

Settlement study of a Singapore 43-storey tower comparing equivalent block model with embedded piles model in 3D finite element analyses

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ABSTRACT

Pile-raft foundations of three 43-storey towers in soft soils deposits overlaying residual soils and granitic rock using jack-in spun piles encountered some difficulty in installation to the required depths. At the time of construction, a soil-pile block model was used for analysis. The stiffness of the soil-pile-raft system was reflected in the assumed compressibility of soil-pile block model. This yielded unrealistic prediction of pile-raft settlement of about 100 mm for Tower 2 as compared with real time building settlement monitoring of 19 mm by electro-level transducers. This paper describes the use of embedded piles to model 380 spun piles and raft as a separate assessment on settlement prediction in view of large settlement prediction by the earlier soil-pile block model. The measured settlement data is used to calibrate the FEM model predictions to get fair agreement of foundation performance.

RÉSUMÉ

Les fondations sur pieu-raft de trois tours de 43 étages dans les dépôts des sols mous recouvrant les sols résiduels et de la roche granitique aide de la prise en piles filé quelques difficultés à l'installation pour les profondeurs nécessaires. Au moment de la construction, un modèle de bloc de sol-pieu a été utilisé pour l'analyse. La rigidité du système sol-pieu-raft s'est reflétée dans la compressibilité supposée de modèle de bloc sol-pieu. Cela a donné de prédiction irréaliste du tassement des pieux-raft d'environ 100 mm pour la tour 2 par rapport à la surveillance en temps réel de règlement de construction de 19 mm par des transducteurs électro-niveau. Ce document décrit l'utilisation de pieux enfoncés pour modéliser 380 nombre des tas de filé et d'un radeau pour la comparaison avec le modèle de bloc-pile du sol plus tôt. Les données de tassement mesuré est utilisé pour calibrer les prédictions du modèle FEM pour obtenir un accord équitable de comportement de la fondation.

1 INTRODUCTION

Analyses of pile raft foundations with the use of finite element method (FEM) have been gaining popularity for many tall towers in the world. There were concerns over the three Singapore tower blocks of 43-storey buildings in soft soil deposits overlaying residual soils and Bukit Timah granitic rock. This was due to difficulties encountered on the installation of jack-in spun piles to the required depths of hard stratum. The use of three dimension (3D) finite element block foundation model using Plaxis 3D Foundation program version 1.5 was the available approach in year 2005 to predict the performance of settlement of three towers to show its adequacy of the proposed remedial piles provision.

This paper focuses on Tower 2 whereby the settlement was the largest among the three tower blocks at 19 mm at the completion of tower construction. Due to the large number of piles (>350) supporting the raft of Tower 2, it was not feasible to model the individual piles numerically at that time. To reduce the problem to a manageable level, the piles were divided into 13 groups with each group being modelled as a soil-pile block. This was the commonly adopted approach described in CIRIA Report 83 (Review of Behaviour of Pile Raft Foundations).

The large settlement prediction by this approach in year 2005 is now reviewed with a separate assessment using the available embedded piles model in Plaxis 3D Foundation program version 2.2

2 SINGAPORE 43-STOREY TOWER CASE STUDY: REVIEW OF NEGATIVE SKIN FRICTION AND PILE RAFT ANALYSES AT TOWER 2

2.1 Comments on Negative Skin Friction (Drag Load) approach using Singapore Code of Practice (CP) 4 for Foundations

There are a total of 10 site investigation boreholes at Tower 2. The site consists of Kallang Formation soft soil deposits (organic and marine clays) ranging from 4.5 m to 13 m thick overlaying residual soils and rock of Jurong Formation followed by Bukit Timah granite. In the normal calculation for pile capacity due to drag load, one would adopt the CP4 for Foundations approach in Singapore:

$$Q_{allow} = \frac{Q_{ult}}{FoS} - Q_{neg}$$

[1]

where Q_{allow} = Allowable pile capacity;
 Q_{ult} = Ultimate pile capacity;
 Q_{neg} = Drag load;
 FoS = Factor of Safety

However, this approach has not been an appropriate approach in Singapore practice. Unified Design Method has rightly pointed out that drag load should not be subtracted from the allowable pile capacity (i.e. Q_{ult}/FoS). One must understand the distribution of drag load along the pile shaft and the influence on the contribution of additional load to the limit set at the allowable pile capacity.

With the increase of load to the pile due to drag load, the maximum load (dead load plus drag load alone) onto the pile at the point of neutral plane should be checked for the pile structural strength divided with an appropriate factor of safety. Hence, negative skin friction or drag load does not diminish pile capacity. It is a matter of pile structural strength. The main question is whether there is a settling of surrounding soil that can cause downdrag.

Hence, assessment of pile capacity due to drag load for this project in the light of thick soft soil deposits which is undergoing consolidation (and all other projects where downdrags are occurring) must be done in the correct approach without deducting the allowable pile capacity away by the drag load. The inappropriate approach often leads to piles having no allowable capacity when the drag load is large and the piles are then increased in penetration length unnecessarily where the inappropriate approach is adopted in CP4.

2.2 Singapore 43-storey Tower 2 soil-pile block foundation model

For this 43-storey Tower 2 with one basement, it has an almost rectangular-shaped footprint area of approximately 50m long by 30m wide. Figure 1 shows the overall site plan near Singapore River with the shaded area being the footprint of Tower 2. The 10 site investigation boreholes are as shown in Figure 2. Figure 3 shows the respective block zoning, uniformly distributed load (UDL) and individual block stiffness E value respectively. This information can also be found in Table 1 which includes the average depth of each soil-pile block and thickness of compressible layer below pile toe to Standard Penetration Test (SPT) N value of 100.

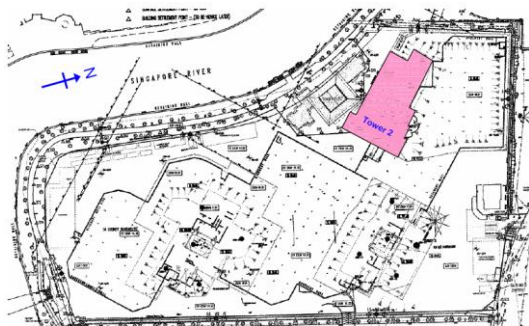


Figure 1. Tower 2 location plan

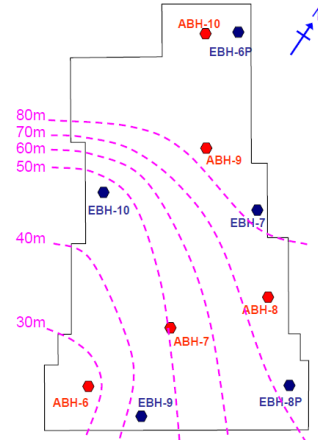


Figure 2. 10 site investigation boreholes & probable rock contours

The subsoil conditions comprised the following as revealed from the site investigation boreholes:

- i. An upper fill layer varying thickness from 3 to 7 m
- ii. An organic clay layer that was about 3 to 5 m thick
- iii. About 5 to 8 m of marine clay
- iv. About 2 to 4 m of fluvial sand
- v. About 10 to 25 m of residual soil (Standard Penetration Test (SPT) N value < 30)
- vi. Localised 5 m of SPT N value 100 residual soil
- vii. About 10 to more than 40 m of residual soil (SPT N value increasing from 30 to 100)
- viii. Weathered granite

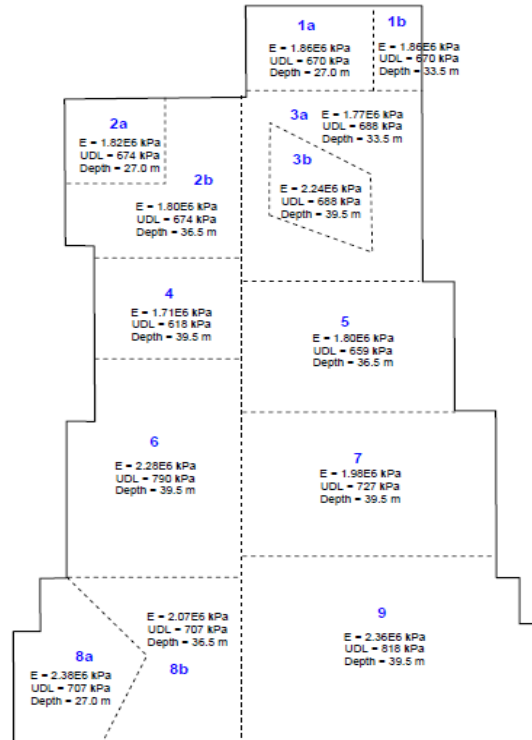


Figure 3. Tower 2 soil-pile blocks division, the applied uniformly distributed load (UDL) and individual block stiffness E value respectively

Table 1. Tower 2 Summary of Soil - Pile Block Information

Block No.	Sub-block No.	E (kN/m ²)	UDL (kPa)	Average Length (m)	Thickness of Compressible Layer below pile toe to SPT N=100 (m)
1	1a	1.86E+06	670	27.0	18.5
	1b	1.86E+06		33.5	8.0
2	2a	1.82E+06	674	27.0	18.5
	2b	1.80E+06		36.5	13.5
3	3a	1.77E+06	688	33.5	8.0
	3b	2.24E+06		39.5	2.5
4	4	1.71E+06	618	39.5	5.5
5	5	1.80E+06	659	36.5	8.5
6	6	2.28E+06	790	39.5	6.5
7	7	1.98E+06	727	39.5	6.5
8	8a	2.38E+06	707	27.0	12.5
	8b	2.07E+06		36.5	7.0
9	9	2.36E+06	818	39.5	5.5

The following idealizations and simplifications were invoked in the study in year 2005. Vertical compressibility of the soil-pile-raft system was reflected in the compressibility of the 13 sub-blocks used to model the foundation system. The equivalent stiffness of each block is obtained by smearing the concrete modulus according to the ratio of the concrete areas to the plan area of the block. The contribution of the soil stiffness was conservatively neglected. Since the pile groups were modeled as blocks, the individual pile lengths could not be modeled. Instead, the average pile length was calculated for the piles within each equivalent block, and adopted as the depth of that particular block. Within each group, the variation of the length was about 3 m. Each block was computed to have a certain value of uniformly distributed load (UDL) acting over the block plan area. Table 2 below summarises the soil parameters used to model the soil-pile block model and Figure 4 is the 3D block model generated from Plaxis 3D Foundation in year 2005.

Table 2. Soil parameters chosen for soil-pile-block model

Materials	Unit weight γ (kN/m ³)	Cohesion C (kPa)	Friction angle ϕ (deg.)	Loading modulus E_{ref} (MN/m ²)	Unloading modulus $E_{ur, ref}$ (MN/m ²)
Fill/Organic /Marine Clay	16	0.1	16	3	-
F1/Jurong Formation	20	0.1	30	15	45
Residual Soil (N=20)	20	0.1	32	20	60
Residual Soil (N=30)	20	0.1	33	30	90
Residual Soil (N=40)	20	5	33	40	120
Residual Soil (N=60)	20	10	33	60	180
Residual Soil (N=100)	20	20	35	100	300
Granite	22	200	38	300	-

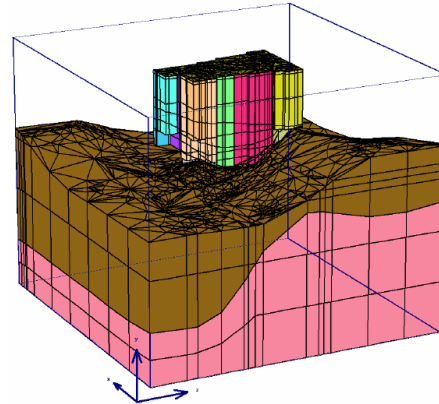


Figure 4. 3D full soil-pile block model with respect to rock below and residual soil of SPT N value = 100 above the rock

Using the following material parameters and stress state, Young Modulus E value of residual soil = 1N MPa, $K_o = 1 - \sin\phi'$ and OCR = 1.0, the computed maximum settlement of Tower 2 was about 100 mm (see Figure 5 below for settlement distribution of the blocks) where maximum settlement was at the top left hand corner on plan view. The maximum computed differential settlement was about 1 in 6000.

The large settlement prediction can be attributed to the conservative soil parameters adopted particularly on the soil stiffness below the piles toe block model. Unfortunately there were no pressuremeter tests done on the founding layer of hard stratum where field soil stiffness could have been obtained to better predict the performance of the pile-raft settlement. There could also be that the generated geometry of the founding hard stratum in the model was not close to the real ground conditions below Tower 2.

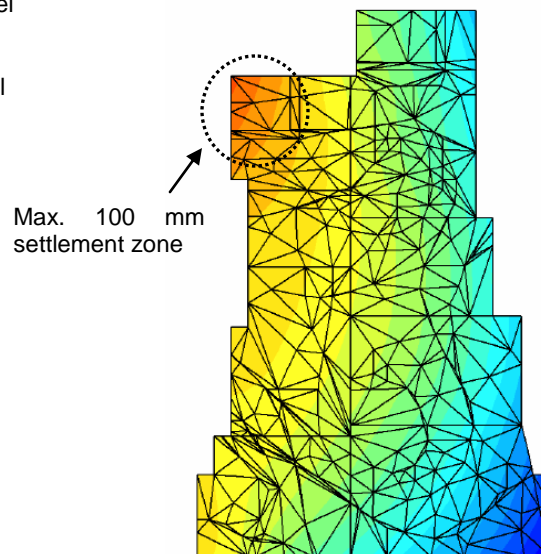


Figure 5. Raft settlement shading plot for Tower 2

2.3 Singapore 43-storey Tower 2: single pile ultimate load test model

Extensive study was carried out to review the ultimate pile load test results in order to calibrate a set of reasonable soil parameters for the full 3D model of pile raft analyses using Plaxis 3D Foundation version 2.2 which is currently available. For ultimate load test nos. 3 (ULT 3) conducted at Tower 2 next to the site investigation borehole ABH-7, Plaxis 2D single pile model and Plaxis 3D Foundation embedded pile are used to model the pile static load test.

The models and settlement plots are depicted from Figures 6 to 9. The pile tested in ULT 3 and modelled is a 600 mm diameter concrete spun pile with Young Modulus $E = 45 \text{ GPa}$. It was founded in completely weathered sandstone grade SV of Jurong Formation. In Plaxis 2D model, dummy plate element was placed inside and together with the solid pile material as spun pile in axisymmetric simulation with a load applied directly to the pile top according to the test loads to 2.5 times the working load (WL). The soil parameters used are as shown in Table 3. The test was done in undrained conditions. The settlement results under various applied loads and axial force in the piles are as shown in Figures 8 and 9. They match very well with the measured settlement of pile top undergoing three cycle of loading and unloading. Only loading settlement plots are shown for clarity purpose with settlement in Plaxis 2D model.

On the other hand, Plaxis 3D embedded pile model also gives similar pile top settlement results with the same set of soil parameters except that the pile has encountered "failure" at a load less than 2 times of WL. (see Figure 8)

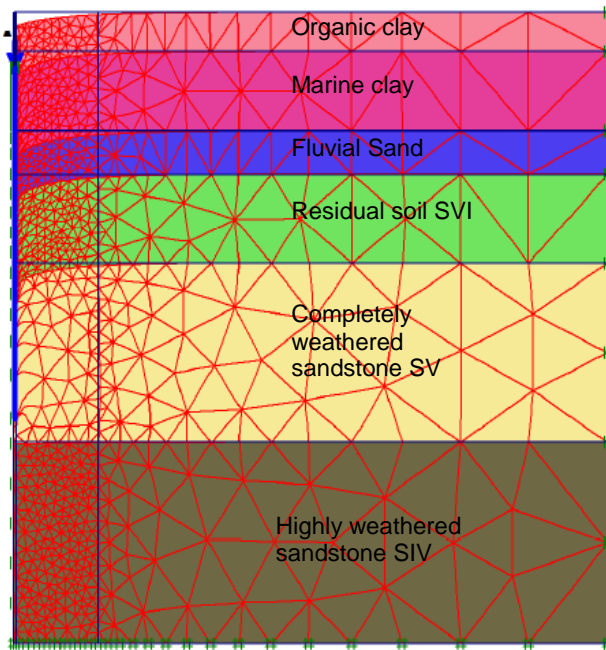


Figure 6. Plaxis 2D model for single pile for ULT 3

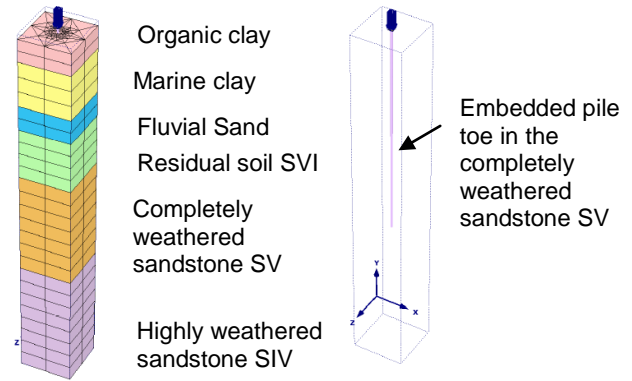


Figure 7. Plaxis 3D embedded pile model for ULT 3

Table 3. Proposed soil parameters in ULT 3 & full 3D embedded piles and soil-pile block modelling in Plaxis 3D Foundation v2.2

Materials	Model used in 2D & 3D PLAXIS	Type	γ_{unsat} (kN/m ³)	γ_{sat} (kN/m ³)	C_u or C' (kPa)	Φ_u or Φ' (deg.)	E_{ref} (kPa)	ν	ψ	SPT N
Fill	Mohr-Coulomb	Drained	19	19	0	30	10000	0.3	0	4~7
Organic CLAY	Mohr-Coulomb	Undrained	14	14	0	5	1000	0.3	0	0~1
Marine CLAY	Mohr-Coulomb	Undrained	15	15	0	22	2000	0.3	0	0~2
Loose to Medium Sand	Mohr-Coulomb	Drained	18	18	0	30	9000	0.3	0	13 ~ 22
Residual Soil SVI	Mohr-Coulomb	Undrained	19.5	19.5	40	45	12000	0.3	0	13 ~ 20
Completely weathered Siltstone SV	Mohr-Coulomb	Undrained	20	20	50	45	100000 (150000)*	0.3	0	23 ~ 47
Highly weathered Sandstone SIV	Mohr-Coulomb	Undrained	20.5	20.5	120	45	150000 (450000)*	0.3	0	100
Concrete Spun Pile ($E=45\text{GPa}$)	Linear Elastic	Non-porous	24	-	-	-	45E6	0.2	-	-

*Changed for full 3D embedded piles model & soil-pile block model in Plaxis 3D Foundation version 2.2

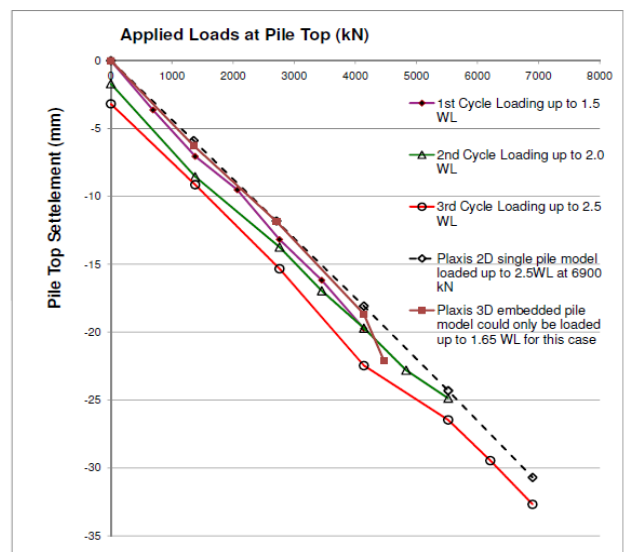


Figure 8. Pile top settlement for pile loaded up to 2.5 Working Load (WL) and comparison with the FEM models

Axial force along the pile in the Plaxis 2D model was checked against the measured load along the pile due to applied load of 2.5 times of WL. This is to validate the reasonable soil parameters to be used in the Plaxis 3D embedded piles model. From the plot of measured axial load along the pile shaft, it appears that there is a reduction of axial load along pile shaft as compared with the analysis result at the bottom half of the pile. This can be attributed to the fact that the pile might have residual load in the pile. It is to be noted that the test pile was socketed in completely weathered sandstone SV material with the proposed E, Young Modulus = 1.0N (MPa) and SIV stiffness being E = 1.5N (MPa).

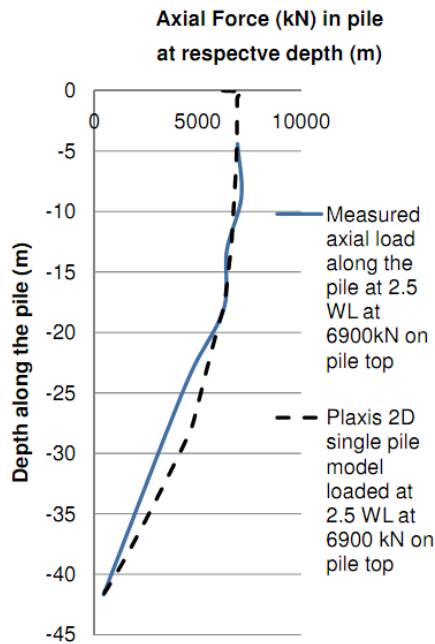


Figure 9. Measured axial load against the axial load along the pile length in the model

2.4 Singapore 43-storey Tower 2: 3D embedded piles model and comparison with field measured results

There are a total of 380 nos. of jack-in spun piles (353 nos. of 600 mm and 27 nos. of 500 mm diameter spun piles). As-built pile length and locations were obtained and carefully input to generate the full 3D pile-raft model with embedded piles. The loading input onto the raft is similar to what has been used before as shown in Figure 3 for zoning and Table 1 for the intensity of loads.

The installed pile penetration ranges from 10 m to 40 m from the cut off level (COL.) – see Figure 11. From the 10 site investigation boreholes and a number of short installed spun piles (21 numbers of piles less than 20m; about 100 piles are less than 30 m penetration), some short piles were within the long piles zone. It was expected that all jack-in spun piles were installed to two times the WL and they would have achieved the hard stratum for refusal. Hence, it would be reasonable to assume that all piles would have been installed to reach completely and highly weathered sandstone layer (SV

and SIV) respectively. Hence, the simplified soil layering from the existing 10 site investigation boreholes information was considered in conjunction with short piles location in order to have realistic soil stratifications for the installed piles in modelling. (See Figures 10 to 12).

From the soil parameters determined from the single pile model for ultimate load test, the predicted raft settlement has shown to be excessive (more than 100 mm settlement). Hence, the realistic soil parameters have been proposed as E = 1.5N (MPa) for SV completely weathered sandstone and E = 4.5N (MPa) for SIV highly weathered sandstone materials where all piles were expected to be socketed in such layers. (See Figure 12)

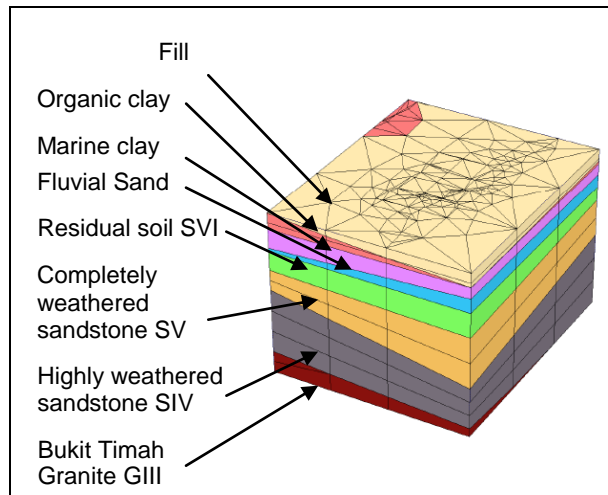


Figure 10. Full 3D model with the simplified soil stratifications based on 10 site investigation boreholes and the review of the as-built piles penetration lengths

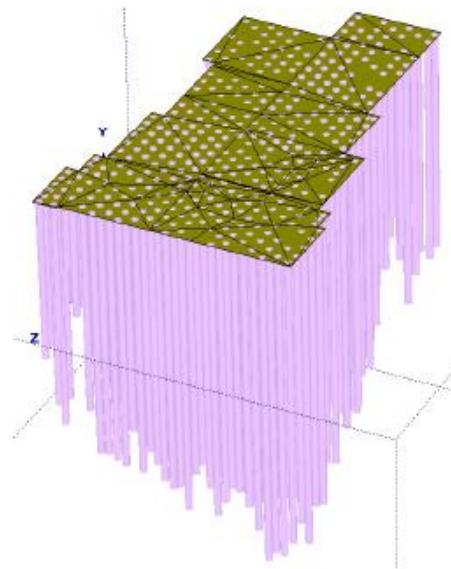


Figure 11. Pile-raft modelling with 380 nos. of actual as-built pile penetration lengths in Tower 2 (short and long piles variation)

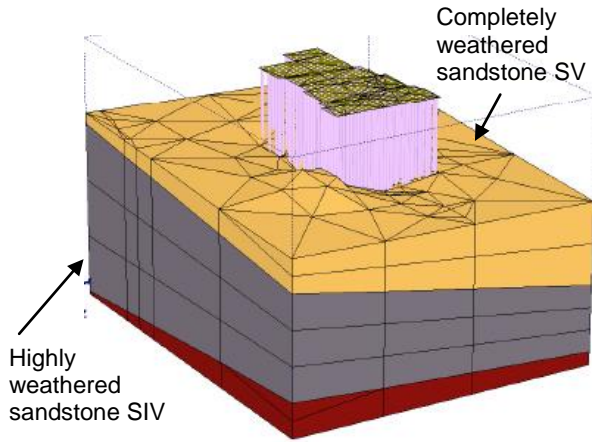


Figure 12. As-built jack-in spun piles are expected to be socketed into hard stratum such as SV and SIV sandstone due to jacking force of 2 times the working load.

Settlement of pile-raft slab was obtained through the various stages of input loading for 4 floors each of upward construction to the roof of this 43-storey tower in the 3D modelling. The settlement plots are as shown in Figure 14 for the two points T2-01 (inner part of tower) and T2-02 (outer part of tower) as shown in Figure 13, for comparison with the measured settlement values. Maximum settlement obtained from analyses is 36 mm vs. 19 mm measured value for Point T2-01 and 31 mm vs. 16 mm measured value at Point T2-02 at the completion of tower construction. Maximum settlement for this embedded pile model is 40 mm.

The trends show that Mohr Coulomb model prediction is in elastic range for the hard stratum below the toe of the piles group. Larger settlement has been observed in the two third zone of the tower footprint toward the right on plan view of Figure 13, where loadings are heavier where lift core walls are located. However, there were no measuring points in the heavily loaded zone.

It is also to be noted that there was no consideration for the consolidation of the soft soil deposits in the 3D analyses. As the tower is fully supported by piles founded in hard stratum, consolidation will have insignificant impact on the settlement of the tower. There are a few piles in tension force in the analysis. There is due to the limitation to model fully on the actual undulation of hard stratum where short piles should have founded.

2.5 Comparison with revised soil-pile block model

An attempt was made to find out the settlement of pile raft with the revised soil-pile block model by using the current geological profiles as shown in Figure 10 and soil parameters as shown in Table 3. Other input parameters such as loading and compressibility of the 13 sub-

blocks are the same to model the foundation system. See Figure 15 for the soil-pile block model made.

Legend of settlement contour shading - scaling showing variation from -22 to -41 mm

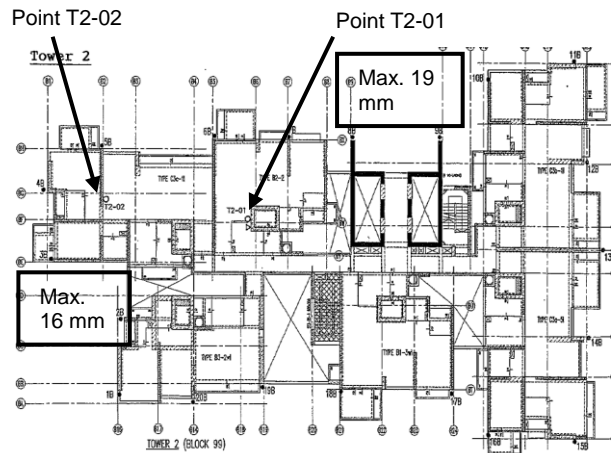
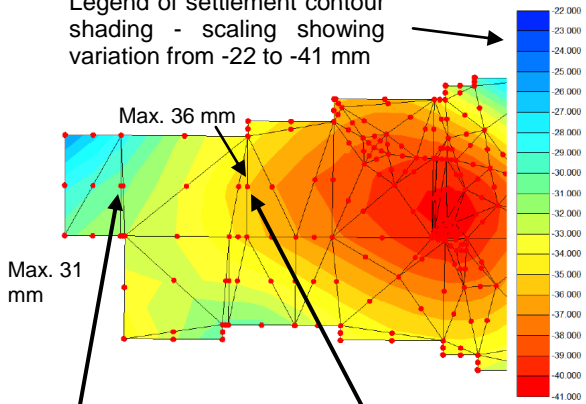


Figure 13. Plan views of Tower 2 where settlement was computed (plan above) and measured (plan below) at the same two points respectively.

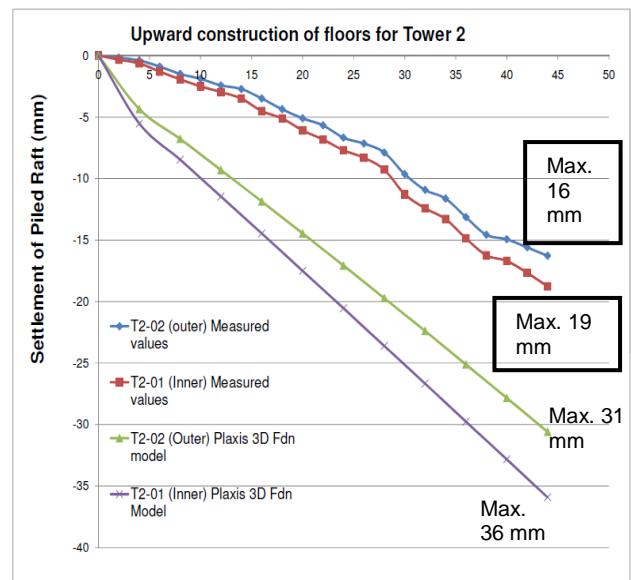


Figure 14. Settlement plots for the measured locations and for the computed values in embedded piles model

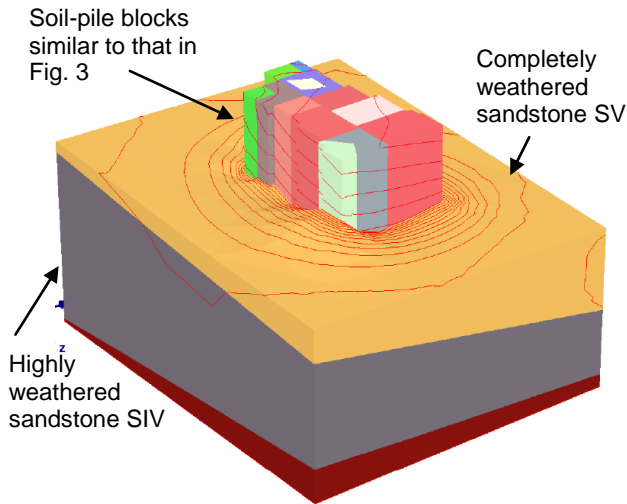


Figure 15. Revised soil-pile block model in the current geological profiles used for embedded piles model with the soil parameters used in the back analysis for the ultimate load test

Maximum settlement for this soil-pile block model is 35 mm which is comparable with the embedded piles model of 40 mm settlement. See Figure 16 below for quite a uniform settlement of the pile raft using soil-pile block model for this case. It is found that the settlement of this soil-pile block model at point T2-01 and T2-02 are 34 mm and 32 mm respectively as compared with 36 mm and 31 mm in embedded piles model at their respective locations.

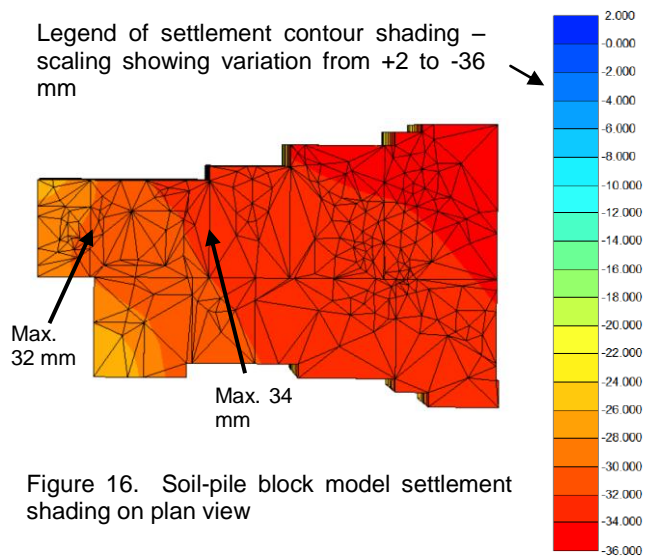


Figure 16. Soil-pile block model settlement shading on plan view

3. CONCLUSIONS

The following conclusions can be made in relation to the review of this past project on piled foundation analyses and design with close monitoring:

- i. Negative skin friction (drag load) should not be taken to reduce the allowable pile capacity of piles where downdrag is occurring.
- ii. Maximum dead load plus drag load should be taken to check for pile structural strength with an appropriate safety factor applied to the structural strength of pile.
- iii. Pile-raft settlement predictions can be carried out through soil-pile block model and embedded piles model. Both models can be found to be comparable in settlement as shown in this case study. However their results are still not close to the measured settlement due to difficulty to determine the actual undulating geological formation. Erratic sub-soils condition may have been encountered on site in view of the presence of some very short piles which were not able to be installed to the design piles penetration.
- iv. Prediction of pile-raft settlement is very much dependent on geological formation of the hard stratum from which the piles toe are important to be properly socketed /supported.
- v. Stiffness of hard stratum governs the prediction of pile-raft settlement. Accurate assessment of such stiffness can lead to more accurate prediction of pile-raft settlement.
- vi. Jack-in spun piles are generally safe even with short piles so long they have been jacked to refusal with two times of working load of piles

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