Performance of Raft Foundation for a High-Rise Building

Kheng-Boon Chin[1(✉)], Yoshikatsu Ogawa[1], and Peng-Boon Ng[2,3]

[1] Overseas Department, Kiso-Jiban Consultants Co., Ltd., Singapore city, Singapore
CHIN_kb@kiso.com.sg

[2] Kiso-Jiban Singapore Pte. Ltd., Singapore city, Singapore

[3] KCL Consultants Pte. Ltd., Singapore city, Singapore

Abstract. In Singapore, high-rise buildings are predominantly supported by piles or piled raft foundations. Only very limited high-rise-buildings are supported by un-piled raft foundations. Amongst the scarce amount of un-piled raft foundations, almost all of them have a deep embedment depth with at least several basement levels. This paper aims to present the performance of an un-piled raft foundation with shallow embedment depth for a 30-storey high-rise building. Close monitoring of building settlement has been carried out during and post construction. The recorded maximum settlement of the 30-storey Tower One was on the order of 20 mm. This value was well within the design expectation and found to be very satisfactory. Back analysis has been carried out to determine the elastic modulus using finite element method program, known as Plaxis 3D. The back-analysed elastic modulus of the competent residual soils was found to be on the order of 500 MPa and compared with the elastic modulus derived from extensive in situ field tests (plate load and pressuremeter) and laboratory tests (oedometer and triaxial). The results showed that the second loading cycle of field tests generally give the more reasonable estimate as compared to the laboratory tests. Using limited data, an empirical relationship between elastic modulus and standard penetration testing blow counts has been proposed under small-strain foundation loading. Finally, raft foundation is recommended for future high-rise buildings to be constructed on competent residual soils.

Keywords: Raft foundation · High-rise building · Finite element · Plaxis 3D · Residual soils · Site investigation

1 Introduction

In Singapore, high-rise buildings are predominantly supported by piles or piled raft foundations. Only very limited high-rise-buildings are supported by un-piled raft foundations. These are probably due to complex heavy loadings, unfavourable ground conditions and authority's stringent requirements. Amongst the scarce amount of un-piled raft foundations, almost all of them have a deep embedment depth with at least several basement levels. This paper aims to present the performance of an un-piled raft foundation with shallow embedment depth for a 30-storey high-rise building.

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The high-rise building known as Tower One, is located at the fringe of Southern Singapore. The construction took slightly more than 2 years to be completed. Close monitoring of building settlement has been carried out up to six months post construction. The observed settlement was back-analysed and the deformation parameter was compared with the elastic modulus derived from field and laboratory tests.

2 High-Rise Building

The commercial building is a 30-storey high tower block (known as Tower One) of reinforced concrete design, with no basement. A typical frame of Tower One is presented in Fig. 1. The Tower One is about 55 m by 77 m in plan and 150 m in height. The building loads to be transferred to the foundations comprised 623 MN in corewall and 1347 MN in columns. The raft foundation has a thickness of 3.4 m, with full embedment in the ground.

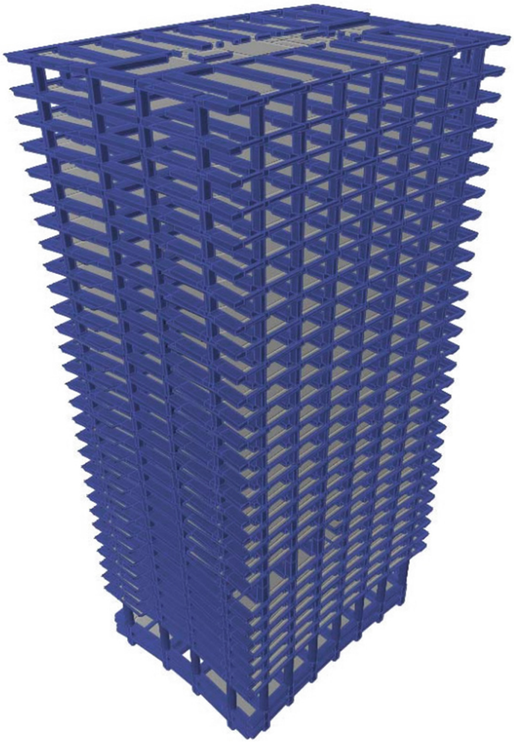


Fig. 1. Typical frame of 30-storey Tower One (Courtesy of KK Lim & Associates)

3 Ground Condition

During detailed design, a total of eleven exploration boreholes has been drilled nearby and within the footprint of the 30-storey Tower One to assess the ground condition. Some of the borehole drilling depths were up to 83 m, conforming to the Eurocode, where a depth of 1.5B (i.e., B is the width of raft) is required. The field exploration tests revealed that the subsurface soil of the site consisted of two layers, namely a thin layer of fill top soil and underlain by residual soils, originated from sedimentary rock (locally known as Jurong Formation rocks). The underlying rocks encountered were of sandstone, mudstone, siltstone and tuff. A typical soil profile within the Tower One's footprint is presented in Fig. 2. Based on drilling record, the groundwater was approximately 1 m below ground surface.

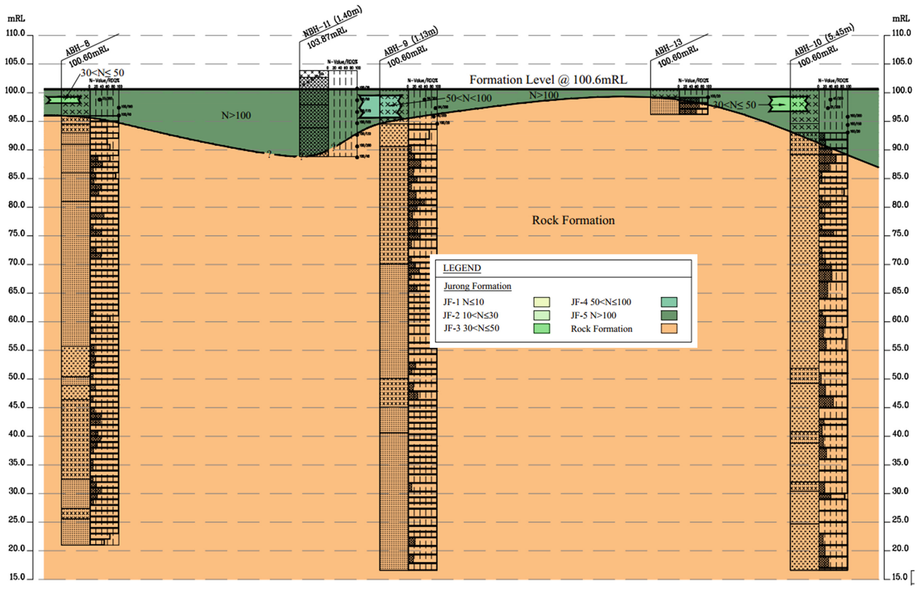


Fig. 2. Typical soil profile across the Tower One's footprint

The topography of the project site is relatively flat with an average ground elevation of +104.0 mRL while the proposed raft soffit was at +100.6 mRL. Based on the soil profile, it can be seen that the raft foundation was directly supported by hard residual soil, predominantly with high standard penetration testing blow counts, SPT-N > 100, with thickness ranging from 1.4 m to 7.6 m, overlying the sedimentary bedrocks. An approximate rock head elevation with the Tower One's footprint is illustrated in Fig. 3.

Figure 4a shows the SPT-N plot with elevation for residual soils with N $\leq$ 100. It can be seen that at relatively shallow depth, localised thin layer of residual soils with SPT-N of about 31 to 56 (35 in average) was encountered in boreholes ABH-8, ABH-9 and ABH-10. At greater depth, the residual soils had a SPT-N close to 100 with an

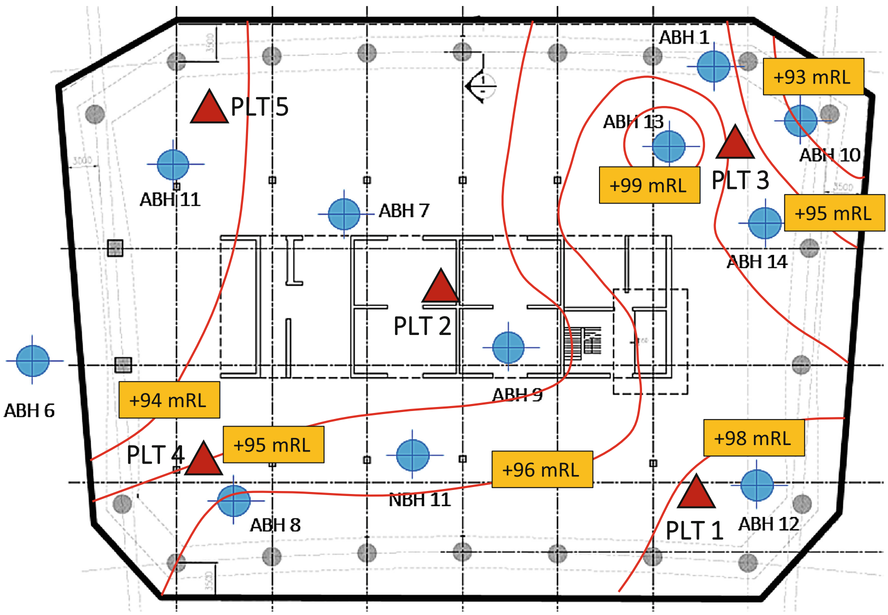
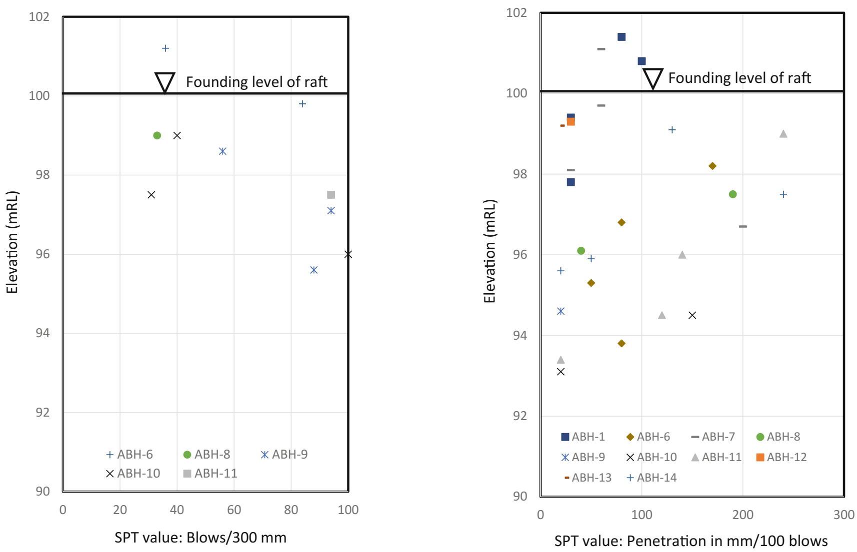


Fig. 3. Approximate rock head elevation



(a) SPT-N plot with elevation for N ≤100 (b) SPT penetration depth for N > 100

Fig. 4. Profile of standard penetration testing with elevation

average value of 90. For residual soil with SPT-N > 100, the SPT values in penetration depth over the 100 blows was plotted with elevation (Fig. 4b), in order to reduce the scattered data. Similar plot has been adopted by Leung et al. (1988). The penetration depth was ranging from 20 mm to 240 mm, with an average value of about 100 mm. When extrapolated, this penetration depth corresponds to a SPT-N value of 300.

The basic soil properties of the residual soil is given in Table 1. It can be seen that the water content was ranging from 5.7% to 13.1% and the unit weight of the residual soil is as high as 23.0 kN/m^3 with a void ratio of 0.22. The residual soils are generally classified as hard silt. Although the site investigation revealed that thin pocket lenses of very stiff residual soils were present below Tower One, however, it was judged that the wide, thick and relatively rigid raft system was able to bridge over the slightly "less competent" (30 < SPT-N < 100) hard lenses. Based on our analysis, the hard residual soils have an allowable bearing capacity of more than 1000 kPa, which exceeds the maximum design bearing pressure of 900 kPa. Thus, it is recognised that settlement was a critical factor under the serviceability load of the raft foundation.

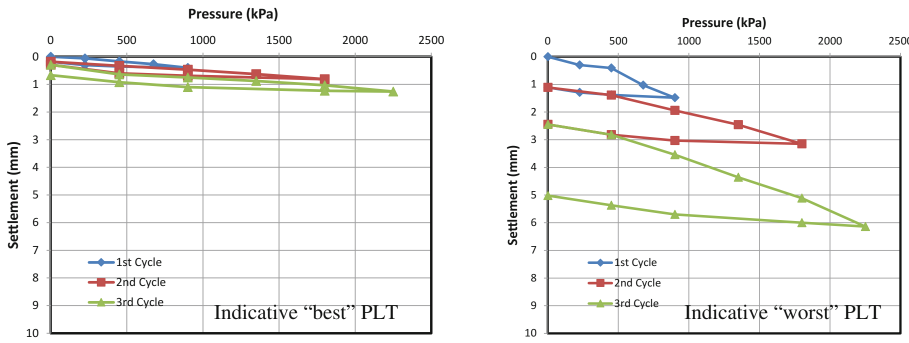
Table 1. Basic soil properties of residual soils with SPT-N > 100

Properties	Values
Water content, w (%)	5.7–13.1
Specific gravity	2.68–2.80
Unit weight, γ (kN/m^3)	19.5–23.0
Void ratio	0.22–0.56
Atterberg Limits:	
– Liquid Limit, LL (%)	36–45
– Plastic Limit, PL (%)	18–22
– Plasticity index, PI (%)	18–23
Grain size:	
– Sand	23–25
– Silt	54–60
– Clay	15–23

4 Evaluation of Deformation Parameter

4.1 Plate Load Test

A total of five plate load tests have been carried out near the founding level of raft foundation. The test has been loaded up to 2.5 times of the design allowable bearing capacity. Three loading cycles have been included in this test. Two typical pressure-settlement curves are presented in Figs. 5a and b, representing the indicative



(a) Pressure-settlement curve for PLT 2 (b) Pressure-settlement curve for PLT 5

Fig. 5. Typical pressure-settlement curve using plate loading test

"best" and "worst" ground conditions, respectively. The elastic modulus has been obtained using the solution reported by Poulos and Davis (1974). The equation is given as follows:

$$E = \frac{\pi q r}{2\delta}\left(1 - v^2\right) \tag{1}$$

where q is the applied pressure, r is the radius of the plate, δ is the settlement and υ is the Poisson's ratio of the soil and taken as 0.33. Using the working stress of 900 kPa, the elastic modulus derived from plate load test for the 1^{st}, 2^{nd} and 3^{rd} cycle were ranging from 74 MPa to 482 MPa (189 MPa in average), 161 MPa to 665 MPa (302 MPa in average) and 125 MPa to 1930 MPa (630 MPa in average), respectively.

4.2 Pressuremeter Test

A total of four pressuremeter tests have been carried out on residual soil with SPT-N > 100. An OYO monocell pressuremeter has been used in this site investigation campaign. A test depth ranging from 2.5 m to 7 m has been investigated in boreholes ABH-8, ABH-10 and ABH-11. Figure 6 shows the pressuremeter modulus of the hard residual soil. It can be seen that the pressuremeter modulus was ranging from 40 MPa to 230 MPa (135 MPa in average) and 160 MPa to 700 MPa (435 MPa in average) for 1^{st} cycle and 2^{nd} cycle, respectively. It should be noted that in some tests, the failure pressure cannot be determined, as it was well beyond the pressure capacity measurement (i.e. 5 MPa) of pressuremeter.

4.3 Oedometer Test

A total of four consolidation tests have been carried out using oedometer. The specimens were subject to two loading cycles. A typical oedometer loading curve is shown in Fig. 7. The oedometer modulus, E_{oed}, or known as constrained modulus, has also been determined at the effective vertical stress of interest. Based on theory of elasticity,

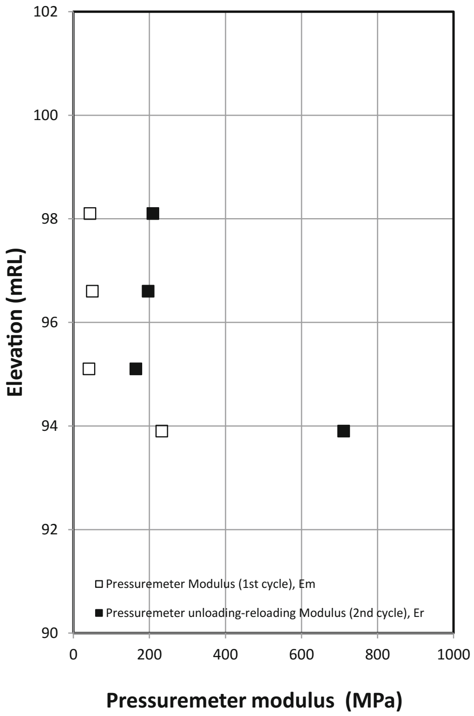


Fig. 6. Pressuremeter modulus with elevation

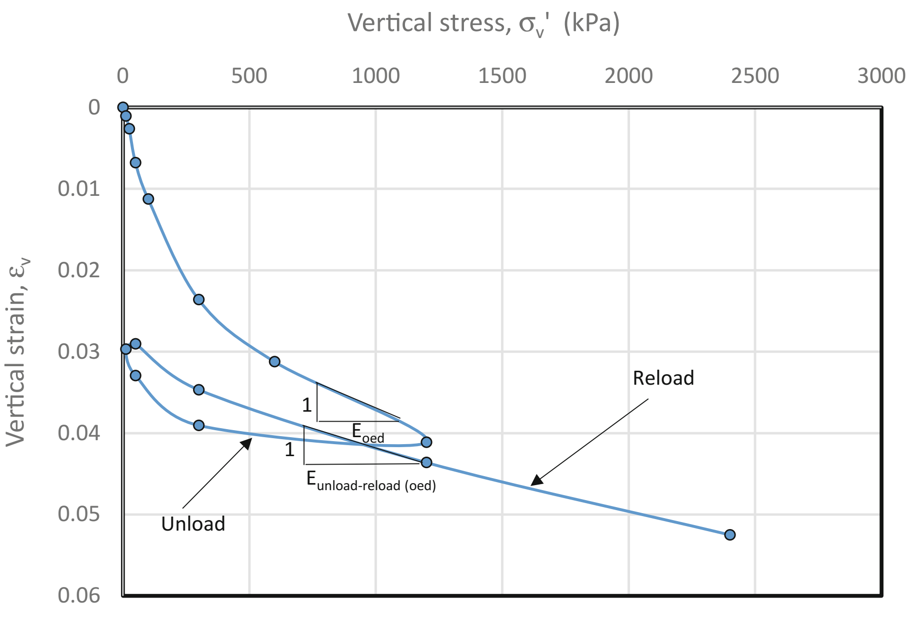


Fig. 7. Typical oedometer loading curves with modulus determination

the relationship between elastic modulus and oedometer modulus can be written as follows:

$$E = \frac{E_{oed}(1+v)(1-2v)}{(1-v)} \tag{2}$$

where υ is the Poisson's ratio. Under working load condition, the operational υ is in the range from 0.1 to 0.2 (Tatsuoka et al. 1994; Lo Presti et al. 1995). Using a Poisson ratio of 0.15, the elastic modulus of the residual soil was ranging from 27 MPa to 86 MPa while the unload-reload elastic modulus was ranging from 52 MPa to 181 MPa under an average effective vertical stress, σ_v' of 900 kPa.

4.4 Triaxial Test

Three single-stage consolidated drained (CD) triaxial tests have been carried out on the hard residual soil. The soil specimens were loaded at a slow speed with unload-reload cycle up to an axial strain of about 20%. Figure 8 shows the typical triaxial test with unload-reload cycle with elastic modulus determination. The secant elastic modulus derived from triaxial test was ranging from 21 MPa to 99 MPa while the unload-reload modulus was ranging from 151 MPa to 354 MPa, under effective confining pressures ranging from 300 kPa to 1200 kPa.

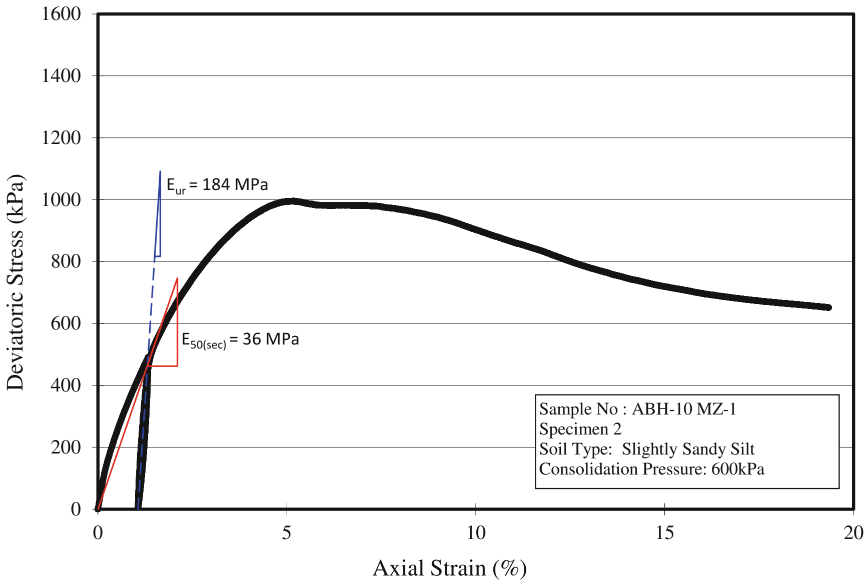


Fig. 8. Typical triaxial test with modulus determination

5 Monitoring and Observation Results

A total of eight building settlement markers have been strategically placed to monitor the settlement behaviour of the raft foundation. The performance of the raft foundation was closely monitored during both the construction and post-construction stages. The settlement readings for all the eight settlement markers are presented in Fig. 9. It can be seen that the settlement increased as the construction progressed, at a rate of approximately 1 mm for every 2 storeys. A final settlement ranging from 14 mm to 18 mm has been recorded with the maximum value being measured at the centre of the raft. Upon completion of construction, most of the settlement readings appear to have stabilised. The instrumentation monitoring was terminated six months post construction and the final settlement reading of each of the markers is presented in Fig. 10.

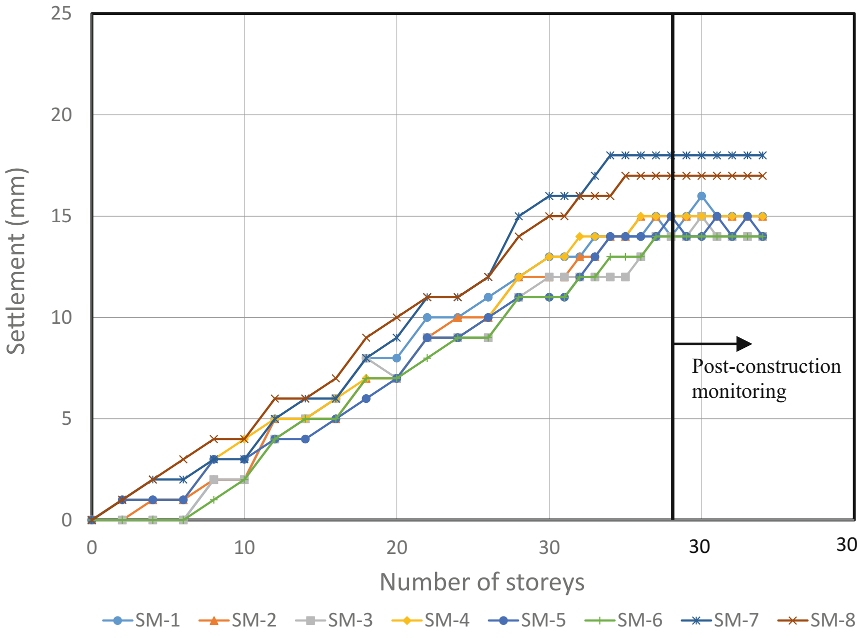


Fig. 9. Settlement readings for Tower One

5.1 Finite Element Model

Back analysis has been carried out using finite element method program, known as Plaxis 3D. Mohr-Coulomb model has been chosen in the analysis due to its simplicity and widely acceptance by the local authority. The raft has been modelled using plate element. The column and corewall loads have been modelled using point load and uniformly distributed load, respectively. A total load of 1970 MN was imposed on the raft with approximately 32% was supported by corewall and the remaining by columns.

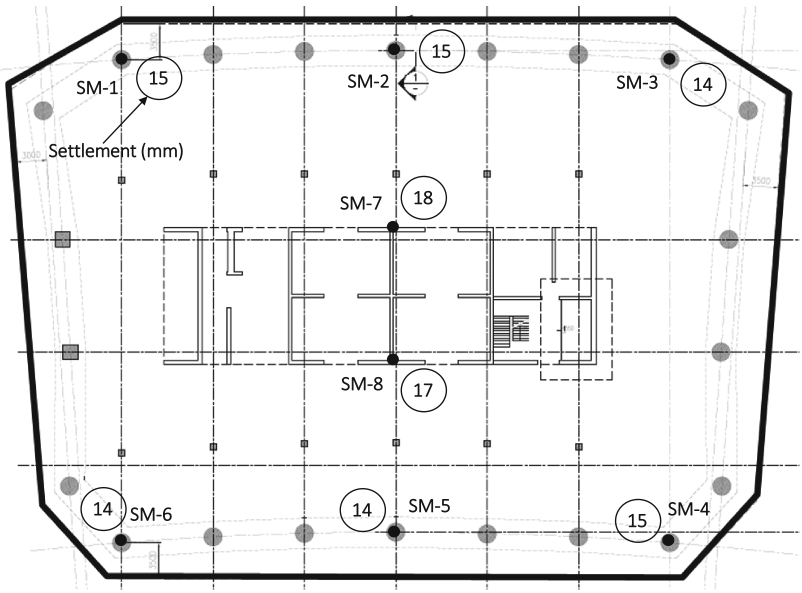


Fig. 10. Final settlement readings across the Tower One

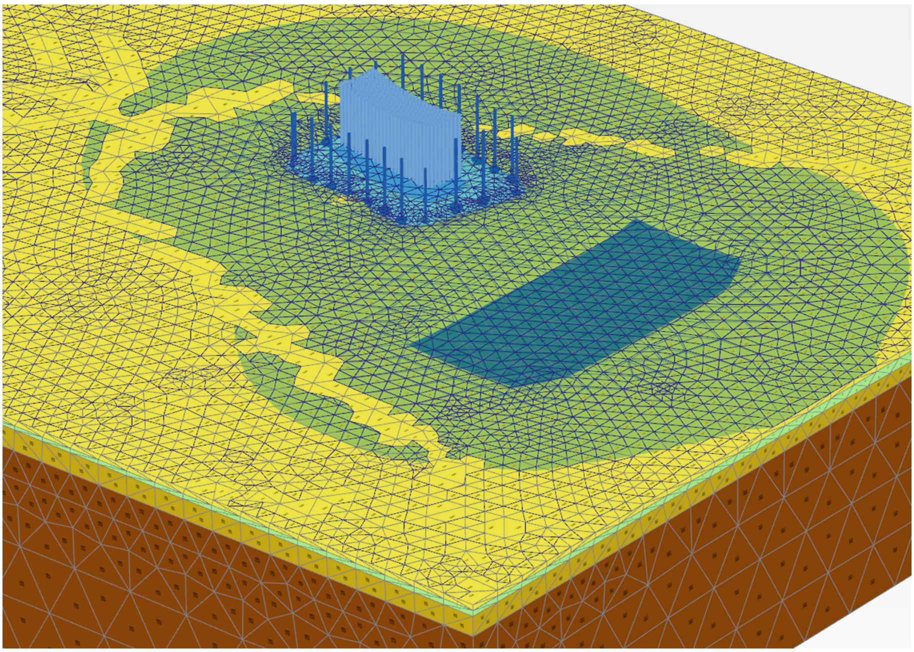


Fig. 11. Finite element model of raft foundation

Based on our past experience on the adjacent building founded on similar rocks, an elastic modulus of 2 GPa was adopted in this study. A typical finite element model of the raft foundation is illustrated in Fig. 11.

Based on the finite element method, the back analysed elastic modulus for the competent residual soil (SPT-N > 100) is on the order of 500 MPa. This value is about the same magnitude reported elsewhere in Singapore where the raft foundations were founded on bouldery clays (Adachi 1987; Ooi 1994; Wong et al. 1996). The resulting settlement contour based on the finite element analysis is presented in Fig. 12. As expected, the maximum settlement can be observed at the corewall centre with a slightly smaller settlement at the perimeter of the raft.

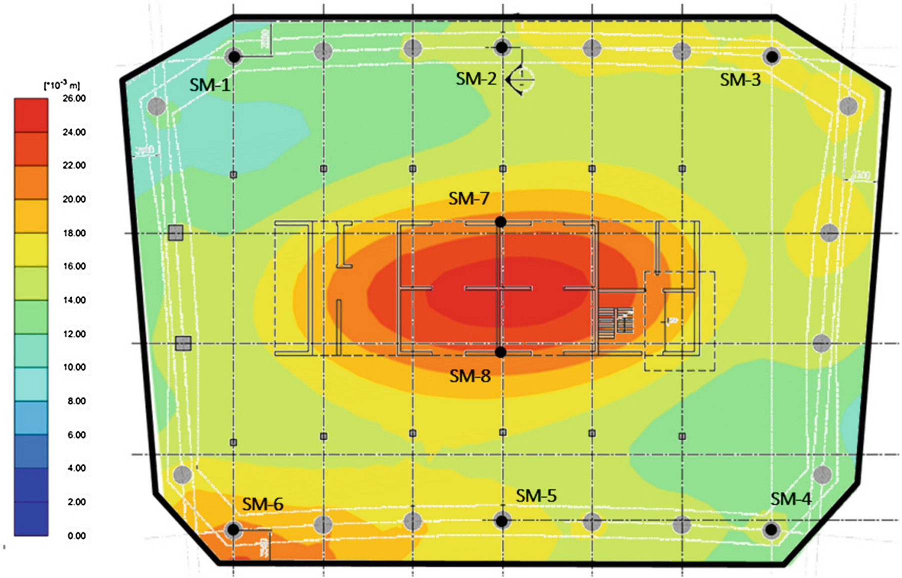


Fig. 12. Settlement contour of raft foundation based on finite element analysis

6 Discussion

Table 2 shows the summary of elastic modulus derived from both the field and laboratory tests. A comparison has been made amongst the field, laboratory and back-analysed elastic modulus. It was found that 2nd loading cycle for plate loading test and pressuremeter test give the more reasonable estimate when compared to the back-analysed value. The 3rd loading cycle of plate load test slightly over estimated the back-analysed elastic modulus. Based on the field test results, it can be postulated that a lower elastic modulus measured in the first loading cycle was likely because of the soil disturbance induced due to drilling of borehole for pressuremeter test and excavation for plate load test.

Table 2. Summary of elastic modulus derived from both the field and laboratory tests

Tests		Elastic modulus (MPa)
Plate load test	1^{st} loading cycle	74–482 (189)
	2^{nd} loading cycle	161–665 (302)
	3^{rd} loading cycle	125–1930 (630)
Pressuremeter test	1^{st} loading cycle	40–230 (92)
	2^{nd} loading cycle	160–700 (320)
Oedometer test	1^{st} loading cycle	26–81 (61)
	2^{nd} loading cycle	49–171 (108)
Triaxial test*	1^{st} loading cycle	21–99 (52)
	2^{nd} loading cycle	151–354 (230)

Notes: (1) Values in parenthesis indicate average values.
(2) *Stress ranging from 300 kPa to 1200 kPa.

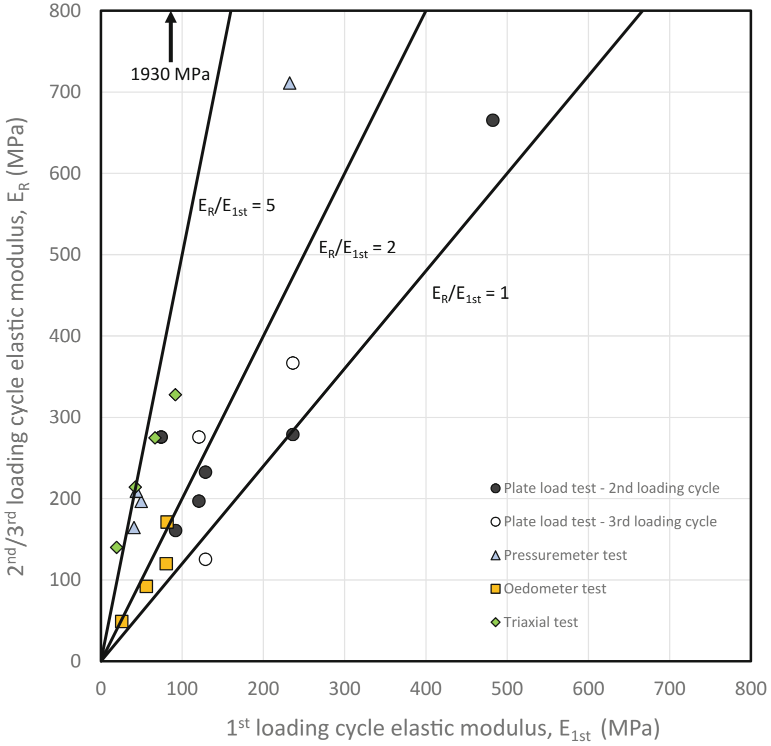


Fig. 13. Relationship between 1^{st} loading and reloading cycles elastic modulus

For laboratory test, the unload-reload elastic modulus derived from triaxial and oedometer tests was much lower than the back-analysed value. Using the laboratory value, the estimated settlement would have been much higher and not realistic. Based on this observation, field tests generally provide a more realistic modulus deformation as compared to laboratory test. This is largely due to the sampling disturbance (i.e., difficult sampling for hard soil and stress relief) for laboratory tests.

From Fig. 13, it can be observed that the average field and laboratory elastic modulus determined from $2^{nd}/3^{rd}$ to 1^{st} loading cycle has a ratio ranging from 1 to 5. This is generally consistent with the values reported in the literature (Adachi 1987; Wong et al. 1996). In the absence of unloading-reloading test cycle, it is suggested that the average elastic modulus determined from single loading cycle can be multiplied by a factor of 2 for practical purpose.

In Singapore, it is widely accepted that the elastic modulus can be correlated to SPT-N with a generalised equation as follows:

$$\frac{E}{p_{atm}} = k \times N \tag{3}$$

where k is the empirical constant and p_{atm} = atmospheric pressure (≈100 kPa).

An attempt has been made to establish a correlation for the elastic modulus with SPT-N under raft foundation loading. Based on the limited data, it appears to suggest

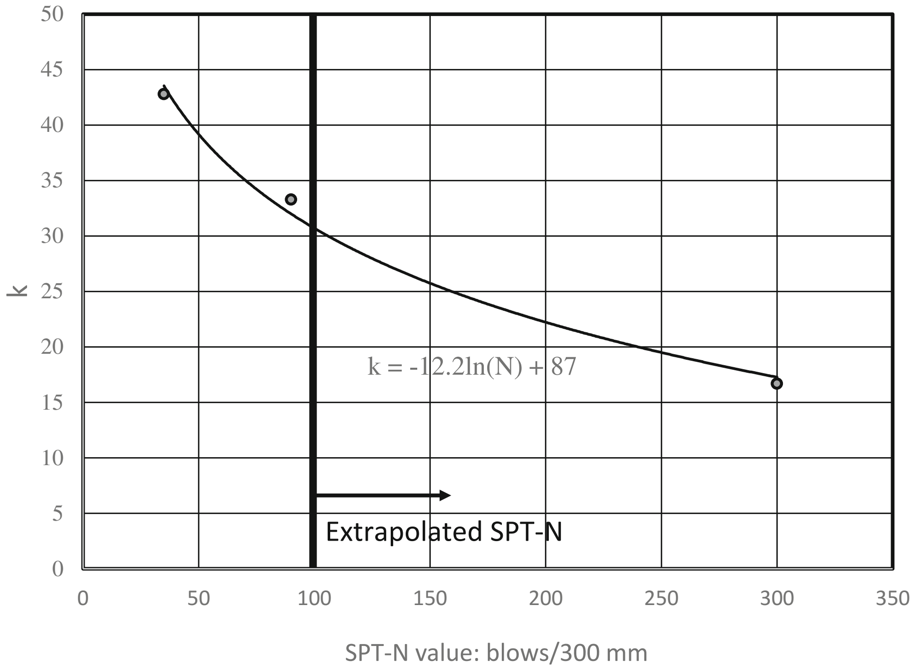


Fig. 14. Variation of k with SPT-N

that elastic modulus of the residual soil is not linearly related to SPT-N. A logarithmic equation is proposed in this study and given below.

$$k = -12.2\ln(N) + 87 \tag{4}$$

where the proposed k generally is ranging from 18 to 45 for $35 < N \leq 300$, as depicted in Fig. 14. This finding is generally in good agreement with the values reported by Goh et al. (2012) where k values were ranging from 25 to 96 under the mobilised radial strains of 0.1% to 1% using pressuremeter test.

Combining Eqs. (3) and (4), the elastic modulus can be re-written as follows:

$$\frac{E}{p_{atm}} = -12.2(N)\ln(N) + 87(N) \tag{5}$$

Using Eq. (5), the increasing elastic modulus with SPT-N is illustrated in Fig. 15. It should be noted that the proposed equation has been developed under foundation loading where the mobilised strain is expected to be in the region of 0.05% to 0.1% (Mair 1993). Further study is required to refine this relationship.

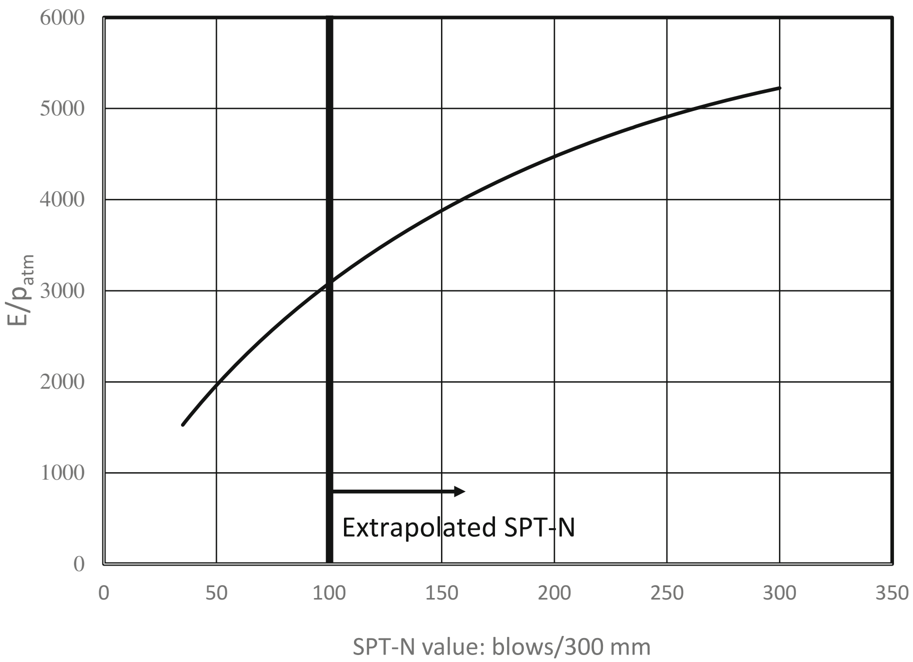


Fig. 15. Proposed relationship between elastic modulus and SPT-N

7 Conclusions

The performance of the 30-storey high-rise building's raft foundation with shallow embedment depth in Jurong Formation residual soils has been evaluated. The recorded maximum settlement of the 30-storey Tower One was on the order of 20 mm. This value was well within the design expectation and found to be very satisfactory. Back analysis has been carried out to determine the elastic modulus of residual soils using finite element method. The back-analysed elastic modulus of the competent residual soils was found to be on the order of 500 MPa. It has also been observed that the second loading cycle of field tests generally give the more reasonable estimate as compared to the laboratory tests. Using limited data, an empirical relationship between elastic modulus and SPT-N has been proposed under small-strain foundation loading. Finally, raft foundation is recommended for future high-rise buildings to be constructed on competent residual soils.

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