

Sustainable Design Techniques for Foundation Structure

- *green initiative!*

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Abstract—*this technical paper serves to provide engineering guidance from the perspective of optimization and valance as the engineering tends to lean on conservatism for practitioners. Thus, the ultimatum is to research and produce some sustainable foundation design techniques for both unpiled-raft and piled-raft foundation structures.*

Keywords—*load bearing and settlement curves; unpiled-raft; piled-raft; short-term settlement; soil-structure interaction relationships.*

1. Introduction

1.1 Background

Piled-rafts structure foundation provides an economical option when an unpiled-raft does not satisfy the design requirement. Under these circumstances, the addition of a limited number of piles will improve the ultimate load capacity and the settlement performance.

In the conventional design approach, piled-raft foundation designs usually ignore any contribution from the raft, and assume that piles carry all the superimposed loads. As a result, the conventional piled-raft designs are often conservative. The overall settlement of piled-raft in such conventional designs is often very small, owing to the installation of longer or more piles than are necessary. Obviously, more economical solutions can be obtained by accounting for the contribution of the raft.

Thus, series of extensive parametric studies of piled-raft behaviour have been performed to determine any significance contribution from the raft in the pile-raft-soil interactions to produce some sustainable design techniques for foundation structure.

1.2 Problem Definition

- Many structures founded on pile-raft structure foundations on soft clay in Singapore have been conservatively designed without considering the contribution from the raft due to the lack of knowledge (and thus design confidence) on the soil-structure interactions, soil load-bearing and settlement behaviours of piled-rafts. This generally resulted in very expensive foundation costs particularly in the soft clay conditions.
- Total settlement is rarely damaging but not differential settlement. However, this can be reduced by prudent design. As highlighted by Terzaghi & Peck, most buildings can tolerate up to 20mm differential settlement. These differential settlements are unlikely to exceed 75% of average total settlements. As such, a maximum settlement of 25mm will be used as a safe guide for buildings on isolated foundation in this paper.

1.3 Objectives

The objectives for this paper:-

- Investigate the undrained bearing and vertical settlement behaviours of raft and piled-raft in the soft clay using 3-D finite element analyses;
- Compute the load bearing contribution by the raft through various simulation from the loaded piled-raft models;
- Develop simplified techniques to permit a rapid preliminary assessment and design of raft and piled-raft for project planning & cost estimation purposes, and safety and risk analysis study; &
- Develop design pedagogy with self-explanatory design flowchart.

2. Geology of Singapore

2.1 General



Singapore is a small Island covers about 700km² that includes the offshore. Climate is hot and humid with an annual rainfall ranging from 1600mm in the southwest to 2500mm in the central regions. Based on these conditions, the rocks are deeply weathered. Hence, various types of sub-soils can be found, and they range from very soft peat and marine clay in the low lying areas to hard rock such as sandstone and granite.

Two main formations; Kallang and Jurong formations have post numerous problems to engineers with regard to the construction of foundations and substructures. This geology, combined with the urbanisation of the island has further highlights the importance of settlement control to all construction projects in Singapore.

2.2 Diagrams Considered

The basic problem addressed is illustrated in *Figure 2.2a* and *Figure 2.2b*.

For *Figure 2.2a*, the concrete unpiled-raft foundation is located on the soft clay. Following ranges of matrix parameters were used to establish a sustainable unpiled-raft model:

- raft size, $L = 5 \times 5, 10 \times 10, 20 \times 20 \text{ m}^2$
- raft thickness, $t = 5\%L, 10\%L, 15\%L$
- short term maximum vertical settlement, $\delta = 25 \text{ mm}$

For *Figure 2.2b*, the concrete piled-raft foundation is also site on the soft clay. Following ranges of matrix parameters were used to establish a sustainable piled-raft model:

- raft size, $L = 5 \times 5, 10 \times 10, 20 \times 20 \text{ m}^2$
- raft thickness, $t = 5\%L, 10\%L, 15\%L$
- pile = $0.25 \text{ m} \times 0.25 \text{ m}$
- pile-length = $12 \text{ m}, 24 \text{ m}, 36 \text{ m}$
- square grid pile-spacing = $2 \text{ m}, 3 \text{ m}$
- short-term vertical settlement, $\delta = 25 \text{ mm}$

2.3 Finite Element Model

A quarter of the model is used due to symmetry about both axes. Based on the cohesion materials considered, it is preferable to use a simple constitutive model (i.e Mohr Coulomb model). Vertical uniformly distributed load is applied as total load onto the model. Boundaries are placed sufficiently remote so as not to restrict or constrain movements in the area of interest.

2.4 Numerical Analysis

The desktop study and the assessment works done for both unpiled-raft and piled-raft foundation models are used to create some sustainable foundation structure design techniques through the load bearing against settlement computation results retrieve from the 3D-FEM analysis.

All results developed into design techniques (chart & formula) will be validated with theoretical calculation done manually.

3.0 Debriefs on Findings

3.1 Unpiled-Raft Foundation

- Raft model of 5mx5m having highest bearing capacity compared with other larger slabs e.g 10mx10m & 20mx20m;
- Thickness of the raft foundation has little influence on the bearing-settlement behaviour except having bending stresses generally increase with it;
- Raft model loaded with uniformly distributed loads has acted and behaved as a flexible structure and displayed a profile of bowl-shape or saddle-shape curve;
- Critical settlement is observed to be at the centre point of the raft and its differential settlement is worst from the centre of the raft to the corner of the raft;
- Elastic displacement formula is used to evaluate the newly developed design chart (Figure 3.3a). It fits well with variation of the results between numerical to theoretical studies of saving of up to 10% due to the rigorous 3D FEM modelling effect;
- When using theoretical method, values of the coefficients μ_0 and μ_1 are very sensitive to the results and interpolation to read from the chart has posed quite a challenge;

3.2 Piled-Raft Foundation

- Thickness of the raft foundation has little influence on the load bearing against settlement behaviour except having bending stresses generally increase;
- The piled-raft raft model loaded with uniformly distributed loads has acted and behaved as a flexible structure and displayed a profile of bowl-shape or saddle-shape curve;
- The critical settlement point is observed to be at the centre point of the raft and its differential settlement is worst in the direction of centre to corner of raft;
- Factors of influence on the bearing capacity is higher for closely spaced piles followed-by lengthen of piles;
- Generally, the contribution of the raft is found to be of significance in the piled-raft foundation, especially as the piles spacing increased followed by short pile length;
- Piles spacing plays an important role on the performance of the piled-raft foundation. It affects greatly the maximum settlement, the differential settlement, the bending moment in the raft and the load shared by the piles;
- Longer pile length might not necessary be an effective approach since the end-bearing capacity would not be fully utilised especially for foundation settlement during the short-term periods. Another reason is that the load-sharing and moment-sharing are not affected much by increasing of the pile lengths;
- The axial load is the maximum at the top of the pile, and it reduces with depth reaching a minimum at the tip of the pile. With increase in load intensity, the axial load in the pile increases;

- Elastic displacement formula are used to evaluate the newly developed chart (Figure 4.2) and the newly formed formula (Section 4.1);
- The newly formed formula is found to be more effective when compared with the existing elastic displacement formula against the numerical results done due to the soil-pile-raft interactions effect in the rigorous 3D FEM modelling (Figure 3.3b);
- When using theoretical method, values of the coefficients μ_0 and μ_1 are very sensitive to the results and interpolating it from the chart had posed quite a challenge;
- The Elastic displacement formula and the newly formed formula have the same limitation as both did not take into the effect of the spacing of piles and the number of piles;
- A sustainable design chart and a new formula which took into consideration of the raft's contribution in a piled-raft foundation which permit rapid preliminary assessment and design of piled-raft foundation, have been established and evaluated; &
- The differential settlement increases with spacing of piles.

3.3 Evaluation Methods on Developed Design Techniques

- Elastic theory has been found to be useful for evaluation of immediate settlement for cohesive soil condition as highlighted in the book of *U.S Army Corps of Engineers, Settlement Analysis 1994*. Thus, the elastic displacement formula calculation by *Christian and Carrier (1978)* where uniform pressure q is given by: $S_i = (qB/E)\mu_0\mu_1$ for the immediate settlement is used for evaluating these developed design techniques;
- Computation results from the rigorous 3D finite element modelling which allow very rigorous treatment of soil-structure interaction to take place are expected to produce the least conservative load bearing against settlement threshold limit; &
- Lastly the use of the newly formed formula (Section 4.1 for detail) to calculate the load bearing capacity of the foundation.

In general, above-mentioned three methods relationship can best be presented in Figure 3.3b. It can be seen that the newly formed formula has performed better when compared with the existing elastic displacement formula by *Christian and Carrier (1978)*, against the computation results.

4.0 CONCLUSIONS

4.1 Developed New Formula

The newly formed formula is a modification to the existing elastic displacement formula by *Christian and Carrier (1978)*. The new formula takes into consideration of the raft's contribution on the piled-raft foundation by using superposition principle. This newly formed formula is presented as follows :

$$q = S_i EK / (B \mu_0 \mu_1) \text{ -----TanKL (2014)}$$

Where:-

- S_i is depth of the immediate settlement
- E is the undrained soil young's modules at the at top layer
- K is calculated using B/B_e
- ($K = 1$ for unpiled-raft condition)
- B_e is the distance between 2 outermost piles (Figure 4.1a)
- B is the breadth of the equivalent raft (Figure 4.1a)
- μ_0 depends on the depth on the earth of embedment and μ_1 depends on the layer thickness and the shape of the loaded area.
- Values of the coefficients μ_0 and μ_1 for Poisson's ratio equal to 0.5 are given in Figure 4.1b.

4.2 Developed Design Charts

Design Chart (Figure 4.2) presents the total permissible load for both the unpiled-raft foundations and piled-raft foundations. Interpolation works are permissible so long they are within the limits e.g raft foundation to be from 5m x 5m to 20m x 20m, and piled-raft foundation from 5m x 5m to 20m x 20m with a maximum pile length of up to 36m deep.

4.3 Design Pedagogy

Design pedagogy is presented in a self-explanation flow chart shown in Figure 4.3.

5. Acknowledgement

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6. References

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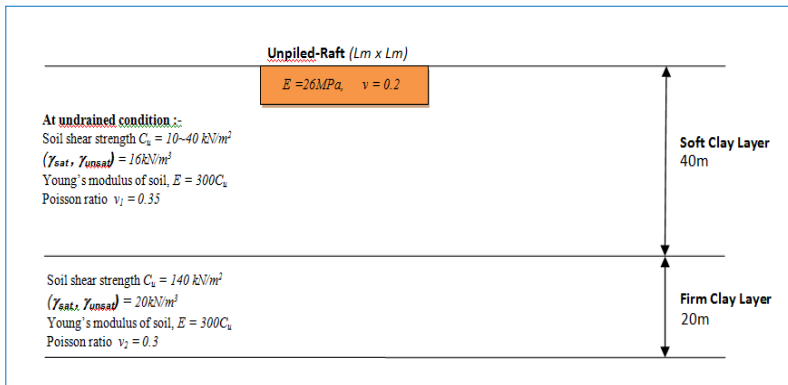


Figure 2.2a

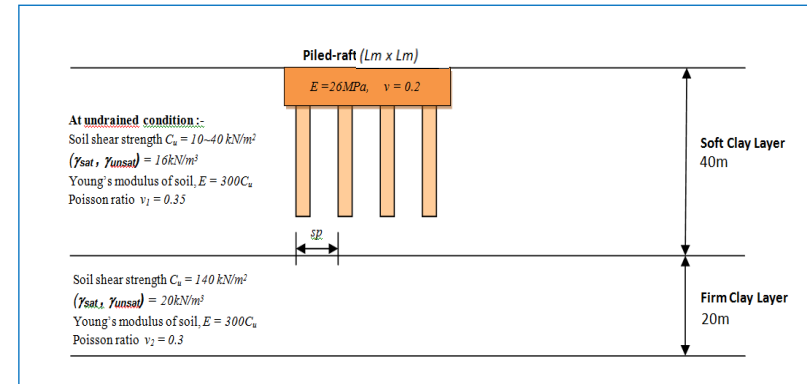


Figure 2.2b

(Sources from Soil Mechanics 5th edition by R.F. Craig)

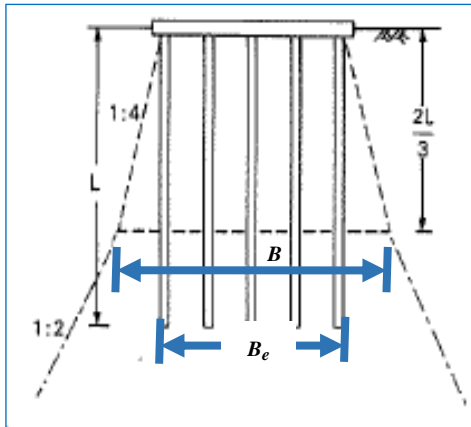


Figure 4.1a

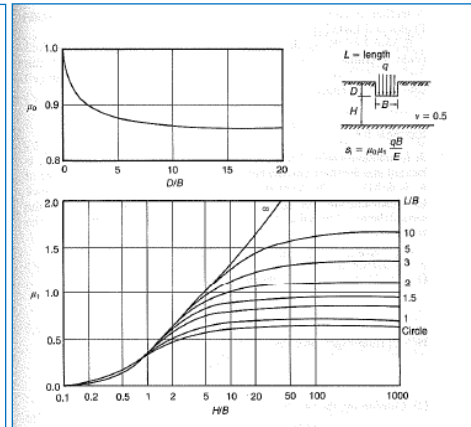


Figure 4.1b

Size of foundation structure	Total permissible load, q (kPa)			
	Raft	Raft with 12m piled	Raft with 24m piled	Raft with 36m piled
5m x 5m	0.023x + 0.001	-0.005x ² + 4.79x + 2.5	-0.0116x ² + 6.7573x + 0.665	-0.0225x ² + 8.8342x - 2.67
10m x 10m	0.0122x + 0.0006	-0.0046x ² + 2.5065x + 1.4858	-0.005x ² + 3.81x + 7	-0.024x ² + 5.1925x + 28.004
20m x 20m	0.064x + 0.0005	-0.0025x ² + 1.095x + 0.25	1.1x + 18	-0.0075x ² + 1.885x + 31.75

NOTES

NOTE 1 : x = shear strength of undrained soil (C_u) from 10kPa to 100kPa

NOTE 2 : The spacing between centre of piles is 2m

NOTE 3 : The values in the table are for im

NOTE 4 : Interpolation work permitted

Figure 4.2

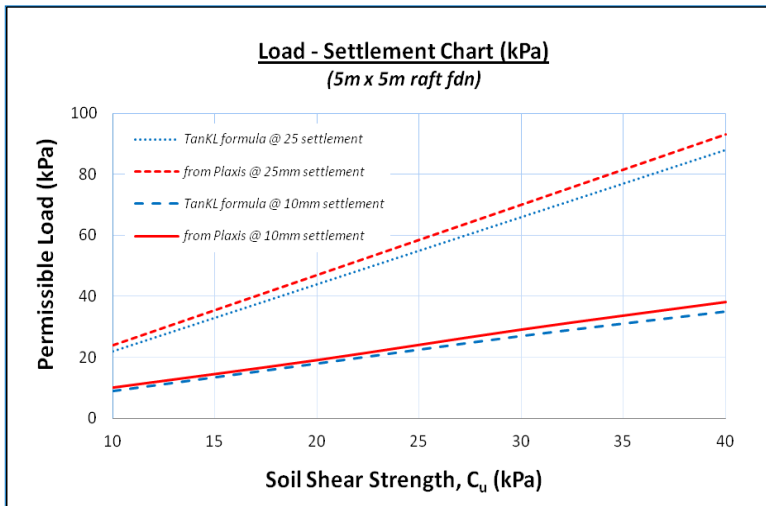


Figure 3.3a

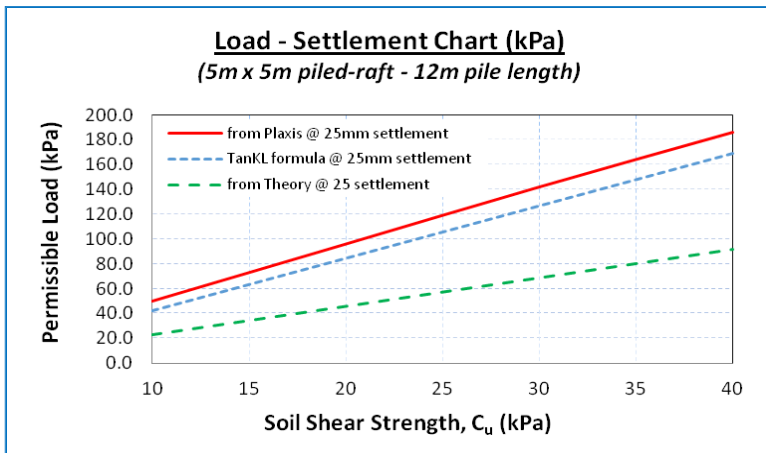


Figure 3.3b

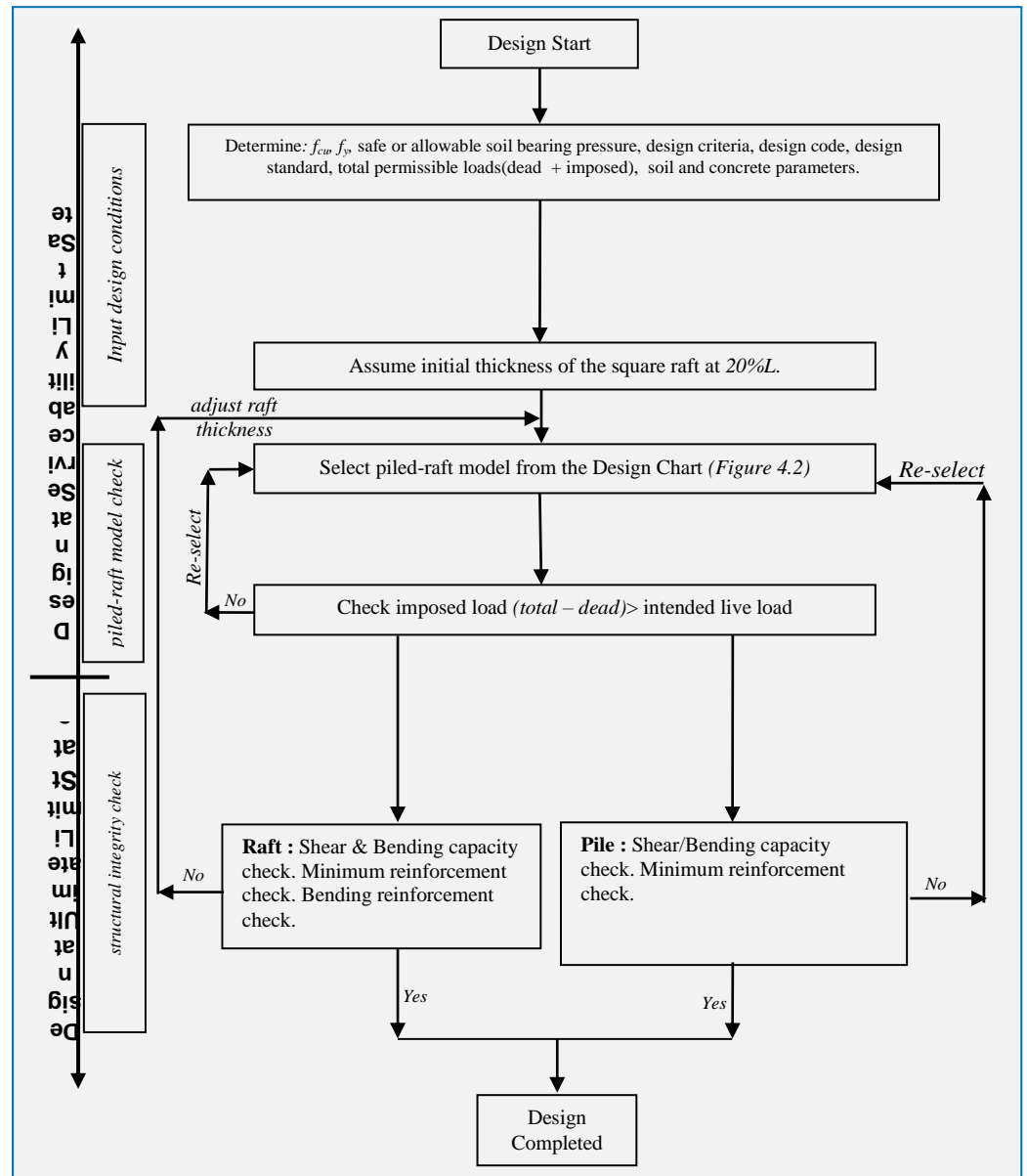


Figure 4.3