Piled Raft over Soft Marine Clay: Comparison of In-situ Measurement and Numerical Analyses

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***Abstract*— Geotechnical works in deep deposit of highly compressible soft clay is always associated with excessive differential settlement. The site evaluation and settlement analysis had been performed on five cylindrical steel tanks situated at Pasir Gudang, Johor in which all of the tanks are currently in service for fuel oil storage. This paper will describes the methodology of geotechnical study and engineering analysis for constructing large scale steel tanks founded on piled raft over compressible soil layers. Discussion on the design method, engineering consideration and hydrostatic test of the cylindrical steel tanks were presented in subsequent sections. Hydrostatic test was conducted to verify the foundation adequacy of the steel tanks constructed on piled raft foundation and to minimize the post construction settlement of the tank to an acceptable limit. Hydrostatic test was carried out by gradually fill up the tank with water until full load, retain for few days and gradually empty the tank. The hydrostatic test data was used to assess the magnitude of displacement (settlement and heave) of the tanks. Forward analyses which predict the magnitude and pattern of settlement were also presented. The estimated and measured settlement had been compared, in which analysis by using all three methods gave good settlement prediction to the actual value. The controlling factors which contribute to various displacement profiles of the tanks, namely subsoil profile, pile termination condition and sea water tide were also discussed.**

Keywords - piled raft; soil; heave; settlement; cylindrical tank

I. INTRODUCTION

The construction of large scale steel tanks over soft ground will be made feasible with advanced geotechnical knowledge and good engineering judgment. This paper describes the performance of five tanks, by assessing the predicted settlement by using SAFE software and 2V:1H stress distribution method in comparison with the measured settlement at site. The details of 5 steel tanks, i.e. pile number, type of pile used, tanks dimension and total weight with water are as tabulated in Table 1. Meanwhile, the tanks layout is as shown in Figure 1.

TABLE 1. PROPERTIES OF TANKS

Tank	Pile Nos.	Pile Type	Height (m)	Diameter (m)	Weight with Water (kN)
Tank 1	317	400x400 RC Sq. Pile	20.12	37.4	260095
Tank 2	265	400x400 RC Sq. Pile	20.12	37.4	260095
Tank 3	265	400x400 RC Sq. Pile	20.12	37.4	260095
Tank 4	265	400x400 RC Sq. Pile	20.12	37.4	260095
Tank 5	317	400x400 RC Sq. Pile	20.12	37.4	260095

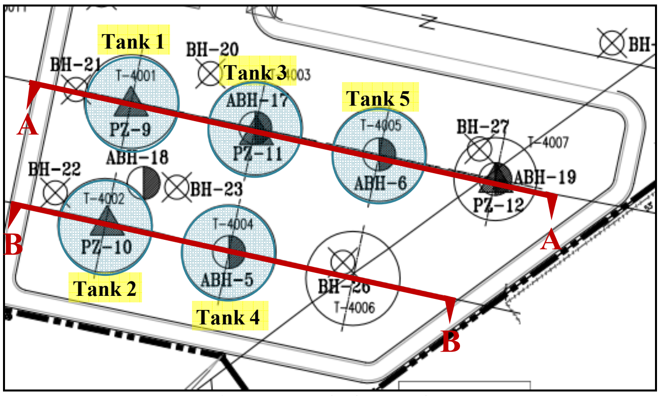

Figure 1. Tanks layout plan

II. OBJECTIVES OF STUDY

The objectives of this paper are to achieve the followings:

1) To conclude which method that predicts the magnitude of displacement closer to the actual value.
2) To study the factors which influence the tanks displacement (settlement and heave) pattern.

III. METHODOLOGY

1) Interpretation of subsurface investigation results
2) Data collection of settlement / heave monitoring results
3) Interpretation of the monitoring results
4) Carry out analyses to predict magnitude of settlement and compare with measured settlement at site
5) Carry out parametric study to check which parameters is sensitive to the results
6) Study the influence of subsoil profile on settlement pattern
7) Study the influence of pile termination condition on settlement pattern
8) Study the effect of pile length on settlement pattern
9) Study the influence of sea water tide on heave / settlement pattern

IV. LITERATURE REVIEW

A. Tank Settlement Profiles

Tanks are relatively flexible structures and can tolerate a large amount of settlement without showing signs of distress.

There are numerous examples of tank failures that have resulted in inoperative floating roofs, shell and roof buckling damage, leaks, and the worst, a complete loss of tank contents. For example, differential settlement has led to

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rupture of a large tank [1]. A study done on large diameter of tanks had undergone average settlement up to 1.8m, with average tilt of up to 1/152, and uniform settlement of up to 0.5m. However, no evidence of structural distress to any of these tanks was observed [2].

Steel tanks are prone to different modes of shell and bottom plate settlements. The basic settlement patterns are uniform settlement, planar tilt and non-planar settlement.

Uniform settlement of tank shell may damage nozzle and piping connections due to differential settlement between the tank shell and external pipe supports, thus may hinder operations. This problem can be avoided by using flexible connections or periodically repositioning the pipe supports. Uniform settlement of bottom plate creates no threat to structural integrity of a tank. However, excessive settlement may consequence to operational problem when one empties the tank.

Planar tilt of tank shell may cause an increase in liquid, which alters the shape of the fluid surface and places additional stress to the shell. It could also affect tank nozzles that have piping attached to them. However, it created no detrimental consequence to the structural integrity of the bottom plate.

Non-planar settlement may radially distort or overstress the tank shell. Tank shell radial distortion may cause malfunction to floating roof. Overstress is however, may cause rupture and spillage of the tank's contents. As for bottom plate, two deformation modes exist; dish-shaped and localized dispersion.

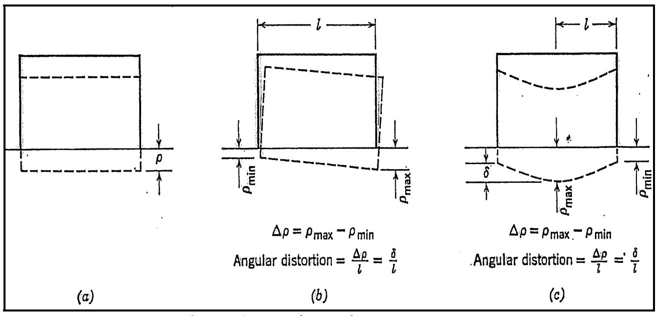


Figure 2. Basic settlement patterns
(a) Uniform settlement (b) Tilt settlement (c) Non-uniform settlement

B. Responses of Piled Raft over Soft Clay

Piled raft foundation has been proven to provide an economical foundation design. The piled raft design assumed the load is shared between the piles and raft, unlike the traditional design, whereas the load is taken either by piles or raft. Therefore, the piled raft foundation offers reduction in settlements and differential settlements in an economic way, as compared to traditional foundation system.

Design concept and instrumentation results of floating piled raft, supporting 2500 Ton oil storage tank overlain on very soft alluvium deposit was presented [3]. Static load tests carried out on spun piles of varying lengths of 24m, 30m and 36m demonstrated that floating pile system is a cost effective design to support heavy structures on very soft compressible deposits with satisfactory performance. The raft settlement recorded by horizontal inclinometer was gradually increased with the increased of water load and reduced during water unloading. The maximum raft settlement at maximum storage load was much lesser than the prediction, so as the raft distortion (maximum distortion 1/762).

Field observations of a four storey reinforced concrete building supported on a raft foundation with friction piles on soil composed of diluvial overconsolidated clay and sand was reported [4]. At the time of building completion, the maximum measured settlement was around 1 cm and the maximum raft distortion caused by differential settlement was about 1/1760 radian. The axial forces on the piles showed continuous growth up to the completion of the building. A year later, the axial forces had converged to almost fixed values. Based on the study, it was concluded that friction piles proved to be effective in reducing the differential settlement of the raft foundation and the effect is permanent. To confirm the validity of the design, the settlement, axial forces on selected three piles and earth pressure on the underside of the raft were measured about three years after the building completion, but no record was found in the literature.

V. SUBSURFACE INVESTIGATION

Based on the boreholes' profiles, the subsoil strata are generally made of three distinct strata, namely Recent Fill, Alluvium and weathered Residual Soils (possible weathered derivatives from granitic formation or sedimentary formation). These strata are distinguished by every borehole at two different cross sections as shown in Figure 1.

The fill is primarily made of yellowish to brownish residual cut materials from the adjacent areas and can vary from 5m to as deep as 7m. Beneath the fill, there is a layer of dark grey to dark green soft marine clay of 5m to 20m thick. The underlying bedrock is granite.

Geotechnical model with some engineering parameters is established from the interpreted geological model. Fig. 3 shows the brief description of the geotechnical model and relevant interpreted engineering parameters.

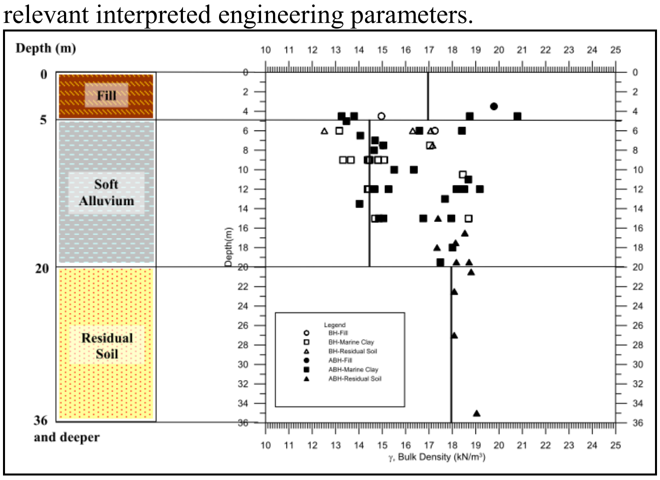


Figure 3. Geotechnical Model

VI. HYDROSTATIC TEST

i. Hydrostatic Test

Hydrostatic test is conducted in order to verify the foundation adequacy of the steel tanks constructed on piled raft foundation and to minimize the post construction settlement of the tank to an acceptable limit. Hydrostatic test is where the tanks gradually being filled up with water until full load, retain for few days, and gradually being emptied. The data was recorded twice a day (morning and evening) at various water heights.

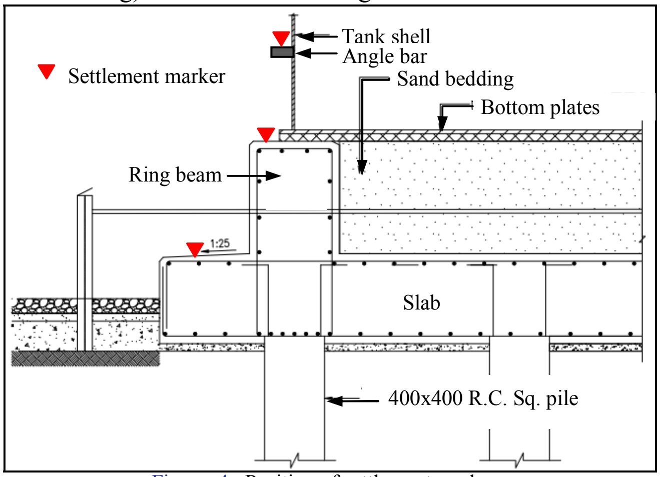
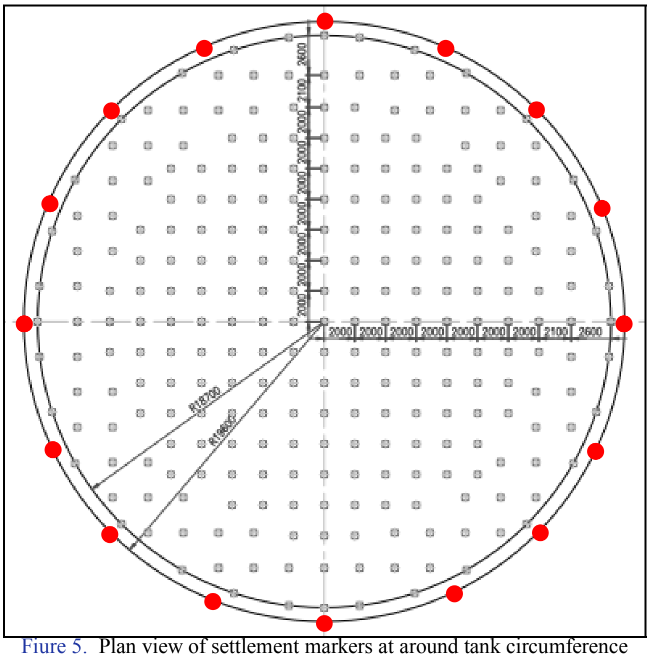


Figure. 4. Position of settlement markers



Fiure 5. Plan view of settlement markers at around tank circumference

16 nos. of precise settlement markers are installed on top of angle bar, which is located at 500mm above bottom of tank steel plate and on the slab or beam to monitor the magnitude of settlement. Angle bar is a steel plate which is attached to the tank circumference. The settlements are recorded by taking elevation measurements at around the tank circumferences and across the tank diameter at a planned frequency as per Standard [5].

Figure 4 shows the position of settlement markers while Figure 5 shows the plan view of settlement markers equally spaced at around the tank circumference.

ii. Monitoring Results of Hydrostatic Test

For discussion purposes, Tank 2 and Tank 4 are selected.

The following measured data are plotted in the same graph:

- Settlement and heave (m) x 0.01 vs. monitoring duration (day)
- Height of water storage (m) vs. monitoring duration (day)
- Water tide (m) x 0.1 vs. monitoring duration (day)

Sixteen sets of displacement were recorded to monitor the performance of the tanks. However, only four sets of reading, located at north, east, south and west side of the tank were presented as the trend of displacement is almost similar from one point of measurement to the other.

- *Reponses during Hydrostatic Test (Tank 2)*

The tank was gradually being filled up with water to maximum tank storage of 20.12m high and was retained for 7 days before gradually being emptied.

The magnitude of settlement increased with increasing water level and decreased with decreasing water level. The maximum settlement recorded was 39mm at maximum water level of 20.12m high. The maximum heave recorded was 12mm during the water level of 12.851m high.

The magnitude of settlement returned to almost its original value after the tank was completely being emptied. Monitoring results are as shown in Figure 6a.

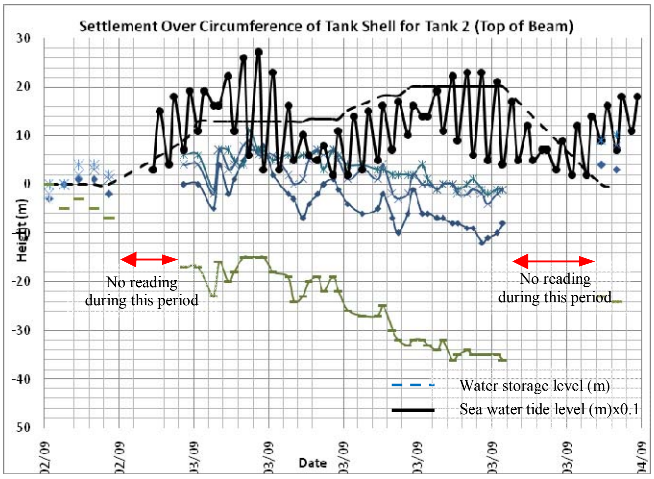


Figure 6a. Monitoring Results for Tank 2

- *Reponses during Hydrostatic Test (Tank 4)*

The water was gradually being filled up to maximum tank storage of 20.12m high and was retained at this maximum level for about 25 days.

It can be clearly seen that the settlement increased with the increase in water level. When the water was remained stagnant at maximum level, the settlement was also steady at about the similar magnitude throughout that level.

The tank was then gradually being emptied until the water level is 0.4m high from tank bottom. The settlement was also reduced with decrement in water load.

The maximum magnitude of settlement recorded was 27mm during maximum water level, and 6mm of heave was recorded at 2.7m and 0.4m water high during water loading and unloading respectively. Monitoring results are as shown in Figure 6b.

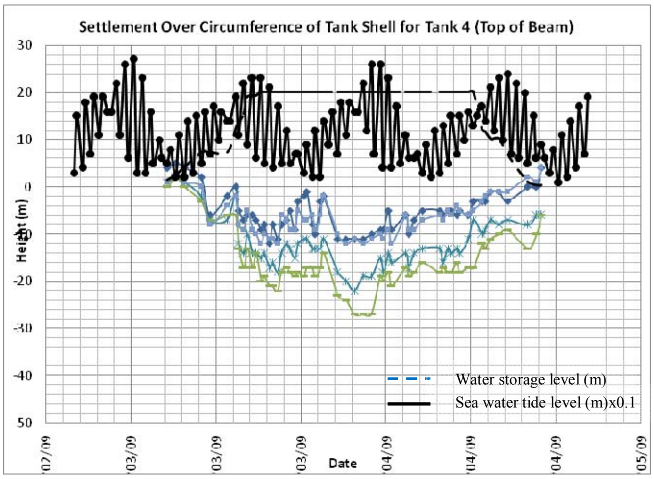


Figure 6b. Monitoring Results for Tank 4

VII. ANALYSES FOR PREDICTING THE MAGNITUDE OF DISPLACEMENT

A. *Simplified linear analysis with interaction factors*

This simple calculation in predicting the magnitude of settlement is compiled based on papers presented by Randolph & Wroth (1978), Fleming et al. and Richart et al. (1970). The method has taken into account the response of pile groups and raft alone.

Behaviour of pile groups has a significant influence on the piled raft. The stiffness of pile groups under axial loading can be evaluated from the stiffness of single pile and appropriate interaction factors.

a) *Single Pile Response*

Randolph & Wroth (1978) presented an approximate solution based on separate treatment on the pile shaft by using the linear load transfer function and pile base, using Boussinesq solution for a rigid punch acting on an elastic half-space.

b) *Pile Group Response*

Further to the solution of single pile, the group response can be calculated based on the principle of elastic interaction between piles. The method to estimate pile group stiffness is 'efficiency' approach as presented by Fleming et al. (1992).

The stiffness of rigid, circular raft acting alone has been estimated by method introduced by Richart et al. (1970). Subsequently, Randolph has proposed a simple piled raft analysis which taking into account the overall stiffness of a piled raft, k_{pr}. The overall settlement can be calculated by dividing the vertical load with piled raft stiffness, Q_g / k_{pr}.

B. *Pile-soil-raft interaction analysis (iterative analysis)*

The analysis for piled raft system (pile-soil-raft interaction) was carried out by using structural analysis software, SAFE, with the aid of excel files to analyse both structural stresses and the deflection performance of the combined pile group and raft structure.

Four loading conditions were considered in the analysis, which are Dead Load, Live Load, Wind Load and Seismic Load.

Iterative analyses of pile-soil-raft interaction were performed on the tank foundation for the following stages of tank condition:

1) Stage 1 (Hydrostatic Test) performed on the foundation of completed tank, which is undergoing hydrostatic test. In this stage, both dead load and live load (water) are applied.
2) Stage 2 (Post Construction), performed on the foundation of storage tank, which is storing the designated fluid to its maximum capacity during its service life. In this stage, platform consolidation settlement is expected to take place as a result of long term dissipation of excess pore pressure induced by the platform fill. Thus, downdrag force was also applied to every pile of the tank to assess the worst possible pile settlement performance.

Higher piles reaction and magnitude of settlement out of these two stages are checked against design criteria adopted to ensure the pile capacity are not exceeded and magnitude of settlement is within allowable limits.

Structural re-assessment for the foundation shall be carried out based on the as-built condition of installed piles (as-built pile position, actual number of pile, penetration length of working piles, additional compensation piles and piles termination condition (pile set to hard, competent soil layer or floating pile).

The analysis can also be carried out using Finite Element Method (FEM) software (e.g. PLAXIS 3-D Foundation) which can model 3-dimentional pile-soil-raft interaction. However, the FEM software will have great limitation on the number of piles that can be modeled practically.

C. *Method 3: Settlement Analysis Using Equivalent Footing Method (Menard Empirical Method)*

Another most common approach for predicting settlement using pressuremeter data is the Menard semi-empirical procedure, in which the pressuremeter is utilised to determine an equivalent Young's modulus. A theoretically correct approach to determine the effective Young's modulus would include utilising sophisticated numerical methods that vary stiffness depending upon the computed stress and strain level, and involve special tests at the stress/strain level anticipated in each soil strata below the bearing level.

At the time, such tests were not available outside the research environment. However, the semi-empirical settlement equation proposed by Menard showed to be an excellent design tool since it was based on correlation with actual load tests. The Menard settlement equation is defined as follows:

VIII. RESULTS AND DISCUSSIONS

Based on the analyses by using Method 2, the estimated maximum raft settlement is always found to be at the centre of the tank. Unfortunately, there is no horizontal inclinometer was installed underneath the tank. Thus, the settlement across the tank cannot be measured to compare with the estimated value. The settlement contour for Tank 2 and Tank 4 is presented in Figure 7a and 7b.

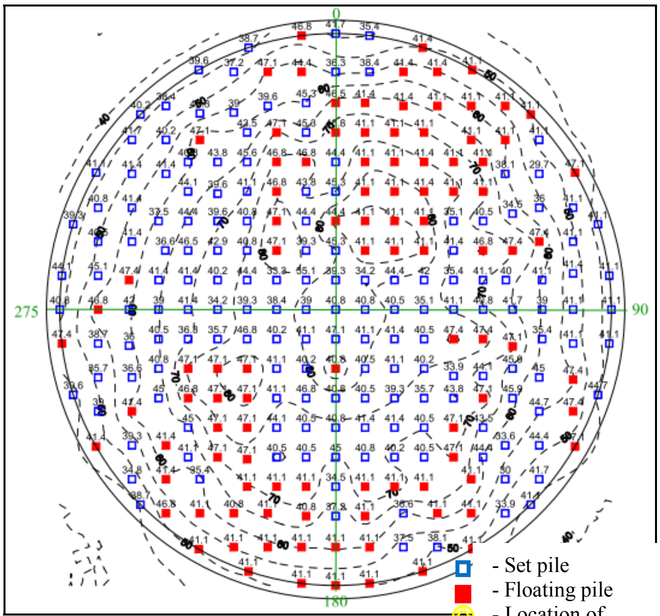


Figure 7a. Predicted settlement Contour for Tank 2

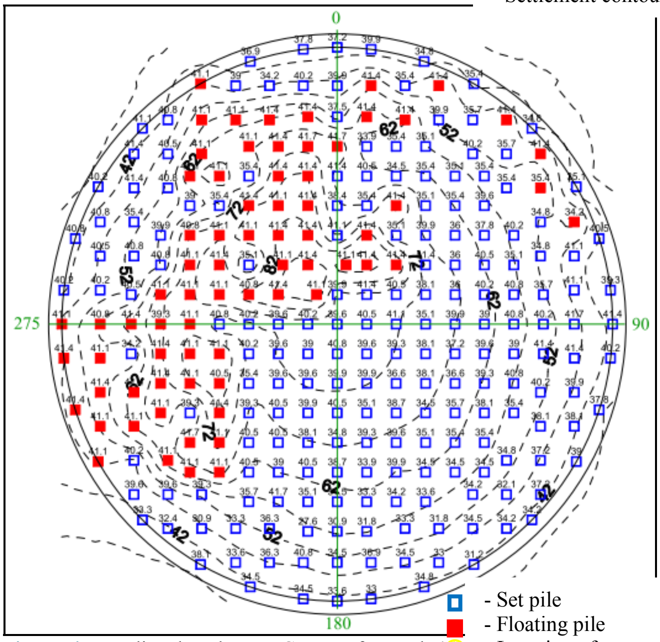


Figure 7b. Predicted settlement Contour for Tank 4

The results of numerical analyses by adopting Method 1, Method 2 and Method 3, in comparison to the measured settlement at site are presented in Table 2.

TABLE 2. PREDICTED AND MEASURED SETTLEMENT OF TANKS

Tank	Settlement (mm)			
	Method 1 (predicted)	Method 2 (predicted)	Method 3 (predicted)	Measured
Tank 1	23.5	35.8	19.9	35.0
Tank 2	**20.7**	**41.3**	**21.1**	**39.0**
Tank 3	24.9	34.4	19.6	17.0
Tank 4	**20.5**	**38.5**	**20.5**	**27.0**
Tank 5	25.8	36.5	20.1	20.0

Detailed analyses have been performed in Method 1 and 2, considering single pile and group pile response, as well as raft and piled raft stiffness. Meanwhile Method 3 mainly taking into consideration modulus information developed from Pressuremeter Test. Based on the analyses results, it can be concluded that all Methods predicted well to the actual settlement. However, careful selection of soil and structural properties is crucial, as well as rigorous analyses which taking into account all possible soil-structure reactions and properties of each structural element (especially for Method 1 and Method 2) is essential so as more reliable result with better prediction can be obtained.

Parametric Study

Proper selection of soil and structural parameters, as well as sensible assumptions in the analyses is vital. Small changes made on a certain parameters may lead to significant effect on the predicted magnitude of settlement. As such, parametric study has been carried out to identify which parameters that affected the results significantly.

i. Method 1 & Method 2
   - Soil properties, especially Shear Modulus
ii. Method 3
   - Young's modulus

Therefore, proper selection of soil properties shall be carefully assessed to avoid over-estimate or under-estimate of results.

Contributing Factors for Various Displacement Profiles

In view of the settlement pattern varies from one tank to the other, it is worth to discuss the controlling factors which contributed to the various displacement patterns. Three factors are identified, and discussed herein:

- *Influence of Subsoil Profile on Settlement Pattern*

The subsoil profiles play important role on the settlement responses of the tanks. From the borehole logs, the interpreted thickness of fill material, soft alluvium and intermediate residual soil for Tank 2 is about 6.5m, 14m and 17m respectively. Hard layer is encountered at about 37.5m below ground level.

As for Tank 4, the interpreted thickness of fill material, soft alluvium and intermediate residual soil is 3m, 16m and 24.5m respectively. Hard layer is encountered at about 43.5m below ground level.

Tank 2 seated on thicker fill material. As the piles were installed through compressible soil layers, part of the pile shaft experiences negative skin friction, which occurs when the downward movement of the surrounding soil exceeds the settlement of the pile. It explains why Tank 2 settled more than Tank 4.

Based on the interpreted soil profiles at Tank 2, there is an existence of about 25m thick of soft marine clay (with traces of silt, sand and gravel at certain depths). Meanwhile, the subsoil profile for Tank 4 consist of soft marine clay of about 17mm thick.

Clay is well known of having low permeability with low consolidation value. Such thick clay does not undergo fast consolidation process and required ample time to fully consolidate. Thus, the soil was rebounded to almost its original position after being unloaded. The soil is however, will slowly settle with time.

- *Influence of Pile Termination Condition on Settlement Pattern*

Termination condition is whether the piles were driven until set to hard stratum or leave as floating piles. There is significant difference in magnitude of settlement for set and floating pile. Floating pile demonstrated more settlement as compared to set pile, which can be clearly seen on Tank 2. The trend is however, not obvious on Tank 4. The pile termination condition for both tanks is as marked in Figure 8a and 8b.

Localized significant settlement can be observed at certain area. Such settlement becomes more prominent when the water load increases. This could be due to inherent localised weak support from either the piles or the soil surface in contact with the raft.

The settlement for floating pile is bigger than set pile area. Nevertheless, the magnitude for floating pile is still within acceptable limit. Therefore, pile may be designed as floating pile, rather than set pile as it is more cost saving. However, thorough study is required and stringent design criteria shall be adopted for safer design.

- *Influence of Sea Water Tide on Heave / Settlement Pattern*

Since the site is located adjacent to the sea, it is worth to study the influence of water tide to the behavior of tank settlement / heave. Tide level was taken at Tanjung Pelepas, which is beside the project site.

It can be seen that even though the water storage level is constant at maximum level, there are fluctuations in the magnitude of settlement, which may be due to the effect of rising and lowering of sea water tide. This effect is apparently can be seen in Tank 4.

As such, sensitivity analysis has been carried out to check the relation between sea water tide level and settlement. Sensitivity analysis is the study of how the variation in the output of a model can be apportioned, qualitatively or quantitatively, to different sources of variation.

Correlation indicates the strength and direction of a linear relationship between two random variables. The best known is the Pearson product-moment correlation coefficient, which is obtained by dividing the covariance of the two variables by the product of their standard deviations. The correlation coefficient pX,Y between two random variables X and Y is defined as the Pearson correlation coefficient, (Reuter & Liebscher, 2008).

The values of the correlation coefficients are located in the interval [-1, 1], where values close to 0 indicate a weak (linear) relationship and values close to -1 (negative relationship) or 1 (positive relationship) a strong (linear) relationship between the Investigated random variables X and Y. It is generally considered that the correlation between two variables is strong when $0.8 \leq r \leq 1$, weak when $0 \leq r \leq 0.5$, moderate otherwise (Montgomery, Runger, & Hubele, 2007).

Positive relationship means that, in general, higher values of one variable tend to be paired with higher values on the other and that lower values on one variable tend to be paired with lower values on the other.

For study purposes, sensitivity analysis on correlation between sea water tide level and magnitude of settlement at settlement marker located at 0^o, 90^o, 180^o and 270^o around the tank circumference on Tank 4. The correlation coefficient, r obtained is -0.230, -0.200, -0.212 and -0.181 respectively for each location of settlement marker mentioned above. The correlation coefficient shows that the relation between water tide level and magnitude of settlement is weak. For illustration, the graph of correlation at 0^o is as shown in Fig. 8.

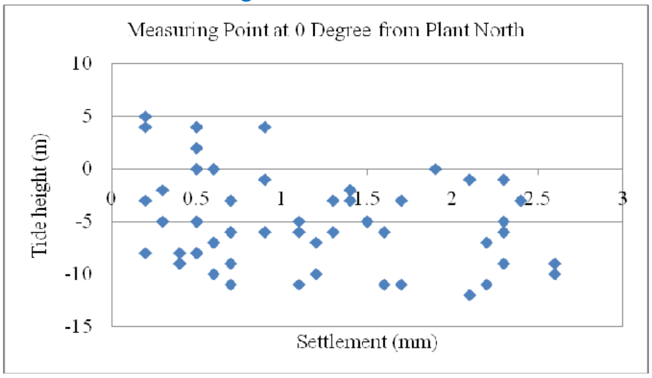


Fig. 7.8: Correlation of sea water tide level and settlement at 0 degree from plant north, r = -0.230

IX. SUMMARY AND CONCLUDING REMARKS

1. Analysis for piled raft by using Method 1, Method 2 and Method 3 give good settlement prediction.
2. Rigorous analyses, taking into account all possible soil-structure reactions and properties of each structural element are essential so as more reliable result with better prediction can be obtained.
3. Proper selection of soil properties shall be carefully assessed to avoid over-estimate or under-estimate of results.
4. The phenomena whereby the magnitude of displacement increased with increasing water level and decreased with decreasing water level proved that the soil underneath the tank has yet to consolidate, but behaves as elastic material which react directly with the load from water. Existence of thick marine clay which has low consolidation properties is one of possible reasons for slow consolidation process.
5. Existence of different thickness of fill material (compressible soil) has induced downdrag force, in which part of the pile shaft experiences negative skin

friction that occurs when the downward movement of the surrounding soil exceeds the settlement of the pile. This explains why the magnitude of settlement is different from one tank to another.

6. Piles which terminated set to hard competent soil stratum demonstrated lesser settlement, as compared to floating piles area.
7. The rising and lowering of sea water tide does not give influence on the heaving of the tank.

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