Performance of reinforced concrete tank raft with upstand ring beam on group piles

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ABSTRACT

This paper shares the experience from grid piling foundation supporting heavy tank structures of diameters from 22.8m to 54m and heights from 20m to 22m over 5m thick untreated reclaimed platform and 15m thick underlying soft marine depositsalong coastal areas of Peninsula Malaysia. Observations and lessons learnt in the construction problems are compiled here: (a) Observable excess pore water pressure within the soft marine clay after massive large displacement piling; (b) Consolidation settlement of lower marine deposits; (c) Soil movement induced vertical and horizontal pile displacements resulting in joint dislodgement; (d) Tensile cracking of upstand ring beam on tank raft under inward torsional action by the bowl-shaped raft deformation during hydrotest; and (e) Detachment of tank roof support from bowl-shaped raft deformation upon unloadingfrom hydrotesting. Solutions and precautionary measures were developed to reduce the impacts. Theoretical structural model was developed for the ring beam inward twisting stiffness of the tank raft, the induced moment along the ring beam and explanation of the tensile crack pattern.

Keywords: Tank Raft, Ring Beam, Torsional Stiffness, Pile Heave, Soft Ground

1 INTRODUCTION

This paper shares experiences learnt from the commonly observed phenomena of large-scale grid piling in quaternary coastal marine deposits as presented by Liew et al (2010). Some mitigating measures adopted to reduce the adverse impacts were executed with reasonably satisfactory performance. In addition, structural behavior of conventional steel tank substructure is also discussed. Spreadsheet developed to compute the twisting stiffness of upstand ring beam restraining the tank raft bowl-shape deformation over grid piling foundation is attached for reference.

2 PILING PROBLEMS IN SOFT DEPOSITS

The observed piling foundation construction problems are summarized in the following sub-sections.

2.1 High Excess Pore Pressure and Consolidation Compression induced by Large Displacement Piling

Rapid insertion of a large displacement pile into the low permeability subsoils with the radial volumetric soil displacement around the base of a penetrating pile is equivalent to wedging the soils inducing significant compressive stresses. In accordance to the theory of cavity expansion, positive excess pore water pressure will normally be generated in the soil shearing process in normally consolidated soils. When such soil displacement is massively reproduced by the repeated grid patterned piling, the accumulated effect of excess pore water pressure can undoubtedly generate high piezometric head within the subsoils, even reaching a state of artesian piezometric level above ground surface as evidenced of approximate 2m piezometric head above the platform in Figure 1. The over-spillage of groundwater is believed seeping through the pile welded joints. The expected long-term effects will be the following time-dependent consolidation settlement of the reclaimed platform as shown in Figure 2 and, also downdrag problem of pile foundation after the complete dissipation of the induced excess pore water pressure.

Fig. 1. Water overflowing from inner pile annulus as evidence of high excess pore water pressure within the subsoils in depth

Fig. 2. Settlement of reclaimed platform below tank raft

These effects are the disturbance from piling works in the post-earthwork or/and ground improvement stage and often no time or additional treatment is allowed for subsiding these adverse effects to a tolerable limit. Hence more practical design approach is to make provision of the downdrag effect in the pile capacity and settlement compatibility to absolve the problems.

2.2 Pile Heave and Pile Joint Dislodgement

The soil displacement around a penetrating pile tends to displace vertically more easily during the stage of shallow pile penetration with relatively lower overburden confinement. As such, the upwards soil displacement will likely induce an uplift force to the adjacent installed piles resulting in pile heave, especially for short end bearing piles. Notwithstanding to the possible structural tension failure of the pile welded joint, pile heave can also significantly reduce the end bearing stiffness response after uplifting the pile base contact. When the pile penetrates to deeper depth, the overburden confinement becomes more prevailing than the lateral confinement, the volumetric soil displacement will be in the form the radial straining the soils from the pile body. The radial soil displacement can induce flexural stress to the adjacent pile, which may also dislodge of the pile joints or also crack the pile body. Figure 3 shows the pile heave monitoring measurement of a pile group of 12 numbers of 400mm by 400mm precast reinforced concrete piles with spacing ranges from the closest of 1.2m to 1.8m. These piles were driven until refusal and terminated with lengths ranging from 27m to 37m below the existing platform level.

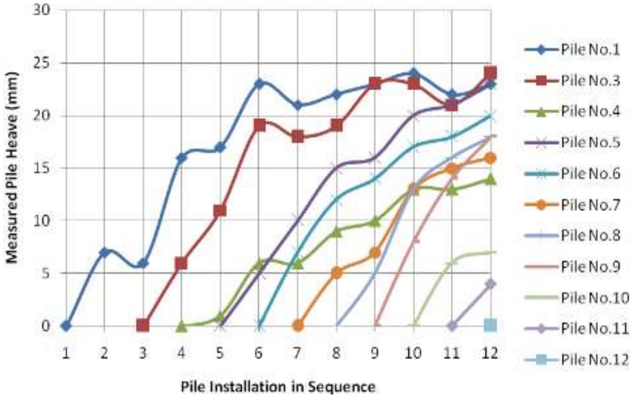

Fig. 3. Pile heave monitoring of 12 piles installed in sequence

Figure 4 provides solid evidence of the close-up of pile joints of a 36m pile allowing the hammer impact wave showing the pile intact length from 12m to 24m and lastly 36m of the full intact length to reach the designed pile capacity in the progressive high strain dynamic pile testing. This proves the points of pile joint dislodgement, which is likely by the vertical soil displacement to dislodge the relatively weak tension capacity of pile joints.

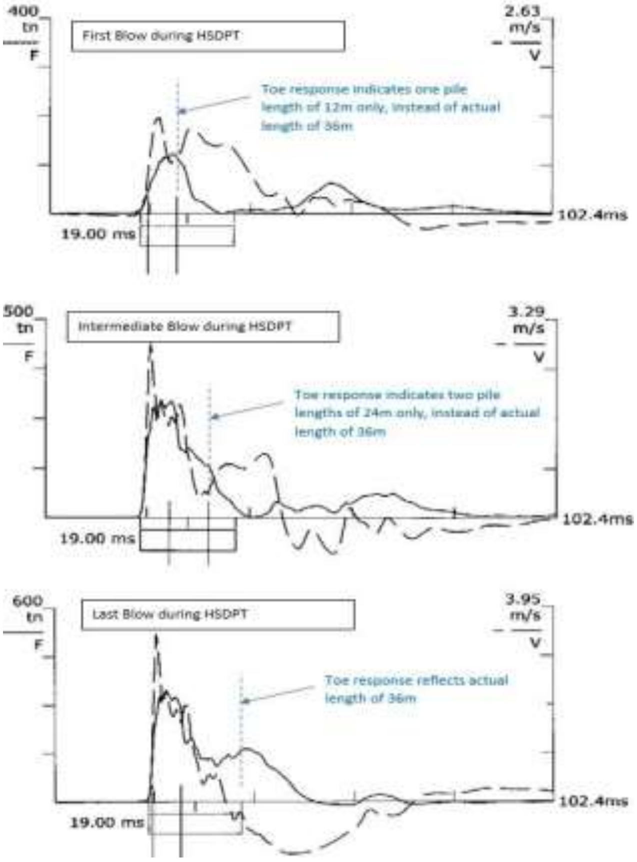

Fig. 4. Evidence of dislodged pile joints from discontinuity reflecting waves in sequential high strain dynamic pile tests

Since the undrained straining is the fundamental soil behavior with volumetric displacement during rapid pile inclusion, the possible mitigating measures to reduce the construction impacts can be as follows:

i. To plan the piling sequence of group piles with symmetrical soil displacement pattern, namely from centre moving gradually outwards,
ii. To increase the pile spacing as the impact of volumetric soil displacement is inversely proportionated to the square of pile spacing,
iii. To restrike the installed piles with re-sitting the pile base contact to attain the necessary base stiffness after all the possible construction disturbances related to stiffness degradation,
iv. To use piles with stronger structural capacity in handling both tension and flexural stresses,
v. To use piles with lower volumetric soil

displacement, likes pipe piles or open-ended piles where practically feasible.

2.3 Structural Restraint of Ring Beam to Tank Raft

Traditionally it is common industry practice to build up-stand reinforced concrete (RC) ring beam over the RC tank raft to contain the granular fill bedding in order to uniformly support the steel tank. Under the uniform distributed loading of the storage product of 200kPa to 220kPa, the tank base normally deforms with bowl-shaped profile resulted from the effect of Boussinesq stress distribution. With the perimeter upstand ring beam attached to the RC raft, which forms extra structural stiffness to resist the inward torsion of the ring beam to the tank centre, the ring beam will have to develop an equivalent flexural stress distribution across the ring beam section to balance off the torsion. The flexural stress requires force couple with both tensioning and compression zones across the ring beam section. As such, tension cracking of the lower external face of the ring beam is evidenced in Figure 5. Appendix 1 presents the theoretical frameworks of analyzing, design and detailing of the RC ring beam in restraining the bowl-shaped deformation of the tank raft. From the inward twisting of the circumferential upstand ring beam due to the Boussinesq deformation of tank raft, it is not difficult to observe the tensile zone the at the lower external face of the ring beam. Hence it is crucial to have sufficient tensile reinforcement to evenly distribute the tensile strain for flexural cracking control.

Fig. 5. Tensile cracking on upstand ring beam after hydrotest

2.4 Permanent Bowl-Shape Tank Base Deformation

As mentioned in Section 2.3 and as shown in Figure 6, Boussinesq effect resulting the permanent bowl-shaped deformation profile of the tank raft, which will lead to unsupported condition of the tank roof column supports after the unloading from the hydrotest during construction stage or initial service loading during operation stage is an inevitable situation. Therefore, it is advisable to allow mechanism of adjusting the detachable column supports after the hydrotest likes steel plate seaming for large gap adjustment or adjustable compression screw joint as usually found in base support of scaffolding, which can also permit maintenance adjustment for smaller gap.

Fig. 6. Detached tank roof support due to irrecoverable bowl-shaped tank raft deformation after hydrotest

3 CONCLUSIONS

From the abovementioned number of observations and case studies, the following conclusions summarize the findings:

i. Generation of high excess porewater pressure by large displacement piling works is highly possible with potential effects of foundation downdrag problems associated with the subsequent consolidation compression of the fine alluvial deposits. Due consideration of these effects shall be allowed in the foundation and platform design.

ii. Pile heave and joint dislodgement shall not be overlooked as most foundation designers consider working piles with accepted termination criteria subject no change of condition even suffering post pile termination disturbance. Thus, rechecking of pile set after all possible disturbance is needed to ensure satisfactory foundation performance. Mitigating measures have been recommended on Section 2.2.

iii. The structural torsional stiffness from the upstand ring beam has been demonstrated. Theoretical frameworks of analyzing structural behavior, design and detailing the ring beam are presented in Appendix A. The circumferential ring beam also offers additional structural stiffness as the boundary restraint to reduce the Boussinesq deformation of tank raft. Such benefit can be modelled with additional twisting stiffness along the tank raft circumference. However, adequate tensile reinforcements shall be provided at the tensile zoning of beam section to control the flexural cracking of the ring beam.

iv. For most tank roof column support, especially for the large diameter tank, the effect of Boussinesq stress distribution at the foundation level will cause differential bowl-shaped tank raft deformation under the loading or hydrotest or service loading, which will result in unsupported condition of the tank roof columns. Hence, it is advisable to incorporate the compression screw joint for necessary gap adjustment after unloading of the tanks.

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APPENDIX A

This appendix presents a simple elastic response of an orthogonally symmetrical ($I_{xy} = 0$) ring beam subjecting to twisting moment along the beam in the circumferential direction resulting from the Boussinesq bowl-shaped tank raft deformation under imposition of product loading over the tank raft. The derivation is based on the elastic beam theory. The plane of beam section is assumed remaining as planar surface after the beam twisting. Figure A1 shows the ring beam sections before and after rotating an anti-clockwise angle of α about the centroid (point c) under twisting moment along circumferential z-direction (out-of-plan direction), T(kN-m/m). Table A1 summarises the changes of ring beam curvatures about the x- and y-axes. The sign convention of curvature is positive when the radius of curvature is on the same side of the positive direction of the corresponding axis.

Table A1. Beam Curvatures about Two Principal Axes After Twisting Moment, T, about z-axis (anti-clockwise rotation)

Ring Beam Curvature	Initial Condition, κ_i	Twisted Condition, κ_t	Change of Curvature, $\Delta\kappa$
κ_x (about x-axis)	0	Sinα/R	Sinα/R
κ_y (about y-axis)	-1/R	-Cosα/R	(1-Cosα)/R

Hence, the two principal moments, M_x and M_y, and the resultant moment, M_R, shall be as below based on elastic theory, whereby E, I_x and I_y denote as Young elastic modulus and moment of inertia of beam section about x-axis and y-axis respectively.

$$M_x' = -EI_x\Delta\kappa_x = -EI_x\text{Sin}\alpha/R$$
$$M_y' = EI_y\Delta\kappa_y = EI_y(1-\text{Cos}\alpha)/R$$

With the two principal moments after anti-clockwise rotation, these moments can be transformed into two orthogonal moment components of the x-y coordinate system, in which the moment component in y-axis will be self-canceled as they are parallel, but in opposite direction.

$$\begin{bmatrix} M_x \\ M_y \end{bmatrix} = \begin{bmatrix} Cos\alpha & -Sin\alpha \\ Sin\alpha & Cos\alpha \end{bmatrix}\begin{bmatrix} M_x' \\ M_y' \end{bmatrix}$$

$$\Rightarrow \quad M_x = M_x'\text{Cos}\alpha - M_y'\text{Sin}\alpha$$

$$\Leftrightarrow \quad M_x = -\frac{E}{R}[I_x\text{Sin}\alpha\text{Cos}\alpha + I_y(1-\text{Cos}\alpha)\text{Sin}\alpha]$$

$$\Leftrightarrow \quad M_x = -\frac{E}{R}[(I_x - I_y)\text{Sin}\alpha\text{Cos}\alpha + I_y\text{Sin}\alpha]$$

From Figure A1, the relationship between the unit twisting moment, T, along the infinitesimal circumferential chord length, Rδβ, and the resultant moment (TRδβ) of the two applied moments (M_x) shall be as follow:

$$TR\delta\beta\text{Cos}(\delta\beta/2) = M_x\text{Sin}(\delta\beta)$$

$$\Leftrightarrow \quad T = \frac{1}{R}M_x\frac{Sin(\delta\beta)}{\delta\beta}\frac{1}{\text{Cos}(\delta\beta/2)}$$

$$\Leftrightarrow \quad \lim_{\delta\beta \to 0} T = \frac{Mx}{R}$$

$$\Leftrightarrow \quad T = -\frac{E}{R^2}[(I_x - I_y)\text{Sin}\alpha\text{Cos}\alpha + I_y\text{Sin}\alpha]$$

The above expression shows that the twisting moment is linearly proportional to the Young elastic modulus and inversely proportional to the radial distance of the ring beam from tank centre. This implies the ring beam restraining stiffness is drastically reduced when the tank diameter increase. The moment of inertia about x-axis has more impact to the restraining stiffness.

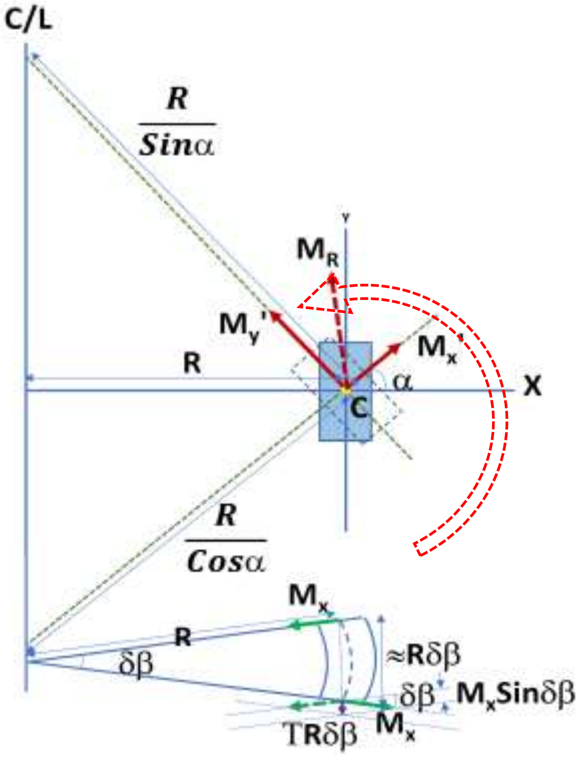

Fig. A1. Schematic diagram of circumferential ring beam subject to twisti