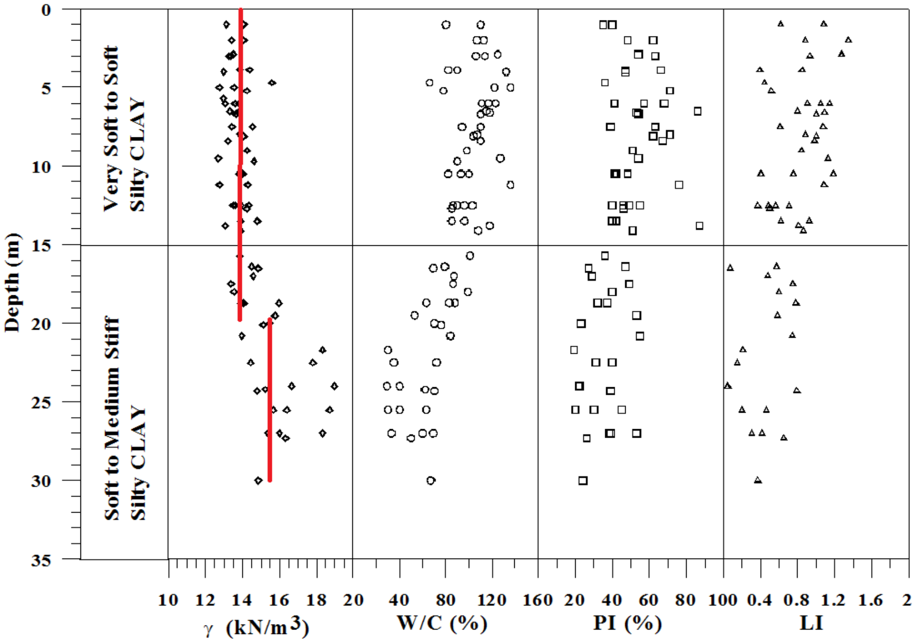
Scope of Works (Case Studies – 2-storey terrace houses)

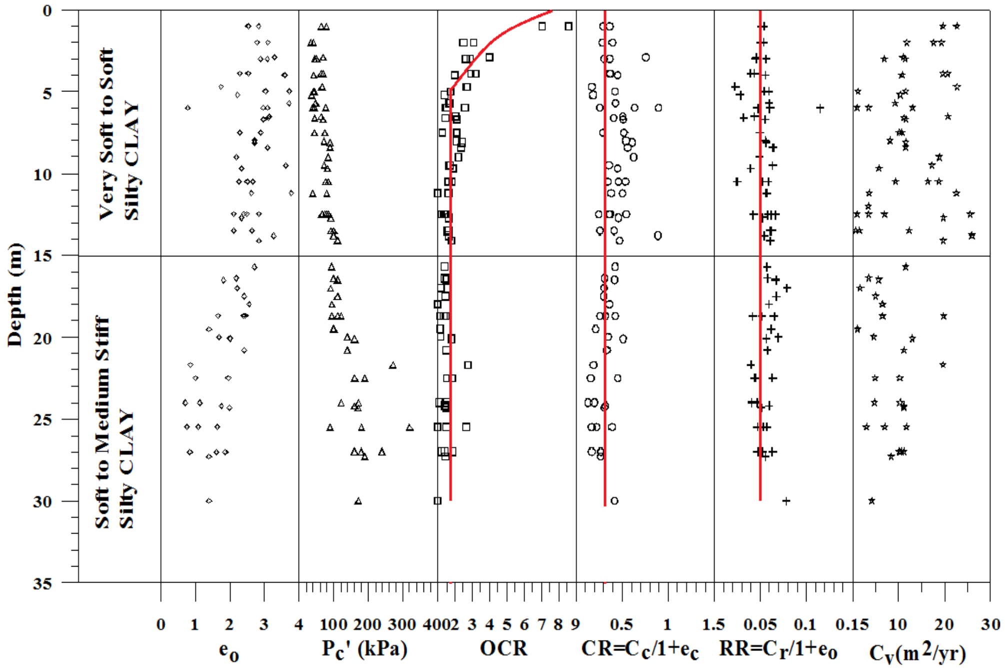


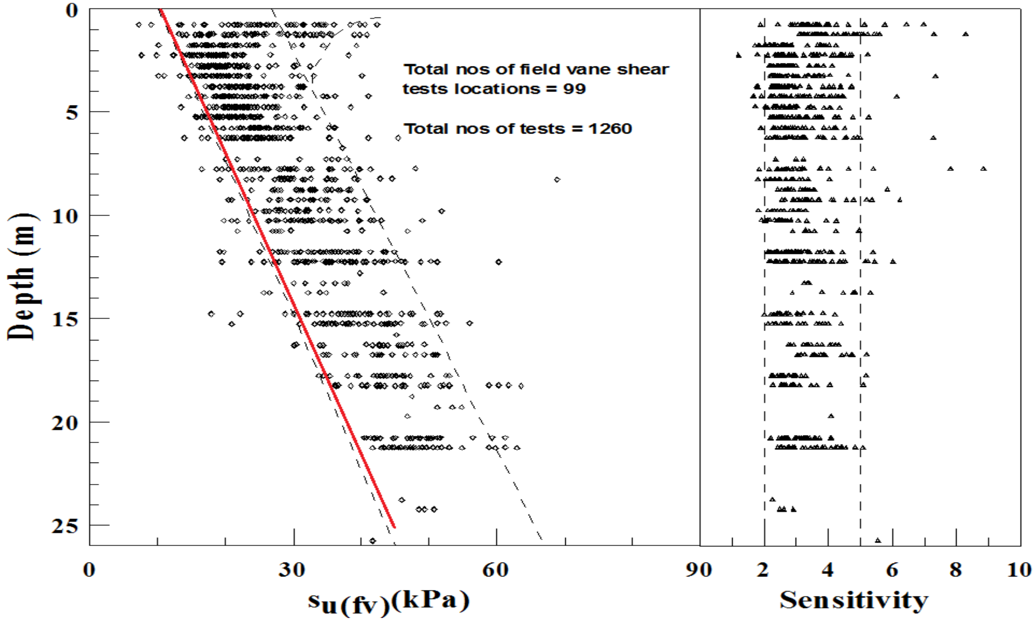
Scope of Works (Case Studies – 5-storey medium rise apartments)



Subsoil Parameters







Design Value

Results Interpretation and Discussions

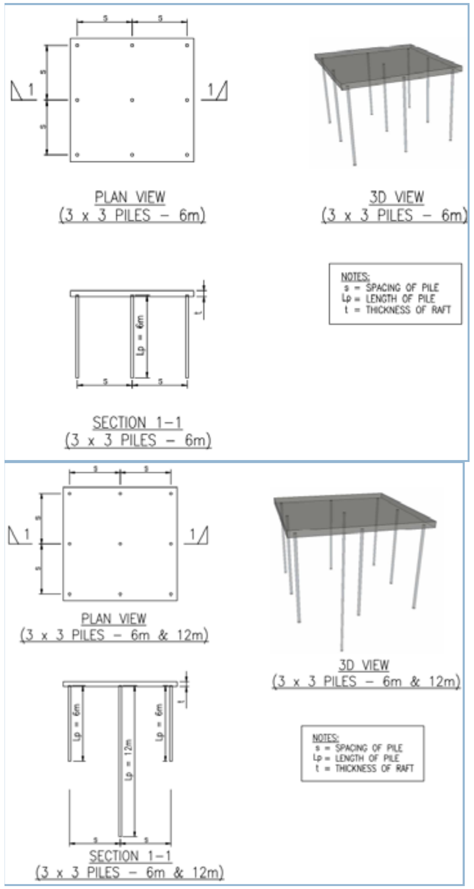
Key Results

- Differential Settlement ($\Delta\rho$)
- Maximum Settlement (ρ_{max})
- Pile Raft Coefficient (α_{pr})
- Bending Moment in the Raft
- Settlement Profile & Angular Distortion (β)

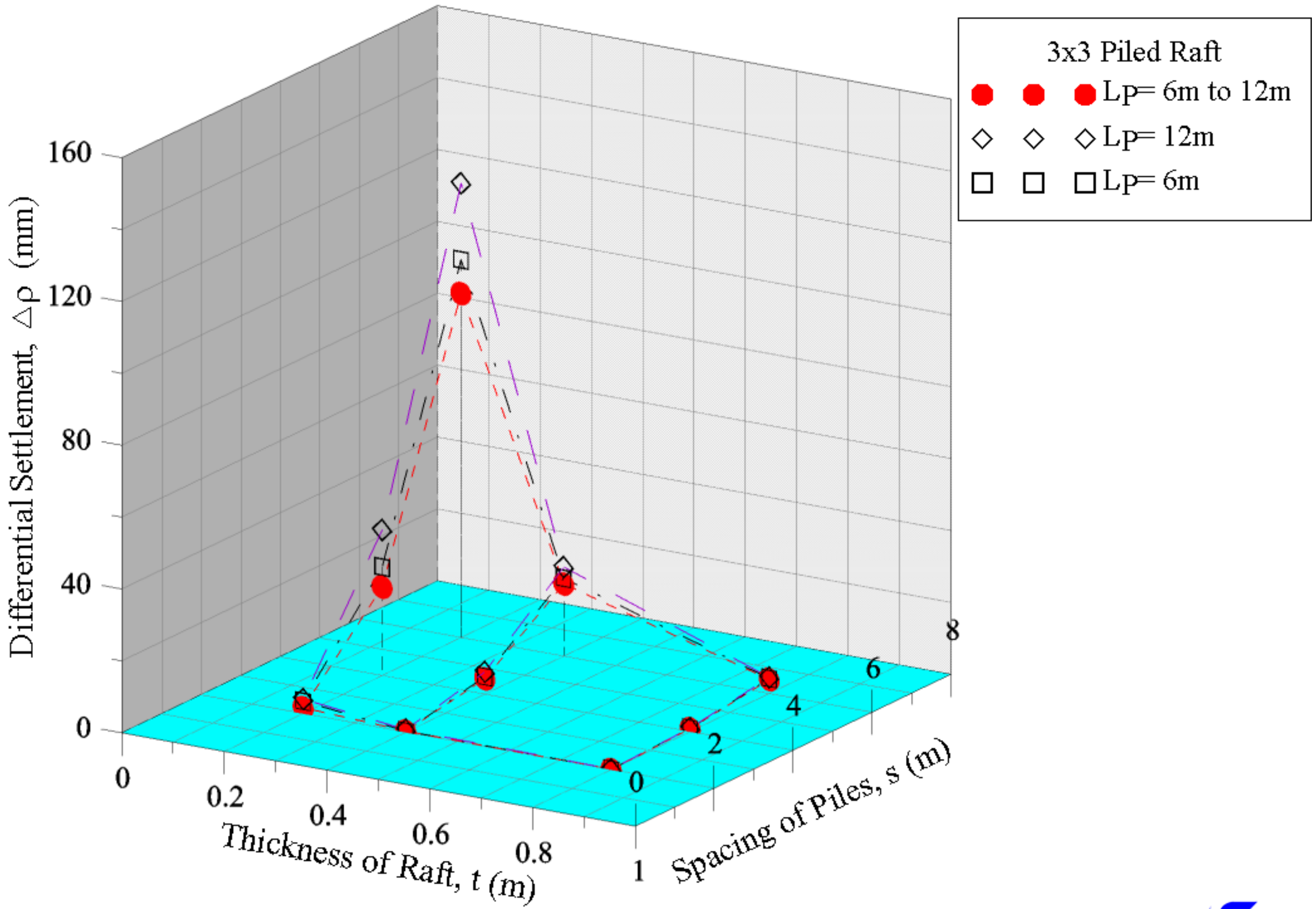
Differential Settlement ($\Delta\rho$)

Note : Section 5.1.1 (Pg. 79)

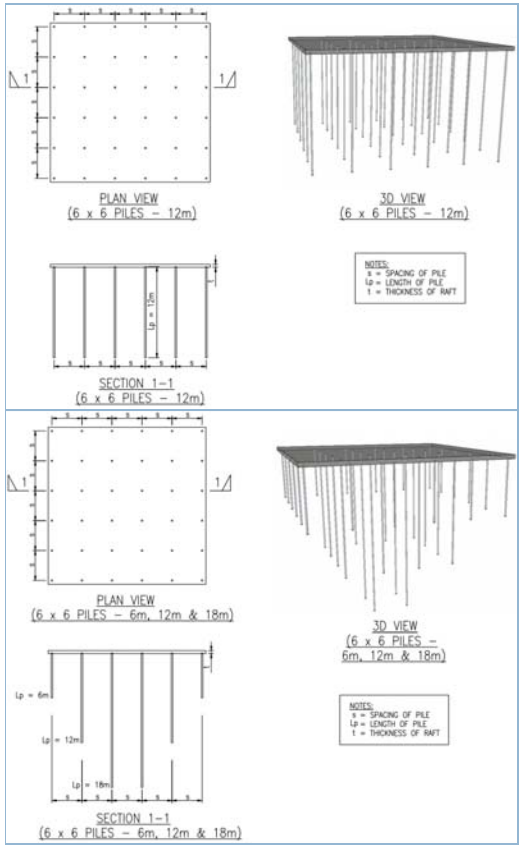
Differential Settlement (Δρ) of 3x3 Piled Raft



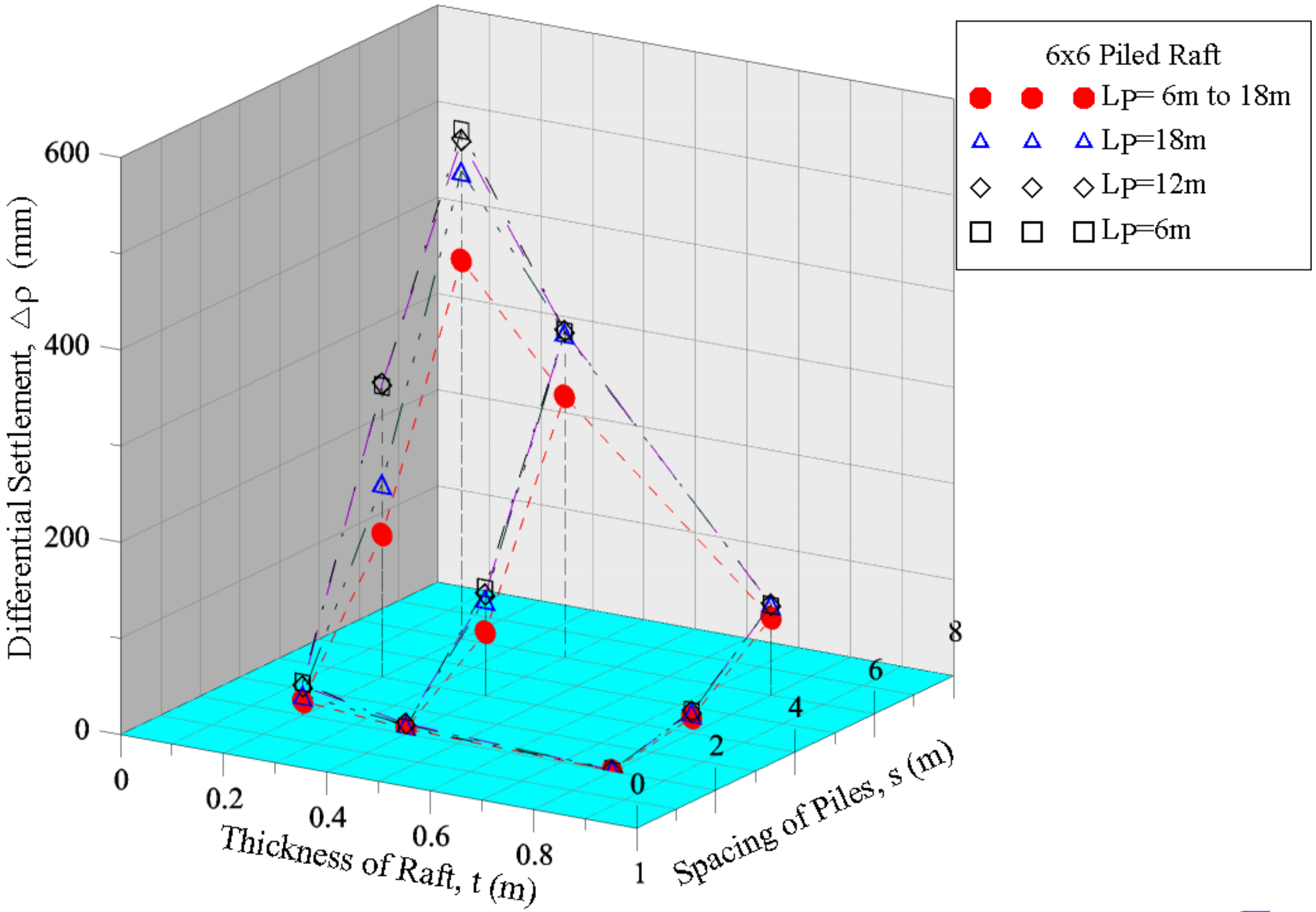
3 x 3 Piled Raft



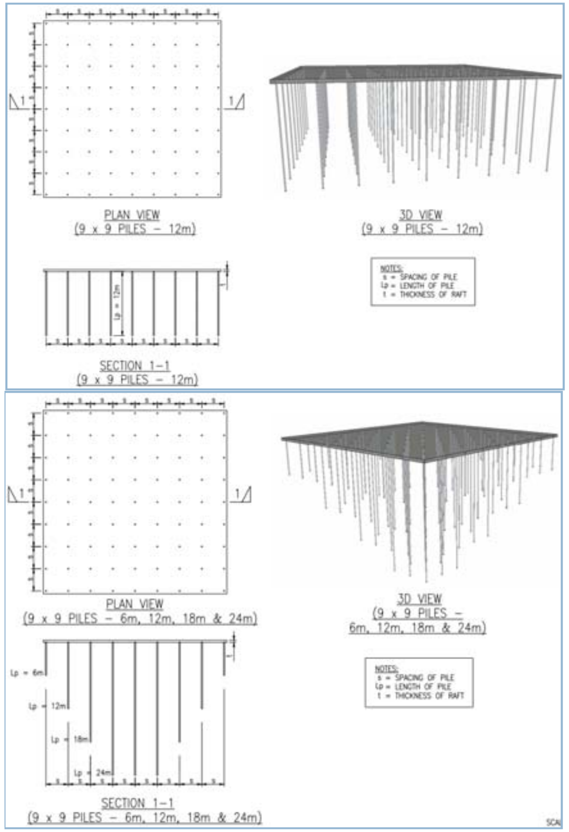
Differential Settlement (Δρ) of 6x6 Piled Raft



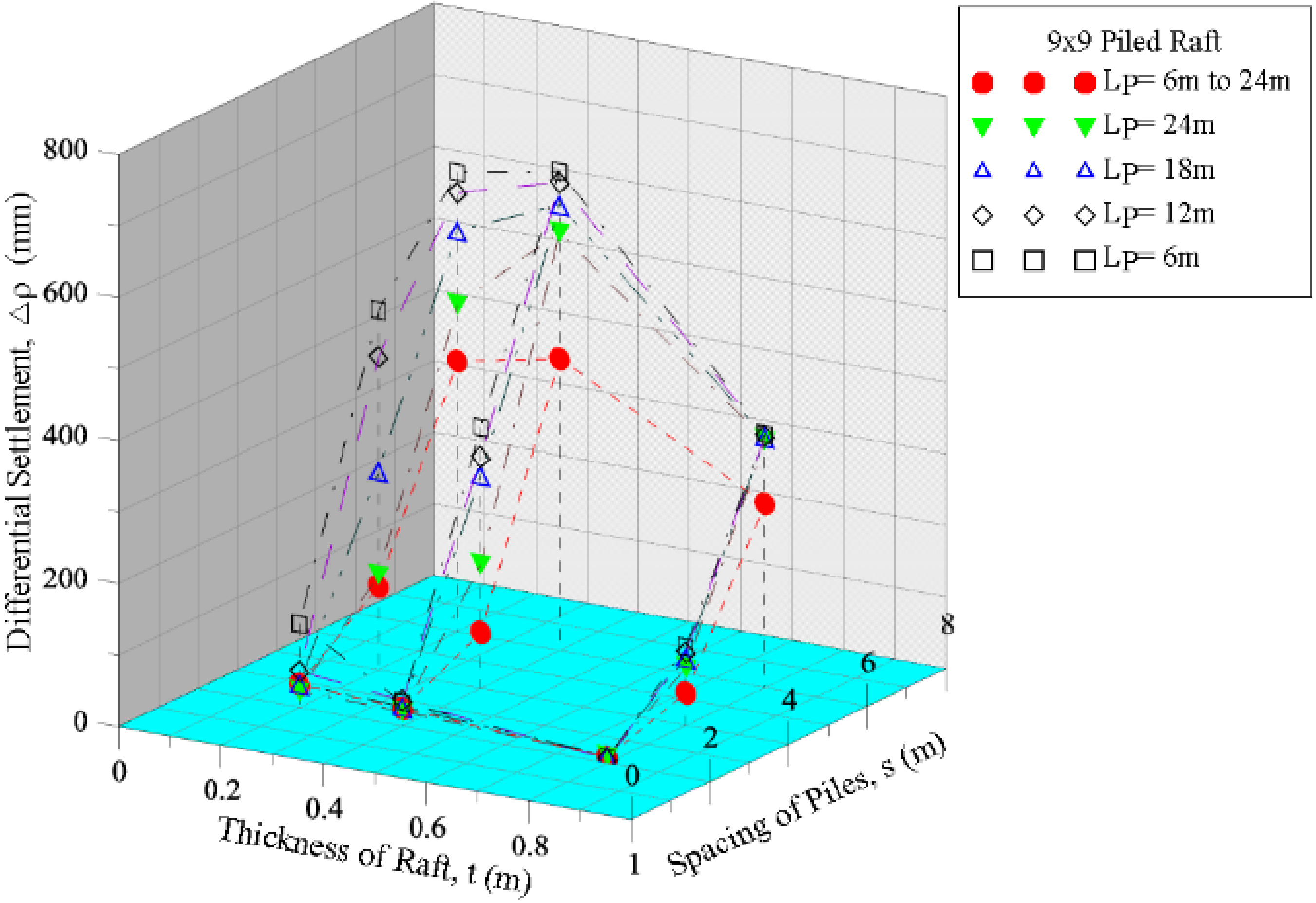
6 x 6 Piled Raft



Differential Settlement (Δρ) of 9x9 Piled Raft



9 x 9 Piled Raft



Findings and Discussions on aspects of **Differential Settlement (Δρ)**

a) Combination of *varying pile lengths* in a piled raft will be more effective in controlling differential settlement compared to using same pile lengths in a piled raft.

b) The reason is for a flexible raft under uniform loading, the total settlement will tends to be larger at the centre compared to the edge. Therefore, by placing longer piles at the middle of the raft while shorter piles are placed at the edges, it will evenly smoothen the differential settlement.

c) By placing longer piles at the middle of the raft while shorter piles are placed at the edges will allow more load to be transferred to the longer piles in the middle of the raft thus reducing the load intensity acting on the subsoil at the middle of the raft compared to the edges. This will reduce relatively the settlement of the subsoil at the centre of the raft thus reducing the differential settlement. The effect is similar to stiffen the overall stiffness of the piled raft system to behave like rigid footing to even out differential settlement.

Findings and Discussions on aspects of **Differential Settlement ($\Delta\rho$)**

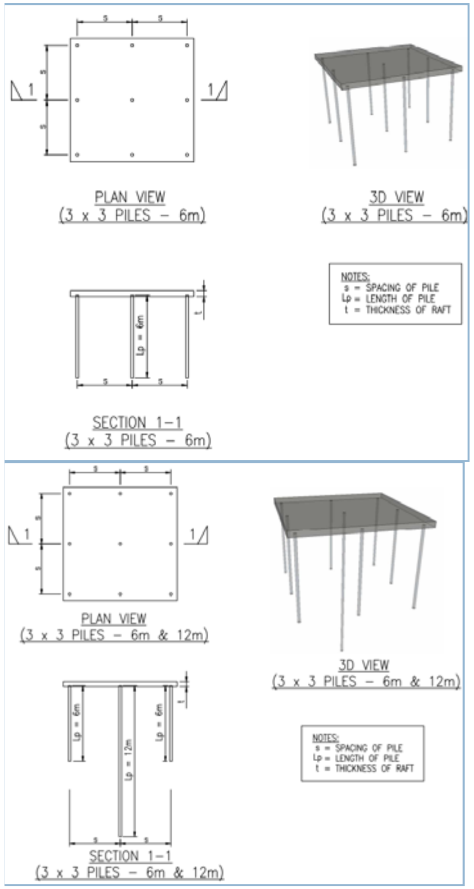
d) Piled raft with longer same pile lengths (e.g. L_p of 24m throughout for 9x9 piled raft, L_p of 18m throughout for 6x6 piled raft and L_p of 12m throughout for 3x3 piled raft) will have smaller differential settlement compared to piled raft with shorter same pile lengths. The reason is longer piles will be able to support more imposed load thus reduce the load transferred by the raft directly onto the subsoil beneath the raft.

e) Piled raft with combination of varying pile lengths is still more effective than Piled raft with longer same pile lengths (e.g. L_p of 24m throughout for 9x9 piled raft, L_p of 18m throughout for 6x6 piled raft and L_p of 12m throughout for 3x3 piled raft) by having lowest magnitude of differential settlement.

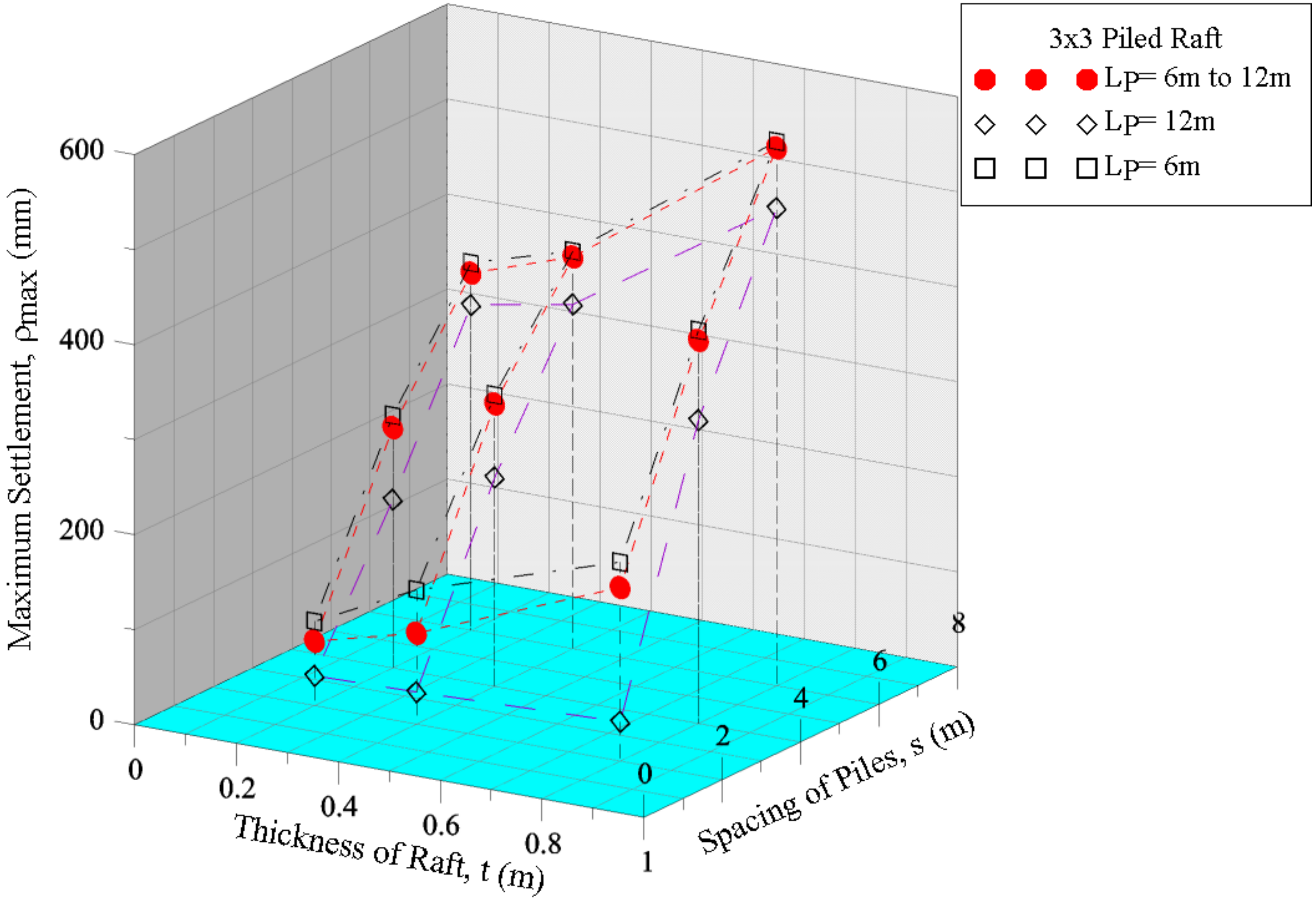
Maximum Settlement (ρ_{max})

Note : Section 5.1.3 (Pg. 88)

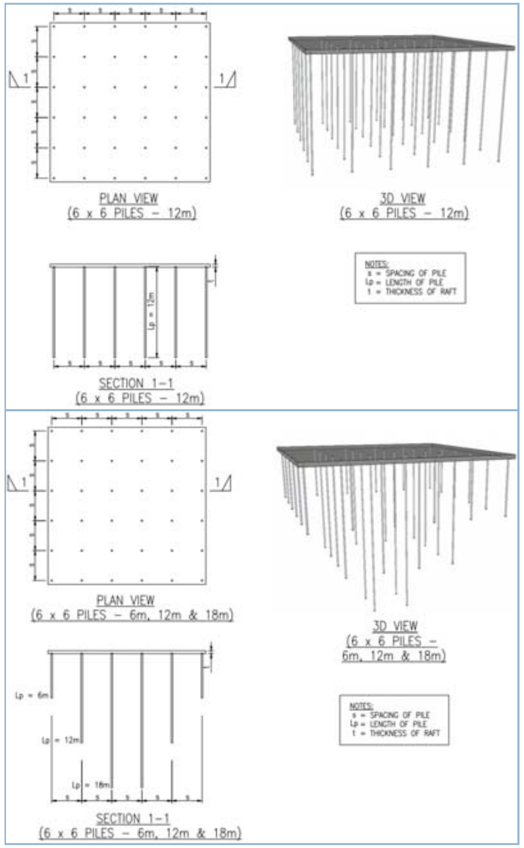
Maximum Settlement (ρ_{max}) of 3x3 Piled Raft



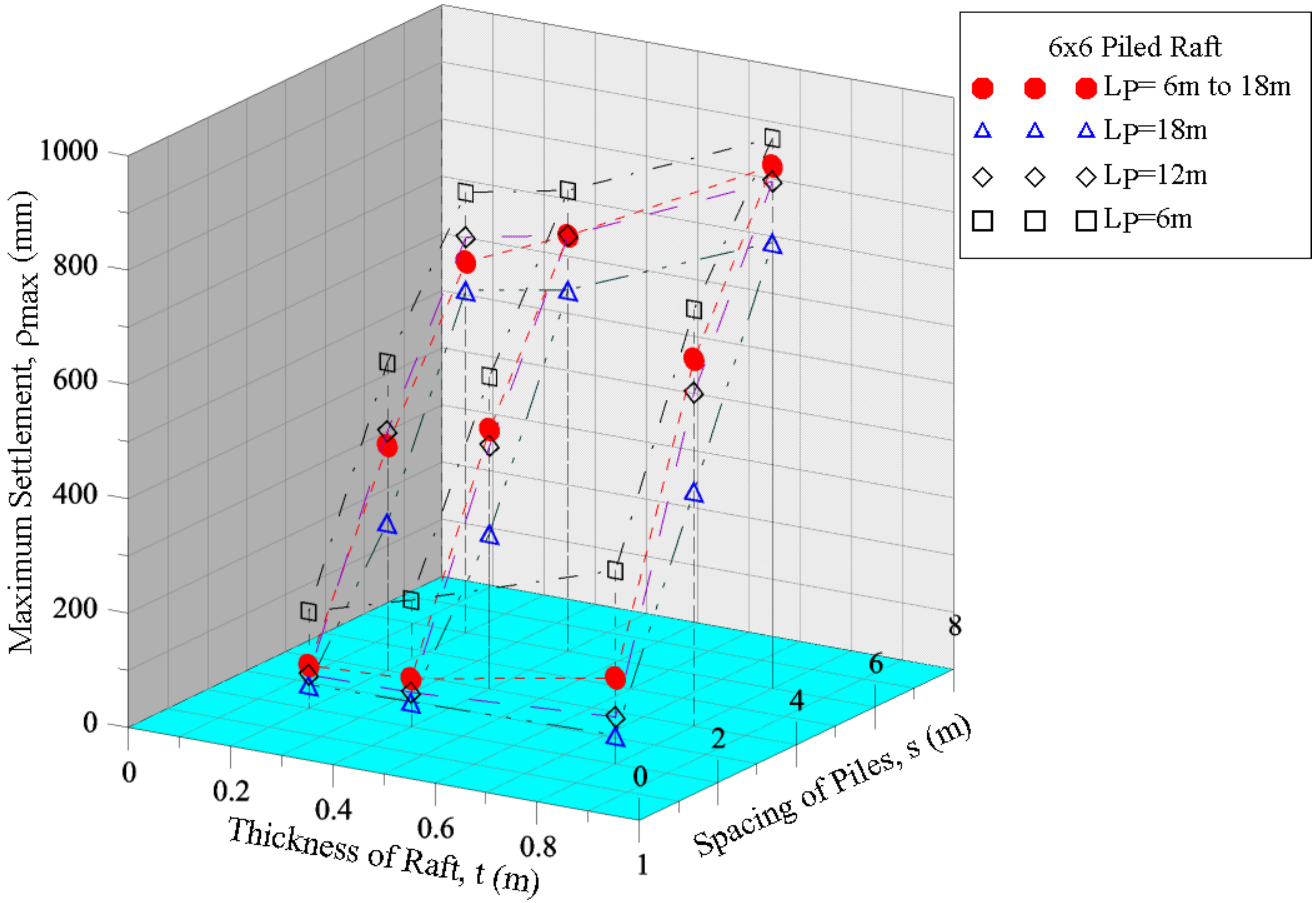
3 x 3 Piled Raft



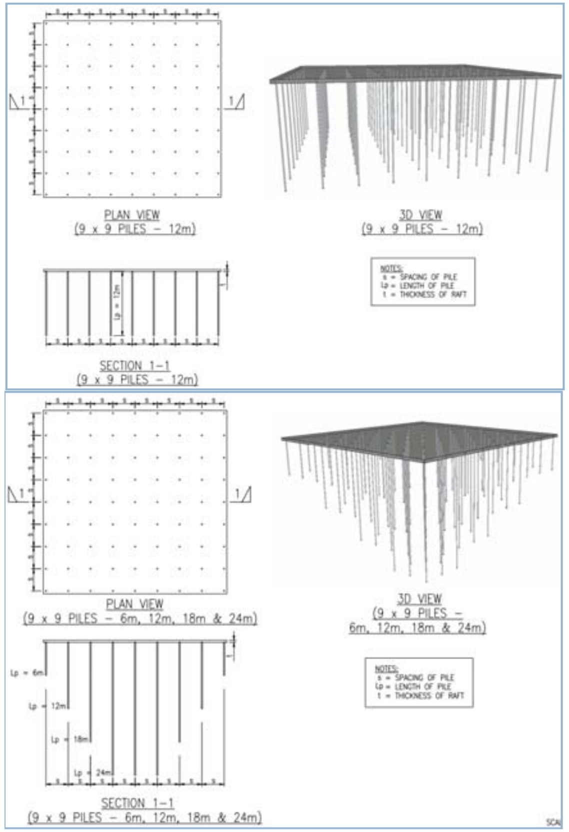
Maximum Settlement (ρ_{max}) of 6x6 Piled Raft



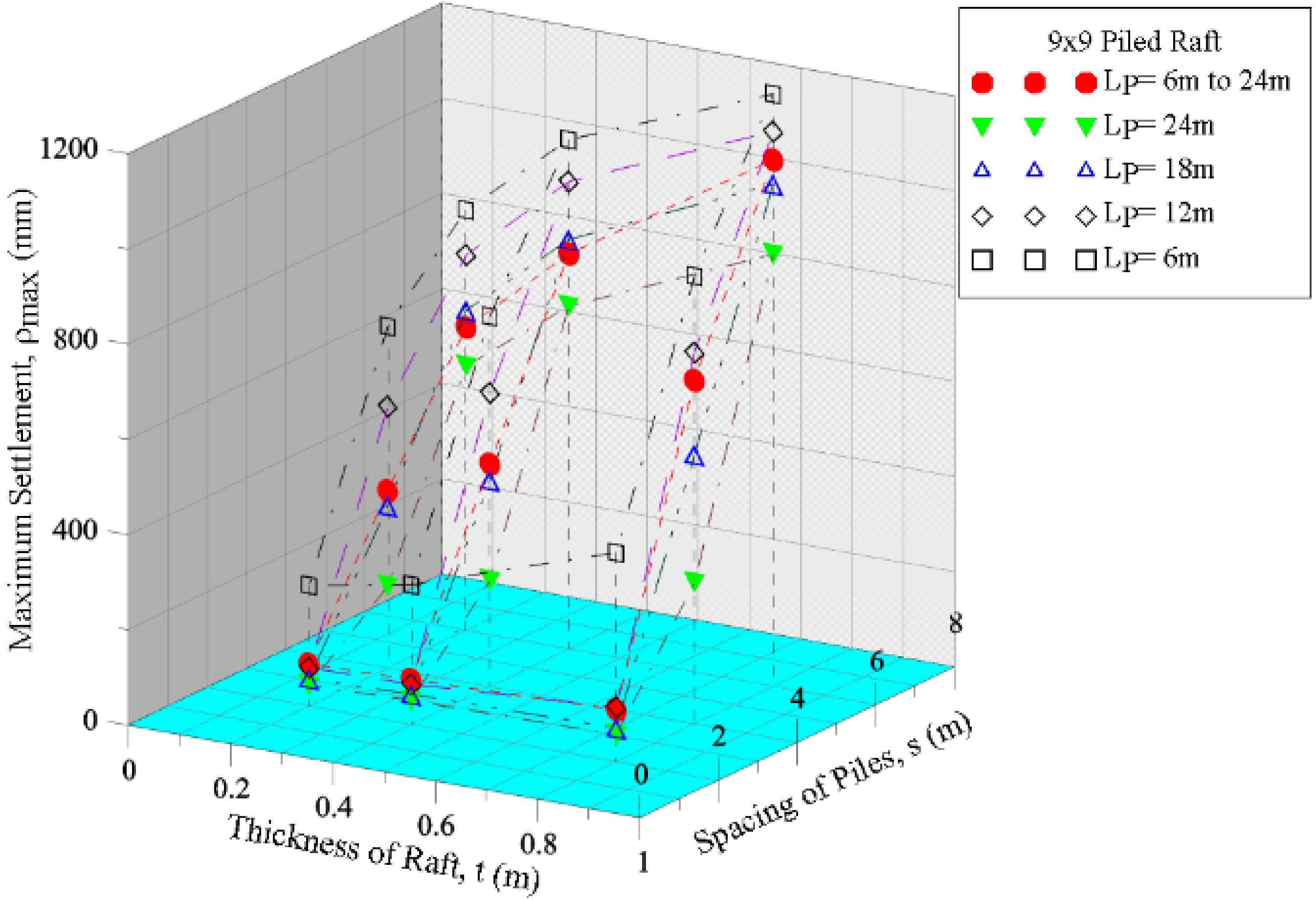
6 x 6 Piled Raft



Maximum Settlement (ρ_{max}) of 9x9 Piled Raft



9 x 9 Piled Raft



Findings and Discussions on aspects of **Maximum Settlement** (ρ_{max})

a) Maximum settlement is largest for piled raft of 9x9 piles followed by piled raft of 6x6 piles then piled raft of 3x3 piles. This is because the larger the pile group, the larger is total load (in kN obtained from [uniform load x area of the raft]) acting on the piled raft system.

b) Maximum settlement also increases with increases in spacing of the piles for all piled groups. This is because as the spacing of the piles (s) increases, there will be an increase in load transferred to the raft thus more load acting on the subsoil beneath the raft causing larger settlement from the subsoil.

c) Maximum settlement also increases with increases in thickness of the raft for all piled groups. This is because as the thickness of raft (t) increases, the self weight of the raft also increases causing more load acting on the whole system.

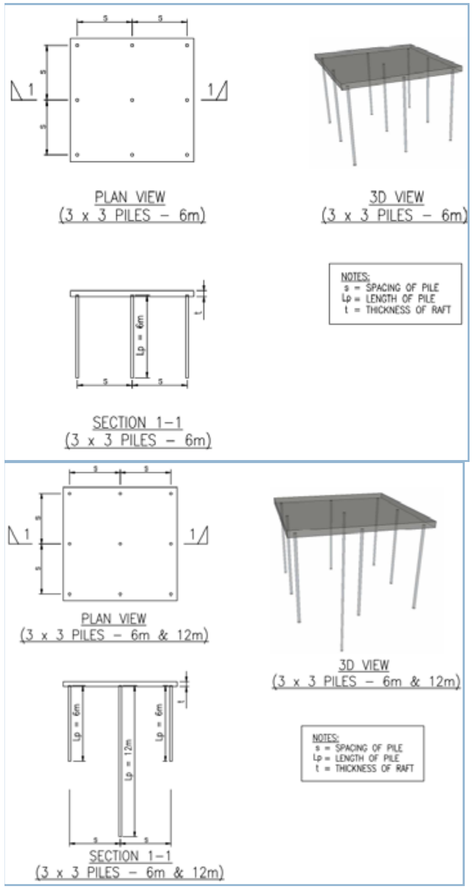
d) The piled raft with combination of varying pile lengths is not so effective in reducing maximum settlement compared to piled raft with longer same pile lengths.

Ratio of Differential Settlement over Maximum Settlement ($\Delta\rho/\rho_{max}$)

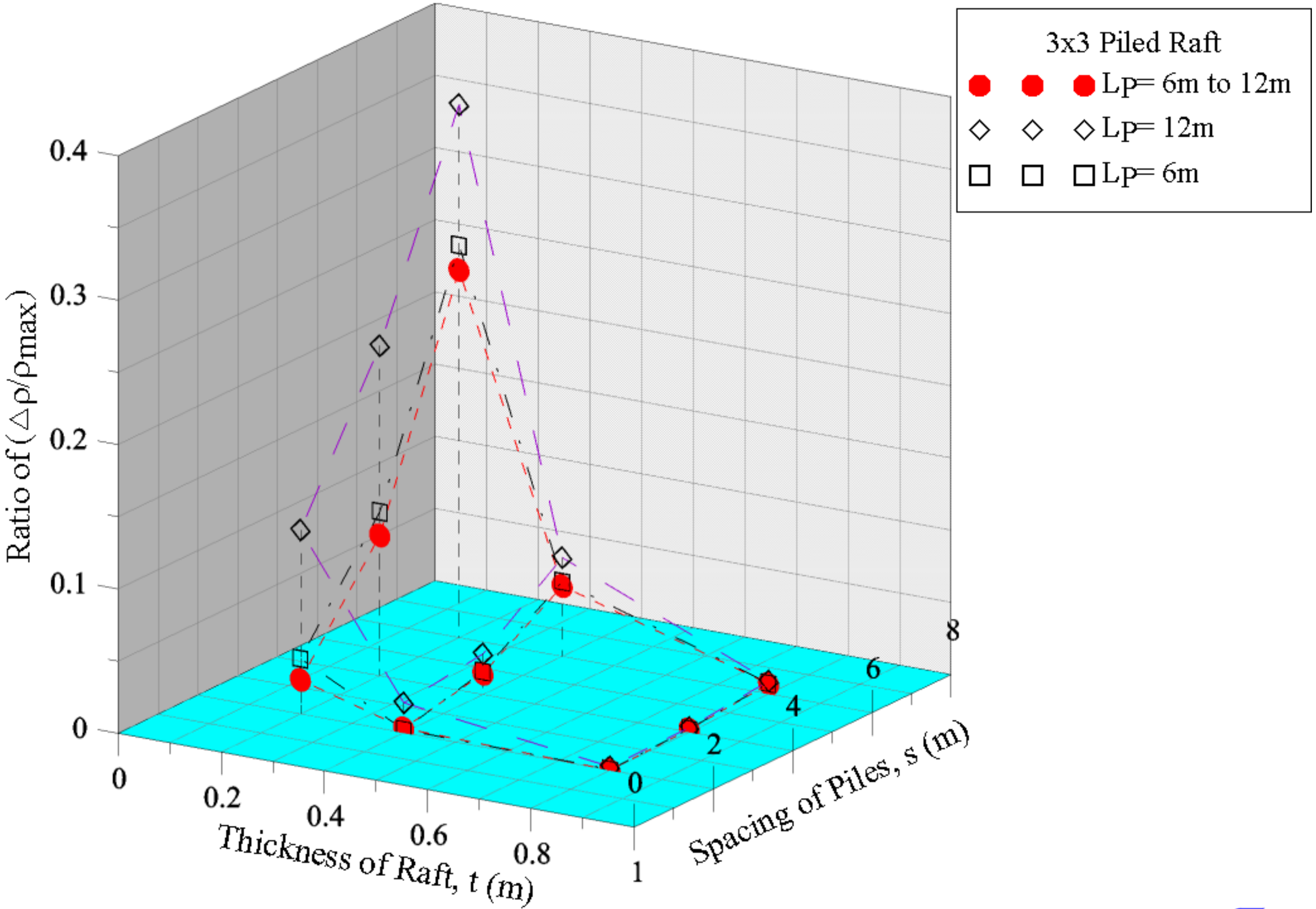
Ratio of Differential Settlement over Maximum Settlement ($\Delta\rho/\rho_{max}$)

The ratio of ($\Delta\rho/\rho_{max}$) is being used to benchmark the efficiency of using piled raft in controlling differential settlement for same value of maximum settlement. The lower the ratio of ($\Delta\rho/\rho_{max}$), the better or more effective is the performance of the piled raft.

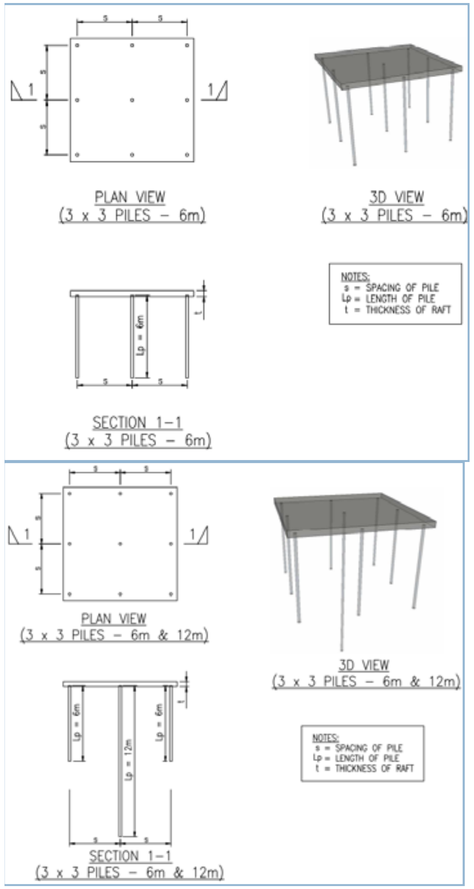
Ratio of $(\Delta\rho/\rho_{max})$ of 3x3 Piled Raft



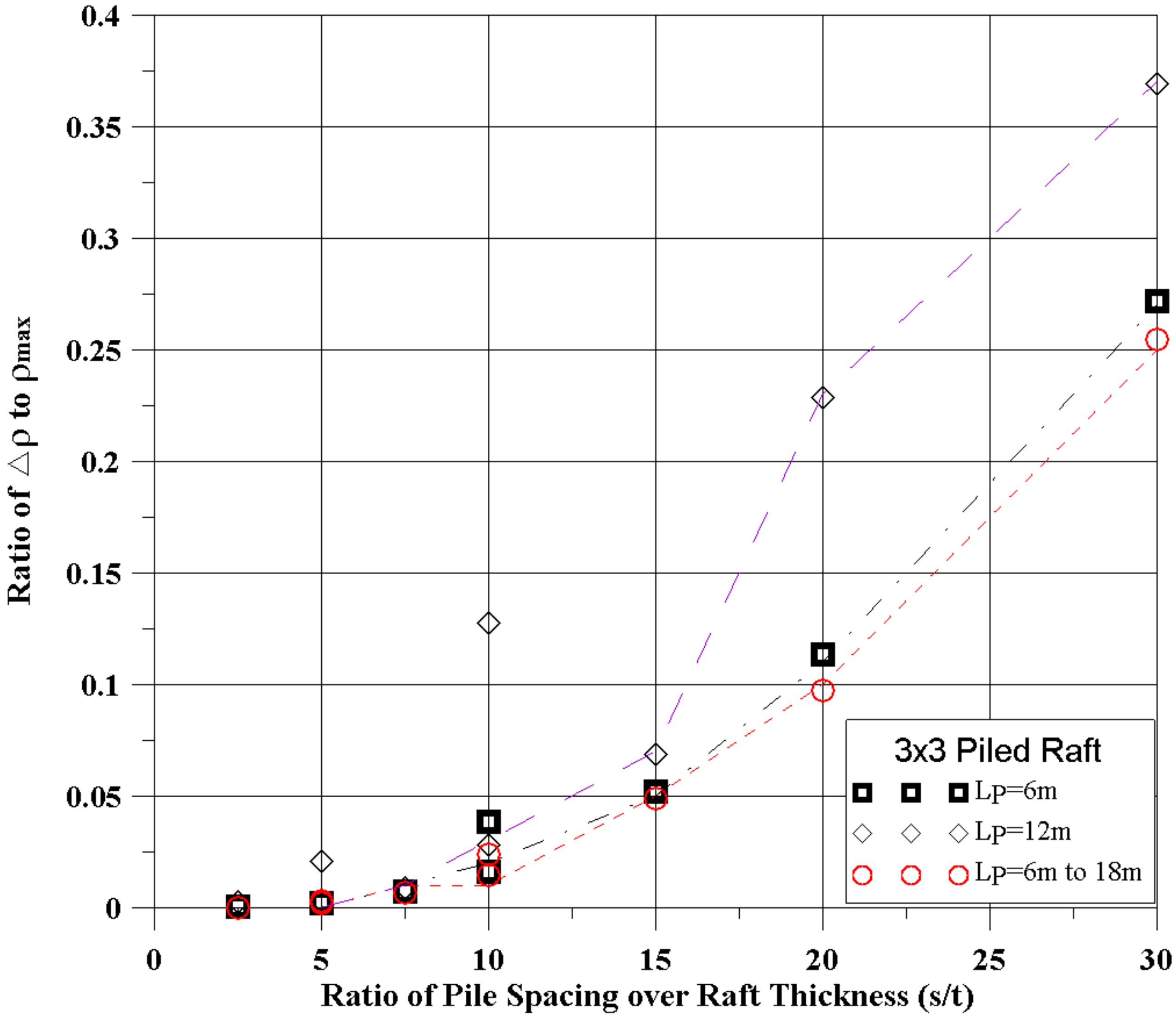
3 x 3 Piled Raft



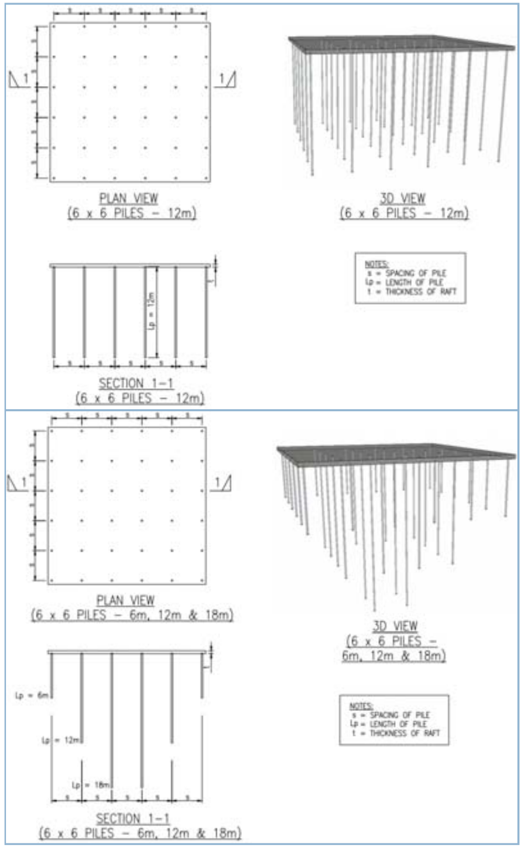
Ratio of ($\Delta\rho/\rho_{max}$) of 3x3 Piled Raft



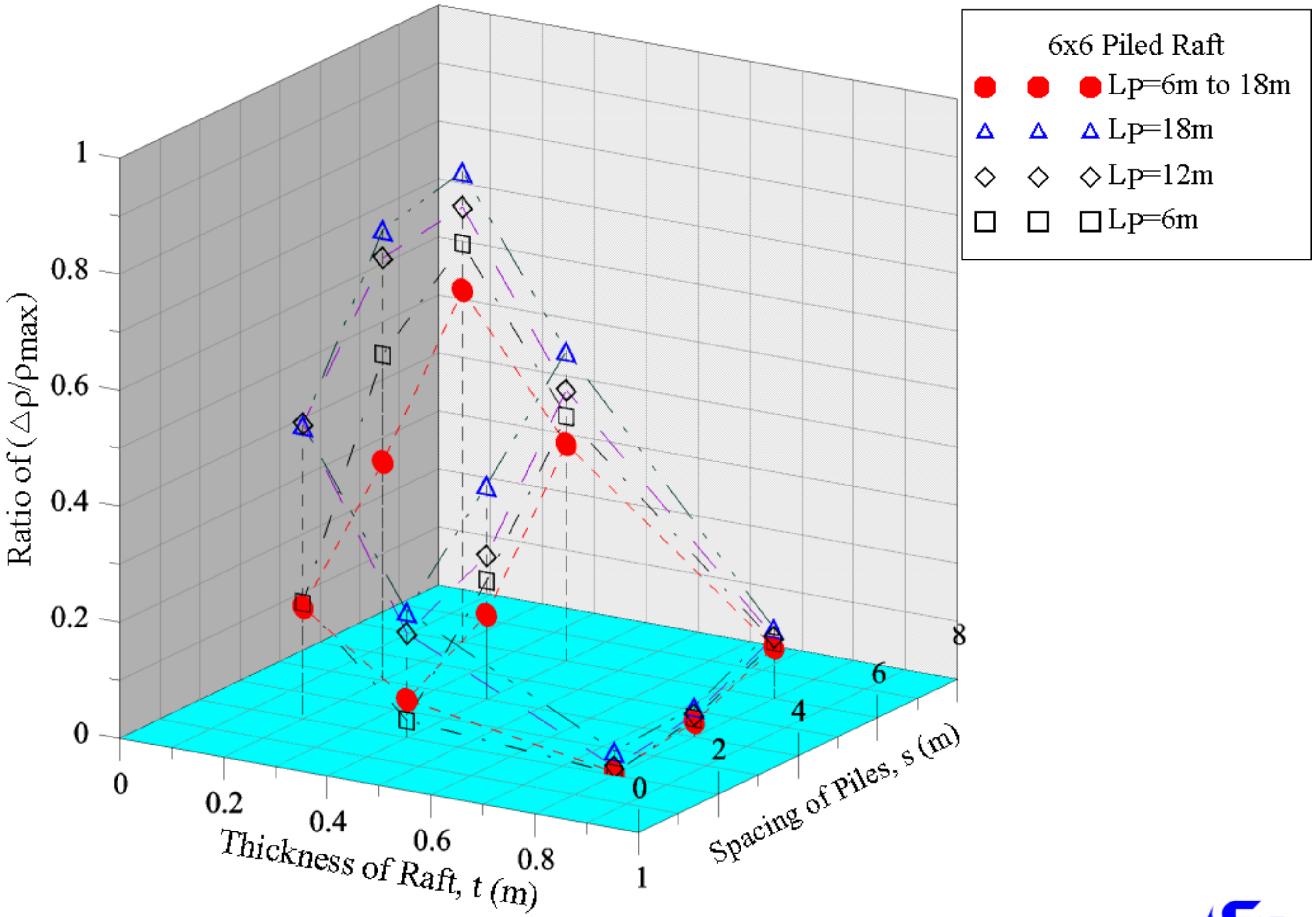
3 x 3 Piled Raft



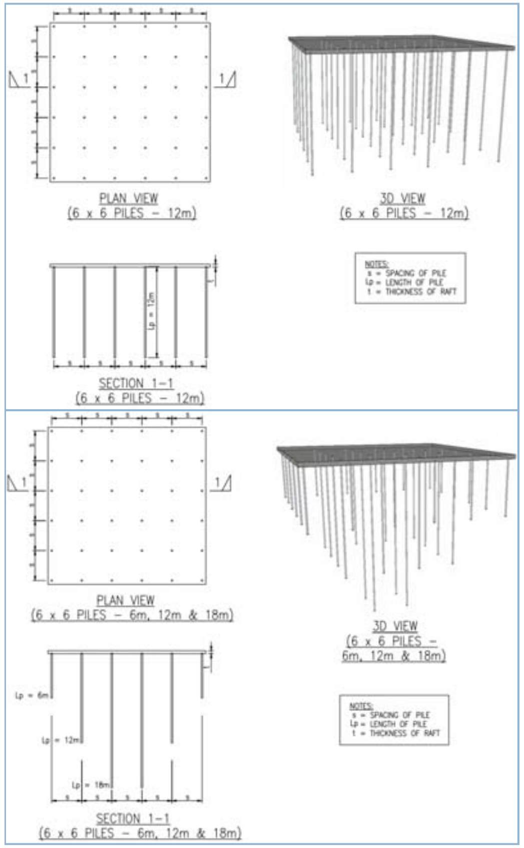
Ratio of ($\Delta\rho/\rho_{max}$) of 6x6 Piled Raft



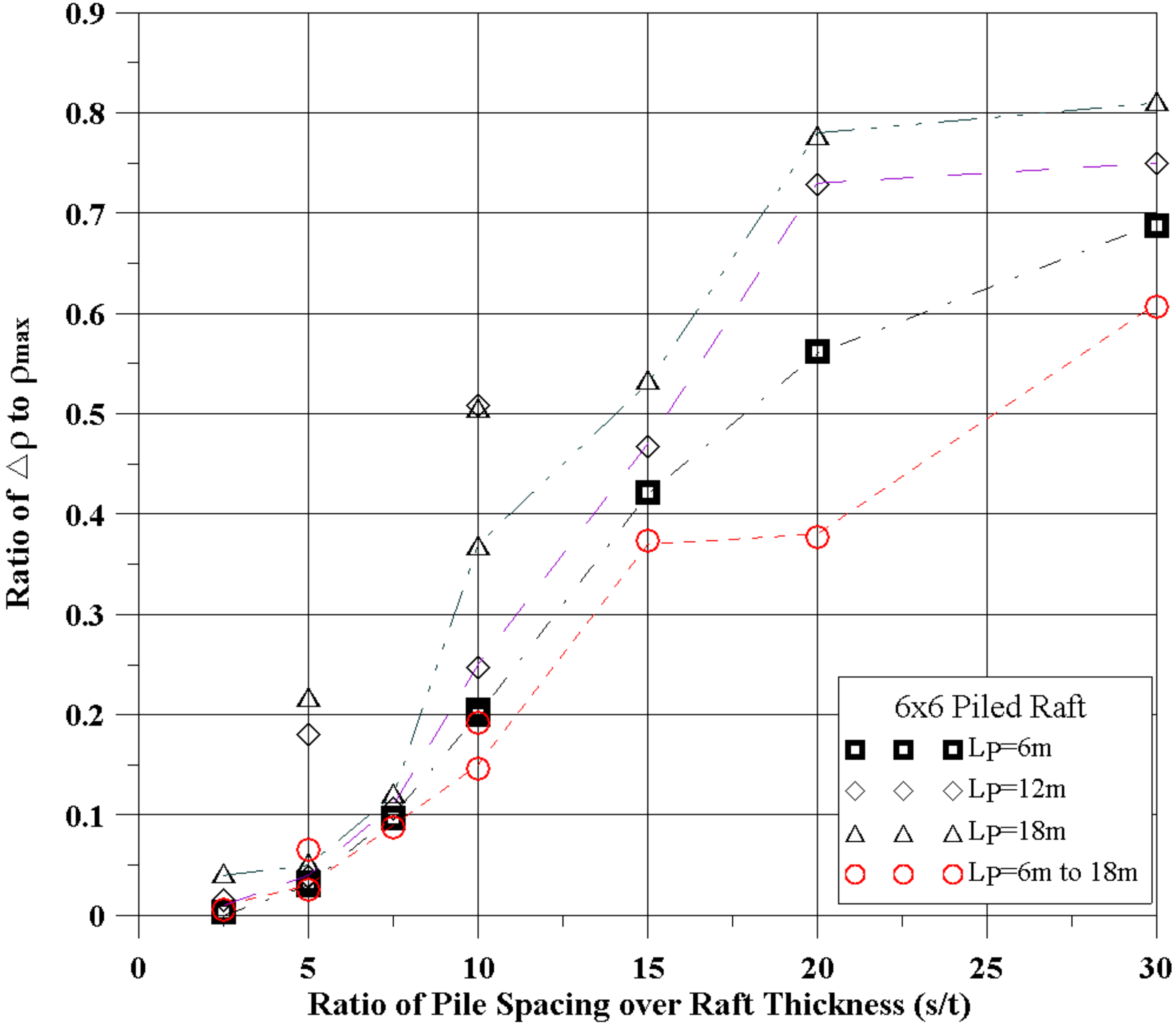
6 x 6 Piled Raft



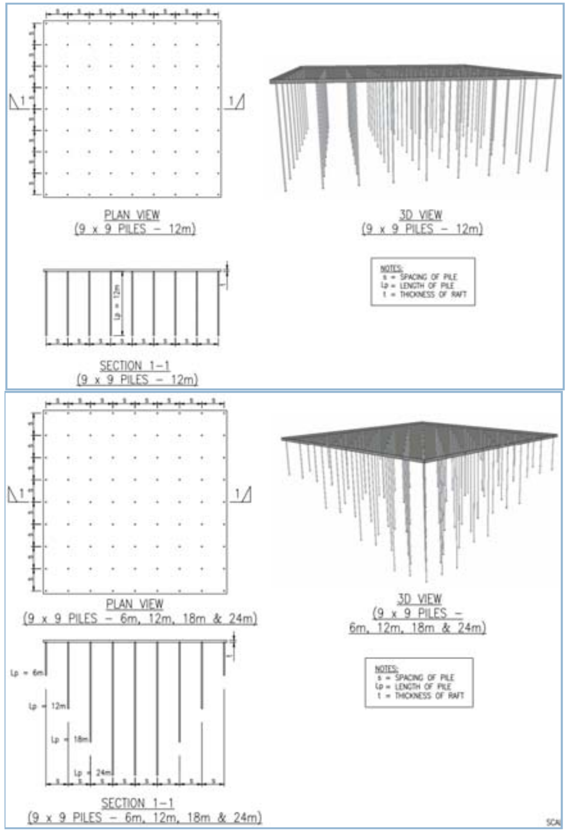
Ratio of ($\Delta\rho/\rho_{max}$) of 6x6 Piled Raft



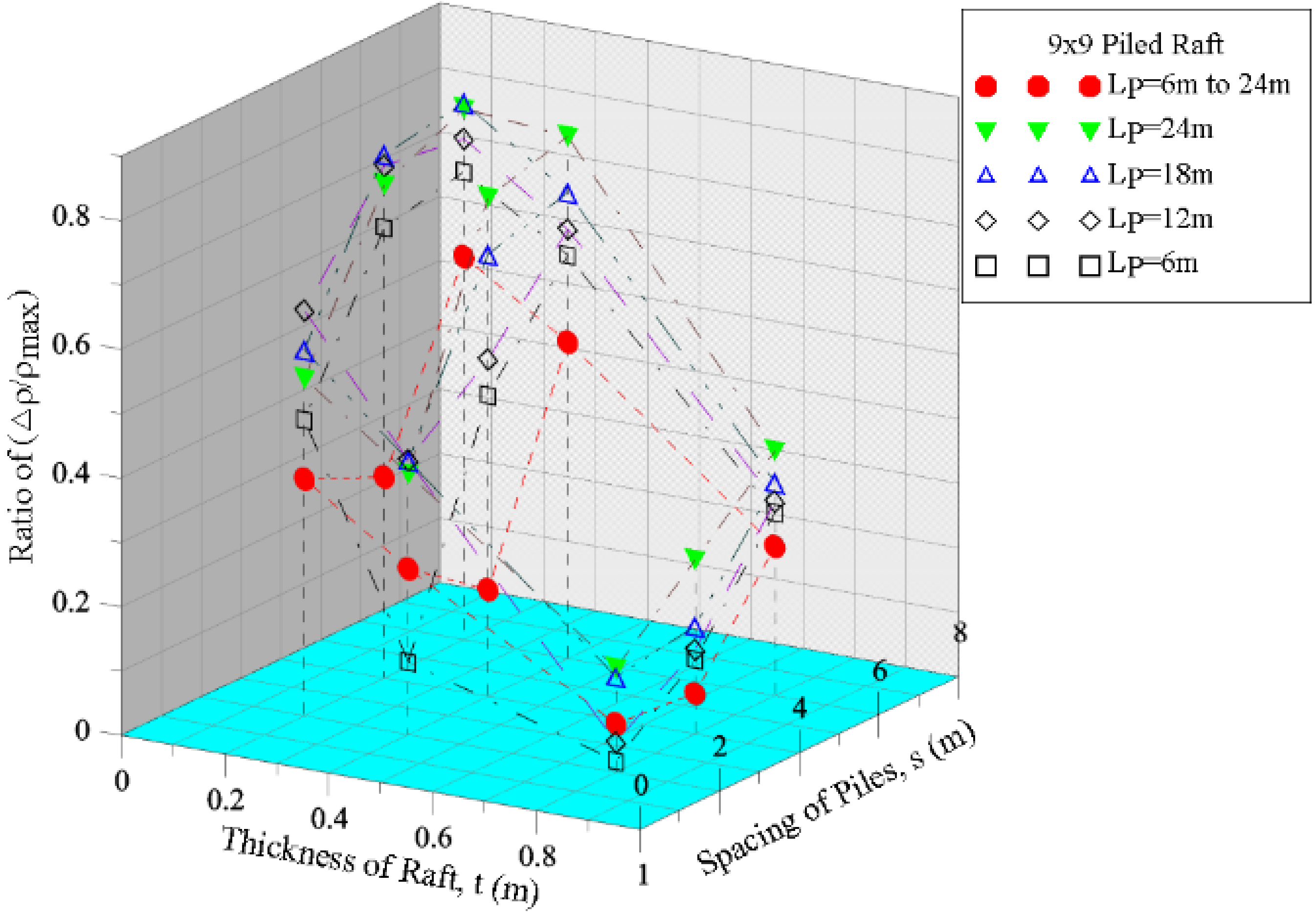
6 x 6 Piled Raft



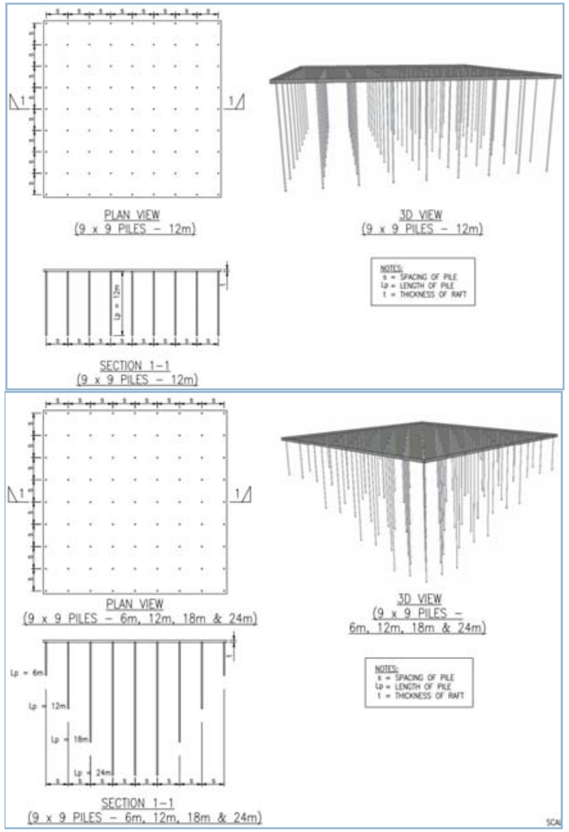
Ratio of $(\Delta\rho/\rho_{max})$ of 9x9 Piled Raft



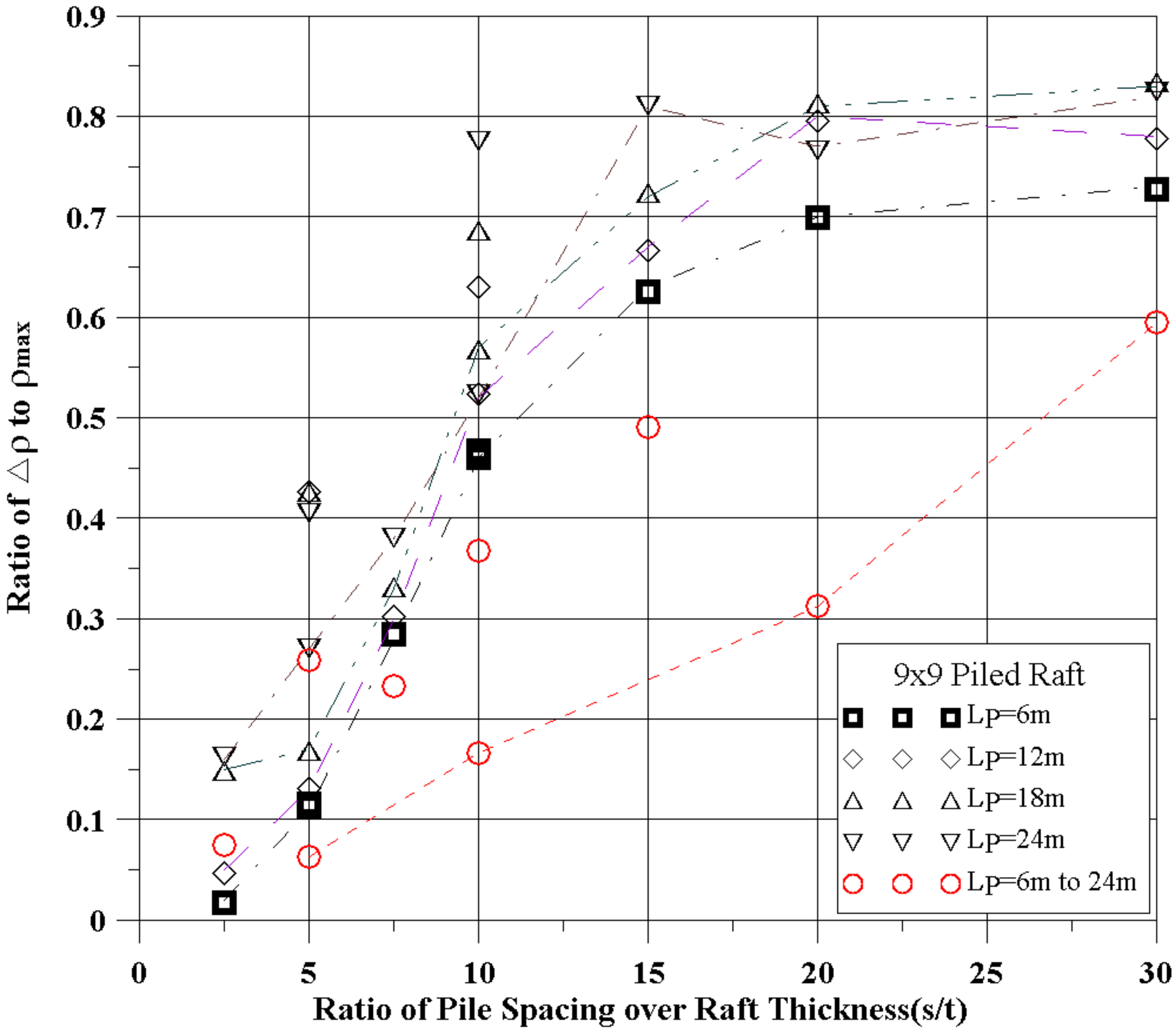
9 x 9 Piled Raft



Ratio of $(\Delta\rho/\rho_{max})$ of 9x9 Piled Raft



9 x 9 Piled Raft



Findings and Discussions on aspects of **Ratio of** ($\Delta\rho/\rho_{max}$)

a) Combination of varying pile lengths in a piled raft generally has the lowest ratio of ($\Delta\rho/\rho_{max}$) thus it is the more effective compared to using same pile lengths in a piled raft. The only exception is when the pile spacing is 2m with thicknesses of the raft are 0.4m and 0.8m (total 2 cases for each piled raft configurations of of 3x3, 6x6, 9x9).

b) The ratio of ($\Delta\rho/\rho_{max}$) is largest for piled raft of same pile length using longer piles compared to shorter piles.

c) As the thickness of the raft reduces (more flexible), the ratio of ($\Delta\rho/\rho_{max}$) generally increases.

d) For 6x6 and 9x9 piled raft of same pile length, when the thickness of the raft is 0.2m (thinnest raft analysed), the ratio of ($\Delta\rho/\rho_{max}$) do not vary too significant with pile length.

e) Ratio of ($\Delta\rho/\rho_{max}$) increases with increases in spacing of the piles for all piled groups.

f) Ratio of ($\Delta\rho/\rho_{max}$) reduces with increases in thickness of the raft for all piled groups.

Pile Raft Coefficient (α_{pr})

Note : Section 5.1.5 (Pg. 102)

Pile Raft Coefficient (α_{pr})

The ratio of total imposed load taken up by the piles in the piled rafts is similar to pile raft coefficient (α_{pr}) which is defined as below:-

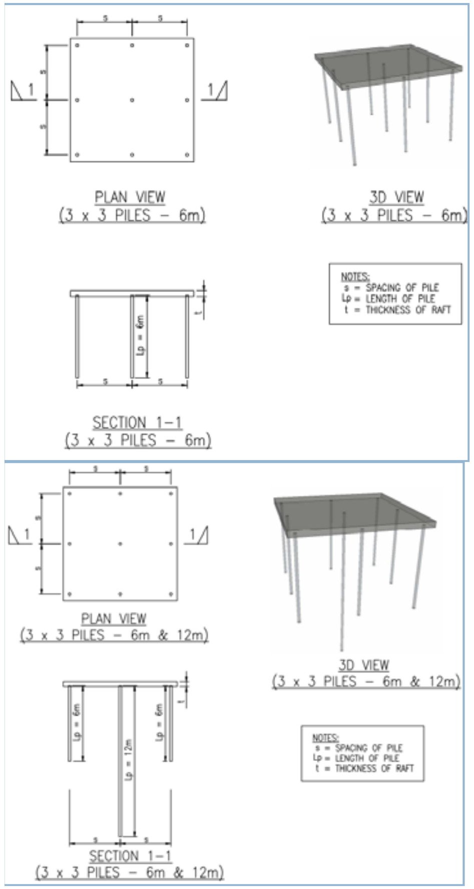
$$\alpha_{pr} = \frac{\sum R_{piles}}{R_{total}}$$

where, α_{pr} = pile raft coefficient

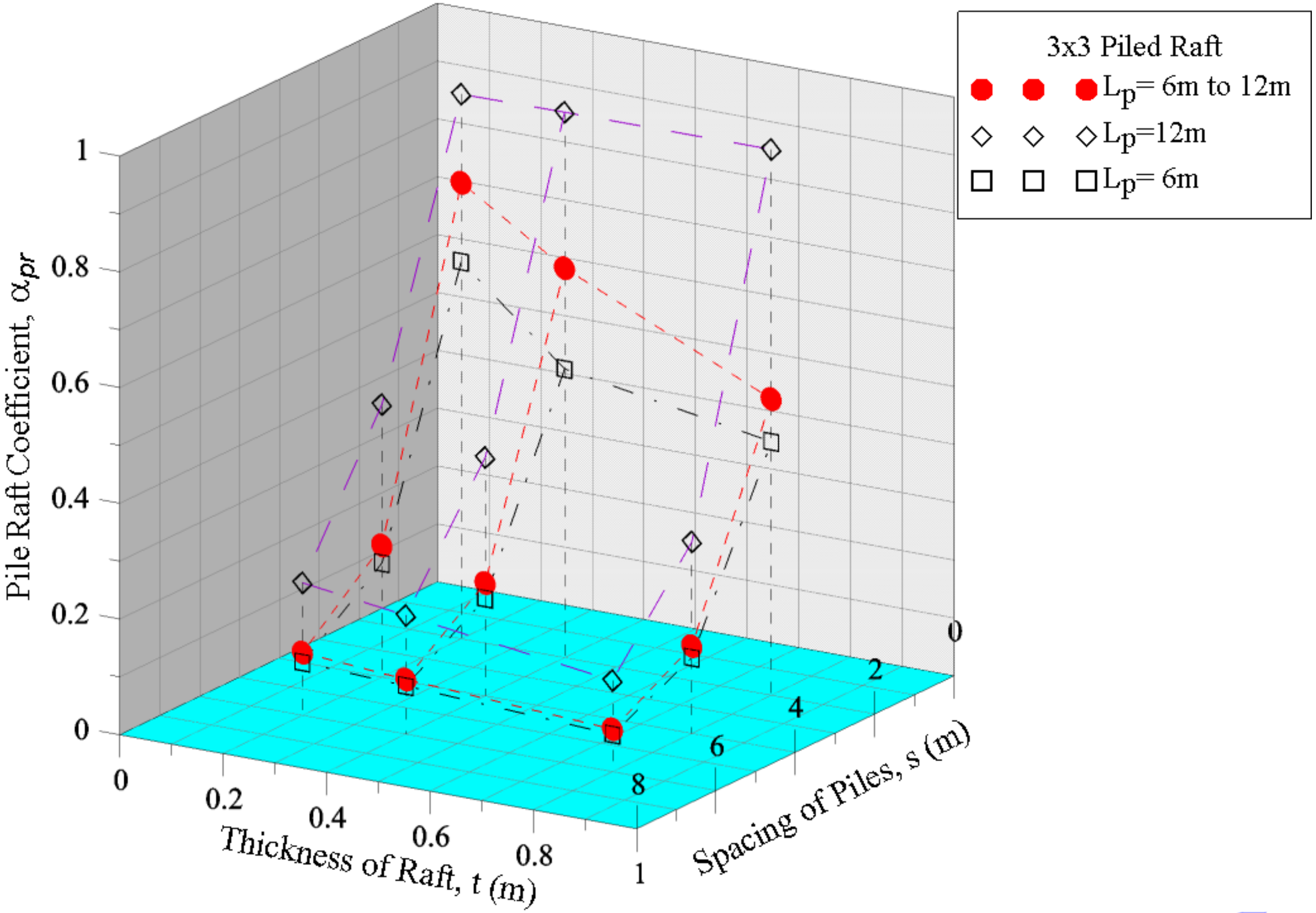
$\sum R_{piles}$ = sum of piles resistance

R_{total} = Total imposed load

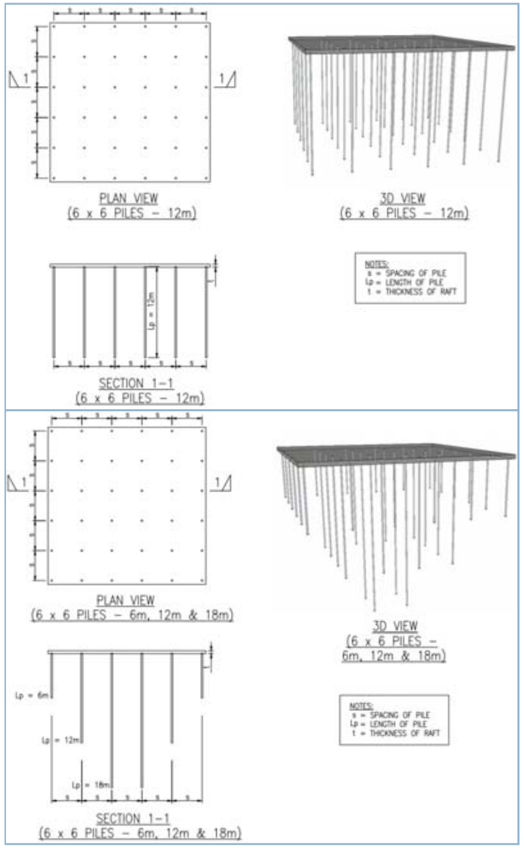
Pile Raft Coefficient (α_{pr}) of 3x3 Piled Raft



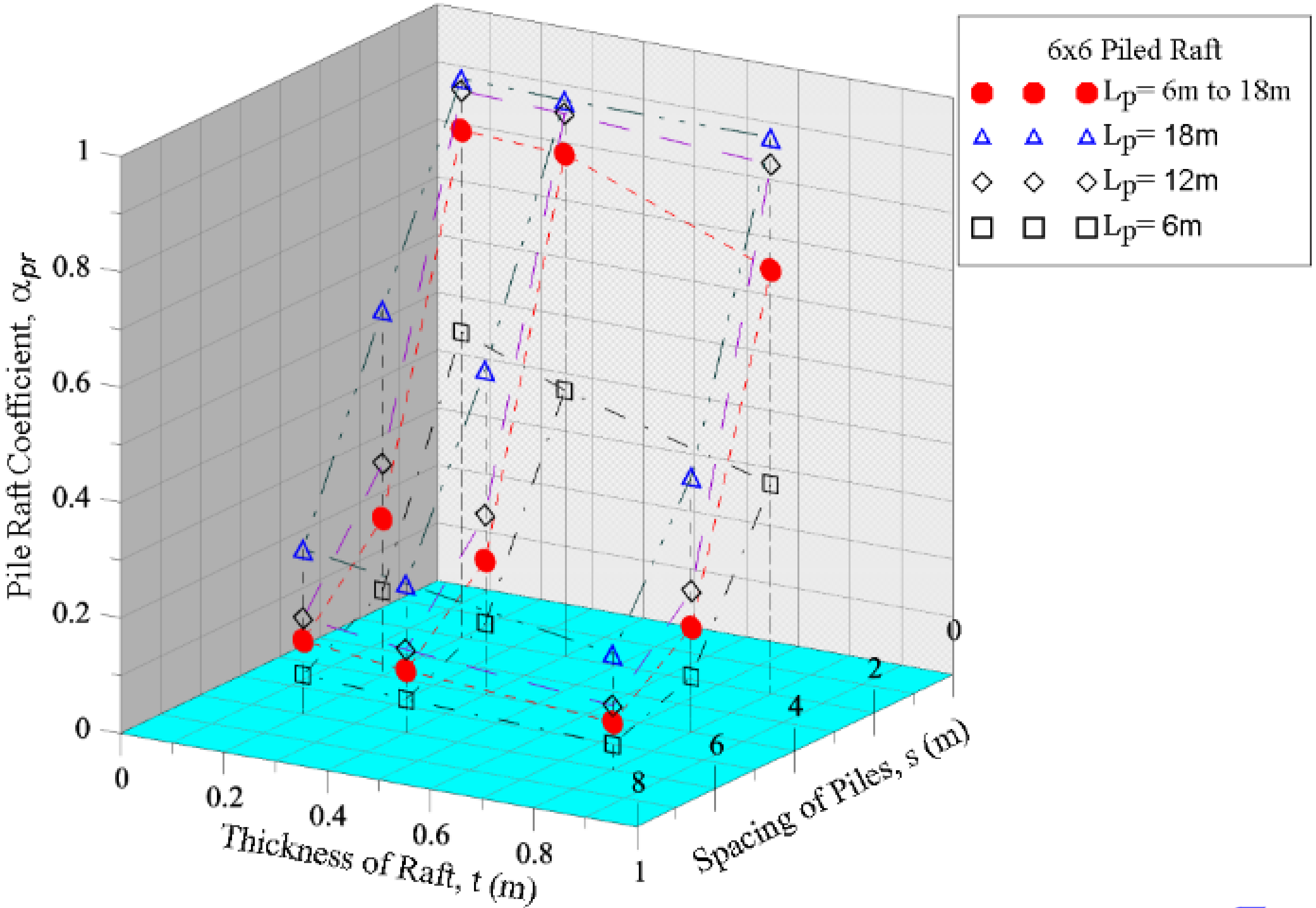
3 x 3 Piled Raft



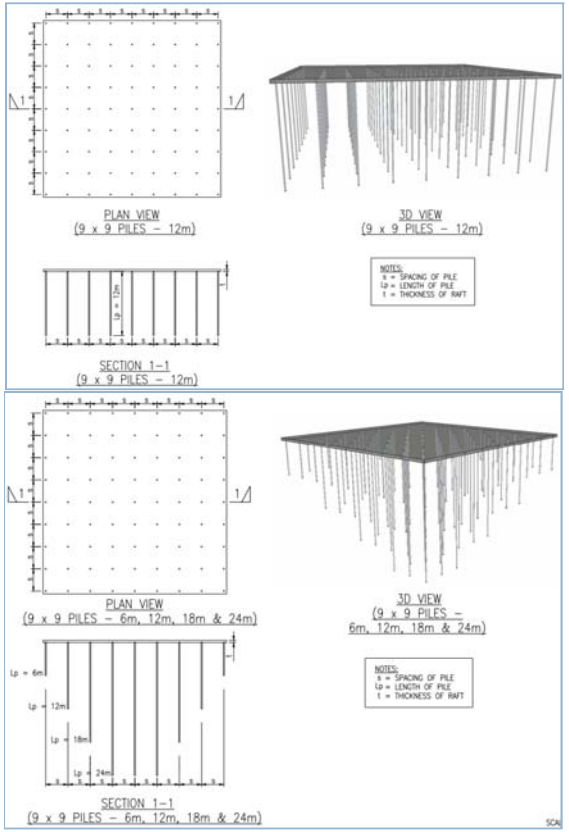
Pile Raft Coefficient (α_{pr}) of 6x6 Piled Raft



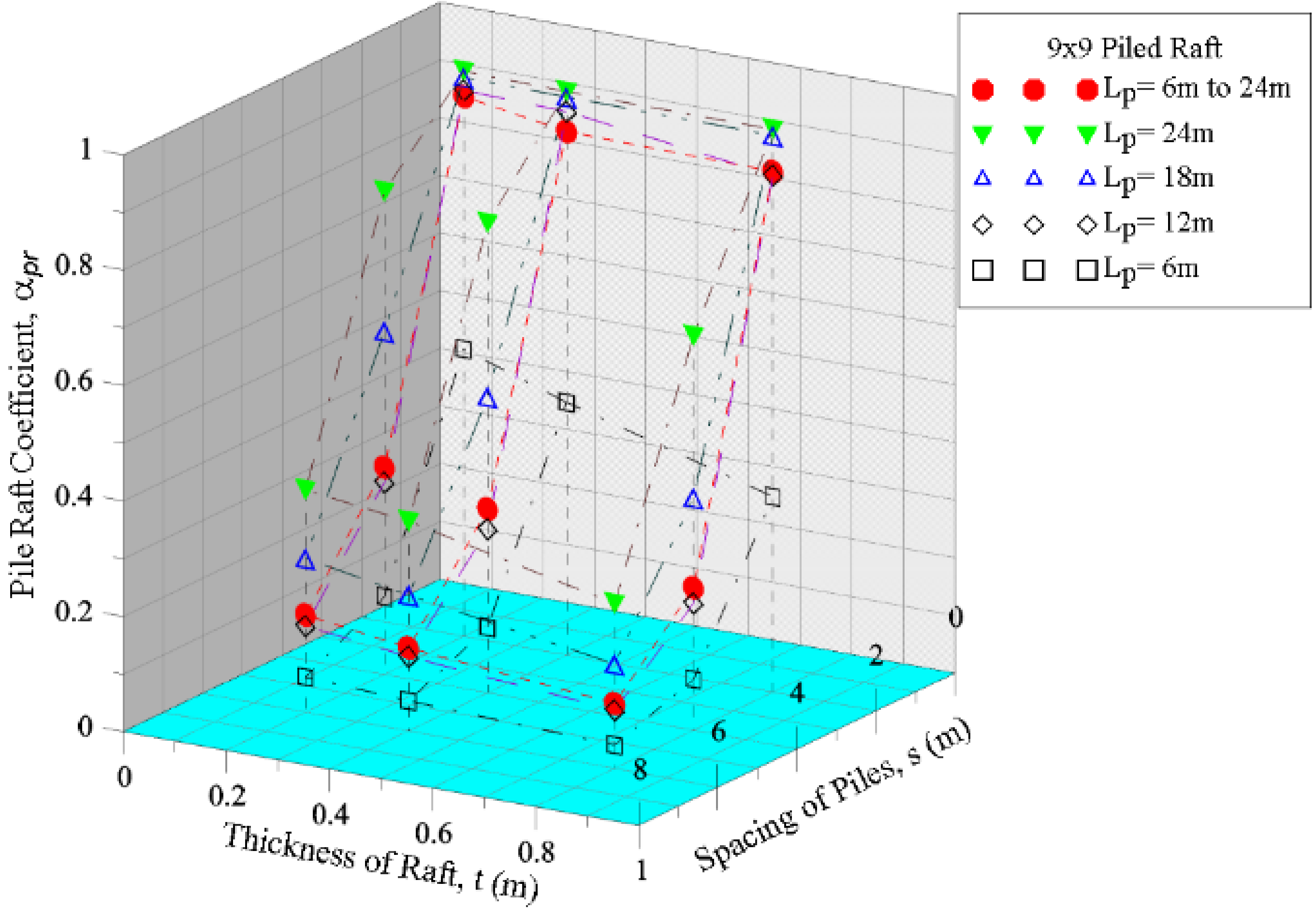
6 x 6 Piled Raft



Pile Raft Coefficient (α_{pr}) of 9x9 Piled Raft



9 x 9 Piled Raft



Findings and Discussions on aspects of **Pile Raft Coefficient** (α_{pr})

a) For 3x3 and 6x6 piled raft analysed, the piled rafts combination of varying pile lengths generally have pile raft coefficient (α_{pr}) in between the shortest and second shortest pile length of piled raft with same pile lengths.

b) For all cases of 9x9 piled raft analysed, the piled rafts with combination of varying pile lengths generally have pile raft coefficient (α_{pr}) quite similar to piled raft of 12m pile length.

c) As the thickness of the raft reduces (more flexible), the pile raft coefficient (α_{pr}) only increases slightly.

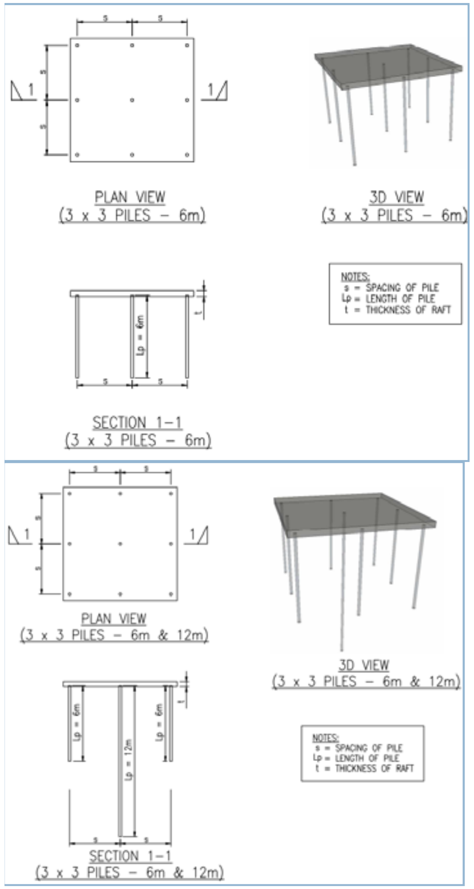
d) Pile raft coefficient (α_{pr}) increases significantly with decrease in spacing of the piles for all piled groups.

e) Pile raft coefficient (α_{pr}) is near 1 (pure pile foundation) when the spacing of the piles (s) is 2m irrespective of the thickness of the raft (t)

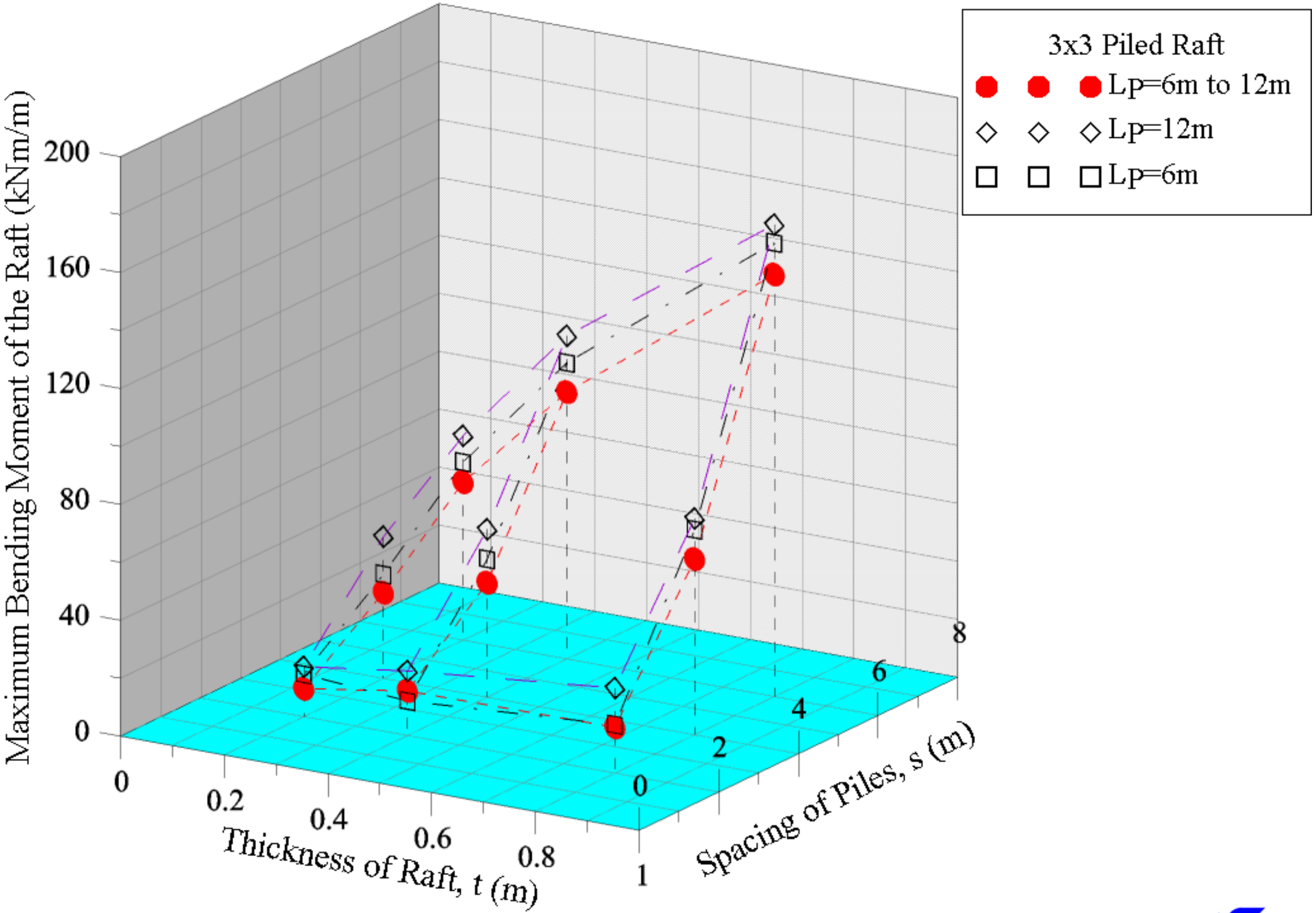
Maximum Bending Moment (BM_{max})

Note : Section 5.1.6 (Pg. 105)

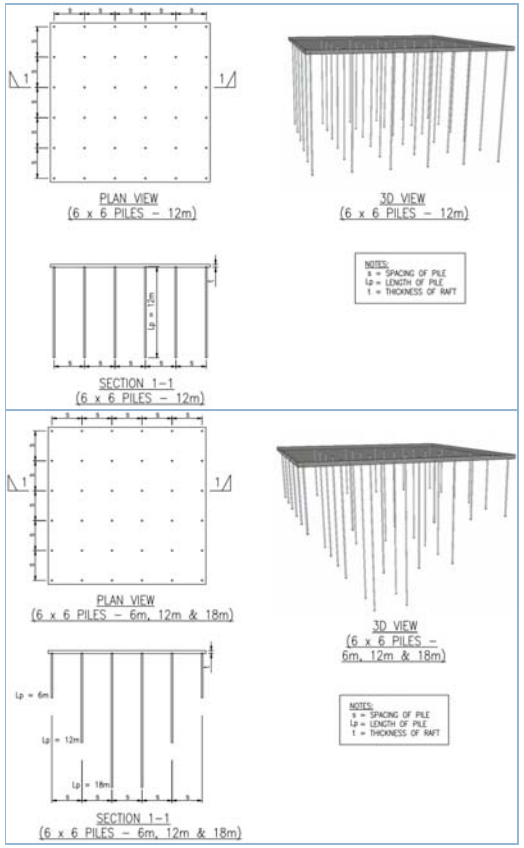
Maximum Bending Moment of 3x3 Piled Raft

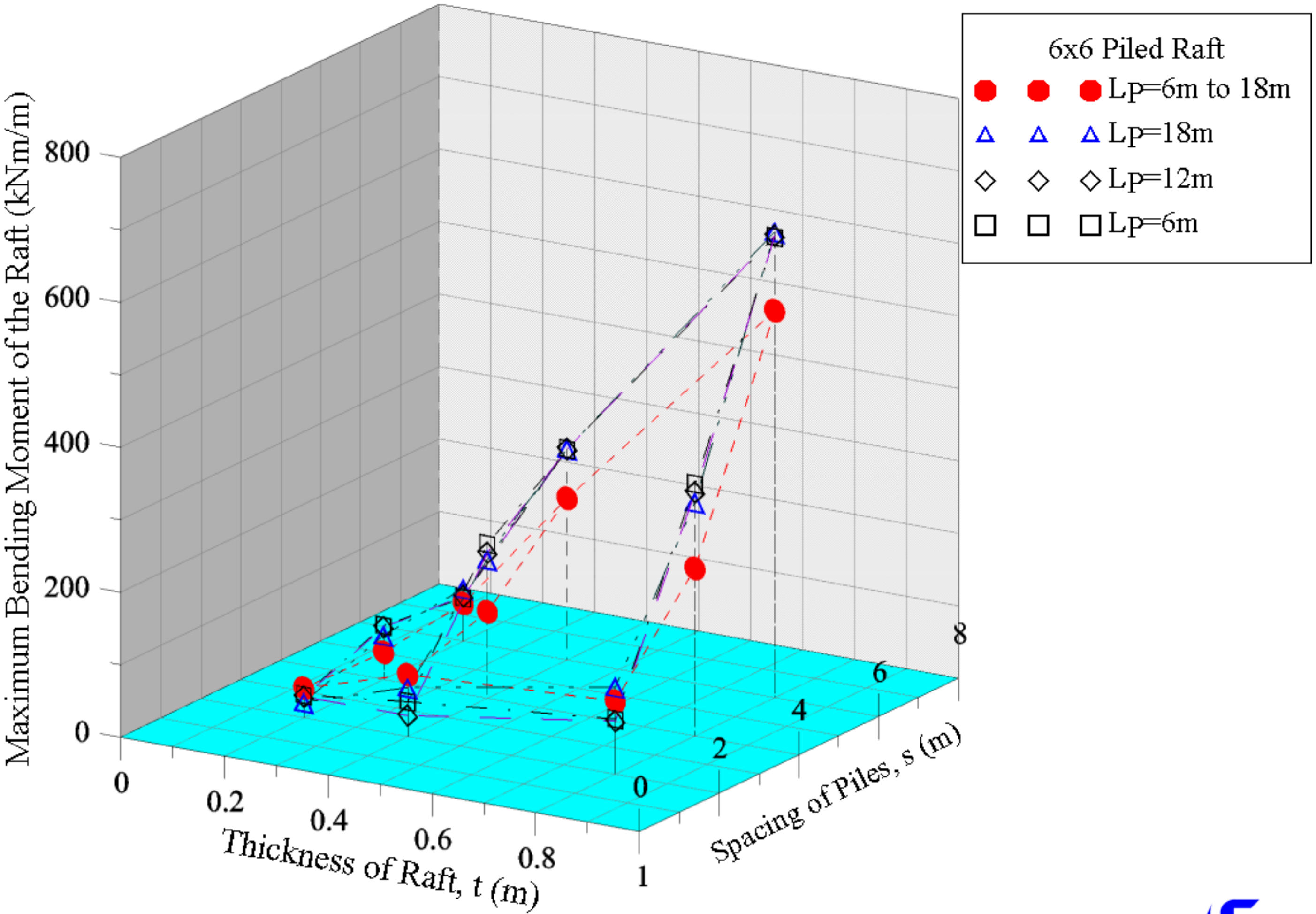


3 x 3 Piled Raft



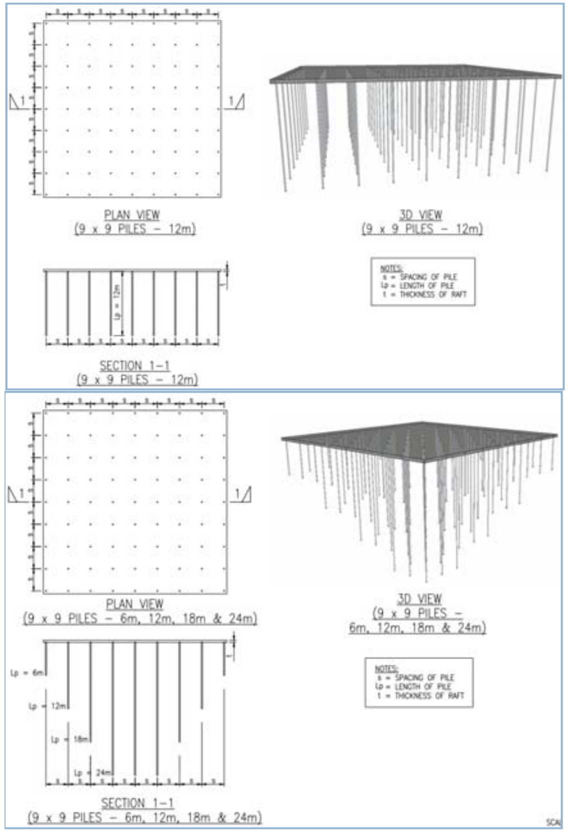
Maximum Bending Moment of 6x6 Piled Raft



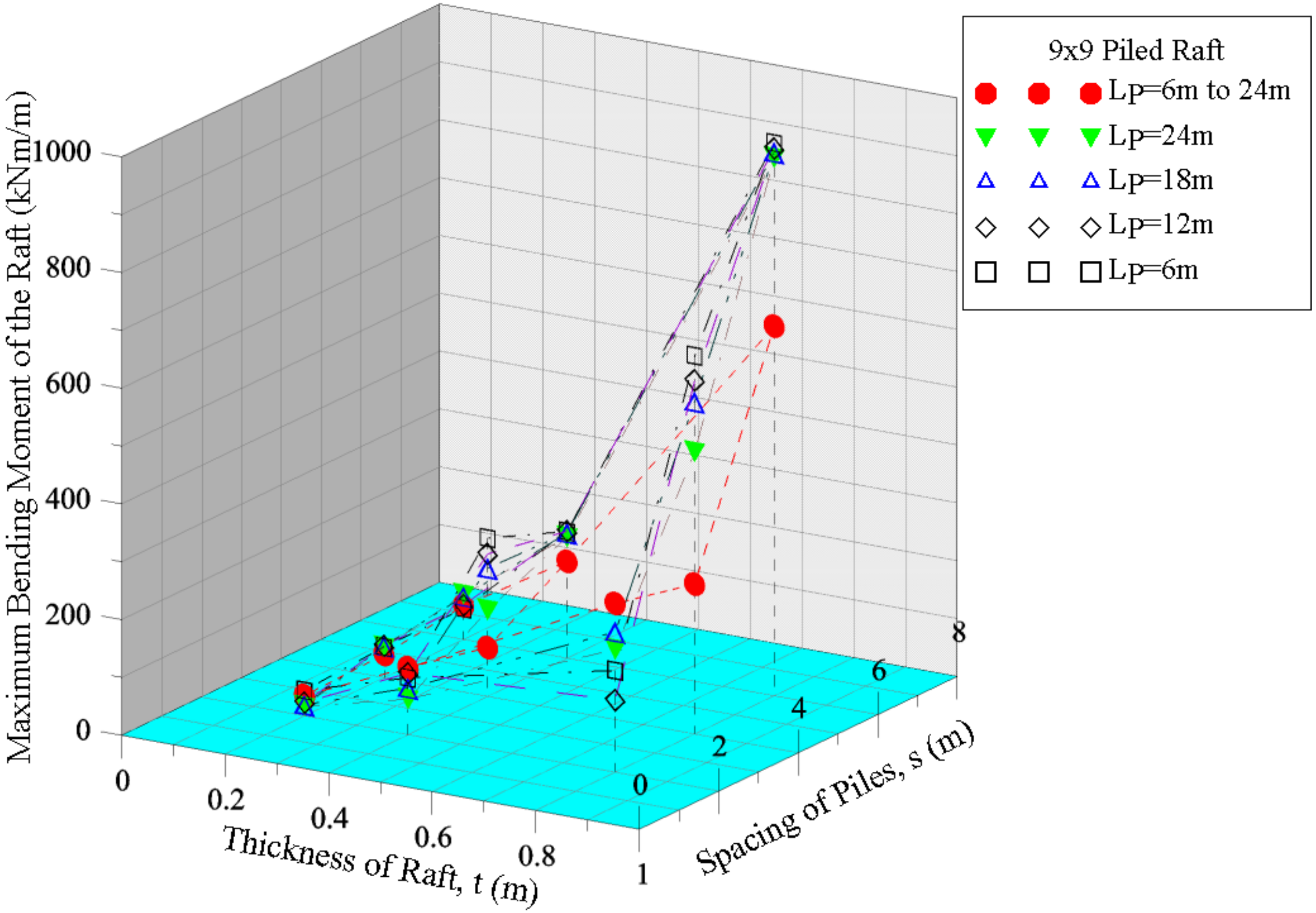


<u>6 x 6 Piled Raft</u>

Maximum Bending Moment of 9x9 Piled Raft



9 x 9 Piled Raft



Findings and Discussions on aspects of **<u>Maximum Bending Moment in the Raft</u>**

a) Smaller piled raft tends to have smaller bending moment in the raft.

b) The <u>piled rafts with combination of varying pile lengths</u> generally produce the <u>lowest maximum bending moment</u> (BM_{max}) in the raft except when the spacing of the piles are closest at s=2m. This indicates piled rafts with combination of varying pile lengths are more efficient and economical as lower BM_{max} will required less reinforcement steel for the raft.

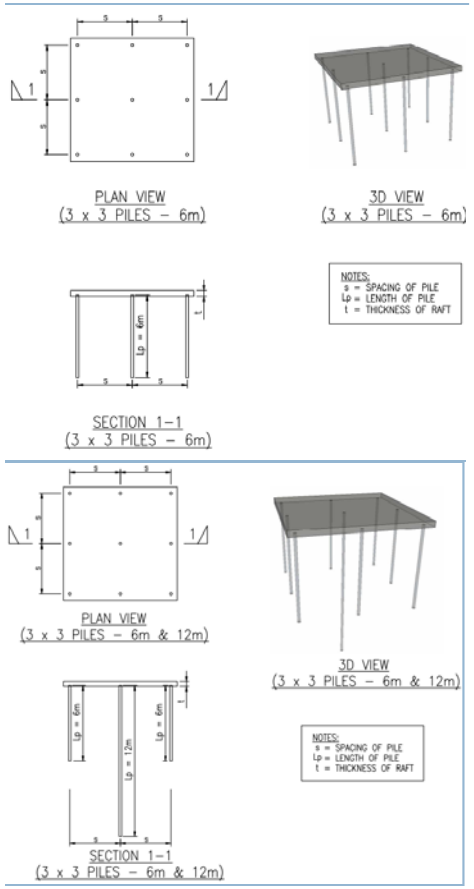
c) Maximum bending moment (BM_{max}) increases significantly with increase in spacing of the piles (s) for all piled groups.

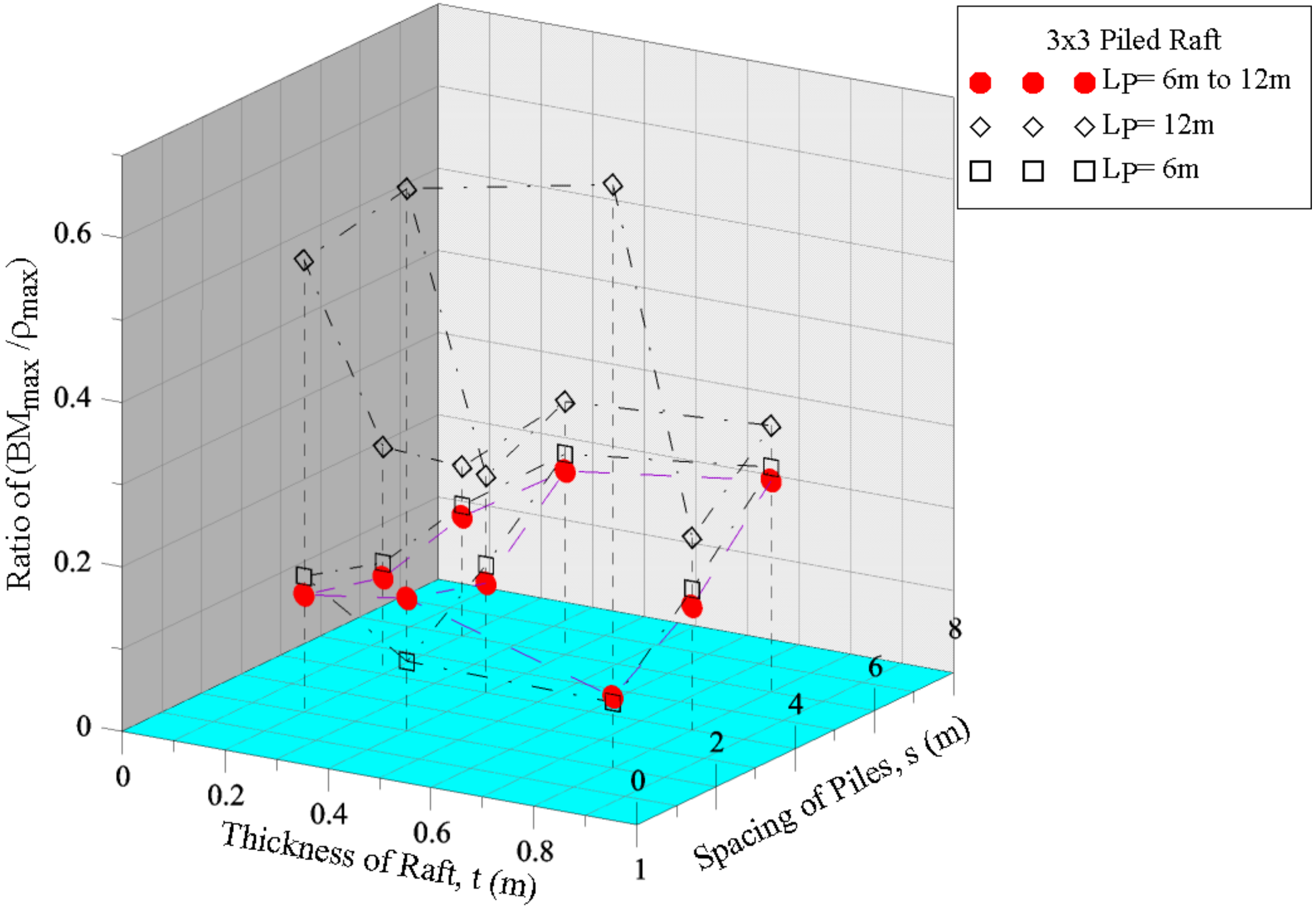
d) As the thickness of the raft reduces (more flexible), the maximum bending moment (BM_{max}) of the raft also reduces.

Ratios of Maximum Bending Moment (BM_{max}) over Differential Settlement (ρ_{max})

Note : Section 5.1.6 (Pg. 111)

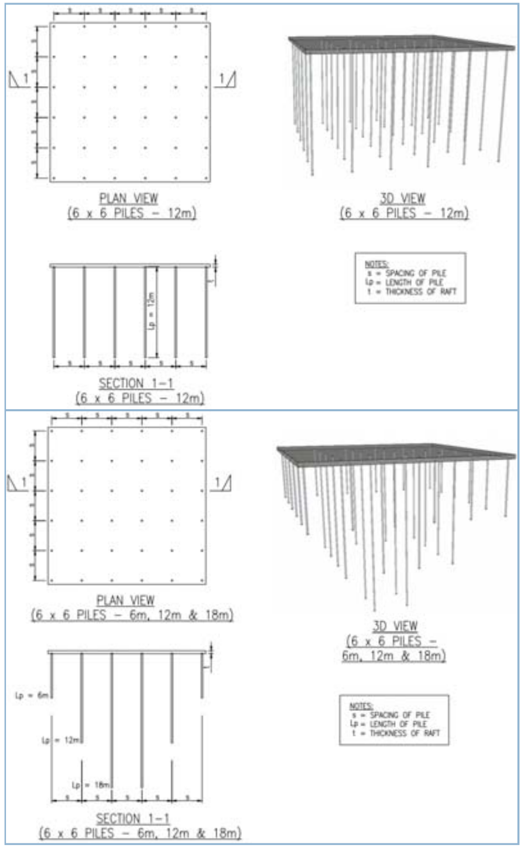
Ratios of (BM_{max}/ ρ_{max}) of 3x3 Piled Raft



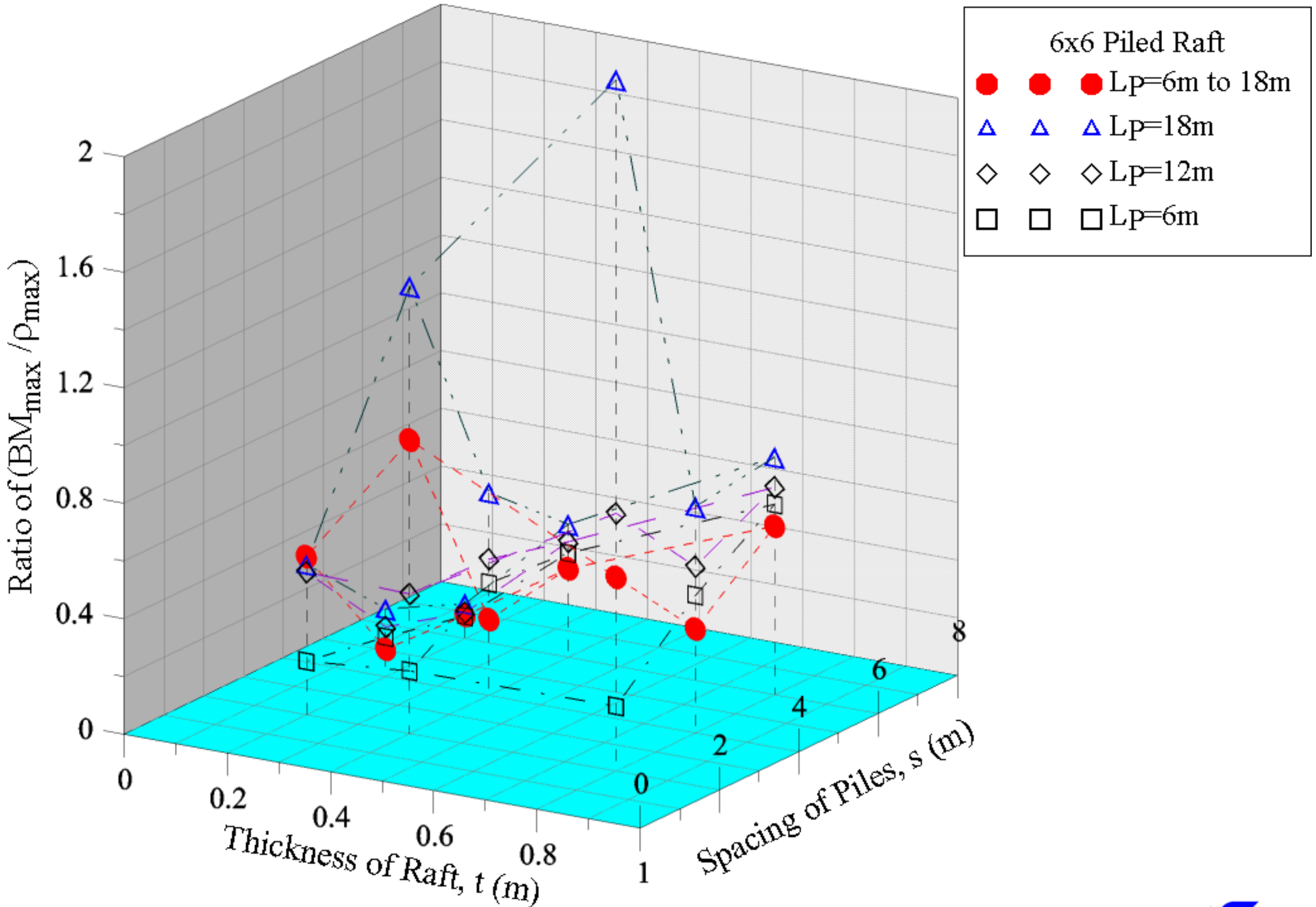


3 x 3 Piled Raft

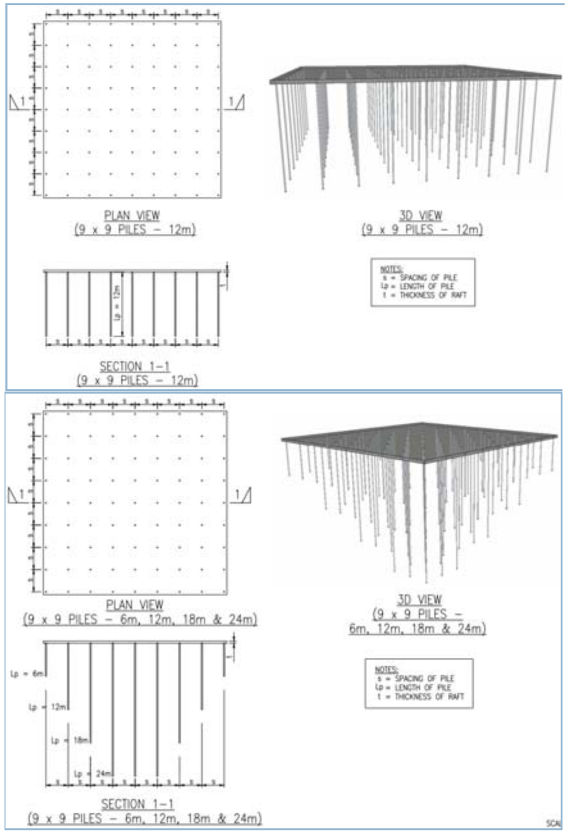
Ratios of (BM_{max}/ρ_{max}) of 6x6 Piled Raft



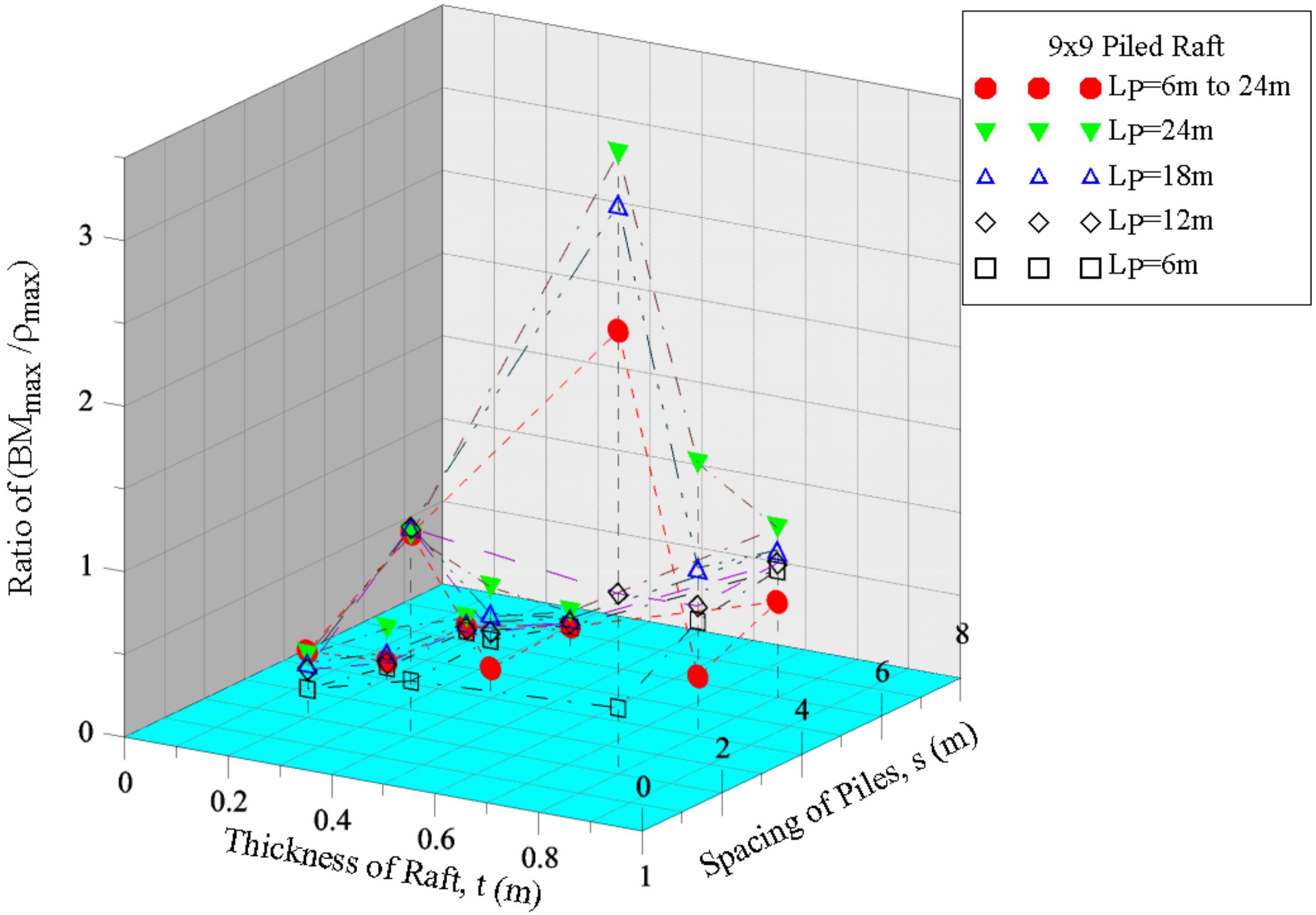
6 x 6 Piled Raft



Ratios of (BM_{max} / ρ_{max}) of 9x9 Piled Raft



9 x 9 Piled Raft



Findings and Discussions on aspects of **Ratios of** (BM_{max}/ ρ_{max})

a) For most cases, combination of varying pile lengths in a piled raft generally has the lowest ratio of (BM_{max}/ρ_{max}). The only exception is when the spacing of piles (s) is 2m which has value of approaches one (1) and behave more like pure pile foundation.

b) This again shows that piled raft with combination of varying pile lengths is most efficient in reducing bending moment generated in the raft.

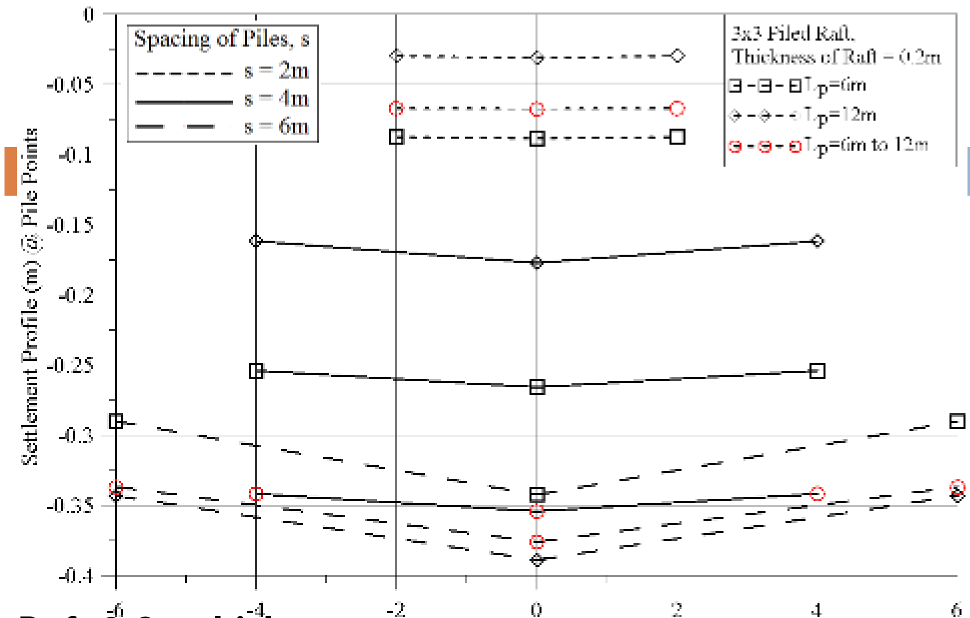
c) There is no clear trend on the ratio of (BM_{max}/ρ_{max}) when the spacing of the piles (s) changes.

d) The ratio of (BM_{max}/ρ_{max}) generally increases when the thickness of the raft (t) increases. This is similar to increase in BM_{max} with increase in thickness of the raft.

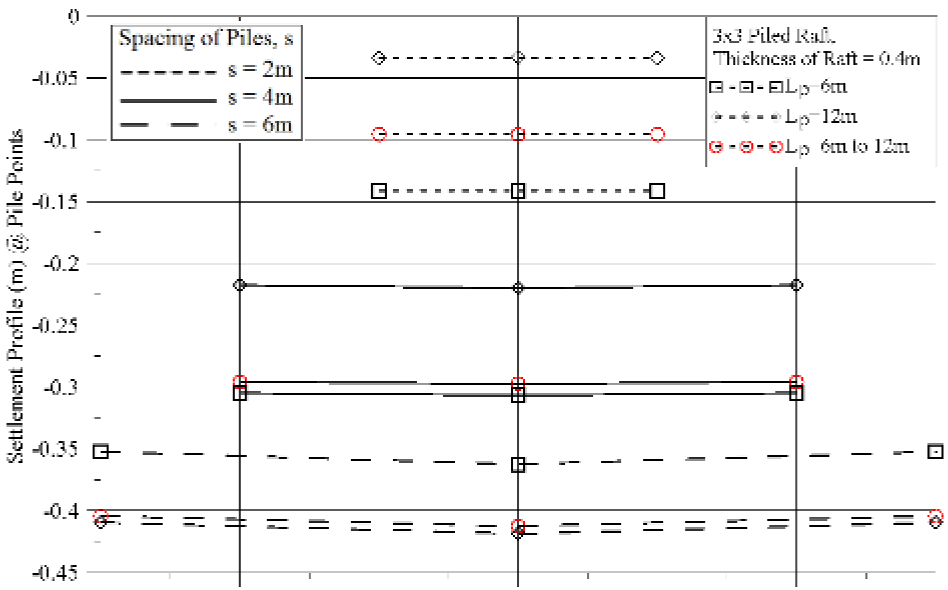
Settlement Profile and Angular Distortion (β)

Note : Section 5.1.7 (Pg. 113)

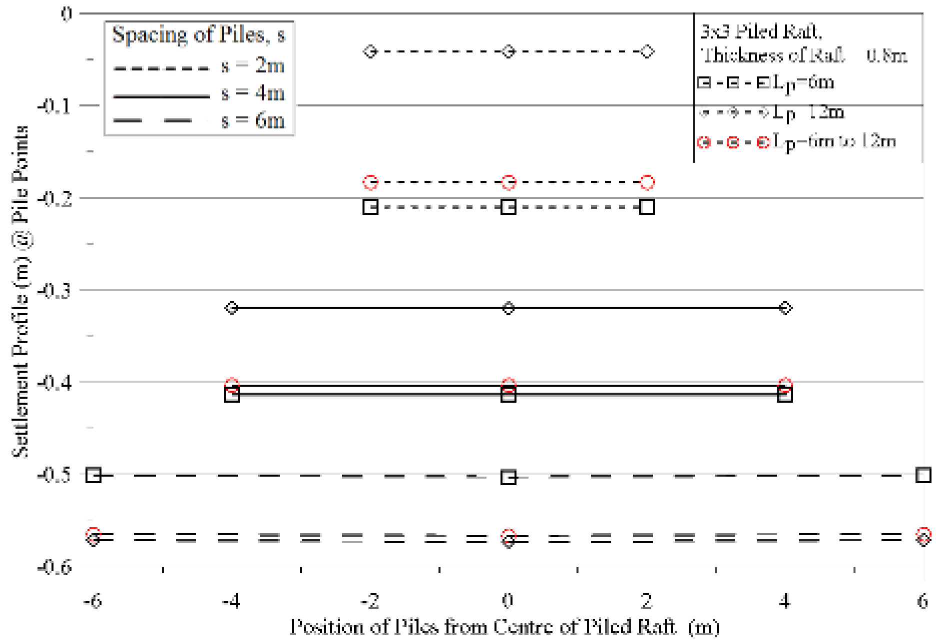
Settlement Profile of 3x3 Piled Raft



Raft 0.2m thick

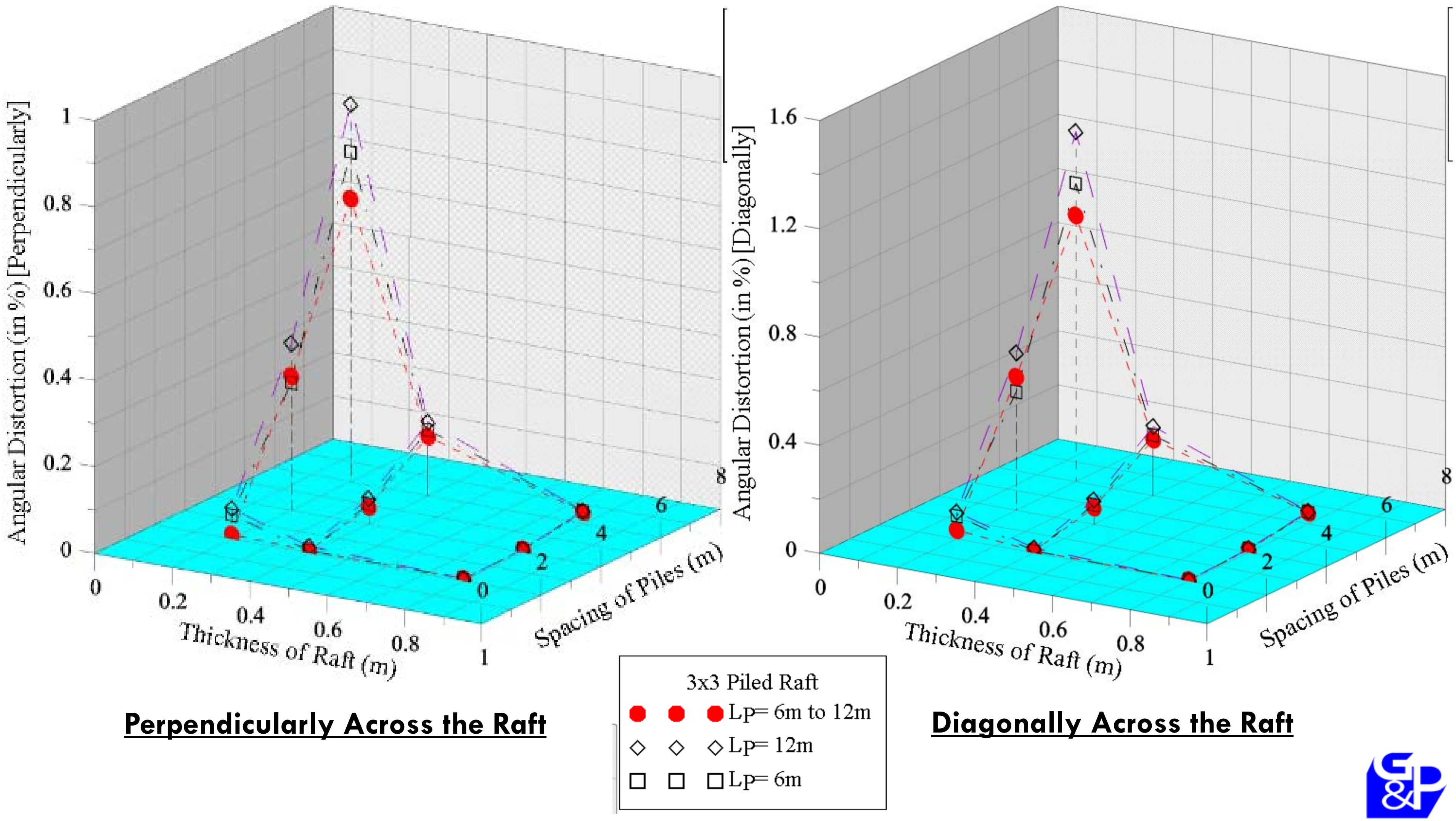


Raft 0.4m thick



Raft 0.8m thick

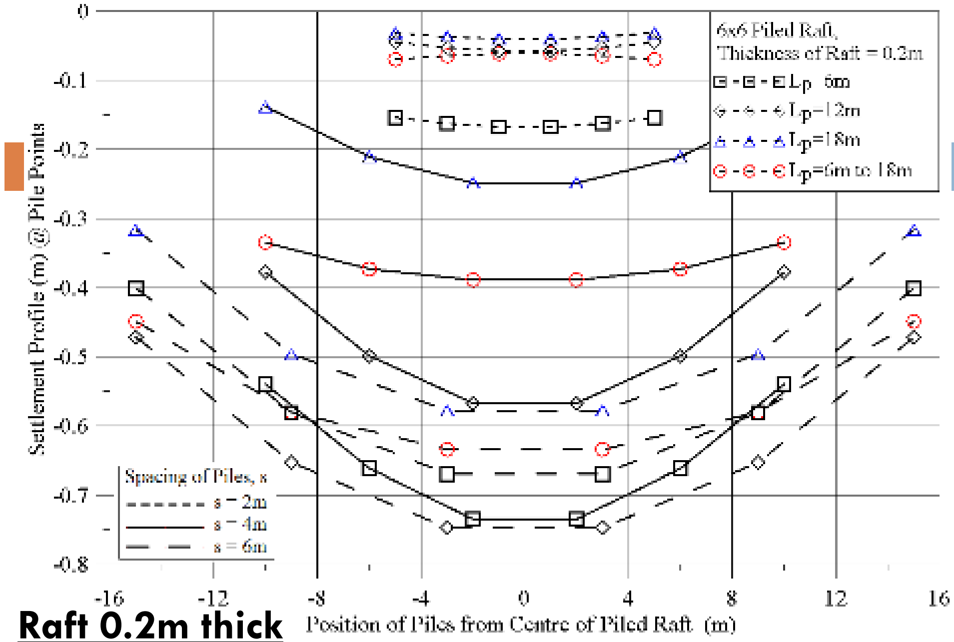
Angular Distortion (β) of 3x3 Piled Raft



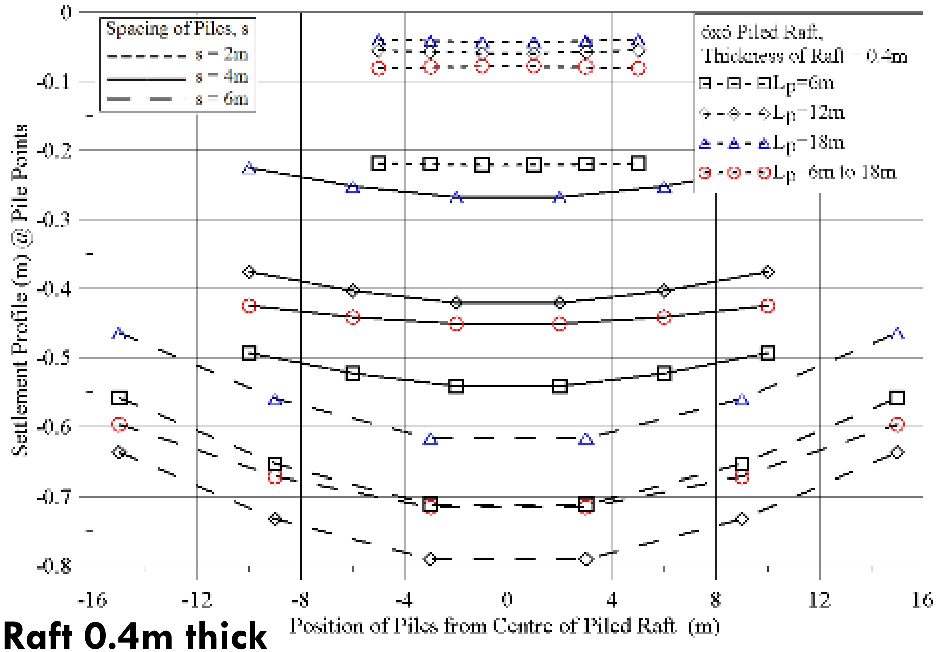
Perpendicularly Across the Raft

Diagonally Across the Raft

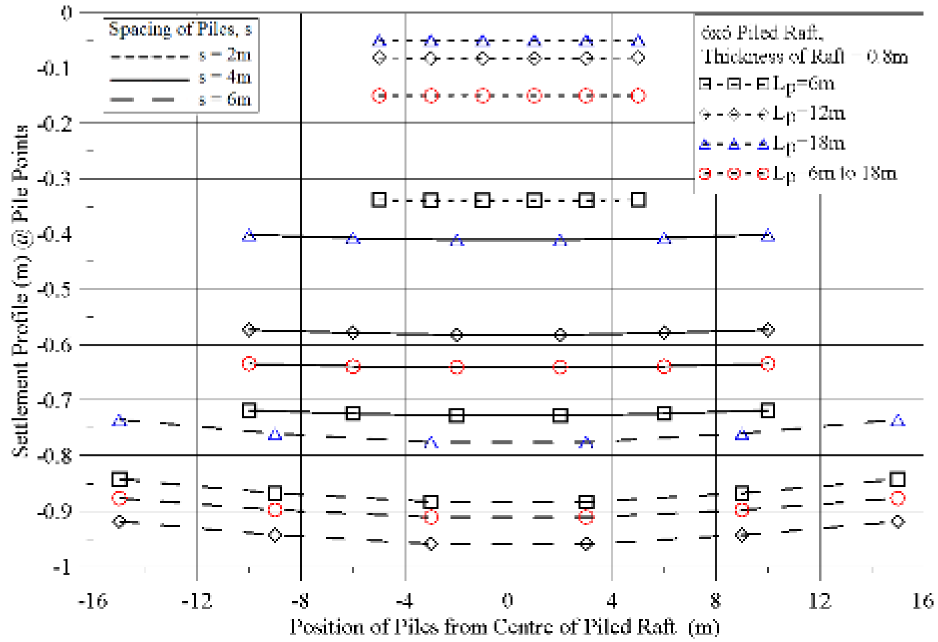
Settlement Profile of 6x6 Piled Raft



Raft 0.2m thick

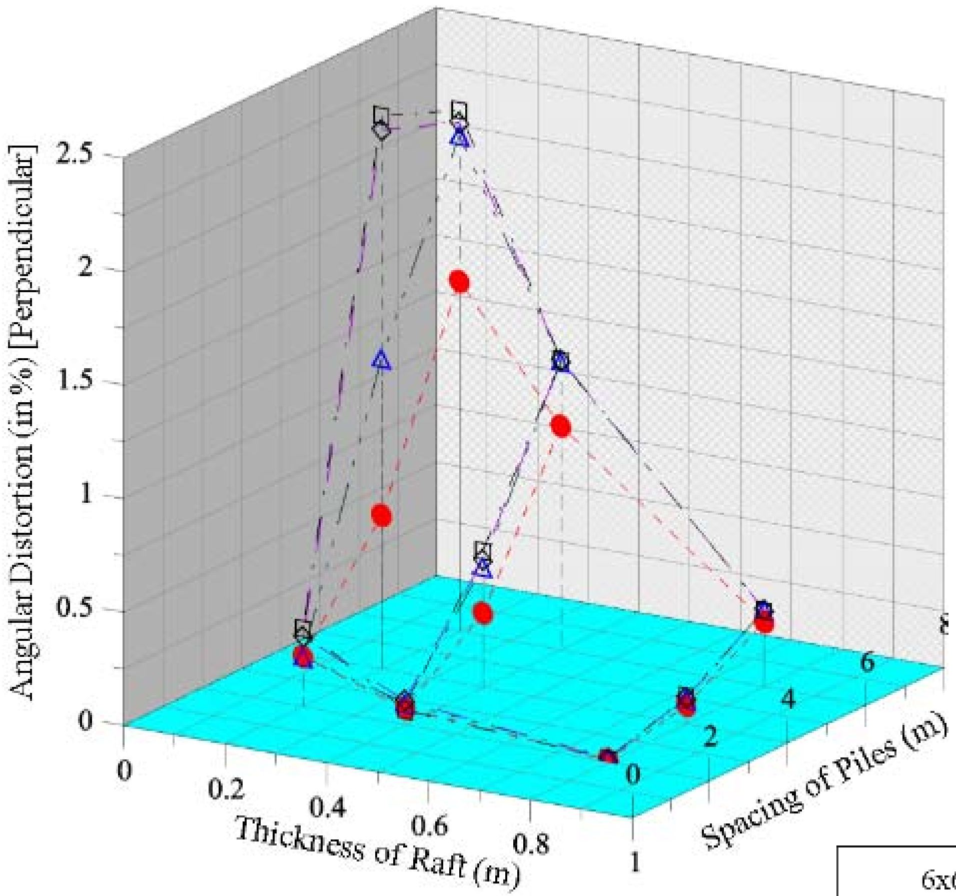


Raft 0.4m thick

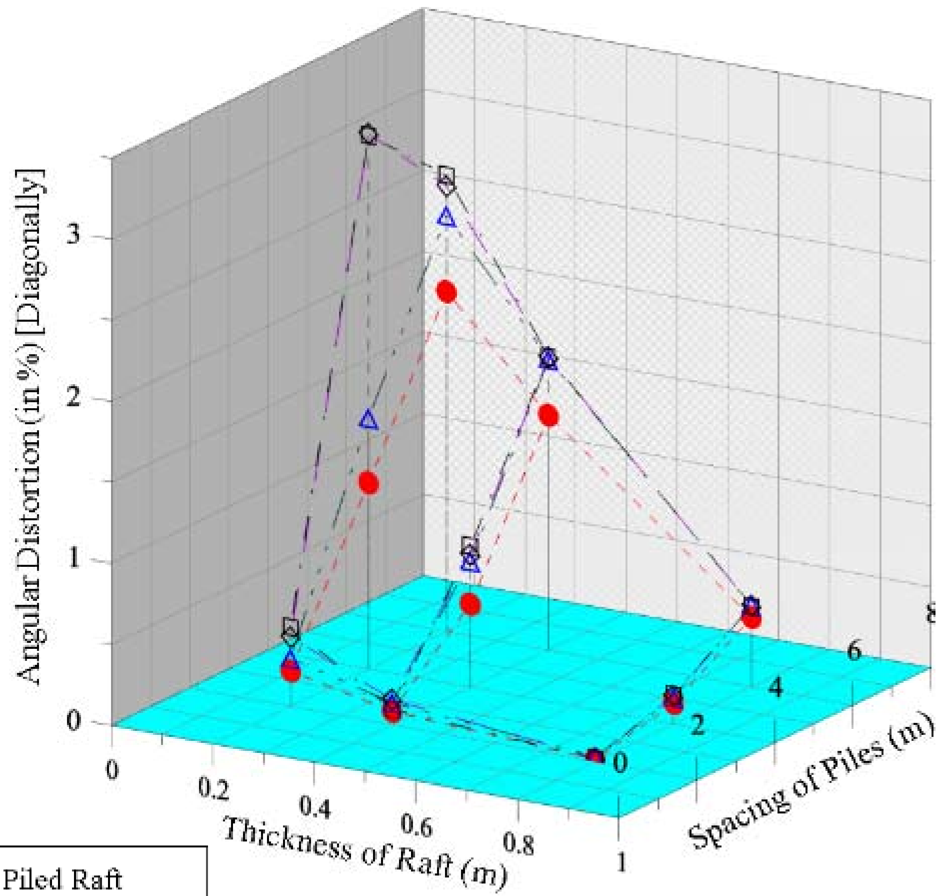


Raft 0.8m thick

Angular Distortion (β) of 6x6 Piled Raft



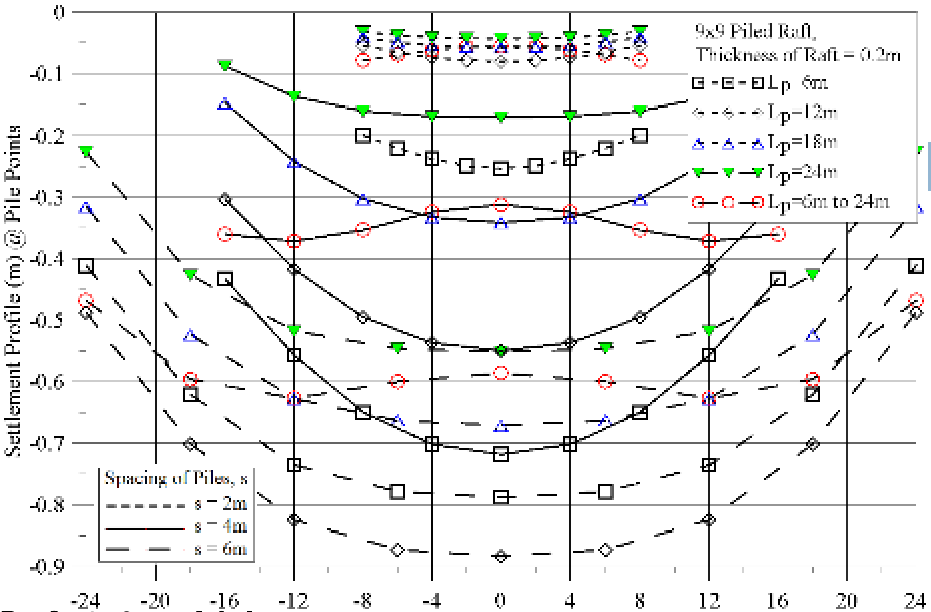
Perpendicularly Across the Raft



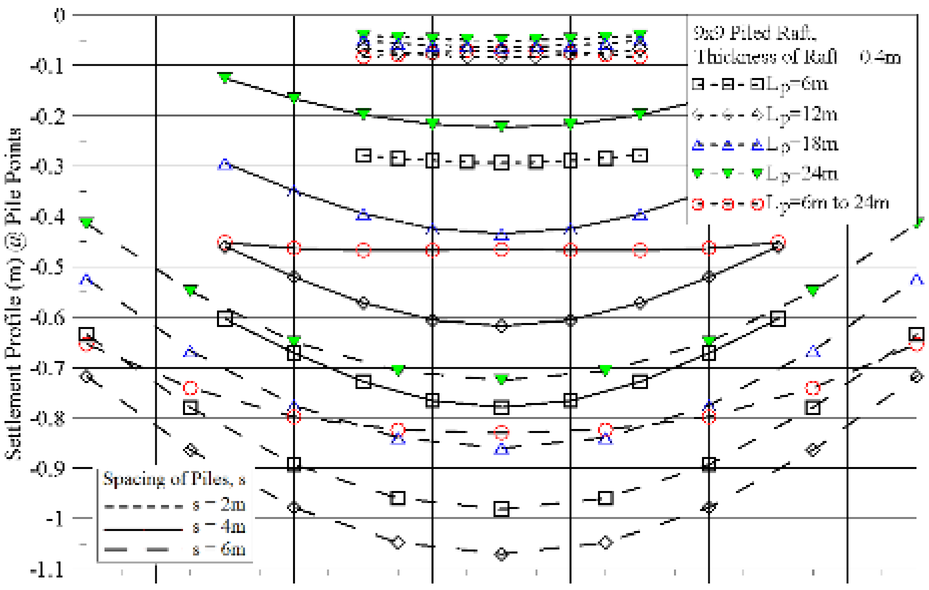
Diagonally Across the Raft

6x6 Piled Raft
● Lp=6m to 18m
△ Lp=18m
◇ Lp=12m
□ Lp=6m

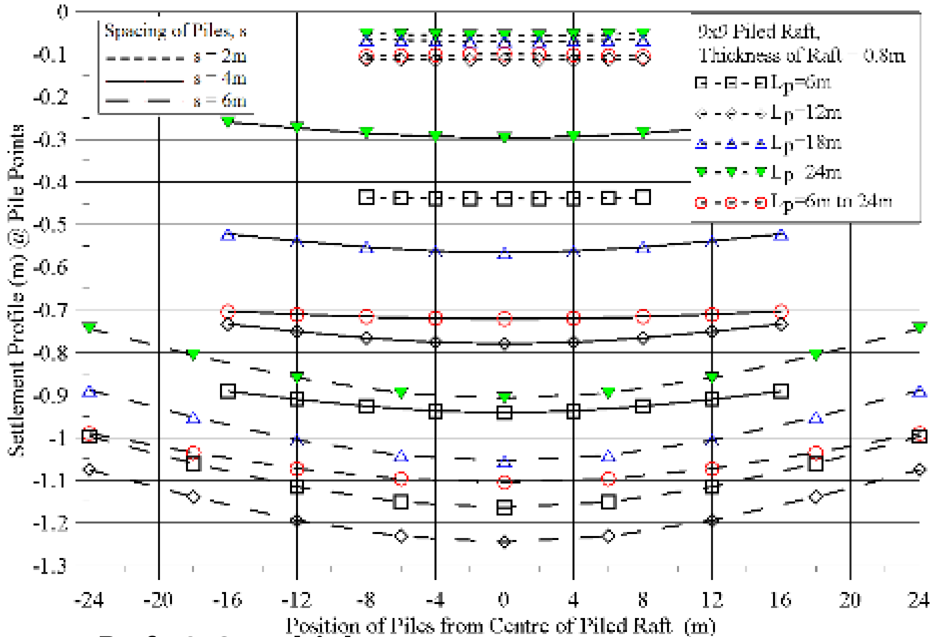
Settlement Profile of 9x9 Piled Raft



Raft 0.2m thick

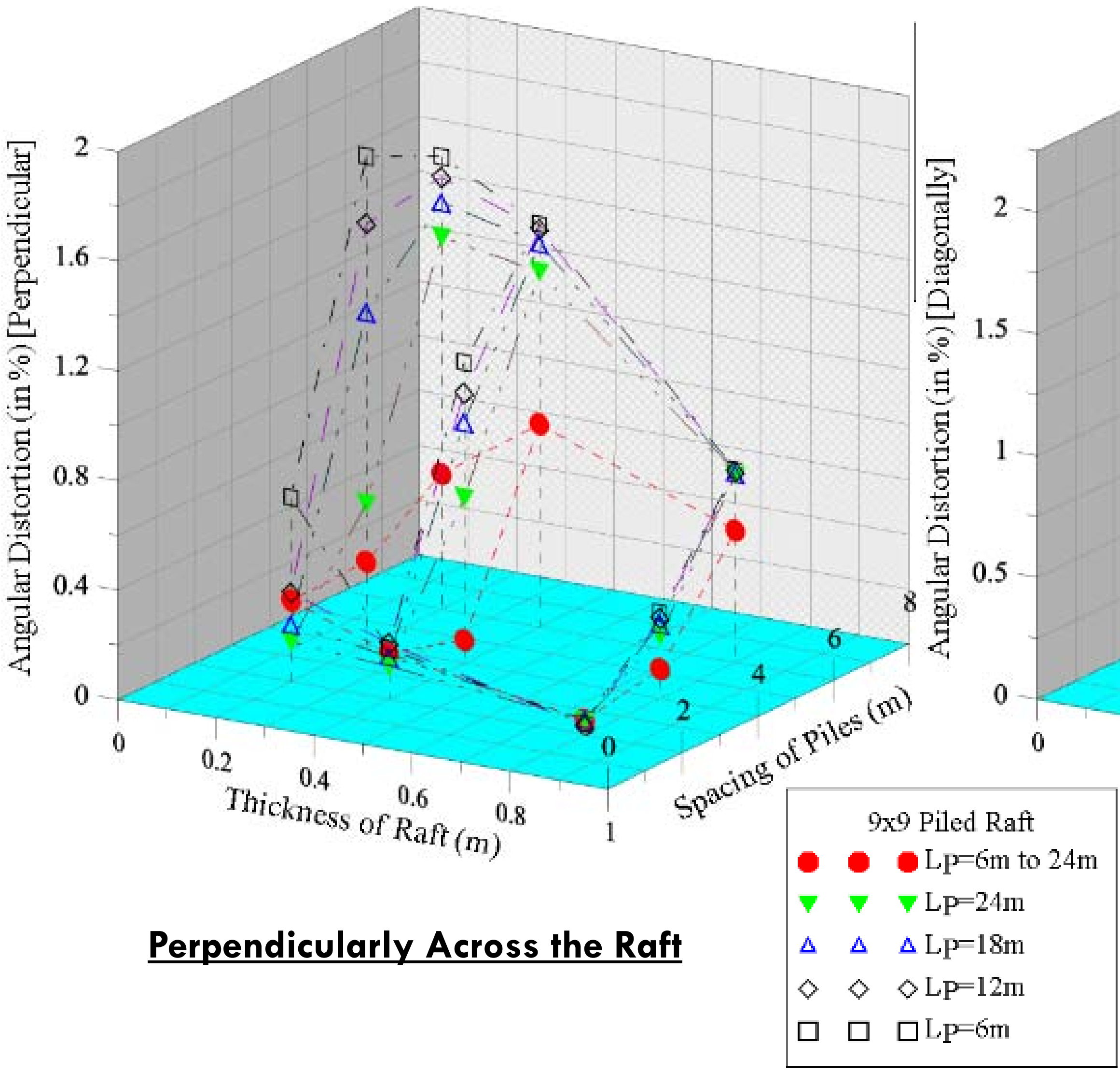


Raft 0.4m thick

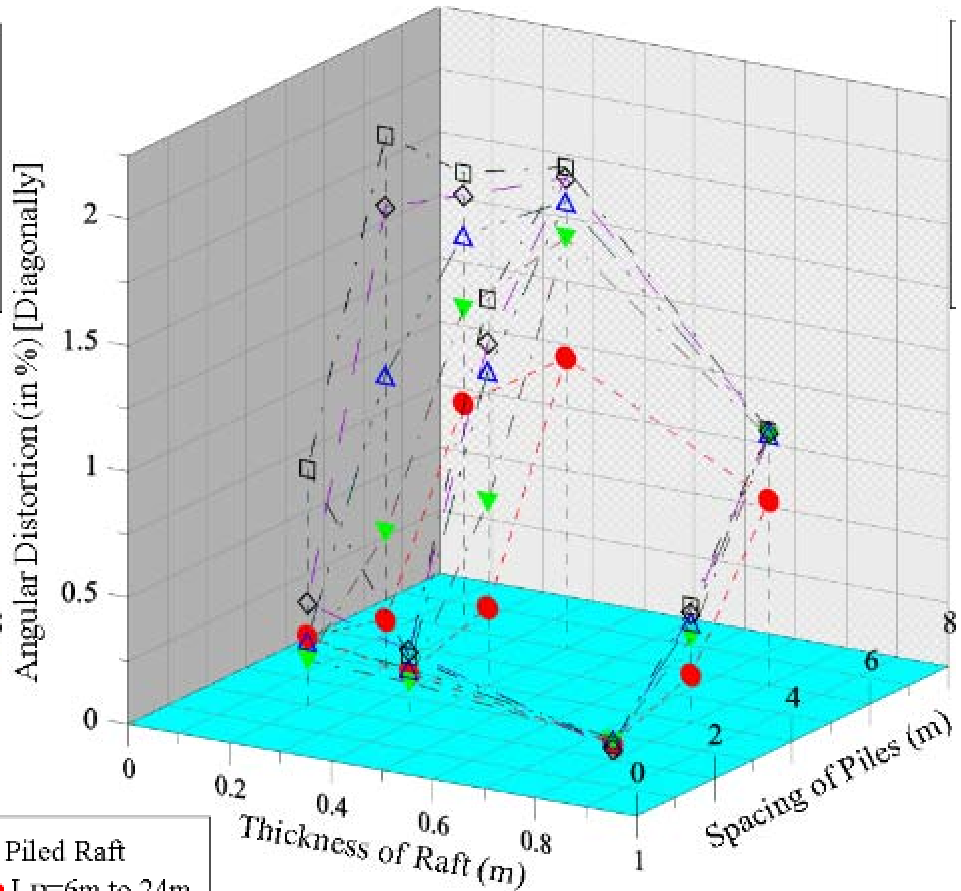


Raft 0.8m thick

Angular Distortion (β) of 9x9 Piled Raft



Perpendicularly Across the Raft



Diagonally Across the Raft

Findings and Discussions

Settlement Profile and Angular Distortion (β)

a) The angular distortion (β) decreases (improved) as the thickness of the raft (t) increases. Compared to 3x3 and 6x6, the trend of decreasing angular distortion (b) with increasing raft thickness (t) is observed for all pile spacing (s) in 9x9 piled raft because the area of the raft is much bigger for 9x9 piled raft.

b) The angular distortion (β) increases (degrading) as the spacing of the piles (s) increases. Compared to 3x3 and 6x6, the trend of increasing angular distortion (b) with increasing spacing of the piles (s) is observed for all raft thickness (t) in 9x9 piled raft because the area of the raft is bigger for 9x9 piled raft.

c) The angular distortion (β) obtained perpendicular across the centre of the piled raft is generally smaller than that obtained diagonally across the centre of the piled raft.

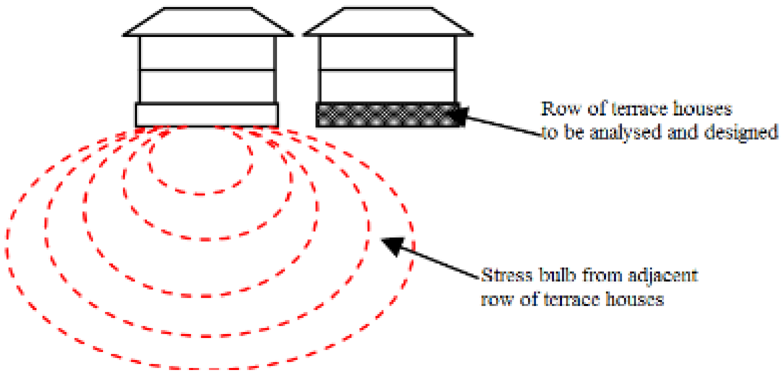
d) Piled raft with varying pile length is more efficient in reducing angular distortion (β) when the spacing of the piles (s) are the further apart (for s=4m and s=6m).

e) Piled raft with varying pile lengths produce lowest angular distortion (β) compared to pile raft with same pile lengths for most cases. It is clear that pile raft with varying pile lengths is very effective in controlling angular distortion (β).

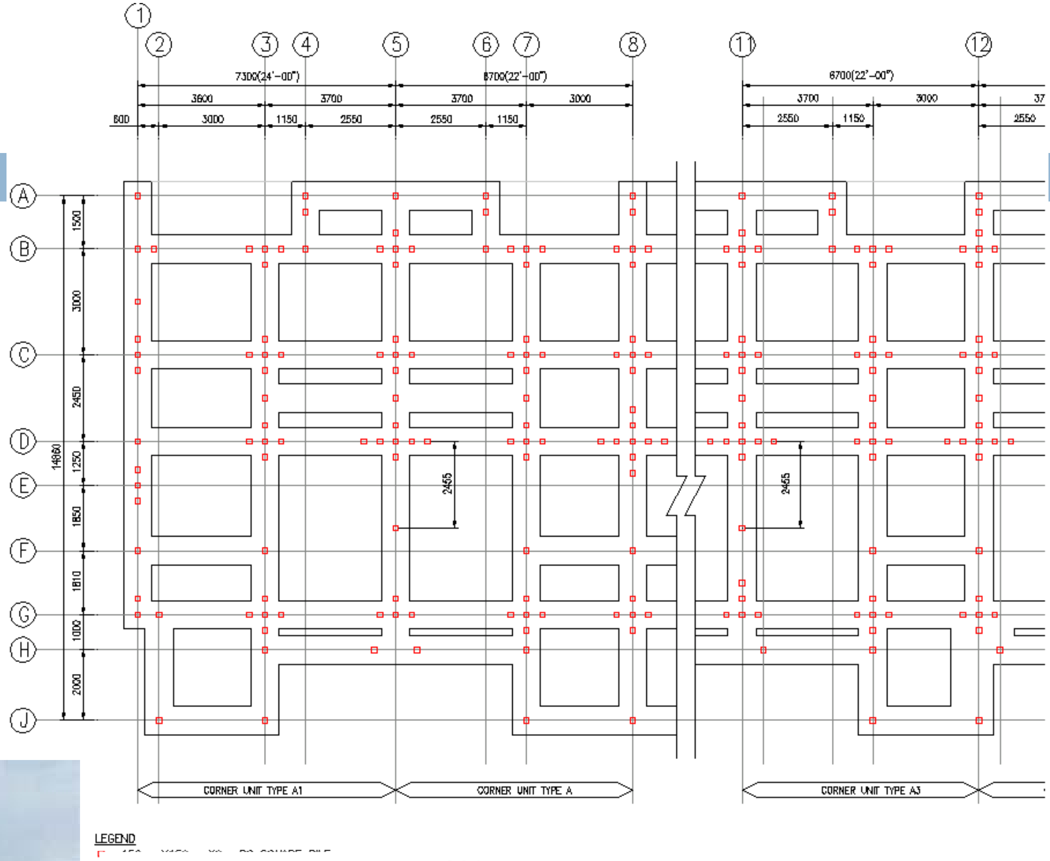
Case History of 'Floating' Piled Raft of Same Pile Lengths for 2-storey Terrace Houses

Note : Section 5.2 (Pg. 132)

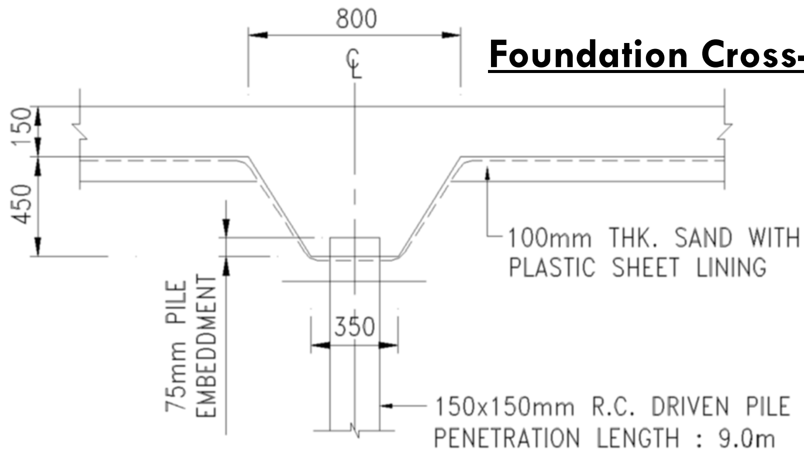
2-Storey Terrace Houses



Foundation Layout

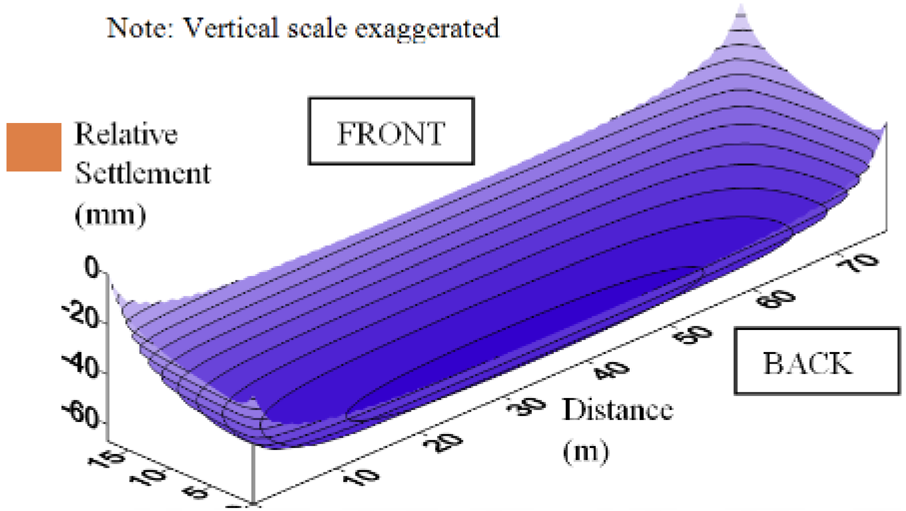


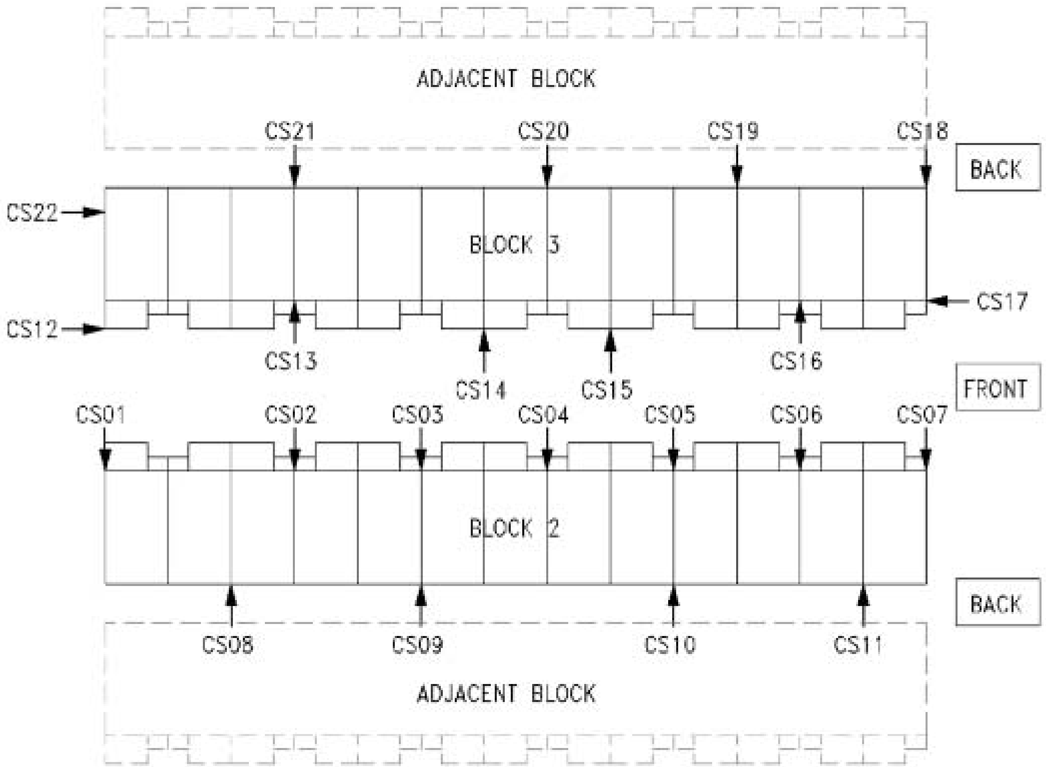
Foundation Cross-Section

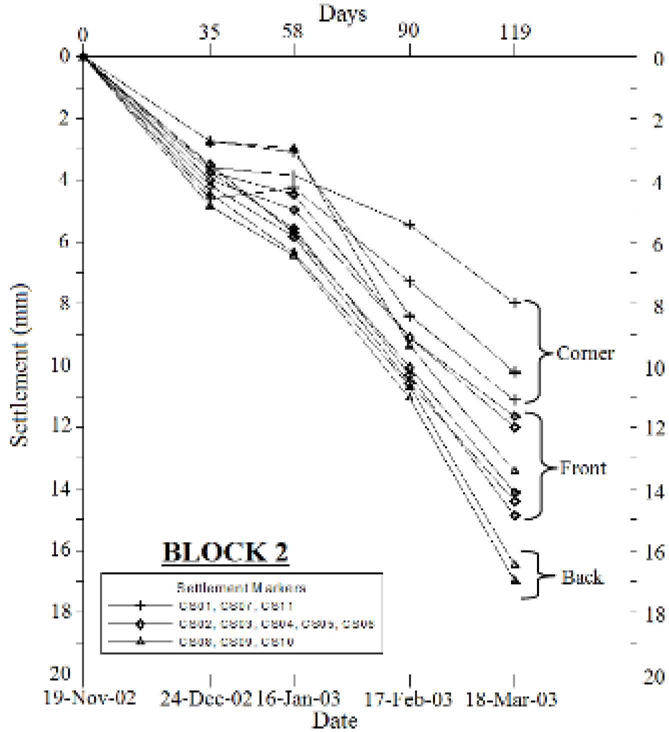


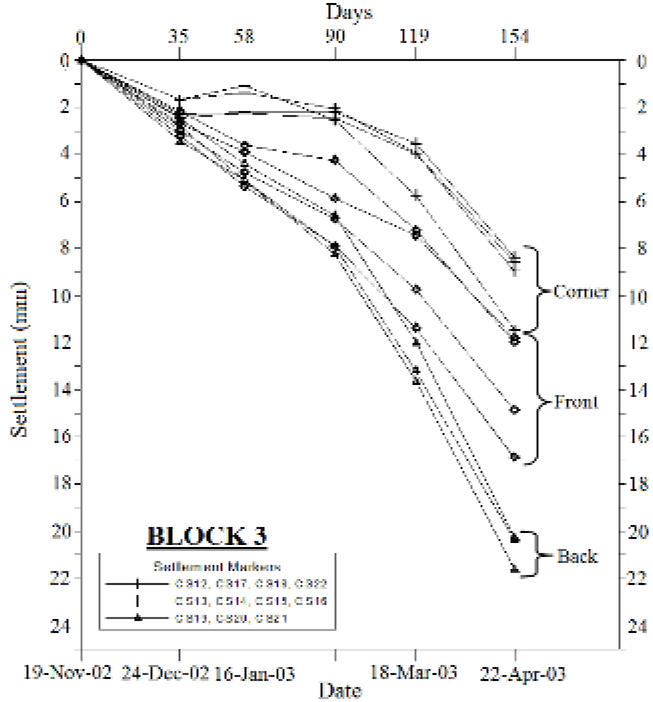
2-Storey Terrace Houses

Note: Vertical scale exaggerated









Findings and Discussions on **2-Storey Terrace Houses**

a) The settlement monitoring results 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**.

b) 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.

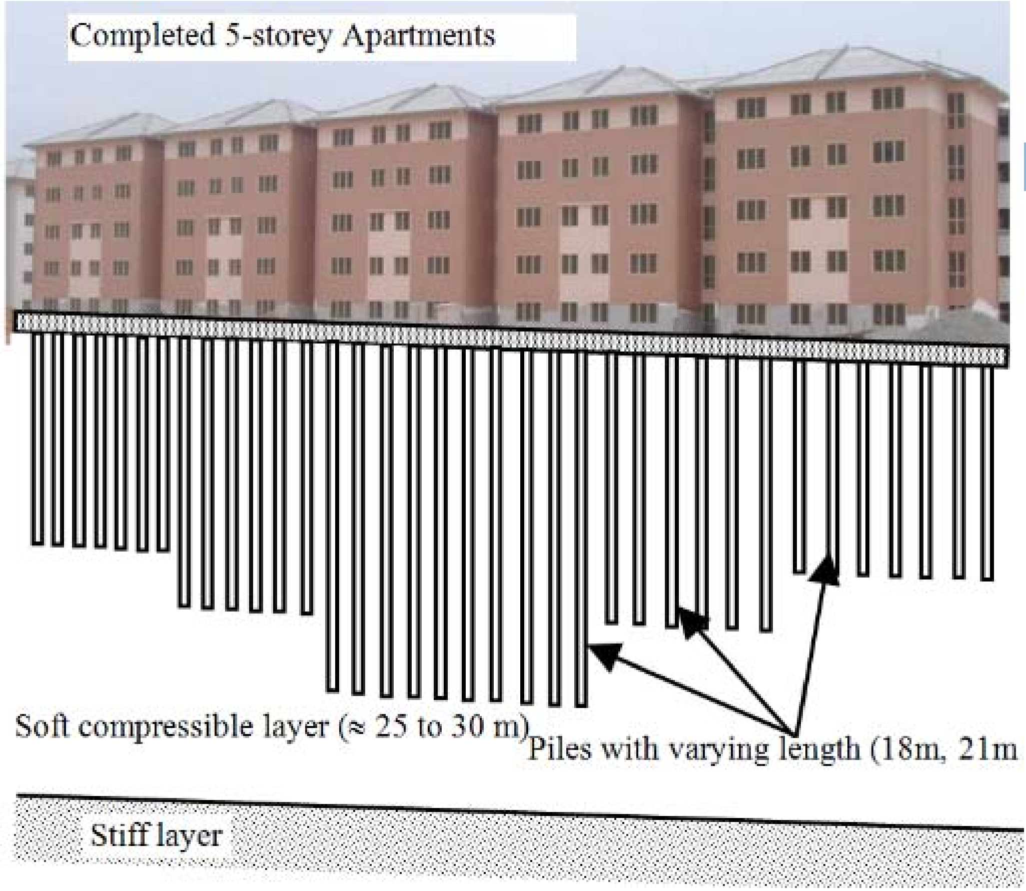
c) Such findings agree well with the **<u>predicted settlement trend</u>.**

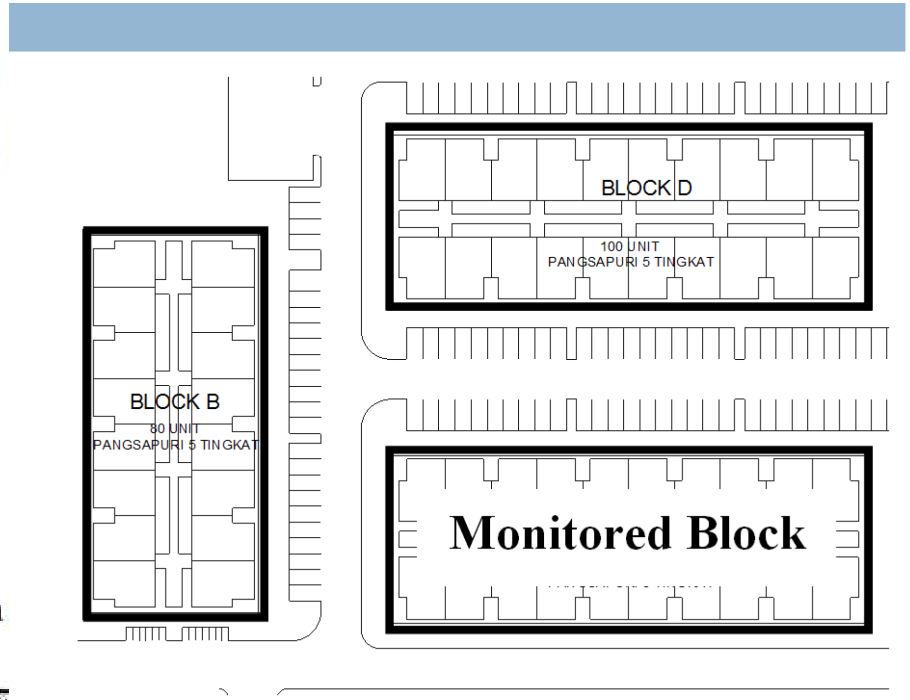
d) The actual houses constructed and occupied since then has performed satisfactory without any architectural, structural and services damages due to differential settlement within the buildings and also between the houses and surrounding platform. This is a clear evidence that the proposed foundation system and design methodology are satisfactory.

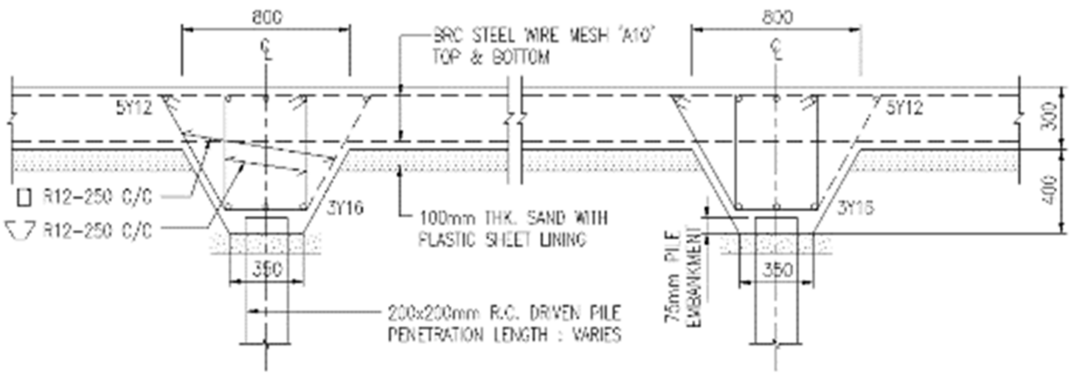
Case History of 'Floating' Piled Raft of Varying Pile Lengths for 5-storey Apartment

Note : Section 5.3 (Pg. 136)

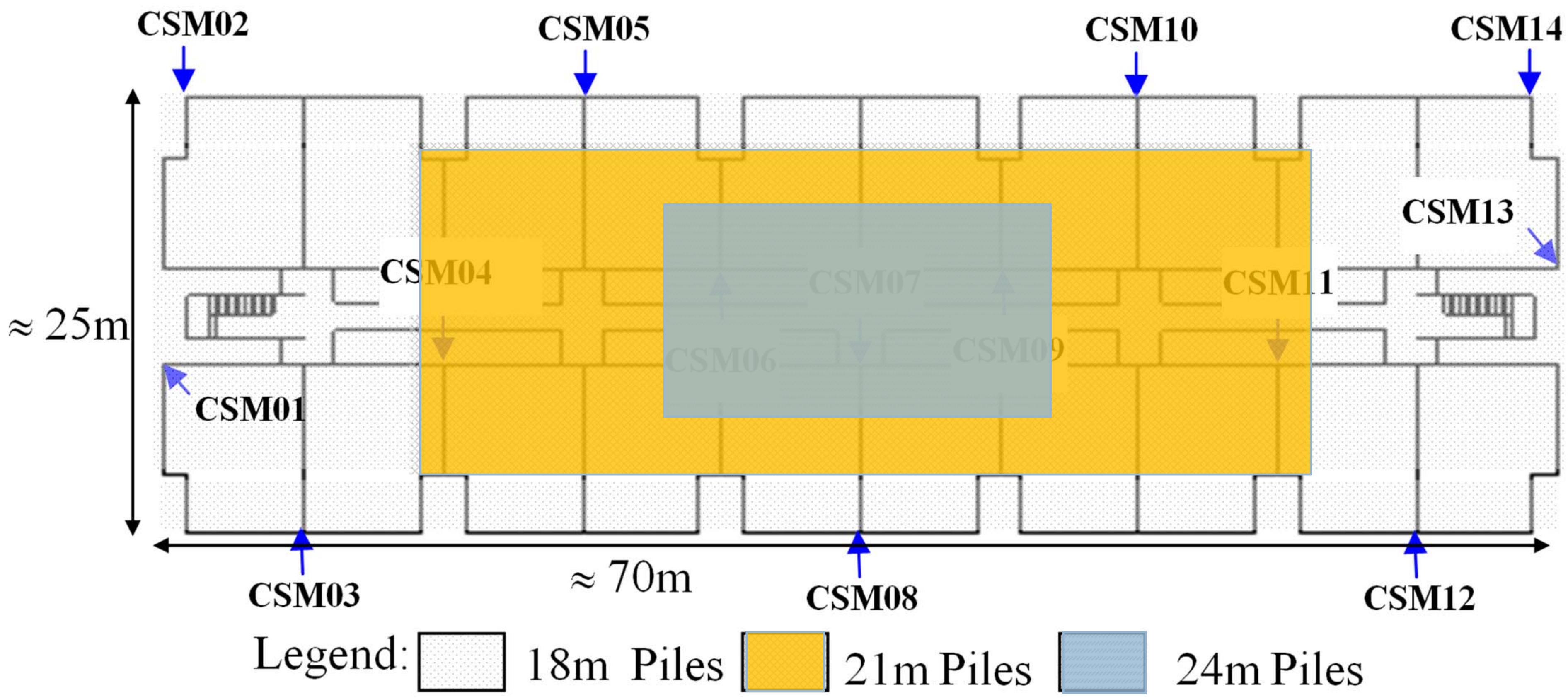
5-storey Apartment



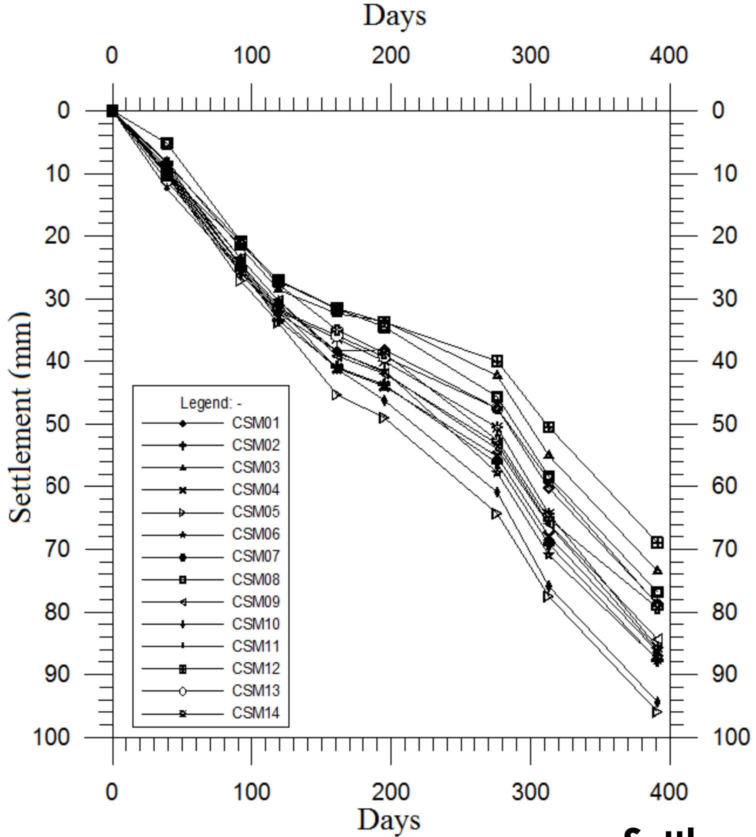


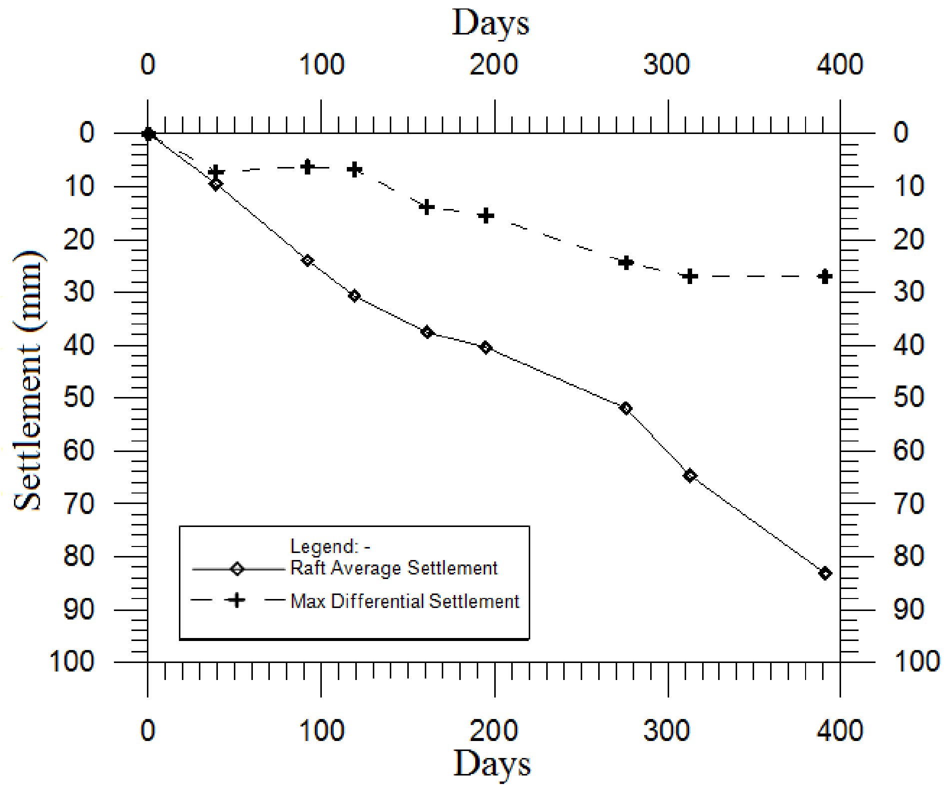


5-storey Apartment

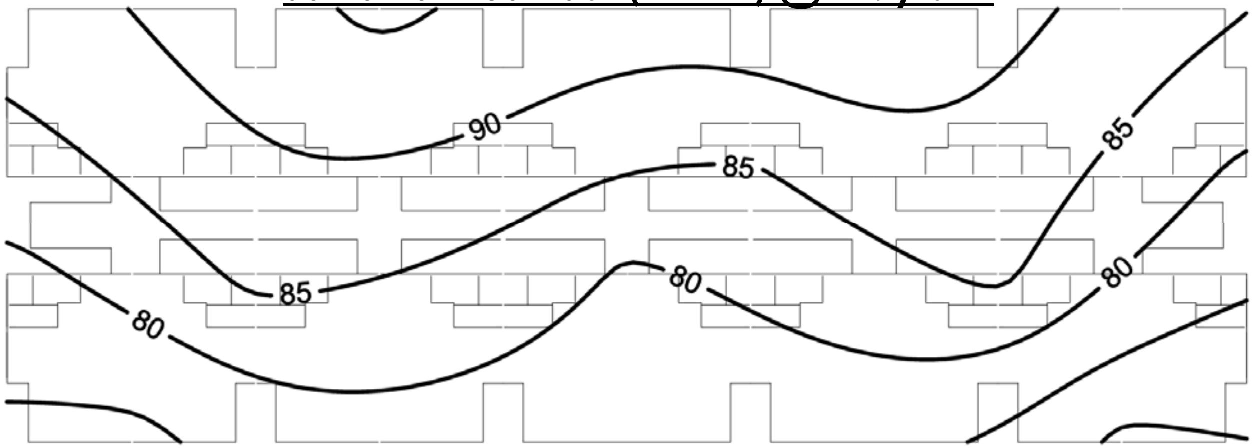


5-storey Apartment



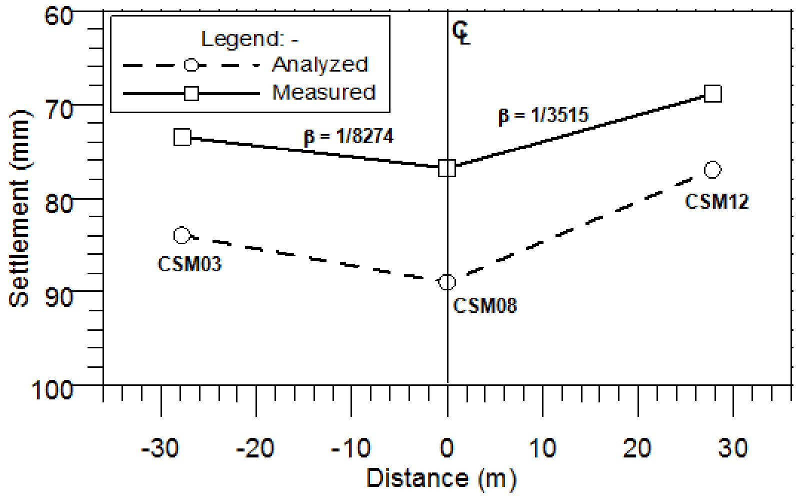


Settlement Contour (in mm) @ Day 391

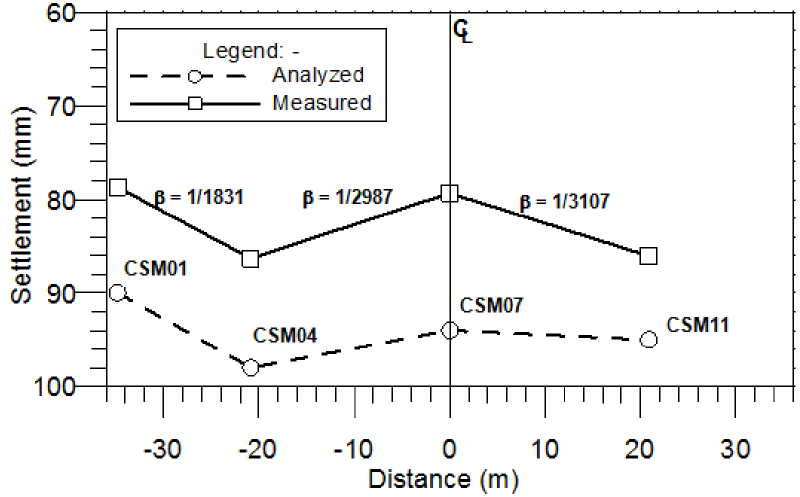


5-storey Apartment

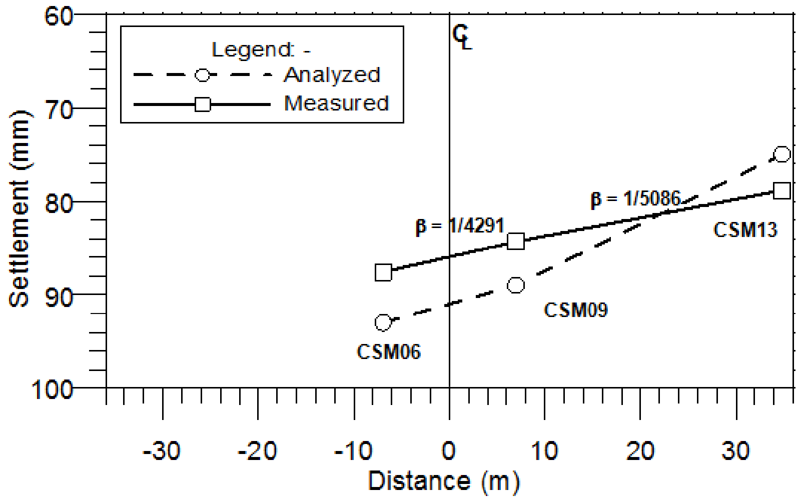
Angular Distortion (β)



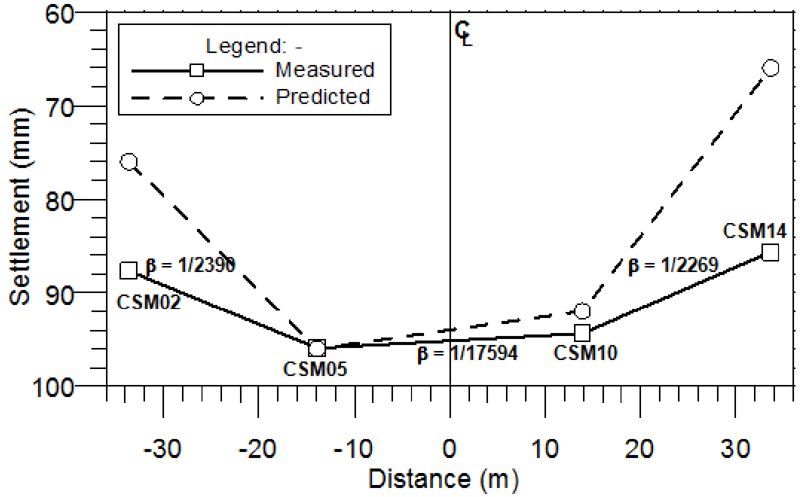
Settlement profile across CSM03, CSM08 and CSM12



Settlement profile across CSM01, CSM04, CSM07 and CSM11



Settlement profile across CSM06, CSM09, and CSM13



Settlement profile across CSM02, CSM05, CSM010 and CSM14

Findings and Discussions on
5-storey Apartment

a) The monitoring results also show that the apartment experiences tilting towards the adjacent blocks (towards left and top side of the apartment) due to the stress influence from adjacent blocks.

b) 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.

c) The monitoring results proofed that the **piled raft with varying pile lengths are technically suitable to control differential settlement and angular distortion of buildings** constructed on very soft and deep layer of compressible subsoil.

d) These buildings has been occupied and without complaint from the residents since 2005 which is more than 10 years duration since completed.

Conclusions and Recommendations

Note : Section 6 (Pg. 141)

Conclusions :

Differential Settlement (Δρ)

1. Piled raft with **varying pile lengths are more effective** in controlling differential settlement compared to piled raft using longer piles throughout with same pile lengths.

2. The reason is for a flexible raft under uniform loading, the total settlement will tends to be larger at the centre compared to the edge. Therefore, by placing longer piles at the middle of the raft with shorter piles are placed at the edges, it will even out (smoothen) the differential settlement.

3. More load to be transferred to the longer piles in the middle of the raft →
   Reduce the load intensity acting on the subsoil at the middle of the raft compared to the edges. →
   Thus reduce the settlement of the subsoil at the centre of the raft and even out (smoothen) the differential settlement.
   = Behave like RIGID footing.

Conclusions :

Maximum Settlement (ρ_{max})

1. It is also concluded that the piled raft with combination of ***varying pile lengths is less effective in reducing maximum settlement*** compared to piled raft with longer similar pile lengths.

2. However, it should be noted that the performance of a piled raft is less affected by maximum settlement (ρ_{max}) compared to differential settlement ($\Delta\rho$) as buildings will not crack with large maximum settlement (ρ_{max}) if the differential settlement ($\Delta\rho$) is still within the acceptable range.

Conclusions :

Ratio of ($\Delta\rho/\rho_{max}$)

1. Combination of ***varying pile lengths in a piled r***aft generally has the lowest ratio of ($\Delta\rho/\rho_{max}$) which ***confirmed the system effectiveness.***

2. Piled raft of same pile length using longer piles produce larger ratio of ($\Delta\rho/\rho_{max}$) compared to shorter piles. The reason is longer piles for piled raft of same pile length are effective in reducing the magnitude of differential settlement ($\Delta\rho$). However, it is not so effective in reducing the ratio of ($\Delta\rho/\rho_{max}$). Thus it is less economical to use piled raft of longer piles of same lengths compared to piled raft of varying pile lengths.

Conclusions :
Pile Raft Coefficient (α_{pr})

1. Combination of varying pile lengths in a piled raft generally has a lower pile raft coefficient (α_{pr}) compared to piled raft with longest piles or second longest piles of same lengths (e.g. 3x3 piled raft with L_p of 12m; 6x6 piled raft with with L_p of 18m and 12m; 9x9 piled raft with with L_p of 24m and 18m).

2. This conclude that when the piles are taking less overall load distribution, the piled raft with varying pile lengths will still be able to control differential settlement, angular distortion and bending moment effectively.

Conclusions :
Maximum Bending Moment (BM_{max})

1. The bending moment of the raft is use as a parameter to determine the effectiveness of the piled raft performance. For a piled raft with similar thickness and same total length of piles, it would be more efficient if it has smaller differential settlement and smaller bending moment compared to other piles configuration. The lower bending moment for same raft thickness will required less steel reinforcement thus more cost effective.

2. It is shown that the ***piled rafts with combination of varying pile lengths*** generally produces the ***lowest maximum bending moment (BM_{max})*** .

3. The ratio of (BM_{max}/ρ_{max}) is an indicator on the effectiveness of the piled raft. Normally as ρ_{max} the increases, the bending moment will also increase because normally larger total settlement will likely to cause larger differential settlement which is the factors contributing to bending moment in the raft. Therefore, if the ratio of (BM_{max}/ρ_{max}) is small for certain pile configuration which uses the least material (most cost effective), it is a good indication of its effectiveness as a piled raft on very soft subsoil.

4. For most cases, combination of varying pile lengths in a piled raft generally has the lowest ratio of (BM_{max}/ρ_{max}) thus it is the most effective compared by using piled raft with same pile lengths.

Conclusions :
Angular Distortion (β)

1. The angular distortion (β) of the piled raft is the most important deformation criteria that governs the buildings serviceability limits.

2. From small piled raft of 3x3 to large piled raft of 9x9, ***piled raft with varying pile lengths consistently produce lowest angular distortion*** (β) compared to pile raft with same pile lengths for all s/t ratio.

3. ***Piled raft with varying pile lengths is most efficient and effective in controlling angular distortion*** (β) compared to pile raft with similar pile length (even with longest piles).

4. The efficient control of angular distortion also contributed to lower bending moment in the raft.

Conclusions :
Case Studies

1. The conclusion is the ***proposed analysis and design methodology*** for 'floating' piled raft foundation system **has been successfully used to design** and construct 2-storey terrace houses and 5-storey apartment on on very soft and deep layer of compressible subsoil.

2. These structures have been completed and occupied since 2004 and 2005 respectively without any architectural, structural or services damages due to differential settlement within the buildings and also between the structures and surrounding platform.

3. The settlement monitoring results also proofed that the proposed analysis and design methodology are both correct and effective in controlling differential settlement and angular distortion of buildings constructed on very soft and deep layer of compressible subsoil.

4. The findings also 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.

5. 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.

Executive Summary of Conclusions

- The ***proposed 'Floating' Pile Raft foundation system*** is ***SUITABLE*** to support low-rise buildings on on very soft and deep layer of compressible subsoil.
- Piled raft with **varying pile lengths** (with longer piles at the middle and shorter piles at the side) are **generally more effective** in controlling differential settlement, angular distortion and bending moment compared to piled raft using same pile lengths.
- The ***proposed analysis and design methodology*** in this research has been **proven acceptable** based on the the actual buildings constructed (e.g. 2 case studies that represent more 3000 units of buildings constructed and occupied for more than 10 years.)

Recommendations for Future Research

1. To devise solutions to track the deformation of the piled raft, pile loads and reaction of the subsoil continuously with time following the construction sequence and loads acting as the building is being constructed. The design engineers able to verify the design based on the actual performance of the building with time via monitoring of instruments that will allow them to improve the design for future projects.

2. To cater for heterogeneous subsoil conditions, such as subsoil with mixture of soft compressible soil with intermediate sand or man-made materials that are commonly found in reclaimed ex-mining land. One of the method that can be considered for the solutions to design piled raft of same and varying pile lengths is the load transfer (t-z) methods. Future research can devise solutions for piled raft in heterogeneous subsoil with the load transfer method with pile interactions.

3. To develop solutions for piled raft with same and varying pile lengths that can cater for both vertical and horizontal load. To include raked piles so that bridge abutment can be design and constructed using 'floating' piled raft rather than conventional piled to set with pile cap.

THANK YOU

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