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

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This paper presents the design concept using floating piles to support 2500Ton oil storage tanks on a very soft alluvial clayey soil of about 40m thick in Riau Province of Sumatra, Indonesia. The floating piles of various penetration lengths were designed to support seven numbers of such storage tanks seating on a 20m diameter and 500mm thick reinforced concrete (RC) circular raft. The pile points have been strategically located at the RC raft. Varying pile penetration lengths have been designed to minimize the angular distortion of the thin RC raft and the out-of-plane deflection at the tank edge. Vibrating wire strain gauges were installed at different levels inside the ϕ350mm prestressed reinforced concrete piles to measure the load transfer profile during the static load tests and water-loading test. The installation and interpretation of the instrumentation are described and discussed. Boreholes, in-situ tests like piezocones, vane shear tests and standard penetration tests, and laboratory testing were carried out to obtain geotechnical parameters for the pile designs. Static load tests were also carried out on the spun piles of varying lengths of 24m, 30m and 36m respectively. It has been demonstrated that the floating pile system can be a cost effective design to support heavy structures on very soft compressible deposits with satisfactory performance. Finally, the design concept validated with the results of instrumentation is discussed.

INTRODUCTION

A palm oil mill has been constructed over the sand filled platform with an area of about 83,000m^2 on soft swampy ground. Figure 1 shows the location of the proposed site, which is about 50km away from Sg. Guntung of Province of Riau, Sumatra, Indonesia.

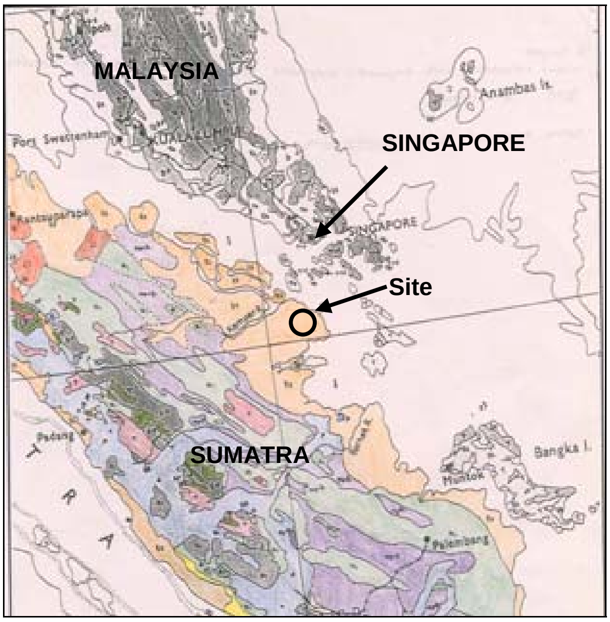

Figure 1 Location of the Site

At the proposed site, there are seven numbers of heavy steel tank structures for the storage of processing water and processed palm oil. The total weight of the tank structure is about 3500Ton including maximum storage capacity of 3000Ton for water. The steel tanks are seated on 0.5m sand bed coated with bitumen strips in order to have uniform seating between the coned-down tank base and the reinforced concrete raft of 500mm thick. A total number of 137 of 350mm diameter hollow circular prestressed concrete (PC) spun piles with concrete strength of 60MPa have been designed and installed to support the tank through the RC raft. The pile lengths are varied to control the deflection profile of the raft.

In order to monitor and validate the actual performance of the piled raft during water-loading test, strain gauges and horizontal inclinometer and settlement markers have been installed in the piles and also the raft. Seven working piles were instrumented with strain gauge at the pile top. Among the seven instrumented piles, three piles were installed with strain gauges at various depths in the pile shaft and had been calibrated with the static load tests prior to the water-loading test.

This paper presents the available subsurface information for initial prediction of the piled raft performance and also the back-analyses of subsoil stiffness based on the instrumention results.

SITE CONDITIONS

Subsurface Investigation (SI)

There were three boreholes carried out in the preliminary SI planned by the initial designer. During the detailed design, additional SI comprised of four boreholes, eight piezocones and vane shear tests inside the boreholes were carried out before platform filling to obtain necessary subsurface information. Figure 2 shows the layout of the additional SI. The relevant borehole and piezocone at the instrumented tank are BH-1and PZ-1 respectively.

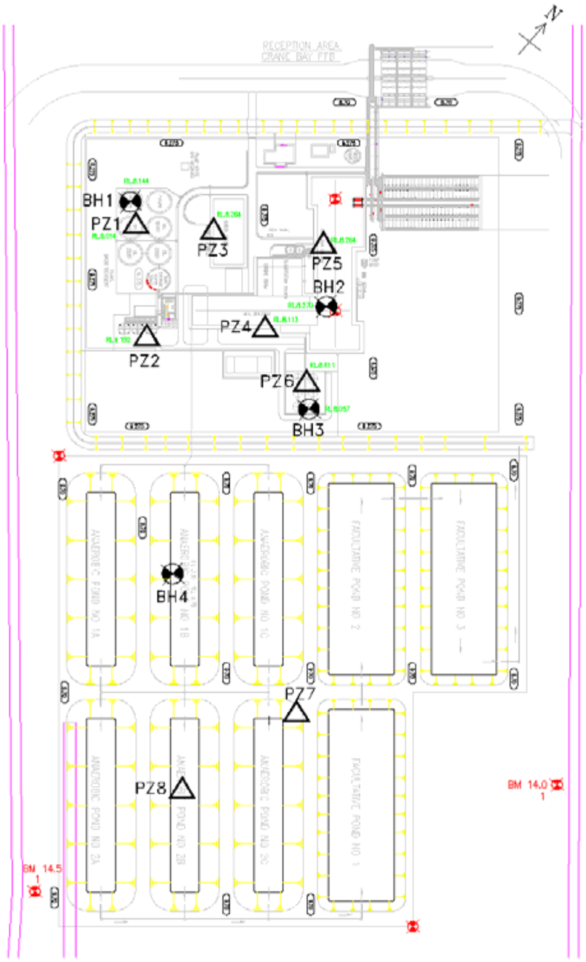

Figure 2 Layout of Subsurface Investigation

Geological Conditions and Subsurface Profile

The site is underlain by recent alluvium and coral reefs of Quaternary age.

The original and the surrounding ground conditions of the site are generally flat with reduced level of RL+8.3m. The water level is almost at the original ground surface.

Figures 3 and 4 show the logging description of borehole BH-1 and the penetration records of piezocone PZ-1 respectively. From the interpretation of the SI information, a geotechnical model as shown in Figure 5 has been established for the analyses. Generally, the top one metre of the subsoil is organic materials of peat and decayed tree roots at the surface. No obvious dessicated weathered crust has been observed. The top 5m subsoil has over-consolidated ratio (OCR) of 1.6 at the top and gradually reduces to 1.0. Underneath the organic materials, the subsoil mainly consists of very soft normally consolidated clayey deposit of 34m thick followed by 12m thick medium stiff clay overlying the white medium dense fine sand and dense clayey sand. Most of the undisturbed samples collected are almost fully saturated indicating high groundwater table.

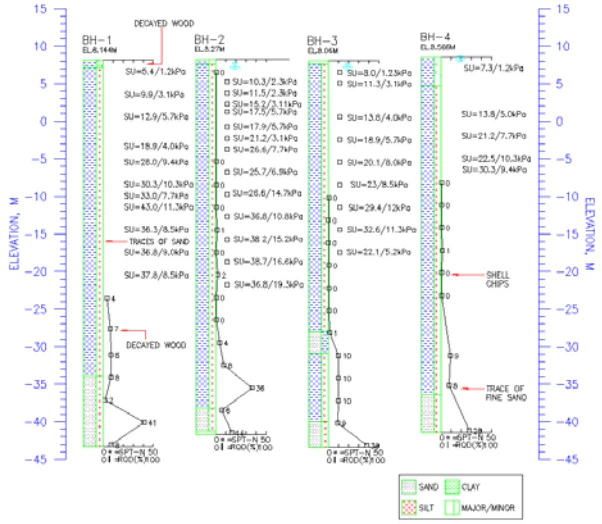

Figure 3 Profile of Borehole Logging

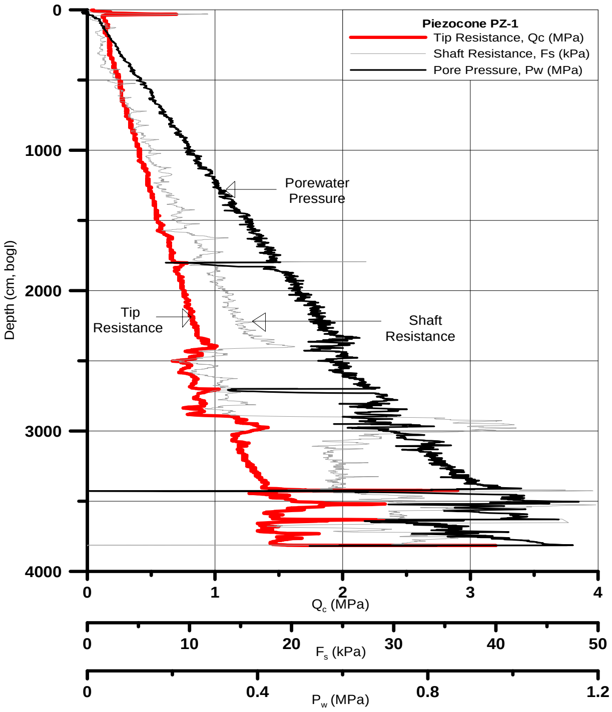

Figure 4 Penetration Profile of Piezocone, PZ-1

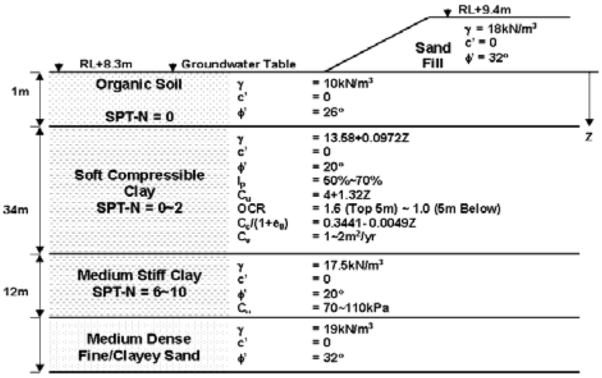

Figure 5 Geotechnical Model for Analyses

TANK STRUCTURE

Piled Raft Foundation

The tank structure is a 12.2m high steel tank with external diameter of 17.5m and shell plate thickness of 8mm. All the tanks with coned-down base slope of 1/39 are seated on the 0.5m thick sand bed contained on the 0.5m thick reinforced concrete (RC) raft. There are a total of 137 numbers of 350mm diameter hollow circular prestressed concrete spun piles spaced at 1.5m square grids. Piles with lengths of 24m (68 piles), 30m (48 piles) and 36m (21 piles) respectively have been strategically located with the pattern of longer piles at the center rim and shorter piles at the outer rim of the raft to control the raft distortion under the imposed loading. These piles are designed as floating piles as the end-bearing stratum is expected at the depth of at least 70m. The overall safety factor of the group piles against ultimate bearing capacity failure is about 2.0. The pile spacing of 1.5m is also decided partly based on the number of pile points to achieve such safety factor. The global safety factor of 2.0 on ultimate bearing capacity failure is adopted because some localized piles at the outer rim are expected to be over-stressed in order to have even deflection profile of the raft in the floating piled raft design. Figure 6 shows the details of the piled raft for the instrumented tank structures. Randolph (1994) has presented a similar foundation scheme for the 256m high Messe Turm Tower with 64 floating piles of varying lengths from 26.9m to 34.9m in Germany.

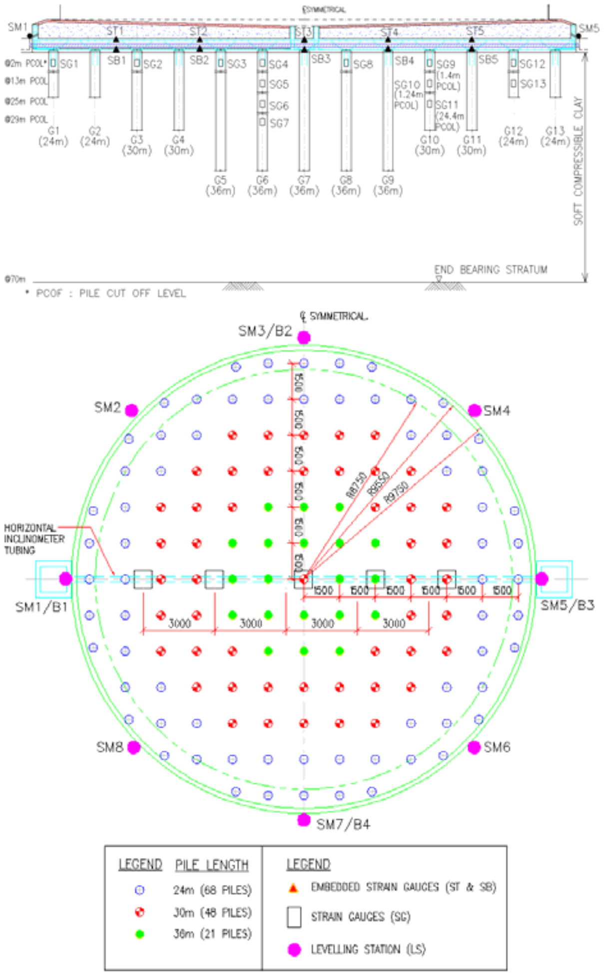

Figure 6 Layout of Instruments

Instrumentation of Piles and Raft

In the pile installation, three working piles, namely G6, G10 and G12, have been selected for instrumentation to reveal the load transfer behaviour of a single pile during load testing and also to assess the group pile behaviour during water-loading test. Thirteen strain gauges (SG1-SG13) have been installed in the annulus of the seven working piles, including the three aforementioned working piles with multi-level strain gauges, to monitor the axial compression load in the pile shaft. The strain gauge at the top level, which is free from the interaction of soil resistance, of all instrumented test piles is used to calibrate with the load cell during static load test. The calibration is used for interpreting the axial load at other strain gauges at lower levels in the same test piles.

To verify the stresses and the deflection profile in the raft, five pairs of embedded strain gauges (ST1-ST5 at top reinforcements and SB1-SB5 at bottom reinforcements) have been installed at various locations of the top and bottom reinforcements to measure both the sagging and hogging flexural stresses and a horizontal inclinometer has been installed at the mid depth of the raft through the raft centre. Eight settlement markers (SM1-8) have also been installed at the perimeter of the RC raft and four settlement markers (B1-B4) on the steel tank.

For all instruments, initial readings were taken immediately after installation and subsequent changes of readings at various stages of construction were also recorded.

ANALYSIS OF PILED RAFT

Loading Conditions

The uniformly distributed load on the tank base including the fluid storage and the tank base is about 113kPa for full palm oil storage and 130kPa for full water storage. However, the water storage tank will only be loaded not exceeding 2500Ton during operation. The line load of the tank shell with roof is about 15kN/m. The compacted sand bed and the RC raft impose a pressure of about 10kPa and 12.5kPa on the raft respectively.

Design Criteria

The main design criteria of a steel tank with sloping base are limited with distortions as follows:

a. Dishing Settlement of Tank Base : 1/75
b. Over-stressing Criteria of Tank Base with Initial Coned-Down Gradient of 1/39 : 1/152
c. Structural Distortion of RC Raft : 1/150

The critical criterion for distortion control on raft deflection is the over-stressing criteria, which is 1/152.

Soil-Structure Interaction Analyses

In order to assess the pile group soil-structure interaction effect of the closely spaced circular piles supporting the RC raft, a linear elastic computer program named "PIGLET" has been used to predict the piled group performance, which produces the pile support stiffness at individual pile. Randolph (1987) has given an elaborative description about PIGLET 1.0 (for pile group less than 100 piles) and PIGLET 3.0 (for pile group up to 300 piles). As PIGLET only allows one length configuration in each analysis, three separate pile group analyses with respective pile lengths of 24m, 30m and 36m were carried out to derive the pile stiffness response during the design stage. This is an approximation to the actual behaviour of pile group with various lengths due to limitation of the program.

The subsequent assessment requires an integration of the computed pile group response to the structural raft. Computer program named "SAFE Plus" was used to assess the raft deflection, structural stresses and the induced reaction at various pile supports based on the pile reaction stiffness obtained from pile group analysis. SAFE Plus is a structural program modeling structural slab element with linear elastic spring point supports and surface support using subgrade modulus. The ultimate bearing capacity of the piles for respective pile lengths are estimated as the limiting reaction threshold for the computed pile reaction in the SAFE Plus analyses. Manual adjustment on the pile reactions is required as the SAFE Plus program that models the piles as linear elastic spring does not limit the pile reaction force. Manually reducing the support stiffness at the overloaded piles in the SAFE Plus program for each stage of iterative analysis is needed in order to keep the reaction not exceeding the respective limiting values. Figure 7 shows the summary of load test results of the six test piles with various pile lengths. Table 1 tabulates the predicted and actual ultimate pile capacities of the piles with various pile lengths. The individual pile stiffness (about 100,000kN/m) of these six test piles with varying lengths appears to be very similar to each other and is linear until reaching the ultimate load. It is observed that the actual ultimate pile capacities are somehow 20% to 25% lower than the best estimated capacities except the two 24m long test piles, namely G1-T1 and P1-T3, which were installed and load tested before intensive piling. This can be explained from the short-term strength reduction in the founding subsoil due to the disturbance from the extensive piling at close spacing. However, the soil strength will be improved, so as the pile capacity, after dissipation of the excess pore pressure generated from the extensive piling. Based on the short-term behaviour of these test pile, the overall safety factor of the pile group against ultimate failure is reduced from 2.0 to about 1.5 due to the piling disturbance.

Table 1 Summary of Predicted and Actual Ultimate Capacity of Piles

Pile Penetration	Predicted Ultimate Capacity *	Ultimate Capacity in Load Tests
24m	330kN	250kN (Pile G12-T1) 315kN (Pile G1-T1) 440kN (Pile P1-T3)
30m	550kN	440kN (Pile G10-T1)
36m	835kN	625kN (Piles H5-T3 and G6-T1)

*Note: Based on α-method with undrained strength

Manual iterative process between the pile stiffness obtained from PIGLET and the distribution of imposed load on individual piles from the SAFE Plus analyses is required to arrive at a converged reaction force at individual pile supports and also the deflection profile, in which as equilibrium state within the piled raft system is achieved. When this is achieved, the analysed stresses in the raft and the deflection profile in the final SAFE Plus analysis are extracted for reinforcement detailing of the raft.

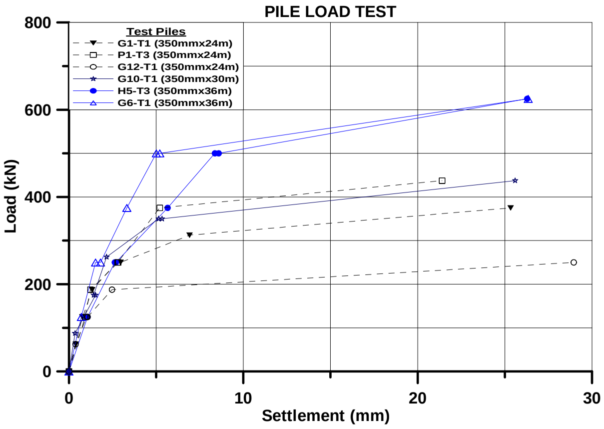

Figure 7 Load-Settlement Curves of Test Piles

For these initial analyses, the input parameters are tabulated in Table 2.

Table 2 Summary of Input Parameters for Prediction

PIGLET	
Pile Diameter, D	0.35m (OD) 0.20m (ID)
Pile Grid Spacing, S	1.5m
Pile Penetration Length, L	24m 30m 36m
Shear Modulus at Ground, G_0	1250kPa
Rate of G Increment	72.9kPa/m (24m) 91.6kPa/m (30m) 104kPa/m (36m)
Shear Modulus at Pile Base, G_b	3000kPa (24m) 4000kPa (30m) 5000kPa (36m)
Poisson Ratio, ν	0.5 (Undrained)
Type of Pile Connection	Rigid
SAFE Plus	
Raft Thickness, t	0.5m
Modulus of Concrete, $E_{concrete}$	26,000,000kPa
Rotational Stiffness of Pile Connection	3194kN-m/rad (24m) 2555kN-m/rad (30m) 2129kN-m/rad (36m)
Poisson Ratio, $\nu_{concrete}$	0.2

These assessments do not include the time dependent consolidation settlement in long-term, but this is likely to be insignificant, particularly the differential settlement, as the rigidity of the entire piled raft with the subsoil reinforced by group piles is fairly high. In the case of water-loading test, the nature of loading is also relatively short for consolidation. Therefore, the scope of this paper only addresses on the short-term behaviour of the piled raft. For simplicity, the interaction from the subsoil to the raft is also not considered as the underlying subsoil to the raft is fairly weak and compressible, particularly with the expected relatively small overall raft settlement due to pile supports.

COMPARISON BETWEEN PREDICTED AND ACTUAL BEHAVIOURS OF PILED RAFT

Water-Loading Test Result

In order to validate the foundation design and also to ensure no leakage of the tank, water-loading test has been carried out at the completed tank with instrumentation with maximum water load up to 3000Ton. But all tank storage will be limited to 2500Ton during operation. Figure 8 shows the raft deflection profiles at various stages of water-loading test. The deflection profiles are the cumulative raft settlement due to water-loading load, excluding the raft and sand bed weights. It is obvious that there is some slight differential settlement at the corresponding mirrored locations of the tank base. Such differential 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.

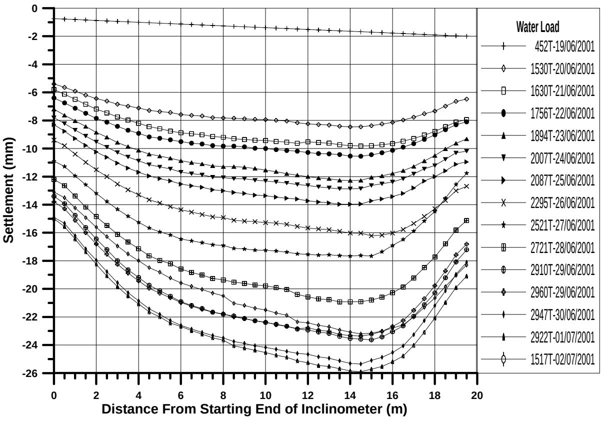

Figure 8 Raft Deflection Profiles During Water-Loading Test

Raft Deflection Profile

Figure 9 shows the predicted and actual measured raft deflection profile at the water load of about 2500Ton. The raft settles much less than the predicted settlement, so as the raft distortion (maximum distortion: 1/762).

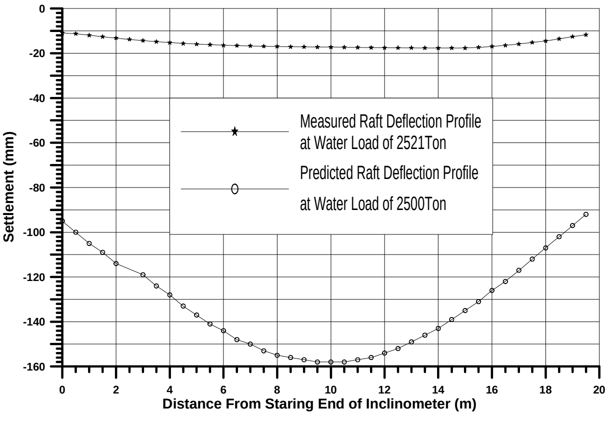

Figure 9 Predicted and Actual Raft Deflection Profile

Bending Moment

Best fitting method has been applied to back-analyse the bending moment on the raft based on the deflection profile of the horizontal inclinometer. The bending moment is assumed uniformly spread across the section of a 1m wide imaginary strip on the raft with pile supports. A six degree polynomial function is used to best fit a cluster of seven adjacent data points and the curvature of the forth data point is then computed. Figure 10 shows that the interpreted bending moments on the raft fall within 200kN-m/m-run. As expected, hogging moments are observed at or near to the pile support whereas sagging moments are observed at the mid span of the raft between the pile supports. This indicates that the surface contact stiffness between the soil and the raft is less stiff than the pile support stiffness and therefore leading to the sagging profile at the mid span and hogging profile at the pile supports. Poulos et al (1997) have shown that the bending moment of raft in various methods of pile raft analyses can vary by factor of two and lead to different requirement of structural reinforcement.

The embedded strain gauges do not yield meaningful results as most readings record insignificant strain profile in the raft for the interpretation of bending moment. Investigation is currently carried out to reveal the causes of such erratic records.

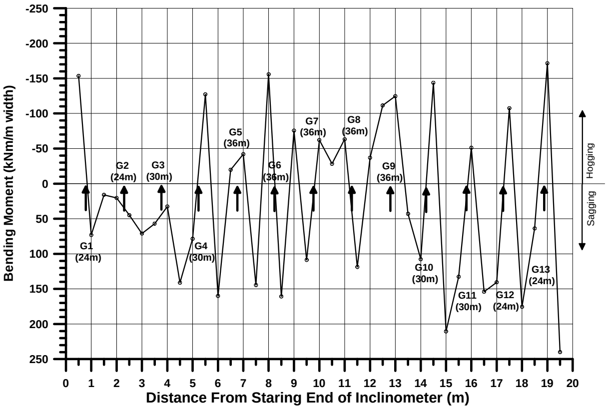

Figure 10 Interpreted Bending Moment in Raft from Horizontal Inclinometer Results

Pile Support Reactions

The interpreted pile support reaction forces at water load of 2500Ton excluding the raft and sand bed weights are tabulated in Table 3. The interpreted pile support loads are somehow less than the predicted reaction load at the perimeter piles, but are more on the internal pile cluster. This seems to indicate the internal pile cluster has more support stiffness than the perimeter piles at the external rim. The safety factors (FOS) of individual pile against ultimate failure in single pile condition as shown in Table 1 and Figure 7 range from 0.84 to 2.10. Poulos (2001) highlighted that the ultimate resistance developed by piles within a piled raft can be significant higher than that for a single pile or a pile in a conventional pile group. This is because of the increased normal stresses generated between the soil and the pile shaft by the loading on the raft and also the load transferred from the piles. The same reason for the increase of soil stiffness within the group piles is applicable.

Table 3 Summary of Interpreted Pile Support Reactions

Pile No (Length)	Strain Gauge	Predicted Reaction	Actual Reaction	FOS
G1 (24m)	SG1	330kN (Failed)	102kN	0.84
G3 (30m)	SG2	276kN	388kN	1.13
G5 (36m)	SG2	284kN	298kN	2.10
G6 (36m)	SG4	273kN	326kN	1.92
G8 (36m)	SG8	273kN	408kN	1.53
G10 (30m)	SG9	231kN	67kN*	-
G12 (24m)	SG12	245kN	150kN	1.29

*Note: Possible erratic error in measurement.

BACK-ANALYSES

Load Tests on Single Pile

Three back-calculations have been carried out for the test piles with penetration lengths of 24m, 30m and 36m respectively. PIGLET 1.0 was used to back-calculate the E_u/C_u ratio with the average strength profile ($C_u = 4+1.32Z$) based on the load-settlement performance of the test piles. Table 4 shows the interpreted stiffness profile of the subsoil. The calculated ratio of E_u/C_u is consistently about 875. This value is very different from the range of E_u/C_u between 140 and 300 in normally consolidated fine soil with plastic index of more than 50% as presented by Jamiolkowski et al (1979). Ladd et al (1977) presented the stiffness ratio (E_u/S_u) of six normally consolidated clays in relation to the shear stress ratio (τ_n/s_u), plastic index (I_p) and over-consolidation ratio (OCR). For soft clay with I_p ranging from 40% to 75%, E_u/S_u varies from 60 to 600 with the descending trend when τ_n/s_u increases from 0.2 to 0.8.

Table 4 Summary of Back-analysed Subsoil Stiffness Profile

Pile Penetration	Pile Load (Settlement)	E_u/C_u
24m	315kN (3.2mm)	≅ 875
30m	440kN (4.4mm)	≅ 875
36m	625kN (6.3mm)	≅ 875*

*Note: The pile base rests on stiff clay with average C_u of 90kPa

Water-Loading Test on Piled Raft

SAFE Plus was used to back-calculate the pile support stiffness with the raft deflection profile being matched to the actual measured deflection profile. The results of the back-calculated pile support stiffness are tabulated in Table 5.

These results indicate that the long piles are relatively stiff even with the pile group interaction. In normal cases, the pile stiffness of central piles will be smaller due to pile group interaction if all pile lengths are the same. Whereas in this case, the long piles at the internal cluster have been overly stiffen by their length. The stiffness of individual pile is about 6.7 to 9.1 times of the apparent stiffness in group piles for the respective pile lengths.

Table 5 Summary of Back-calculated Apparent Pile Support Stiffness for Group Piles

Pile No	Pile Support Stiffness
G1 & G13	11,000kN/m
G2 & G12	11,000kN/m
G3 & G11	14,000kN/m
G4 & G10	14,000kN/m
G5 & G9	15,085kN/m
G6 & G8	15,085kN/m
G7	15,085kN/m

The deflection profile of the raft with the abovementioned configuration of pile support stiffness still shows a bowl shape with more deflection at the center. This is mainly due to the “holding-up” effect by the outmost external piles, in which the tank loading does not directly impose on these external piles, but rather through the interaction of the structural raft. As a result, these external piles settle relatively less than the inner piles.

Although the earlier analyses performed during design stage were intended to do so, it is very difficult to use PIGLET to back-calculate the pile group interaction for pile group with varying lengths. As the problem is in fact a real three-dimensional soil-structure interaction problem, it is more appropriate to perform a three-dimensional finite element analyses for such problem. The earlier analyses during the design stage tend to give excessive sagging moment at the raft center, but virtually no hogging moment on the raft at the pile supports.

CONCLUSIONS

The following conclusions can be drawn in this back-calculation:

a. Piled raft design is a very complicated three-dimensional problem, particularly with varying pile length, as it involves many interaction factors among the structural raft, group piles and the founding subsoil. The high degree of interaction and the non-linearity further complicate the difficulties of the analyses. For rigorous analysis, three-dimensional finite element program should be considered to account for the non-linearity interaction behaviour.

b. The pile length has significant effect to the generated stresses on the raft and also the raft deflection profile, so as the arrangement of the pile location and spacing.

c. The piled raft design using economical floating pile system has shown success in supporting heavy tank structure over very soft clayey deposit with good compliance to the serviceability criteria.

d. The instrumentation programme has provided very good verification of the piled raft performance.

e. There are areas to further optimise the piled raft by either:
    i. shortening the pile lengths;
    ii. reducing the number of pile points;
    iii. taking the soil contact into consideration of bearing capacity and support stiffness.

f. The primary control in the optimised design is to limit the differential settlement of the raft rather than the total settlement.

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