A 3D soil-structure interaction analysis for a piled raft foundation in highly compressible soils

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ABSTRACT
This paper presents the findings of a 3-dimensional, large-strain, soil-structure interaction analysis for a piled raft foundation for a petrochemical plant in a deltaic geological setting using the computer program FLAC^{3D}. The site was originally mangrove swamp terrain underlain by very soft organic soils. Settlements of about 5 m were recorded during the site preparation which included the placement of 8 m sand fill plus dewatering to about 14 m depth. The various process modules need to be supported on piled raft foundations with very tight settlement limits. The purpose of the foundation piles is to act as settlement reducers with raft and piles sharing the structural loads. The analysis included studying the impact of sand fill and de-watering on ground settlements using a 1D, coupled flow-mechanical, large strain FLAC^{3D} model, simulating the site preparation process, comparing the analytical predictions with the field measurements, and a 3D finite difference model which takes into consideration the interactions amongst soils, raft, and piles.

RÉSUMÉ
Cet article présente les conclusions d'une analyse tridimensionelle de structure du sol, à large déformations, faite sur les fondations à radier sur pieux d'une usine petrochimique, située dans un cadre géologique deltaïque, en utilisant le logiciel FLAC^{3D}. Le site était, à la base, une zone de mangrove sous-jacent à un sol organique très mou. Des affaissements d'environ 5m ont été enregistrés durant la préparation du site qui consistait, entre autre, au placement d'un remblai de sable d'une hauteur de 8m ainsi qu'à l'assèchement des 14 premiers mètres du mort-terrain. Les différentes sections de l'usine ont besoin d'être supportées sur des fondations à radier sur pieux ayant peu de tolérance pour les affaisssements. Ces fondations sur pieux ont pour but d'agir comme réducteur d'affaissement: les radier et les pieux partagent le poids structural. Cette analyse étudie premièrement l'impact des remblais de sable et de l'assèchement sur l'affaissement en utilisant le modèle unidimensionel à grande déformation de FLAC^{3D}, avec le couplage débit mécanique et en simulant les étapes de la préparation du site. Deuxièmement, elle compare ces prévisions analytiques avec les mesures faites sur le terrain ainsi qu'avec un modèle tridimensionel qui considère les intéractions du sol, des radiers et des pieux.

1 INTRODUCTION

The project site is located in an area of deltaic swampland, and the near surface soils consisted of very soft to soft organic clay of about 14 m in original thickness which overlay about 4 m of compact to dense sand which was in turn undelain by a layer of soft to stiff high plasticity clay of about 22 m in original thickness. Following the baseline geotechnical investigations completed during the front end engineering design (FEED) phase, ground improvement was recommended and carried out, which included the placement of sand fills of about 8 m in thickness plus the installation of wick drains and pumping wells to drawdown the local water table up to about 14 m (within the middle sand layer). The main geotechnical design challenge was identified as the settlement of compressible clay strata under structural loads. Settlements of about 5 m were recorded during the site preparation / ground improvement stage. The project design criteria require the total settlement of foundations to be less than 80 mm from primary consolidation, and differential settlement to be less than 30 mm between points on a raft/mat foundation not exceeding 30 m in any dimension, and less than 30 mm between mid-points of adjacent foundations after piping hook-up.

The owner's engineers evaluated the foundations for the project and found that shallow foundations may not be suitable for heavily loaded structures or for structures that have a large foundation footprint (even if moderately loaded). The relatively incompressible basal sands exist at depths greater than 40 m, and founding structures on these soils through piling would be expensive and would not eliminate all differential settlement problems. As a result, raft foundations with settlement reducing piles or "piled rafts" as referred hereafter were proposed to support heavy and/or large footprint loads.

The computer program APRAF (Analysis of Piled Raft Foundations) was selected as the main software for carrying out structural analyses and design of the piled raft foundations. This computer code was developed by The University of Sydney, Australia based on the works by Clancy & Randolph (1993), Ta & Small (1996, 1997), Zhang & Small (2000), and Small & Zhang (2002). APRAF is capable of carrying out three-dimensional stress-deformation and soil-structure interaction analyses of piled rafts under the key assumption that all elements within the model including soils, piles, raft and the interaction between these elements behave in a linear elastic manner and small strain assumption is applicable.

Based on the high level of nonlinearity of the site soils as demonstrated during the site preparation stage, the nonlinear interactions (slip and/or separation) amongst soils, piles and the raft, the anticipated high level of strain (deformation), and the lack of documented case histories for the performance of piled raft foundations on soft soils designed with APRAF, it was concluded that a non-linear analysis of one of the project module foundations be carried out as a check and calibration for the design procedure based on APRAF. The computer program FLAC^{3D} (version 3.0, 2005, developed by Itasca Consulting Group Inc. of Minneapolis, USA) was selected to carry out the 3D nonlinear soil-structure interaction analysis for a piled-raft foundation, and the details on the methodology, results, data comparison and conclusions of the analysis are presented in the following sections.

2 METHODOLOGY OF FLAC^{3D} ANALYSIS

The following factors were considered during the development of the modeling methodology: (1) the key aspects of the soil behaviour that will have significant influence on the stress-strain distributions and settlements of the soils must be sufficiently represented by the numerical model; (2) the interactions amongst the soils, piles and the raft must be sufficiently represented by the numerical model; and (3) the numerical model must be simplified as much as possible, and the factors that do not have significant influence on the soil stress-strain distributions or settlements must be ignored. These considerations are important for the successful completion of the analysis.

The modified Cam-Clay model (Roscoe and Schofield, 1963, and Wood, 1990) was selected to represent the constitutive behaviour of the clays and Mohr-Coulomb plasticity model was used to simulate the constitutive behaviour of the sands at the site. Based on the loading conditions to be simulated by the FLAC^{3D} model, the interaction between the piles and soils including the slippage along the pile - soil interface in vertical direction is considered critical, and must be simulated adequately.

The purpose of the FLAC^{3D} analysis is to estimate the foundation settlements induced by the applied loads and the distribution of loads between the piles and the raft. An appropriate establishment of the initial soil conditions (the conditions at the end of ground improvement and prior to the installation of the foundations) is critical when modified Cam-Clay (MCC) model is used to represent the constitutive behaviour of the soils. The initial conditions include, among other state variables, the distributions of the effective horizontal and vertical stresses, the pre-consolidation stresses, the pore water pressure, and the void ratio of the clay soils. The initial conditions for sandy soils (Mohr-Coulomb model) are relatively simple and include primarily the effective stresses and the pore water pressure distributions. In order to establish the initial conditions, the process of ground improvement (placement of the sand fills and dewatering) was simulated using FLAC^{3D}. The computed stress-strain state of the model at the end of the ground improvement stage was used as the initial conditions for the next step of the modeling.

3 SOIL CONDITIONS PRIOR TO GROUND IMPROVEMENT AND KEY SOIL PARAMETERS

Figure 1 shows a simplified original soil layering at the site, which consisted of three upper clay units of 15 m in total thickness, overlying a 4 m thick middle sand unit, which in turn overlies two lower clay units of 22 m in total thickness. A relatively incompressible basal sand layer underlies the Lower Clay Unit 4c, and the total thickness of the native soils above the basal sand is 41 m. The groundwater level was reported to be approximately at the original ground surface. The key input properties for the various soil units used in the analysis are summarized in Table 1.

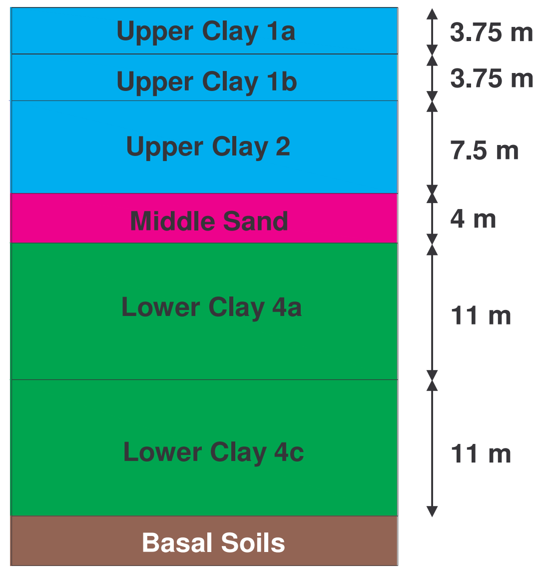

Figure 1. A simplified soil profile prior to site preparation.

These input parameters were developed based on the results of the laboratory tests carried out by the owner's engineer on the soil samples collected from the boreholes put down at the site before ground improvement.

4 SIMULATION OF GROUND IMPROVEMENT PROCESS

The main purposes of simulating the ground improvement include: (1) establish the stress-strain state (including the effective horizontal stresses) of the soils at the site after the completion of ground improvement and prior to the construction of the foundations, and (2) compare the predicted settlement values with those measured in the field.

The actual process of the ground improvement is complicated involving fill placement, wick drains, pumping, and providing vertical and lateral cut-offs in the sand fill to reduce infiltration, etc. Simplified for numerical analysis purposes, the ground improvement included the placement of sand fills of about 8 m in thickness plus the installation of wick drains and pumping wells to drawdown the local water table up to about 14 m. The sand fill was kept in place for more than 2 years, and the full-depth drawdown (pumping) of water table lasted for about 4 months.

Table 1: Soil Properties Used in the FLAC^{3D} Analysis.

	Upper Clay			Middle Sand	Lower Clay	
	1a	1b	2	3	4a	4c
Thickness (m)	3.75	3.75	7.5	4	11	11
Saturated Unit Weight (kN/m^3)	14.1	14.8	15.1	20	17	17.6
Over-consolidation Pressure (kPa)	10	10	10	N/A	60	60
Critical state stress ratio, M	1.14	1.14	1.14	N/A	1.14	1.14
Lambda, **λ**	0.728	0.626	0.52	N/A	0.25	0.228
Kappa, ***κ***	0.0728	0.0626	0.052	N/A	0.025	0.023
Average Initial Specific Volume	3.9	3.35	3.15	N/A	2.3	2.1
Poisson's Ratio	0.34	0.34	0.34	0.30	0.34	0.34
Average Initial Void Ratio, ***e***	2.9	2.35	2.15	0.6	1.3	1.1
Friction Angle (degrees)				35		

An initial analysis for simulating the ground improvement was carried out using a 1D coupled flow-mechanical model. The placement of fill and the resulting generation and dissipation of excess pore water pressure as well as changes in stress strain state were simulated in the coupled analysis. Due to the excessive computational effort required for this coupled analysis, the 'drained' assumption was introduced in the subsequent 3D models for numerical analysis purposes. It was assumed (in the model) that the excess pore water pressure generated by the placement of sand fill and dewatering process will dissipate relatively quickly (with the help of wick drains) in comparison with the rate of fill placement and dewatering.

The 8 m thick sand fill was introduced to the model in 4 stages (2 m per stage) in order to reduce the numerical disturbance to the model. After the 8 m thick sand fill was in place and the stress-strain state within the numerical model reached equilibrium, the groundwater level was drawn down in three stages from the initial level to the final level. After the completion of the dewatering process, the native soils have been compressed due to the increased effective stress. The groundwater level was then brought up to the original ground surface level in three stages. In each of the loading or de-watering stages, the model was solved to equilibrium and the soil settlements, stress distribution, volume change, and mass conservation were computed by FLAC^{3D}, and verified manually.

The predicted settlements at the various soil depths near the center of the raft footprint at the end of the ground improvement are shown in Figure 2. As shown in the figure, the computed vertical displacements (settlements) at each of the loading steps are illustrated by the terrace-shaped displacement plots. The first 4 stages (terraces) correspond to the placement of sand fills. The 5th to 7th stages correspond to drawdown of the groundwater, and the 8th to 10th stages correspond to the restoration of the groundwater level. Average settlements in the order of 5.5 m to 5.8 m were computed at the top of the Upper Clay Unit 1a (surface of the original ground). The measured settlements are shown in Figure 3 to be just under 5 m.

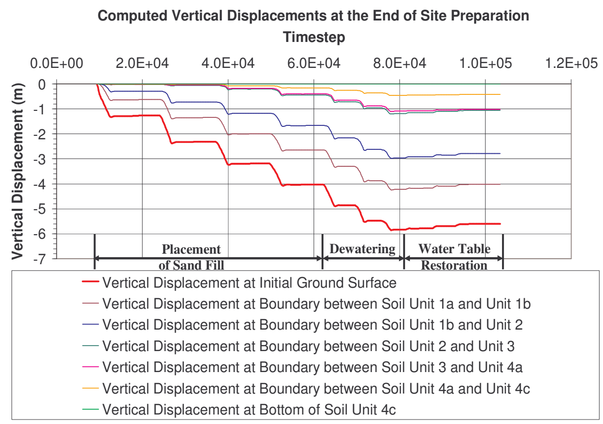

Figure 2. Computed settlements at the end of site preparation.

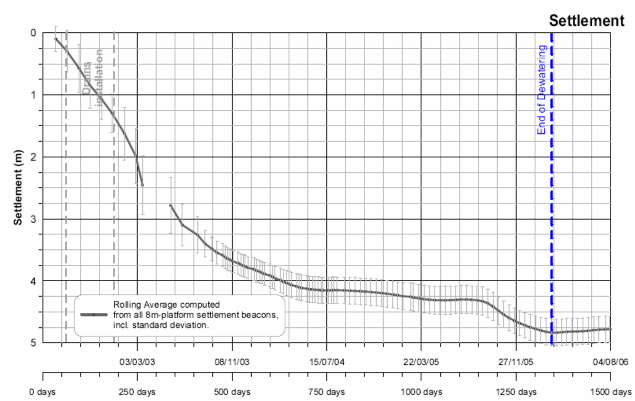

Figure 3. Measured ground surface settlements during site preparation.

Due to the high level of nonlinearity of the numerical model resulting from (1) the highly nonlinear soil behaviour of the clayey soils and (2) the excessively high level of strain (deformation or settlement), numerical procedures were developed to ensure that the FLAC^{3D} model correctly simulated the process of fill loading, dewatering and the resulting settlements. These procedures included the following:

- The change in soil density as a result of the large deformation needs to be correctly represented within the FLAC^{3D} model at each step of the numerical analysis. In other words, the mass conservation law must be preserved at all times;

- The change in pore water pressure associated with the large deformation needs to be correctly represented within the FLAC^{3D} model at each step. The static pore water pressure governed by the water depth must be adjusted with the settlement of the soils;
- Special care needs to be taken in all numerical manipulations to minimize the numerical disturbances to the model. This is especially important when the modified Cam-Clay constitutive model is used. The response of a Cam-Clay soil to new loads depends not only on the current stress-strain state, but also on the current void ratio and pre-consolidation pressure. Inappropriate modeling technique or procedure may cause numerically-introduced over-consolidation that can alter the behaviour of the soil inadvertently.

5 PILED RAFT FOUNDATION AND THE FLAC^{3D} MODEL

The subject raft is 24.5 m by 26.6 m in plan and 1 m in thickness to be supported by 16 settlement reducing steel pipe piles. Piles are open ended, 762 mm in diameter, 19 mm wall thickness, and 36 m long. Figure 4 shows the foundation layout and the identifiers (e.g. pile numbers in pink blocks, column numbers in red blocks) of the various columns, piles and other elements incorporated in the APRAF model. Taking into consideration the symmetry of the foundation, only the top-right quadrant of the piled raft (12.25 m by 13.3 m) was included in the FLAC^{3D} model. The zone of the soils included in the model was 57.25 m by 58.3 m (about 4.5 times of the raft dimension). A 3D view of the model is shown in Figure 5. Shell structural elements were used to simulate the raft, and pile structural elements were used to simulate the piles. After the model was established, the column loadings were applied in four stages to reduce numerical disturbance to the raft-soil-pile system. Table 2 shows the total load applied to the model at the four column locations as well as the self weight of the raft.

Table 2: Foundation Loads

	Column ID[1]	Loads (kN)
Column Loads	434	3001
	441	1974
	642	2365
	649	1618
Self Weight of Raft Foundation (12.25 m x 13.3 m x 1 m)		3584
Total Applied Force (kN)		**12542**

[1]See Figure 4 for locations of the columns.

6 RESULTS OF FLAC^{3D} ANALYSIS FOR THE PILED RAFT FOUNDATION

The distribution of the computed vertical displacements in the X-Z plane is shown in Figures 6. The computed vertical displacements (settlements) of soils at the underside of the raft are in the order of 50 mm. The soils immediately underneath the raft moved downwards

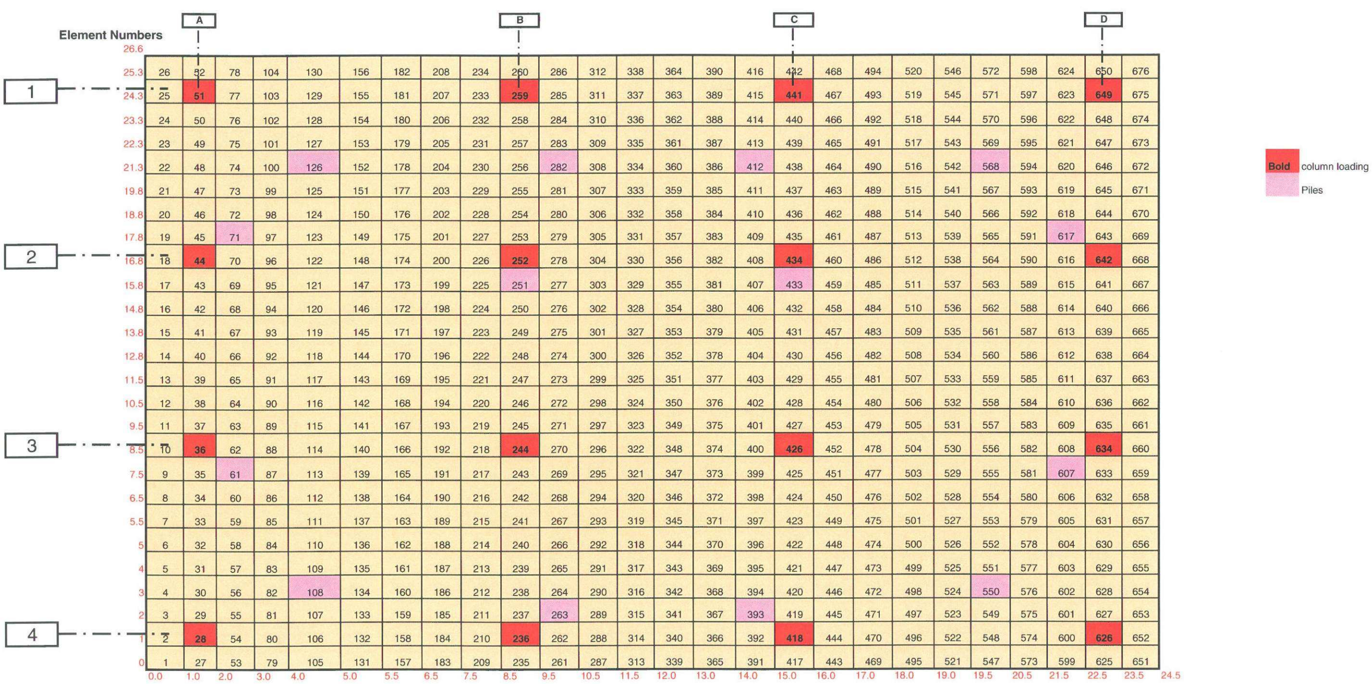

Figure 4. Foundation layout and the IDs of the various columns, piles and other elements incorporated in APRAF model.

together with the raft for about the same amount (the dark blues zones as shown in the figure), and the soil vertical displacements decrease with depth. This figure also shows that the soils immediately surrounding the piles underwent significantly more vertical displacements (settlements) than the soils away from the piles. A 3D view of the deformed piled raft, with the deformation magnified by 500 times for illustrative purposes, is shown in Figure 7. The four corners of the raft are referred as *a, b, c, and d*, and the vertical displacements computed at these four corners are 51, 49, 48, and 47 mm respectively. The distributions of the computed vertical displacements of pile structural nodes and adjacent soil zones, and the relative shear displacement between the pile nodes and the adjacent soil zones for a typical pile is shown in Figures 8 (a), and the variation of the axial forces along the corresponding pile is shown in Figures 8 (b). The computed vertical displacements are 49 mm and 42 mm at the pile top and tip respectively, and the elastic compression of the pile is about 7 mm. The estimated loads applied to the piles by the raft foundation are summarized in Table 3. About 68% of the total load is carried by the piles, and the remaining portion of the total loads is distributed over the raft-soil interface.

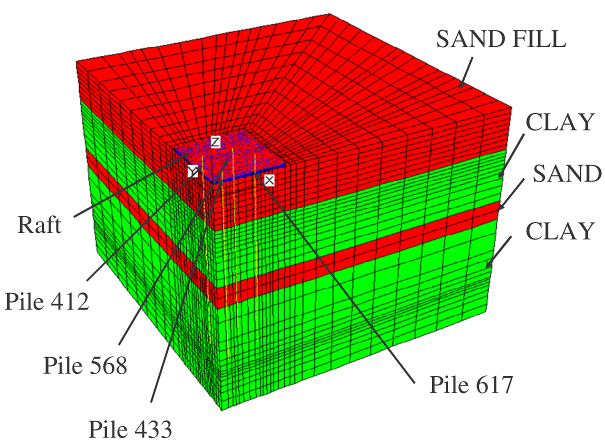

Figure 5. A 3D view of FLAC^{3D} model with structural elements for piles and raft.

Table 3: Estimated Loads Applied to the Piles by the Raft

Pile #	Location ID[1]	Vertical Loads Taken by Piles (kN)	Total Loads Including Column Loads and Raft Weight (kN)	Percentage of Loads Taken by Pile (%)
1	412	2,140		17
2	443	1,940	**12,542**	15
3	568	2,245		18
4	617	2,244		18
Total		**8,569**		**68**

[1]See Figure 4 for locations of the piles.

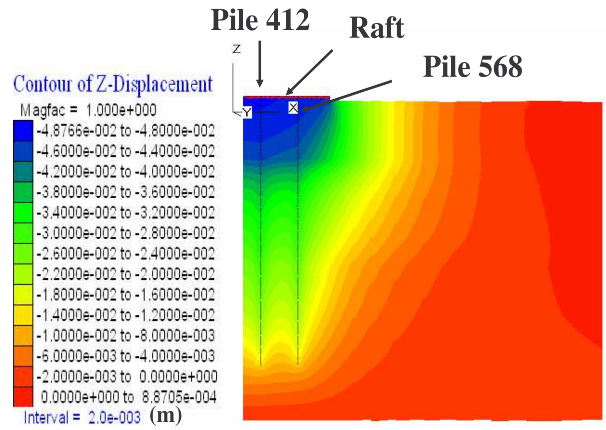

Figure 6. A 2D view of the computed vertical displacements under structural loads.

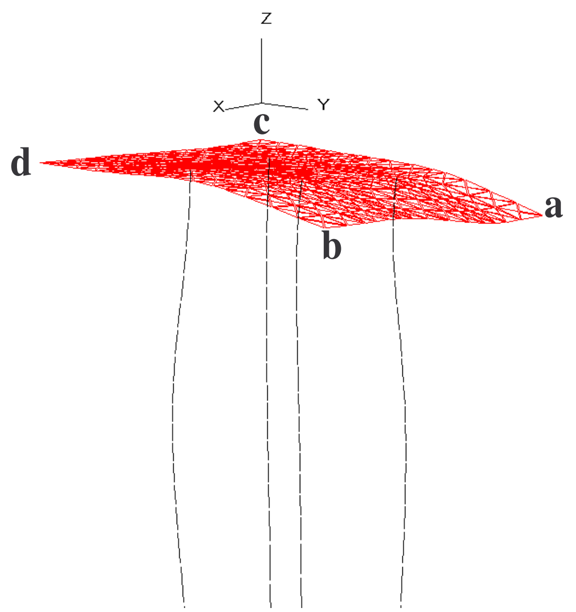

Figure 7. A 3D view showing the deformation (magnified by 500 times) of the piled raft system induced by the structural loads.

7 COMPARISON OF FLAC^{3D} AND APRAF RESULTS

The following provides a summary of the comparisons between the APRAF and FLAC^{3D} results.

The foundation (raft) settlements computed by APRAF along 2 lines are shown in Figure 9 (a) and (b) and the corresponding results from FLAC^{3D} analysis are shown in the figure for comparison. The settlements predicted by APRAF are somewhat higher than those predicted by FLAC^{3D}, but they are generally in the same order of magnitude, and the overall pattern of the settlements is generally similar.

The vertical displacements along a typical foundation

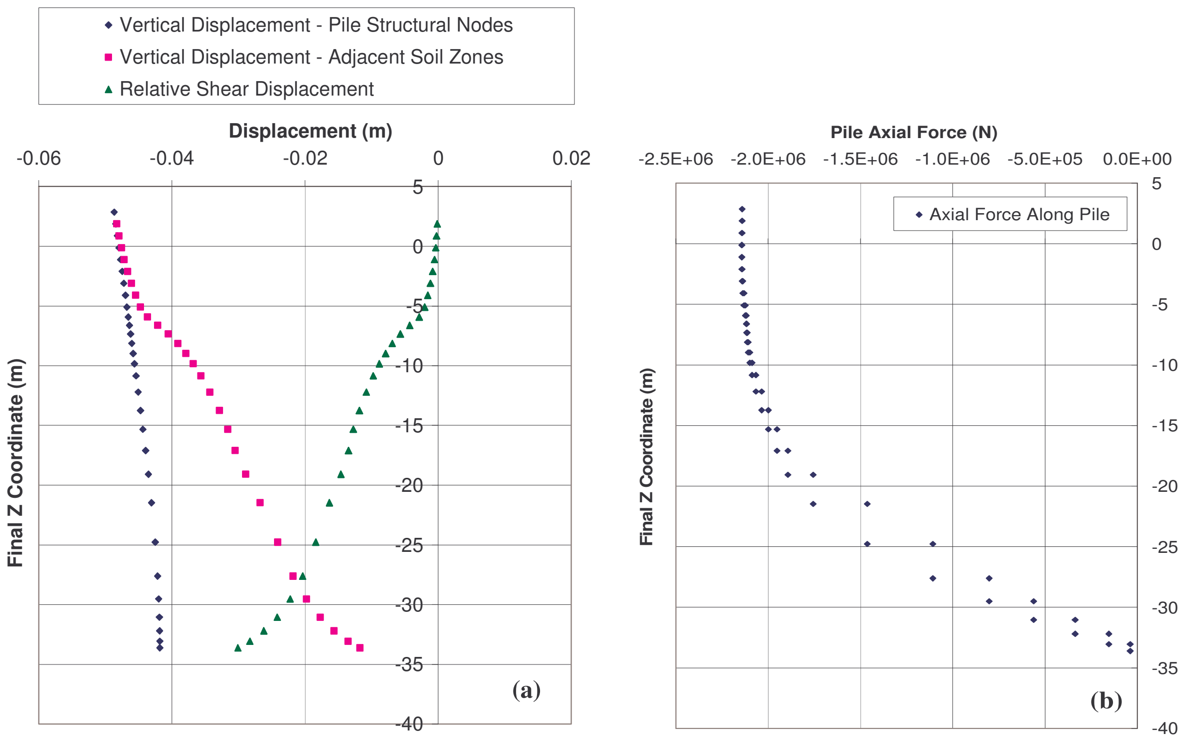

Figure 8. (a) Computed vertical displacements at the pile structural nodes and adjacent soil zones, and relative displacements (slips) between the pile nodes and adjacent soil zones, (b) Computed pile axial forces.

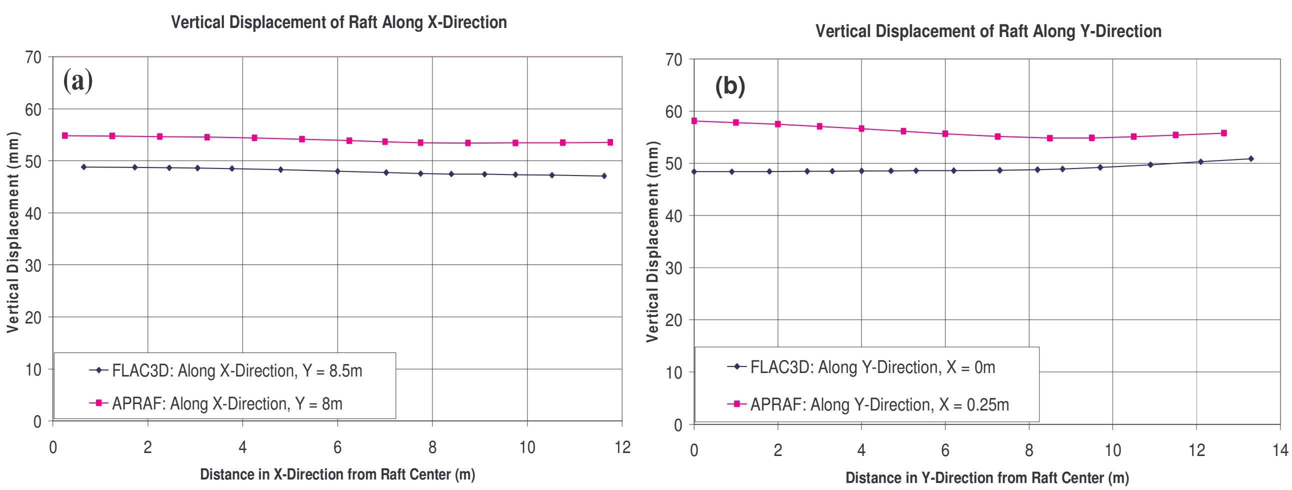

Figure 9. Comparison of raft settlements from APRAF and FLAC^{3D} analyses (a) X-direction settlement, and (b) Y-direction settlement.

pile computed by APRAF are compared with those predicted by FLAC^{3D} in Figure 10 (a), and the computed axial forces along the same pile are compared in Figure 10 (b).

As shown in Figure 10 (a), the pile vertical displacements predicted by FLAC^{3D} vary from 49 mm at the pile head to 42 mm at the pile tip, and the displacement difference between the pile head and pile tip is about 7 mm which represent the elastic compression of the pile. The pile vertical displacements computed by APRAF vary from 61 mm at the pile head to 31 mm at the pile tip. This large discrepancy is an artefact of the modeling approach using APRAF and is discussed in the next section.

As shown in Figure 10 (b), the pile axial forces computed by APRAF are also significantly higher than that predicted by FLAC^{3D}. As discussed shown in Table 3, the FLAC^{3D} analysis indicates that the total loads taken by the four piles are approximately 68% of the total vertical loads (column loads and self weight of raft). However, the sum of the pile forces predicted by APRAF is close to the total vertical load.

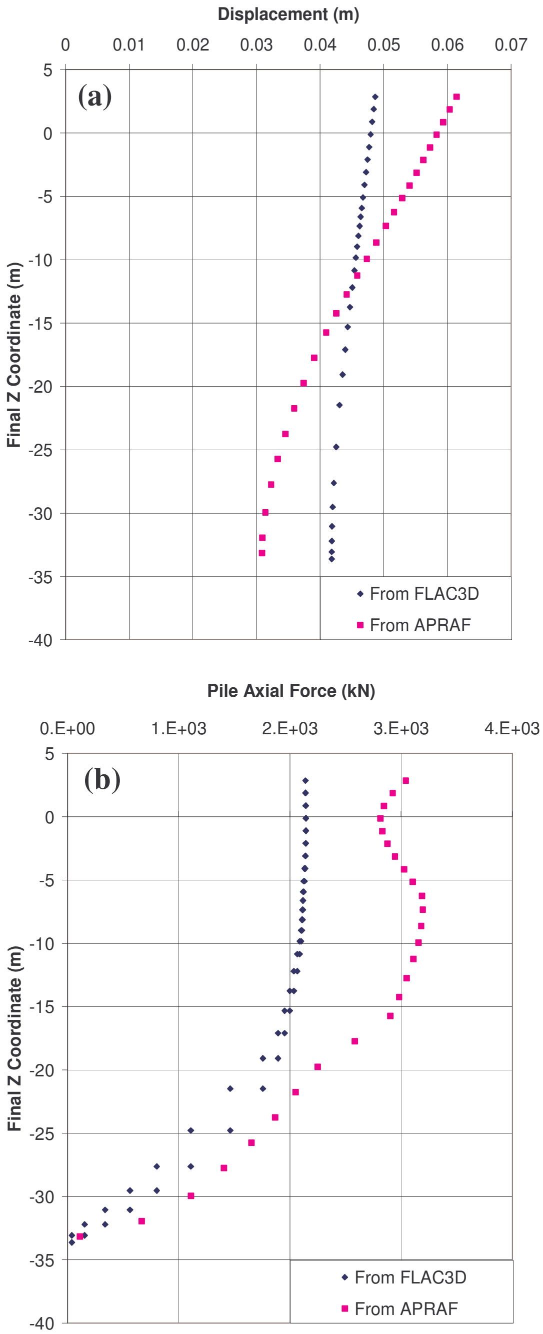

Figure 10. Comparison of analysis results of APRAF with that of FLAC^{3D} in terms of (a) pile vertical displacements and (b) pile axial forces.

8 DISCUSSIONS AND CONCLUSIONS

Average settlements in the order of 5.5 m to 5.8 m were computed at the top of the Upper Clay Unit 1a (surface of the original ground) during the site preparation (sand fill and dewatering) stage using the FLAC^{3D} model. The settlement values measured near the end of the site preparation process in March 2006 were in the order of 4.5 to 5 m as shown in Figure 3. Considering that the full-depth dewatering period was only about 4 months, the 4.5 to 5 m measured settlements are considered to represent approximately 90% of the total primary consolidation settlements. The 5.5 m to 5.8 m settlements computed by FLAC^{3D} model represent the theoretical values corresponding to 100% of total primary settlements. Based on the comparison of these values with those measured in the field, we consider that the predicted settlements are in a good agreement with those measured in the field, considering the fact that the input soil properties to the FLAC^{3D} model were developed using the data obtained from the soil investigation completed at the site prior to commencement of site preparation. No adjustment to the soil input property values was made during the FLAC^{3D} simulation of the site preparation stage.

A sufficient simulation of the site preparation process is one of the critical steps for the subsequent successful modeling of the 3D interactions amongst the soils, piles and the raft. This is especially important when the modified Cam-Clay constitutive model is used since the responses of the soils (represented by Cam-Clay) to the structural loads depends on the initial (prior to the introduction of the structure) conditions including the vertical and horizontal stresses as well as the void ratio and pre-consolidation stress. The initial vertical stress distribution can be determined relatively easily. However, a correct estimation on the initial horizontal stress and void ratio will involve some significant uncertainties without a sufficient simulation of the site preparation process.

The simulation of the site preparation stage served two purposes including (1) established the initial conditions for the subsequent modeling of the raft-soil-pile system and (2) partially confirmed that the input soil property parameters can appropriately represent the behaviour of the site soils.

In comparison with FLAC^{3D}, APRAF is easy to use with a minimum number of required input parameters, and the computational effort is also very small. The load-induced foundation settlements predicted by APRAF are generally in the same order as that predicted by FLAC^{3D}. However, due to the linear elastic material models within the APRAF program, the input parameters need to be carefully selected to represent the known large (plastic) strains in the soils as a result of consolidation and creep.

In this case the soil moduli were selected to achieve a *"reasonable"* settlement prediction to enable the structural analysis of the raft.

The predicted pile vertical displacements by APRAF also reflect an artefact of the linear elastic model. The large displacement differences between the pile heads and pile tips result from an adjustment to the axial stiffness of the piles to simulate slippage between the soil and the pile. Since the piles are not allowed to have relative movements (slippage) with respect to the soils nor to have local yielding at the pile tip, the piles will attract an unreasonable amount of load if the axial stiffness values of the piles are not reduced. Even after this reduction in pile stiffness, the lack of soil slippage along the piles results in a tendency to develop tensile stresses between the soil and the raft in the proximity of the piles.

The non-linear FLAC^{3D} finite element analyses appear to provide a realistic prediction of piled raft behaviour on the lightly over-consolidated (improved) soils at the site. The comparison with APRAF highlights the limitations of using a linear elastic model which may, however, be expedient in many cases to achieve a structural design within a reasonable timeframe. Linear elastic input parameters need to be carefully selected to adequately simulate soil consolidation, slippage at the soil-pile interface and plasticity at the base of the piles. These aspects were modelled well in FLAC^{3D}, although care was also needed to ensure reliable numerical results due to the large strains. The non-linear model provides added confidence in the bending moment and shear stresses calculated in APRAF and used in structural design of the raft.

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