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# Settlement analysis of a building supported by raft foundation using 3D numerical modelling

Analyse de l'établissement d'un bâtiment soutenu par une fondation de radeau utilisant la modélisation numérique 3D

Truong Hoang Minh & Ng Tiong Guan

Golder Associates, Singapore, thoang@golder.com.sg

**ABSTRACT:** This paper examines the settlement behaviour of a 32-storey building supported by a 4.2m thick raft foundation using 3D numerical analysis. Two constitutive soil models have been used, i.e. Mohr Coulomb and Hardening Soil-Small Stiffness. A statistic approach is adopted to estimate the lower and upper bound of the Young's modulus for Mohr-Coulomb model. The small strain stiffness parameters derived from empirical correlations have been used for Hardening Soil-Small Stiffness model. The comparison between predictions and measurements demonstrates that whereas upper bound – Mohr-Coulomb model can predict fairly well the large settlements, it fails to replicate the small settlements measured at the lightly loaded zone. This is due to the soil small strain stiffness effect. The settlement prediction is much improved by using Hardening Soil-Small Stiffness model.

## 1 BACKGROUND INFORMATION

The proposed 32-storey new development at Shenton Way occupied the site of an existing 20-storey building with 4 levels basement. The old building, which was built in 1970's, was supported vertically by deep foundation comprises of reinforced concrete bored piles with diameter ranges between 1.1m to 1.5m. The proposed foundation for the new building comprises of a 4.2m thick raft slab supported by 1422 number of 300mm diameter micropiles. In view of hard/very stiff soil condition at the base of the raft slab, it was proposed to re-design the foundation as raft foundation and optimize the number of micropiles required using 3D finite element analysis (FEA).

The ground conditions at the raft slab level are mainly completely weathered Jurong Formation S(V) with SPT N>100 underlain by highly fractured Siltstone Jurong Formation S(IV) with TCR of 100% and RQD of 0%. Out of the 10 boreholes carried out, only 3 boreholes have weaker subsoil condition with very stiff S(V) SPT N~64.

## 2 DETAILS OF 3D FEA

The analyses are modelled using a commercial 3D FEA software, Plaxis 3D AE. Figure 1 shows the 3D model that is 121m wide x 154m long x 60m deep, comprising of 108,965 number of 10-noded tetrahedral elements. Figure 2 demonstrates the micropiled-raft foundation in 3D FEA.

6 numbers of pressuremeter tests were carried out to estimate the subsoil stiffness. 4 of the tests were carried out inof Siltstone S(IV) and 2 in Silt S(V) with SPT-N>100. Owing to a wide range of the results, a statistical approach is used to derive the upper bound and lower bound value of Young's modulus (E). Table 1 presents the input parameters for subsoil adopted in the 3D FEA.

Table 1 Input parameters for Mohr-Coulomb model

| Soil Type     | $\gamma$<br>(kN/m <sup>3</sup> ) | $c'$<br>(kPa) | $\phi'$<br>(°) | E (MPa)     |             |
|---------------|----------------------------------|---------------|----------------|-------------|-------------|
|               |                                  |               |                | Lower bound | Upper bound |
| SV N=30       | 19                               | 0             | 32             | 50          |             |
| SV N=64       | 20                               | 6             | 32             | 100         |             |
| SV N>100      | 21                               | 6             | 32             | 215         | 345         |
| Siltstone SIV | 22                               | 15            | 33             | 312         | 576         |

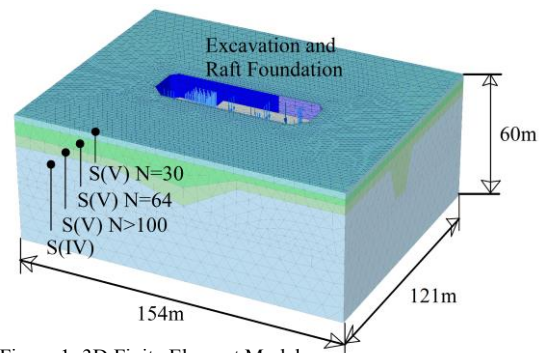


Figure 1. 3D Finite Element Model

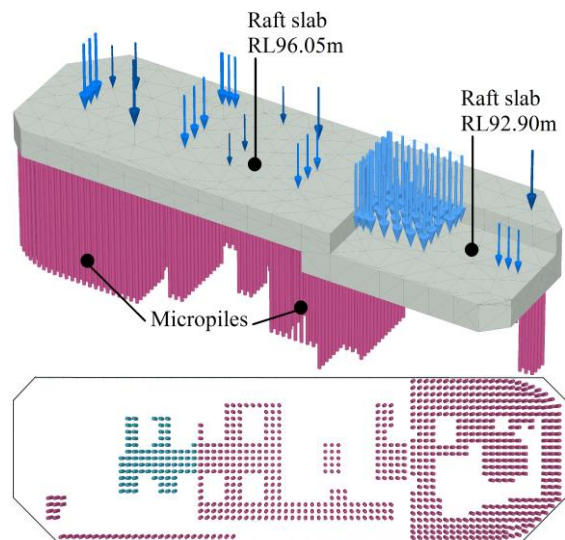


Figure 2. Micropiled-raft foundation in 3D FEA

Burland 1989 and Fahey 1999 emphasized the importance of the non-linear stiffness of soils from very small strain ( $\epsilon = 1 \times 10^{-6}$ ) to engineering strain level ( $\epsilon = 0.0001$  to 0.01). The Hardening Soil-Small Strain Stiffness (HSsmall) model in Plaxis program (Benz 2007) is able to simulate the variation of

soil stiffness from small strain, by introducing the initial shear stiffness ( $G_0$ ) and the shear strain ( $\gamma_{0.7}$ ) at which  $G_0$  is reduced to 72% of the original value. Op de Kelder (2015) demonstrated empirical correlations to estimate these two small strain stiffness parameters. The correlations have been checked with the results from pressuremeter tests based on the procedure proposed by Bellotti et al. (1989).

Table 2 Input parameters for HSsmall model

| Parameters                             | S(V) N>100         | Siltstone          |
|----------------------------------------|--------------------|--------------------|
| $\gamma$ (kN/m <sup>3</sup> )          | 21                 | 22                 |
| $E_{50}^{ref}$ & $E_{oed}^{ref}$ (MPa) | 34.5               | 50                 |
| $E_{ur}^{ref}$ (MPa)                   | 110                | 150                |
| $c'$ (kPa)                             | 6                  | 15                 |
| $\phi$ (deg)                           | 32                 | 33                 |
| $G_0^{ref}$ (MPa)                      | 150                | 200                |
| $\gamma_{0.7}^{ref}$ [-]               | $2 \times 10^{-4}$ | $1 \times 10^{-4}$ |

Three 3D analyses have been carried out, namely Analysis 1, 2 and 3. Analysis 1 and 2 adopted Mohr-Coulomb soil model, using the lower bound and upper bound stiffness value. On the other hand, HSsmall model is adopted in Analysis 3. Other modelling details for the three analyses are similar.

### 3 RESULT OF FEA

This paper presents the comparison of measured and predicted settlement when the building had been constructed to 25th floor, which is equivalent to about 50% of the total working load. Figure 10 compares the predicted settlements for Analysis 1, 2, 3 with the measurements at the corresponding load level. For Analysis 1, the prediction mostly overestimates the settlement by over 100%. For Analysis 2, the prediction matches well the measured settlement, especially at the heavily loaded zones where the deviation ranges from 0.5mm to 2.3mm. Analysis 3 generally predicts settlements 2mm smaller than that of Analysis 2. This obviously brings the results of Analysis 3 very close to the measurements. However, both Analysis 2 and 3 fail to predict the magnitude and location where maximum settlement occurs. Note that the maximum measured settlement locates at P13 where SPT-N is equal to 72. For this soil condition the soil parameters are derived from designer's past experience and judgment. Without a detail soil investigation, selected parameters for this soil condition are likely not able to represents the realistic behaviour.

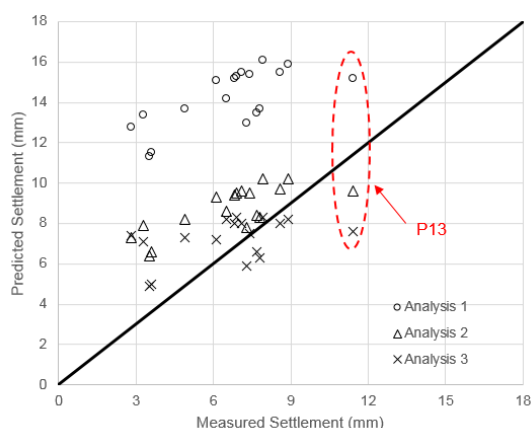


Figure 3. Measured and predicted settlements

Settlement contours resulted from Analysis 1, 2, 3 are compared with the measurement. The general trend of the settlement contour predicted by 3D FEA matches the measured contour well. All contours show large settlement concentrates at

the heavily loaded walls and lift core. The settlements gradually diminish towards the edges which are rigidly connected to the retaining walls. The measured contour however shows only 4mm settlement at the interfaces with retaining walls at short-side of the raft foundation, while the corresponding settlements for Analysis 1, 2 and 3 are 12mm, 7mm and 5mm, respectively.

Generally, the elasto-plastic Mohr-Coulomb model adopted in Analysis 2 have produced a good prediction for the area with large settlements but fails to replicate small settlements at the lightly loaded zone. This could be attributed to the inherent limitation to capture the nonlinear small strain soil's stiffness of the Mohr-Coulomb model. On the other hand, Analysis 3 adopting HSsmall model have improved significantly the accuracy of the boundary's settlements, where the small strain effect is predominant. The Analysis 3 however could not demonstrates a satisfactory prediction at the left-hand side boundary, probably due to the modelling soil profile could not replicate the actual subsoil conditions.

### 4 CONCLUSION

Numerical parametric study using Plaxis 3D has been used to model the settlement behaviour of a piled raft foundation for a high-rise building. Two constitutive soil models have been used to examine the soil behaviour, i.e. Mohr-Coulomb and HSsmall model. For Mohr-Coulomb model, a statistic approach is adopted to estimate upper bound and lower bound of the soil's stiffness. For HSsmall model, empirical correlation combined with validation from pressuremeter tests are used to estimate the soil's small strain stiffness parameters. The prediction using upper bound values shows fairly good agreement with the measured settlements. The predicted settlements nevertheless could not reproduce the settlements at the lightly loaded zones. This problem is considerably resolved by adopting HSsmall model.

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