Piled Foundation for High-Rise Buildings in Singapore

T.G. Ng
Golder Associates, Singapore

T.Y. Poh
Building and Construction Authority, Singapore

ABSTRACT: In Singapore, most high-rise buildings are supported on bored piles. In view of the complex geology in Singapore, each and every geology formation poses different challenges to the pile construction. The migration from Singapore Standard CP4 to EC7 since April 2015 also poses some challenges to the designers due to the change in design philosophy and approach. This paper presents the state of practise in design and construction of pile foundation for high-rise buildings in Singapore. The evolution of design approach from SS CP4 to EC7 and the salient differences in the structural and geotechnical designs between the two standards are discussed. This includes the advancement of pile load test method from conventional kentledge system to bi-directional load test and Rapid Load Test. To ensure safe and robust design of deep foundation for high-rise building, relevant building control regulations and advisory notes are issued by BCA over the years. Among others, the emphasis are on the allowable pile settlement during pile load test and building settlement under design loadings. Various method used to predict foundation settlement and key factors affecting the actual building settlement are be presented. Case studies from 29 recently completed high-rise buildings will be used to illustrate the state practice in the pile settlement predictions as compared to the actual measurements.

1 INTRODUCTION

In Singapore, most high-rise buildings are supported on deep foundations. Most these buildings are supported on bored piles with the exception of few supported on large diameter caisson piles. Examples of high-rise buildings supported by large diameter caisson piles include OUB Centre, UOB Plaza, Republic Plaza, Maybank building, Capital Tower and Ocean Financial Building. In areas where the ground condition is favourable, high-rise buildings could also be supported on raft foundation such as Fusionopolis Phase 1, Raffles City Complex, Savu Tower and Shell Tower.

For project where diaphragm walls are adopted as earth retaining system for basement construction, barrette piles, which could be constructed using the same plants and machineries for diaphragm walls, are often use as deep foundation elements.

Examples of high-rise buildings supported on barrette piles includes Marina Bay Sand towers, The Sail @ Marina Bay, ION Orchards and HDB housing development at Clementi.

A survey was conducted on 38 recently completed high-rise buildings, with more than 30 storeys height, to find out the distribution of type of foundation system adopted. Results of survey are summarised in Table 1. It is noted that four types of pile, namely bored pile, barrette pile, large diameter caisson pile and pre-stressed concrete spun pile, have been adopted as the foundation system for these high-rise buildings. The results also show that 84% of the high-rise buildings surveyed are founded on bored piles with diameter up to 3.5 m in diameter. This practice may be attributed to relatively high load carrying capacity of bored piles, and availability of many piling contractors that can install these bored piles though various types of soils and rocks at competitive pricing. There are two cases where large caisson piles were adopted for foundation of high-rise buildings. In one of the sites, the ground consists of boulder clay matrix where conventional small to medium size bored piles is unsuitable and the remaining site, the ground consisted of siltstone and mudstone of Jurong Formation. For the three sites that adopted barrettes pile foundation, diaphragm walls are adopted as the earth retaining system.

Table 1 Distribution of type of piled foundation used in supporting 38 recent completed high-rise buildings with 30 or more storeys.

Type of foundation	Description	Number of cases
Bored pile	Up to 3.5 m in diameter	32
Barrette pile	Up to 1.5 m by 8.4 m	3
Caisson pile	Up to 6 m in diameter	2
Pre-stressed spun pile	Up to 0.6 m in diameter	1

2 CHALLENGES OF PILE CONSTRUCTION

Although Singapore is small in land area, the geological setting of the island state is relatively complex. The first geology map of Singapore was published by Public Works Department (PWD) in 1976. The 2nd Edition of the Geology of Singapore was published by the Defence Science and Technology Agency (DSTA) in 2009.

Building and Construction Authority of Singapore (BCA) initiated a study in 2013 to review and proposed a structured classification for all of the lithostratigraphic units of Singapore in compliance with the recommendations of International Commission of Stratigraphy (ICS). The BCA study is still in progress and the final report has yet to be officially published though the preliminary findings of the study have been shared with the construction industries through public seminars.

The names assigned to the geological formations published in the Geology of Singapore publications, which are well-established and widely used by geologist and geotechnical engineers in Singapore, will be referred in this paper. The 5 major geological formations related to pile construction in Singapore include Bukit Timah Formation, Jurong Formation, Fort Canning Boulder Bed (FCBB), Old Alluvium Formation and Kallang Formation.

2.1 Bukit Timah Formation

Bukit Timah Formation underlie about a third of Singapore Island covering the central and the north shore of the island. It comprises of predominantly granite rock with high content of quartz and feldspar. The fresh rock has average UCS of 160 MPa with the highest value in excess of 300 MPa. It exists in various state of weathering from residual soil, typically found at shallower depth, to fresh granite at much deeper depth. Due to the nature of the tropical weathering, the Bukit Timah Formation is characterized by undulating rock head profile and sudden change from residual soil G(VI)/completely weathered granite (GV) to moderately weathered granite (GIII)/ slightly weathered granite (GII). The presence of boulders in Bukit Timah Formation have been reported in projects around Bukit Batok, Hillview, Bukit Panjang, Mandai, Woodlands.

The relatively high strength granite rocks pose great challenge in pile construction in Bukit Timah Formation. High capacity piling machines with suitable rock coring tools are required to form piles with sufficient rock socket to mobilise the shaft and base resistances in the rock stratum. In areas where boulders are known to exist, comprehensive site investigation is required to eliminate the risk of founding the pile on boulder instead of on the bedrock.

2.2 Jurong Formation

Jurong Formation is found predominantly in the western and southwestern part of Singapore Island. It is known to exist in bedded and folded form. Depending on the location where it is found, the lithological components of Jurong Formation may comprise the combination of limestone, mudstone, sandstone and the conglomerate.

The folding nature of Jurong Formation and undulating rock head profile may result in varying pile length within a short distance, or among piles within the same pile cap. For piling in limestone area with the presence of cavity, rock level could be highly variable and present of the cavity could be erratic. Hence, the designer need to be vigilant, conduct adequate site investigation, for instance carry out probe hole at every pile/pile group location, to determine the size and depth of the cavity and to establish proper acceptance criteria for successful installation of the piles.

2.3 Fort Canning Boulder Bed (FCBB)

Fort Canning Boulder Bed underlies part of the Central Business District in Singapore as reported by Shirlaw et al. (2003). It typically consists of relatively fresh quartzite or sandstone boulders in soil matrix comprises of silt and clay particles. The presence of boulders in FCBB, which is random in size and position, poses the same challenge in pile construction as that of boulder site in the Bukit Timah Formation. Adequate site investigation, possibly using the combination of direct boreholes and indirect geophysical method, shall be used to identify the presence of boulders in the FCBB. Suitable piling machineries and tools shall be used to ensure that the piles are able to be constructed to the required depth to ensure safe and efficient design of the foundation system.

2.4 Old Alluvium Formation

The Old Alluvium Formation underlies mainly the eastern part of Singapore Island. The thickness varies from few tens of meters to more than 200 meters. It comprises mainly of interbedded layers of sand, silt and clay sediments. Its weathering grade is typically reducing with depth while the SPT N value is increasing with depth. Old Alluvium Formation is considered to be the most construction friendly material for pile construction as compared with the other geological formations. Results from various pile load tests have shown that though the pile could be form relatively easily in Old Alluvium Formation, the mobilized shaft resistance and base resistance in Old Alluvium Formation may varies depending on the method of pile construction and workmanships of the piling contractors. Hence, care shall be taken in utilising results of pile load tests from adjacent site in the piling design.

2.5 Kallang Formation

Kallang Formation is predominantly found in the low lying areas such as river basin, river mouth, and coastal areas around Singapore Island. Considerable thickness of Kallang Formation has been found deposited around the basins of Kallang River and Singapore River. It comprises sediments with marine, alluvial, littoral and estuarine origins. The main components are Upper Marine Clay, Lower Marine Clay, fluvial sand, fluvial clay and estuarine clay. In areas where the Kallang Formation is overlain by recent reclamation fill, the soft clay is likely to be under-consolidated. Design of deep foundation in such formation will need to consider the negative skin friction or down-drag forces induce by the consolidating soil layers onto the pile shaft. Besides the temporary steel casing, stabilizing fluid in the form of bentonite or polymer slurry are necessary to maintain the borehole stability during the pile construction. To ensure the structural integrity of the piles, which may be subjected to lateral forces induced by soil displacement caused by excavation for pile cap or basement constructions, the pile reinforcement shall be designed adequately and be extended into the competent soil stratum.

3 DESIGN STANDARD FROM CP4 TO EC7

Prior to 2003, foundation design is based on British Standard (SS) BS8004:1986 Code of Practice for Foundations. In 2003, SPRING Singapore published a local version of foundation code namely Singapore Standard CP4:2003 Code of Practice for Foundations. There are a few clauses in SS CP4 that are specifically written to suit the local practices. These include: a) recommended unit shaft resistance and unit base resistance for local soils; b) allowable concrete compressive stress of bored piles limited to 7.5MPa; c) allowable pile top settlements of 15mm and 25mm under 1.5

times and 2.0 times working load test, respectively; and d) use of short column design principal, taking into account the contribution of reinforcement bars, to enhance the structural capacity of pile.

BCA introduced the Eurocodes as Singapore's building codes on 1 April 2013 with 2-year of British Standards and Eurocodes co-existence period. Thereafter, from 1 April 2015 all structural design shall comply with Eurocodes and the relevant design codes based on the British Standards, including SS CP4, were withdrawn and listed as non-contradictory complementary information in the national annex of the Eurocodes.

Eurocode 7: Geotechnical Design is the design code for foundation design among the suit of other Eurocode. The principles of Eurocodes mandate the designers' responsibility to ensure structural safety, serviceability and durability of the designs. From the onset, the designers are responsible for the planning of the geotechnical investigation, including specifying types and quantities of field and laboratory tests, and determination of geotechnical design parameters and characteristic values etc.

To help the construction industry on the transition from BS Code to Eurocode, the Geotechnical Society of Singapore (GeoSS) published the "*Guide on Ground Investigation and Geotechnical Characteristic Values to Eurocode 7*" on 24 April 2015 in conjunction with a *One-day Seminar on Ground Investigation, Design Parameters and Pile Design in Compliance with EC7* held at Ramada Hotel.

3.1 Structural Capacity

In SS CP4, the allowable concrete compressive stress, σ_c is limited to $0.25f_{cu} < 7.5$ MPa. On the other hand, there is no cap in the allowable concrete compression stress in EC7. In the latter, the design concrete compressive stress is depend on whether the pile is reinforced or un-reinforced. The various partial factors applicable to EC7 in determining the structural pile capacity, and its comparison with SS CP4 are summarized in

Table 2.

Table 2 Formula for pile structural capacity

CP4	EC7
Allowable concrete compressive stress, $\boldsymbol{\sigma_c = 0.25\,f_{cu} < 7.5MPa}$ **Pile working load,** $\boldsymbol{Q_{st} = \sigma_c \,.\, Ac}$	SS EN 1992-1: $N_{Rd,p} = A_c f_{cd,p} > N_{Ed} = 1.35G_k + 1.5Q_k$ $f_{cd,p} = \alpha_{cc,p}\, f_{ck} / \gamma_{c,f}$ $\alpha_{cc,p}$= 0.85 (reinforced); $\alpha_{cc,p}$= 0.60 (un-reinforced) $\gamma_{c,f} = \gamma_c \times k_f = 1.5 \times 1.1 = 1.65$ $f_{ck} = 0.8\, f_{cu}$ <u>Reinforced</u> $N_{Rd,p} = A_c \times 0.412 \times f_{cu}$ <u>Un-Reinforced</u> $N_{Rd,p} = A_c \times 0.291 \times f_{cu}$ cast in place piles without permanent casing. A_c should be taken as: - if *d*nom < 400 mm *d* = *d*nom - 20 mm - if 400 ≤ *d*nom ≤ 1000 mm *d* = 0.95.*d*nom - if *d*nom > 1000 mm *d* = *d*nom - 50 mm

Table 3 tabulates a comparison of structural pile capacity between EC7 and SS CP4 using concrete grade f_{cu} of 35MPa and 40MPa. Assuming an average load factor of 1.4 for G_k and Q_k, the allowable structural capacity of an un-reinforced concrete pile constructed using f_{cu} = 40MPa would be equivalent to that of the SS CP4. Conventionally in SS CP4, the main rebar for bored pile shall satisfy As ≥ 0.5% Ac. The length of the rebar cage is typically 12m if the pile is not in soft clay or the pile is not anticipated to be subject to any lateral load. In EC7, the minimum requirement of the main rebar is actually depending on the cross sectional area of the pile as shown in Table 4. For the case of un-reinforced concrete section below the 12m rebar cage, the EC7 is actually having lower structural capacity if f_{cu} < 40MPa as shown in Table 3.

Table 3 Comparison in pile structural capacity EC7 vs CP4

Case 1: f_{cu} = 35MPa				EC7 (Factored capacity, $N_{Rd,p}$)		EC7 (Service load) Avg. Load Factor = 1.4		WL by CP4
d_{nom}	A_{nom}	d	A_c	Reinforced	Un-Reinf	Reinforced	Un-Reinf	σ_c = 7.5MPa
(mm)	(m²)	(mm)	(m²)	(kN)	(kN)	(kN)	(kN)	(kN)
800	0.503	760	0.454	6543	4619	4674	3299	3770
900	0.636	855	0.574	8282	5846	5915	4176	4771
1000	0.785	950	0.709	10224	7217	7303	5155	5890
1100	0.950	1050	0.866	12490	8816	8921	6297	7127
1200	1.131	1150	1.039	14982	10576	10702	7554	8482
1300	1.327	1250	1.227	17701	12495	12644	8925	9955

Case 2: f_{cu} = 40MPa				EC7 (Factored capacity, $N_{Rd,p}$)		EC7 (Service load) Avg. Load Factor = 1.4		WL by CP4
d_{nom}	A_{nom}	d	A_c	Reinforced	Un-Reinf	Reinforced	Un-Reinf	σ_c = 7.5MPa
(mm)	(m2)	(mm)	(m2)	(kN)	(kN)	(kN)	(kN)	(kN)
800	0.503	760	0.454	7478	5279	5342	3771	3770
900	0.636	855	0.574	9465	6681	6761	4772	4771
1000	0.785	950	0.709	11685	8248	8346	5892	5890
1100	0.950	1050	0.866	14274	10076	10196	7197	7127
1200	1.131	1150	1.039	17123	12087	12230	8633	8482
1300	1.327	1250	1.227	20230	14280	14450	10200	9955

Table 4 Minimum requirement of main rebar CP4 vs EC7

CP4	EC7	
A_s ≥ 0.5% Ac	SS EN 1992-1: 9.8.5(3)	
	Cast-in-place bored pile cross-section, Ac	**Min area of longitudinal reinforcement, $A_{s,bpmin}$**
	Ac ≤ 0.5 m²	As ≥ 0.5% Ac
	0.5 m² < Ac ≤ 1.0 m²	As ≥ 25 cm² (0.25%Ac - 0.5% Ac)
	Ac > 1.0 m²	As ≥ 0.25% Ac

3.2 Geotechnical Capacity

In SS CP4, the allowable geotechnical capacity of pile is expressed as the most onerous of the following load cases:

$$Qa_{case1} = \left(\frac{Qs + Qb}{2.5}\right) \tag{1}$$

$$Qa_{case2} = \left(\frac{Qs}{2.0} + \frac{Qb}{3.0}\right) \tag{2}$$

$$Qa_{case3} = \left(\frac{Qs}{1.5}\right) \tag{3}$$

$$Qa = Min\left(Qa_{case1}, Qa_{case2}, Qa_{case3}\right) > WL > (DL + LL) \tag{4}$$

Where Qa = allowable geotechnical capacity; Qs = ultimate shaft resistance; Qb = ultimate base resistance; WL = working load; DL = dead load; LL = live load. Load case shown in Equation (3) are not mandatory but an industry good practice.
By rearranging equation (1), (2) and (3) and define geotechnical Factor of Safety, FoS_geo = Total Geotechnical Resistance / (DL + LL), the variation of FoS_geo with shaft and base resistance contribution for the three equations can be represented in Figure 1.

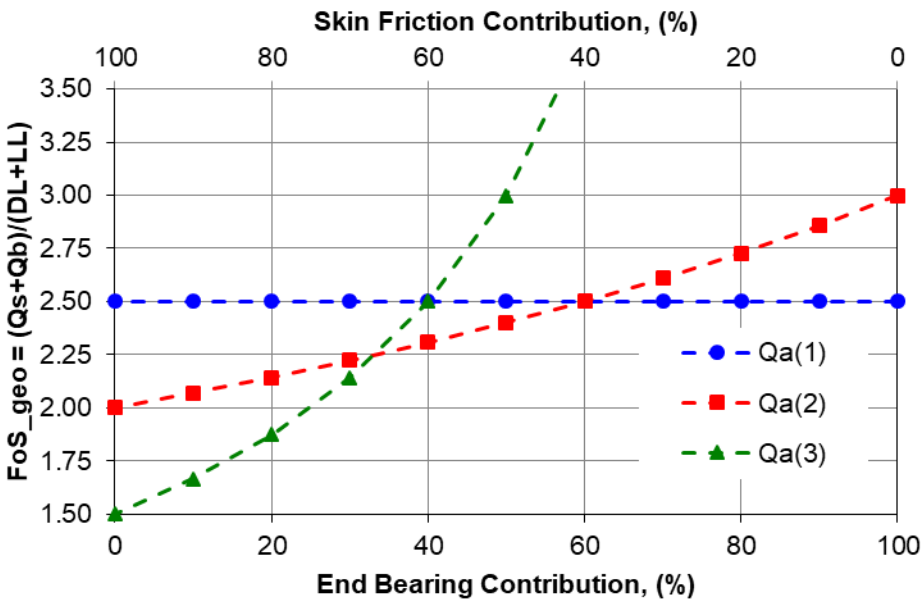

Figure 1 Variation of FoS_geo with shaft and base resistance in accordance with CP4

Using the EC7 Alternative Method, the geotechnical resistance of compression pile, $R_{c;d}$ is expressed in Equation (5)

$$R_{c;d} = \left(\frac{R_{b;k}}{MF * \gamma_b} + \frac{R_{s;k}}{MF * \gamma_s} \right) \tag{5}$$

Where $R_{b;k}$ = characteristic base resistance; $R_{s;k}$ = characteristic shaft resistance; MF = model factor; γ_b and γ_s are partial resistance factor for base and shaft, respectively as specified in Table A.NA.7 for bored piles, i.e. R1 and R4 factors. If maintained load test is used to verified the design resistance by mean of preliminary load test, MF=1.2, else MF=1.4. If serviceability limit state of piles is verified by load tests carried out on more than 1% of the constructed piles to load not less than 1.5 times the representative load, a more favourable partial resistance factor R4 factors could be adopted in DA1-2, else a more onerous R4 factors shall be used.

In order to compare the geotechnical capacity computation between SS CP4 and EC7, the FoS_geo in accordance with EC7 can be derived and showed alongside that from SS CP4 as shown in Figure 2. It can be seen from this figure that if the designer has adopted more favourable model factor and more favourable R4 factor, the average geotechnical factor of safety resulting from EC7 design will be much lower as compared to that from SS CP4. Hence, the decision to adopt the more favourable model factor and R4 factor needs to be justified by the designer.

Figure 3 shows an example where a project site is divided into various zonings. The choice of MF and R4 factors for each zone is determined independently depending on whether ULT and WLT has been carried out for the particular zone. In a special case where the geological condition of the site is relatively uniform and a small selected numbers of ULT is able to verify design resistance for the entire site, a more favourable MF could be adopted for all zones regardless of whether the ULT is carried out within the same zone. However, a more favourable R4 factor could only be used in zone where WLT is carried out.

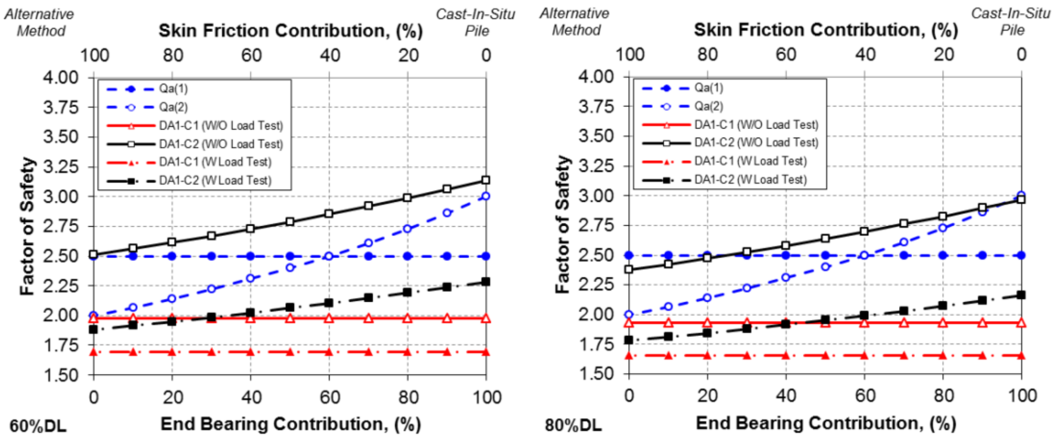

Figure 2 Comparison of FoS_geo from CP4 and EC7

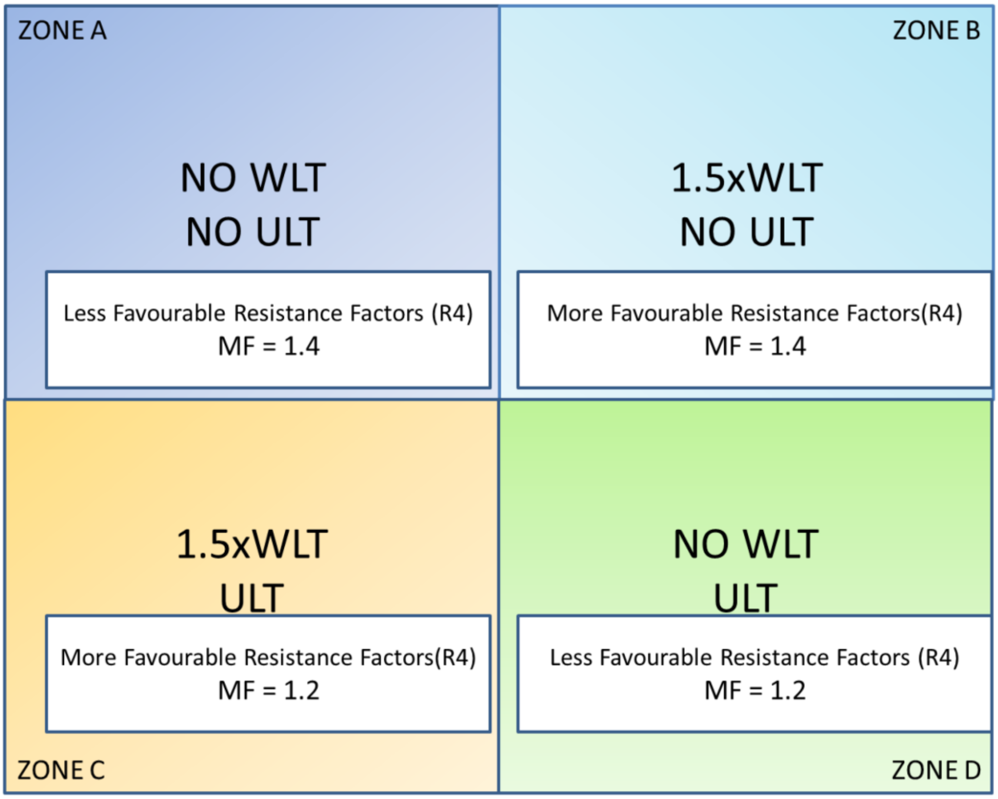

Figure 3 Selection of MF and R4 factor based on load test at each zone

4 PILE LOAD TESTS

4.1 Requirements on pile load tests

The minimum requirements for pile load tests for foundation of high-rise building with 10 or more storey was first specified in BCA/IES/ACES Advisory Note 1/03 issued in 2013. The types of load test prescribed include ultimate load test (ULT), working load test (WLT) and non-destructive integrity test. The minimum requirements for each type of test is provided in the schedule in Advisory Note 1/03 as reproduced in Table 5.

Table 5 Requirements of static pile load tests for foundation of high-rise buildings with 10 or more storey (BCA /IES /ACES ADVISORY NOTE 1/03)

Type of Load Test	Pile Test Schedule
(a) Ultimate load test on preliminary pile (preferably instrumented)	1 number or 0.5% of the total piles whichever is greater.
(b) Working load test	2 numbers or 1% of working piles installed or 1 for every 50 metres length of proposed building, whichever is greater.
(c) Non-destructive integrity test. (high-strain type for bored piles)	2 numbers or 2% of working piles installed, whichever is.

The requirement for pile load test was updated in the joint BCA/IES/ACES//GEOSS Circular 2016 issued on 22 September 2016. In addition to the test schedule specified in Table 5 for buildings of 10 storey or more, buildings of 5 to 9 storeys with footprint larger than $100m^2$ are also required to carry out working load test. The minimum quantity is 1 number or 0.5% of the total number of working piles, whichever is greater. The use of Rapid Load Test is regularized in the joint BCA/IES/ACES//GEOSS Circular 2016. For buildings with 10-storeys or more, up to 50% of the numbers of pile working load tests could be carried out using rapid load test. The result of rapid load test shall first be calibrated against static maintained load test to establish the suitability of the test and reliability of its interpretation before it could be used to replace the maintained load test at the specific site.

4.2 Maintained load tests

The most commonly used maintained load test method in Singapore is the kentledge load test method. It is the most direct method to determine the geotechnical design parameters through instrumented ultimate load tests and to validate the response of representative piles to design action through working load tests. For high test loading, the size and height of kentledge setup can be massive. If not properly designed and erected, it can pose safety hazard to the workers as well as the public in the vicinity.

Stability of the kentledge setup is crucial during the load test, as failure of such large load mass could be catastrophic. The engineer of the piling contractor is required to check and certify that the bearing capacity of the kentledge setup is adequate during the setting up and during testing.

In September 2011, a technical taskforce lead by GeoSS published the "Guidelines on good practices for pile load test using kentledge method in Singapore. The key recommendations of the guidelines includes (1) keep a safe distance of the kentledge setup from the site boundary; (2) avoiding large kentledge setup for test load exceeding 3000 tonnes; (3) limit height to width ratio of the kentledge set-up to 1.5; (4) recommended geotechnical factor of safety for bearing capacity of the kentledge base; (5) supervision regime and safe practices for workers during load test.

In compliance with the above guidelines, stacks of steel plates in replacement of concrete blocks has been used to reduce the height and lower the centre of gravity of the kentledge setup. For project where the logistic to erect the kentledge setup is difficult or not feasible, the reaction for the maintained load tests could be provided by reaction tension piles or ground anchors. A reaction type loading frame shall be designed for such test. The set up for the load test is typically smaller in size as compared to the kentledge method.

4.3 Bi-direction load tests

Bi-directional load testing pioneered by Osterberg (1989) has been used in Singapore since 1990's. In this test method, purposed built bi-directional hydraulic jack assembly, cast within the pile body, are used to apply test load onto the pile to achieve the objective of full scale maintained load test. In a typical application, the hydraulic jacks shall be positioned at a level where the total geotechnical resistance above and below the hydraulic jack is equal as shown schematically in Figure 4.

For specific case where the geotechnical resistance above or below the hydraulic jack is of particular interest, the hydraulic jack shall be positioned in such a way to ensure sufficient reaction is available to fully mobilize the resistance at the area of interest. As the test load is not applied directly through the pile head, the pile top load-settlement response will need to be interpreted from the measured upward and downward movements of the respective pile segments during the load test. Care shall be taken in using such interpreted pile top load-settlement response.

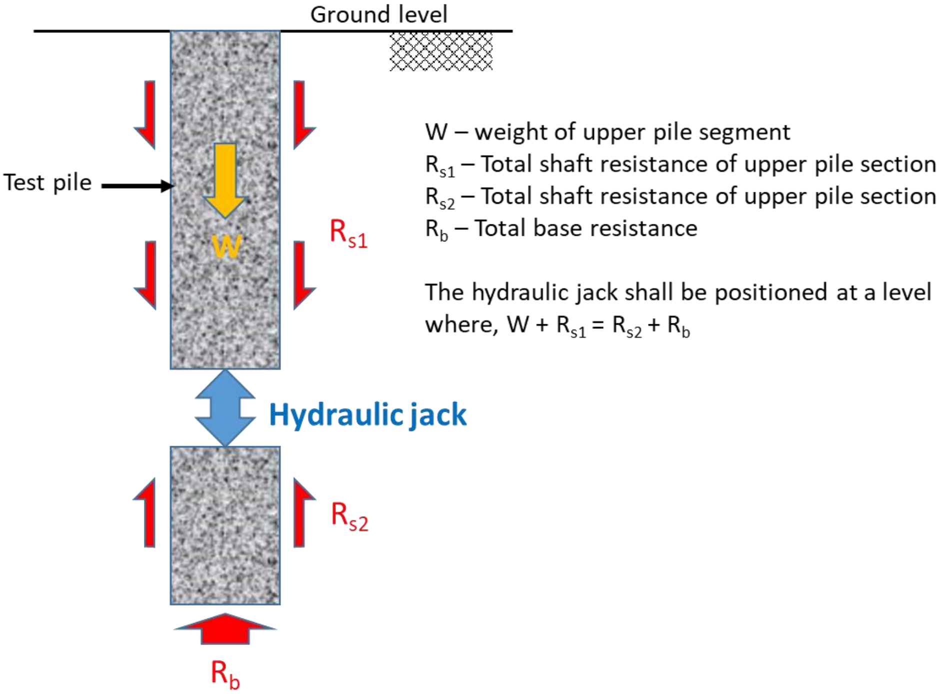

Figure 4 Ideal position of hydraulic assembly in a typical bi-direction load test

The bi-directional load test method requires much smaller testing footprint as compared to kentledge or reaction load test setup. It is particularly useful in sites with limited access or with space constraint. The procedure of bi-directional load test is currently not described in any local or international published standard. A working group in the Technical Committee on Civil and Geotechnical Works appointed by the Building and Construction Standards Committee has been setup to draft a Technical Reference for bi-directional static axial load test. The Technical Reference will provide some guidelines and good practices to the key aspects of bi-directional load test relating to the apparatus, test procedures, safety, design and reporting.

4.4 Rapid load test (RLT) method

In recent years, piling contractors are exploring more productive way in piling and load testing. Rapid load test (RLT) emerges as an alternative for conducting maintained load test which can be done quicker, cheaper and more environment friendly. There are many variants of RLT method reported in the literature. The two commonly used methods in Singapore are Statnamic Test Method and StatRapid Test Method. The main difference between the two methods lie in the loading mechanism.

Stanamic test uses combustion gas pressure test apparatus while StatRapid uses cushioned drop mass test apparatus.
RLT using Statnamic test was first introduced into Singapore some twenty years ago as reported in Chow et al. (1998). However, it did not gain sufficient support and was never accepted as official pile load test method in Singapore. In view of increase effort to promote productivity in construction industry in recent years, RLT uses StatRapid Load Test Method has remerged in Singapore with the strong support from projects by Housing and Development Board. Many correlation tests between RLT via StatRapid and static load tests (SLT) have been conducted for piles installed in variety of soil types. Results of correlation tests, on single pile with RLT first followed by SLT or vice versa, as well as tests conducted on two adjacent piles using SLT and RLT respectively, have been reported in Chew et al. (2016) and presented by various speakers in a one-day seminar on "Use of Rapid Load Test for Pile Foundation", jointly organised by BCA and GeoSS on 20 July 2017. In general, the studies show that the RLT results correlate very well with that of the SLT and RLT is officially accepted to replace SLT for working load test in accordance with the joint BCA/IES/ACES//GEOSS Circular 2016.

5 BUILDING CONTROL REGULATIONS FOR FOUNDATION DESIGN

Building control regulations are to be complied with to ensure a safe and robust structural design in Singapore. The regulations applicable for the design of foundation system for high-rise buildings includes the followings:

a) Plan submission requirements – (1) Minor building works – plan to be submitted by a qualified person (QP) who is a professional engineer; (2) Major building works – plan to be submitted by QP and checked by an accredited checker (AC); (3) Geotechnical building work (GBW) involving foundation supporting building with 30 or more storey – in addition to QP and AC, the geotechnical aspects of the GBW need to be designed and checked by a QP(Geo) and AC(Geo), respectively.
b) Requirements for site investigation and load tests – minimum requirements specified in joint BCA/IES/ACES//GEOSS Circular 2016 shall be complied with.
c) Requirement to assess foundation settlements for GBW – QP need to evaluate the foundation settlement under the design loads. The allowable total and differential foundation settlement, as well as settlement monitoring scheme, shall be specified clearly in the structural plans.
d) Certification of supervision on pile load test - QP Supervision is required to confirm that he has:
    - reviewed and ensure that the static load test procedure is in accordance to code requirements;
    - inspected the test equipment and they are properly calibrated and not faulty
    - implemented measures to prevent manipulation of load test results
    - ensured that all recording and readings are witnessed by QP or site supervisor appointed by QP
    - examined that the test records and results are valid and accurate
    - satisfied with the load test results have validated the design assumptions and parameters used in the pile design

e) Certification of supervision on piling works – the QP Supervision is required to certify that the piling works have been completed under his supervision in accordance with the approved plan and that all the piles had been installed to founding depth which had been determined by him
f) Certification of monitoring of building settlement during construction – the QP Supervision is required to ensure that building settlement markers being installed upon completion of the foundation works. He also required to ensure that these markers being monitored by a registered surveyor. He also need to confirm and satisfy that the building settlement monitoring results do not exceed the design limits in accordance with the approved plan.

6 ASSESSMENT OF FOUNDATION SETTLEMENT

6.1 Common method used

There are many methods to estimate settlement of pile foundations for single pile and pile group (Poulos and Davis, 1980; Tomlinson, 1994; Poulos, 2006). A survey on 38 recently completed high-rise buildings indicated that common methods used by QPs includes equivalent raft method, FEM method and empirical method by design charts. By far, the equivalent raft method is the most commonly used method in the pile group settlement analysis in Singapore. In this method, the settlement of a pile group is equivalent to settlement of a raft foundation of equivalent dimensions located at some representative depth below the surface.

As discussed in Poulos (2006), there are many variants of equivalent raft method. However, the equivalent raft method proposed by Tomlinson (1994) as shown in

Figure 5 appears to be the most popular approach used by the local practitioners. In Tomlinson's approach, the dimension of the equivalent raft is first determined by projecting the plan size of the pile group 1 in 4 downward to a representative depth ranging between 2L/3 to L, where L = average pile length. To estimate the pile group settlement on layered soil, the load on the equivalent raft is assumed to spread at 30° from the edge of the equivalent raft as shown in

Figure 5. The total settlement of the piled group is then taken as the summation of average settlement of each soil layer subject to uniform loading at the top of the layer computed from the load spreading above.

With the advancement of numerical modelling and availability of high computing power personal computer, 3D finite element method (FEM) is gaining more footholds in pile group analysis. The advantage of this method is that the complex soil-structural interaction problem could be modelled in a more holistic way and less assumption has to be made in analysing the pile settlement. Figure 6 shows an example where 3D FEM method was used for estimation of settlement of the pile group.

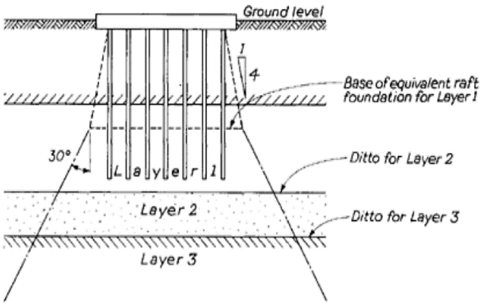

Figure 5 Equivalent raft method (Tomlinson, 1994)

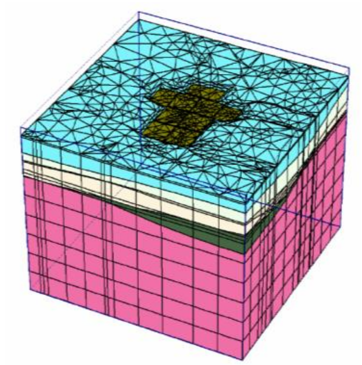

Figure 6 Example of 3D FEM method used for settlement estimation of pile group

6.2 Comparison between methods used for estimation of building settlement

Table 6 shows comparison of estimated building settlement using equivalent raft method and 3D FEM method, using both loading modulus and unloading modulus, for a Site R. The measured building settlement was 19 mm. The computed building settlement using equivalent raft method and 3D FEM method with loading soil modulus was 61 and 70 mm, respectively. The computed building settlement using equivalent raft method and 3D FEM method with unloading soil modulus was 43 and 35 mm, respectively.

Table 6 Comparison between methods used for estimation of building settlement for Site R

Method used for estimation of building settlement		
Site name	Equivalent Raft method	3D FEM
Site R	Soil stiffness: Using loading modulus, E_{50}	
	61 mm	70 mm
	Soil stiffness: Using unloading modulus, E_{ur}	
	43 mm	35 mm
Note: measured building settlement = 19 mm		

It is obvious from the above results that the magnitude of settlement prediction is affected by the method of analysis and soil stiffness used in the computation. It can also be seen that the soil stiffness has a greater influence on the outcome of the prediction as compared to the method of analysis. These results suggest that the used of small strain soil stiffness, and unloading soil modulus where applicable, will provide better estimation of building settlement.

6.3 Estimation of building settlement with the help of results of pile load tests

In estimation of pile settlement, the designer often use conservative soil parameters and seldom make reference to past measurements of building settlement data or load test data. Such practices tend to overestimate the building settlements for high-rise buildings. Sometimes, cases involving excessive overestimation of building settlement may trigger unnecessary scrutiny during plan submission stage in view of the safety concern associated with excessive building settlement. This may result in delay in plan approval. The cause of the overestimation often relates to the choices of method and soil parameters used in the calculations without prior calibration with measured foundation performance in similar ground conditions.

One way to overcome this problem of grossly overestimation of building settlement is to use small strain soil stiffness calibrated using the results of maintained load tests.

6.4 Building settlement monitoring during construction

In the foundation plan submission for high-rise building, the design QP is required to determine and specify the quantity and location of monitoring points for building settlement to be monitored during the construction. Typically, all critical columns at the lowest level accessible for monitoring shall be monitored. The types of monitoring system include conventional optical survey of building settlement markers and multipoint liquid levelling system. Figure 7 shows an example of building settlement marker layout plan while Figure 8 shows an example of the settlement-time history plots of the building settlement monitored during the construction period.

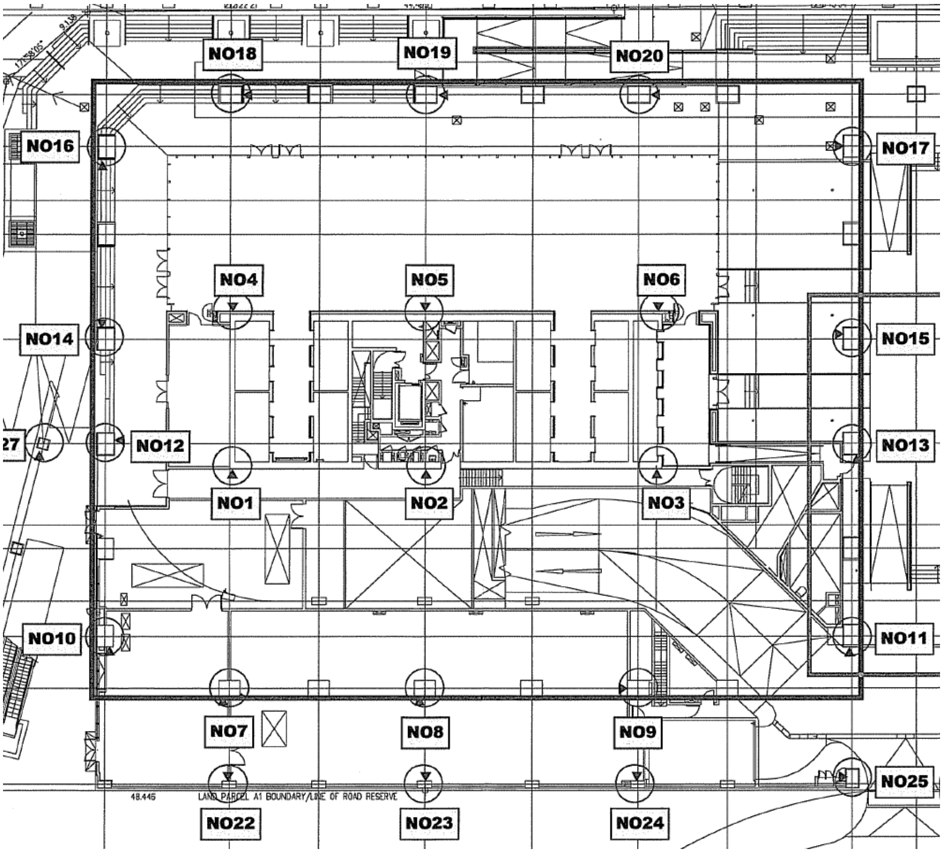

Figure 7 Example of building settlements points selected for monitoring of building settlement

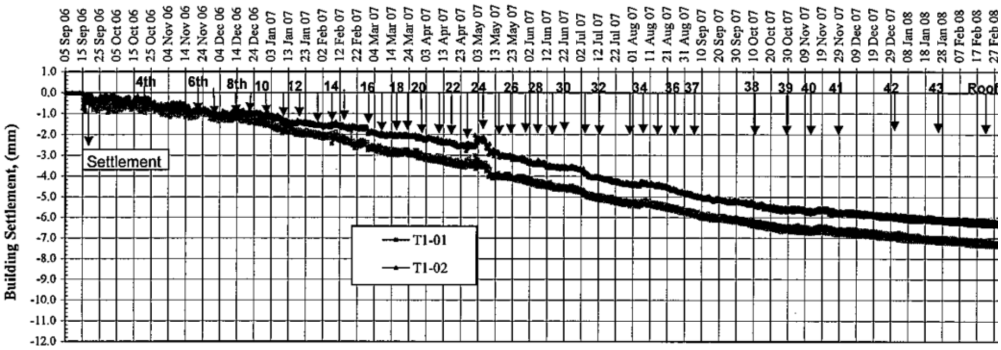

Figure 8 Example of settlement monitoring results plotted against time and milestone

7 PILEGROUP EFFECT IN FOUNDATION SETTLEMENTS

Data from four sites namely Site I, C, K and A are selected to compare pile settlement observed during working load test and the building settlement measured during construction. All four sites involving piles installed into competent soil layer with SPT N value more than 100 blows/30cm. The average pile length for Site I, C, K and A is 45m, 25m, 27m, 27m, respectively. The first two sites involve buildings with isolated pile groups near the edge of tower block and larger combined pile group near the central core area. Sites K and A involve buildings with combined pile cap of 2 and 4 m thick, respectively. The combined pile cap covers the entire tower area with piles spread more or less evenly below the pile cap. The project information, pile settlement measured at 1 time working load from working test pile and the range of building settlement measured during the construction are summarized in Table 7.

Table 7 Comparison of settlements measured in working load and during building construction

Site name	**Pile settlement**	**Measured building settlement**	**Ratio of measured building settlement over pile settlement**
Cases involved isolated pile groups at the edge and combined pile group near the central core area			
Site I	6.7 mm	5.5 to 10.5 mm	0.82 to 1.57
Site C	4.1 mm	4 to 8 mm	0.98 to 1.95
Cases involved combined pile cap for entire tower block			
Site K	5 mm	6 to 8 mm	1.2 to 1.60
Site A	7.4 mm	10 to 13 mm	1.35 to 1.76
Note: Pile settlement refers to settlement of working test pile under one time working loads.			

It is noteworthy that the lower building settlement value corresponds to value at the outer edge of building while the higher values corresponded to building settlement near the core area. Table 7 shows that the ratio of measured building settlement over pile settlement at one time working load ranges between 0.82 and 1.95. For isolated pile group, the value of the ratio at the outer edge of building ranged from 0.82 to 0.98 with average value of 0.9. The measured settlement at the outer edge of the building is less than the pile top settlement measured at 1 time working load. This is reasonable as the full design loadings, in particular the live load, have not been imposed on the foundation when the settlement measurements are taken.

For larger pile group such as those located at the core area for Site I and C, and combined pile cap such as Site K and A, the ratio of the measured building settlement over pile settlement at one time working load ranges from 1.57 to 1.95 with the average value of 1.7. For sites K and A with large combined pile cap, it is observed that the settlement was more evenly distributed across the foundation. The fact that the measured building core settlement during the construction is higher than the pile top settlement at 1 time working load suggests that the pile group effect is significant and shall be taken into design consideration.

8 PERFORMANCE OF FOUNDATION FOR HIGH-RISE BUILDINGS IN SINGAPORE

Twenty nine recently completed high-rise buildings were selected to study the performance of pile foundation supporting high-rise buildings. Both residential and commercial buildings are included in this study. The building height ranges from 29 storey to 70 storey. These buildings are supported by deep foundation (includes bored piles, barrette piles and caisson piles) embedded in competent soil stratum (with SPT N value greater than 100).

Figure 9 shows measured building settlement data collected at the end of the construction stages (i.e. settlement due to pure dead load only) plotted against building height in storey. All the measured building settlements are less than 25 mm with majority of the measured settlement being less than 15 mm. There are five cases involving commercial buildings where the measured building settlements are relatively larger, ranges between 20 and 24 mm. These five buildings involves commercial building with higher design loading located within thick layer of soft clays. As a result of this, the length of the piles is much longer as compare to other buildings located within residual soils. The relatively larger building settlement observed for these five cases may be attributed to larger elastic shortening from the longer piles installed through the thick layer of soft soils.

Figure 9 also shows that there are four cases of commercial buildings located within thick layer of soft soils where the observed building settlement of less than 10 mm (marked with dotted circle), much lesser than those five cases mentioned above. For these four cases, the designer has adopted additional design checked on pile capacity with factor of safety of 1.5 apply on skin friction alone. With this additional check, the pile is behaving predominantly as skin friction pile. The observed low pile settlements suggested that the practice of applying a factor of safety of 1.5 apply on skin friction alone do help to limit the pile settlement.

The remaining cases are buildings with foundation piles founded in the residual soils, with or without the presence of limited thickness of soft soils, and pile toe firmly socketed into competent soil layer with SPT N value greater than 100. The measured building settlement for these cases are less than 15 mm and are relatively smaller as compared to the first five cases involving longer piles installed through thick layer of soil soils.

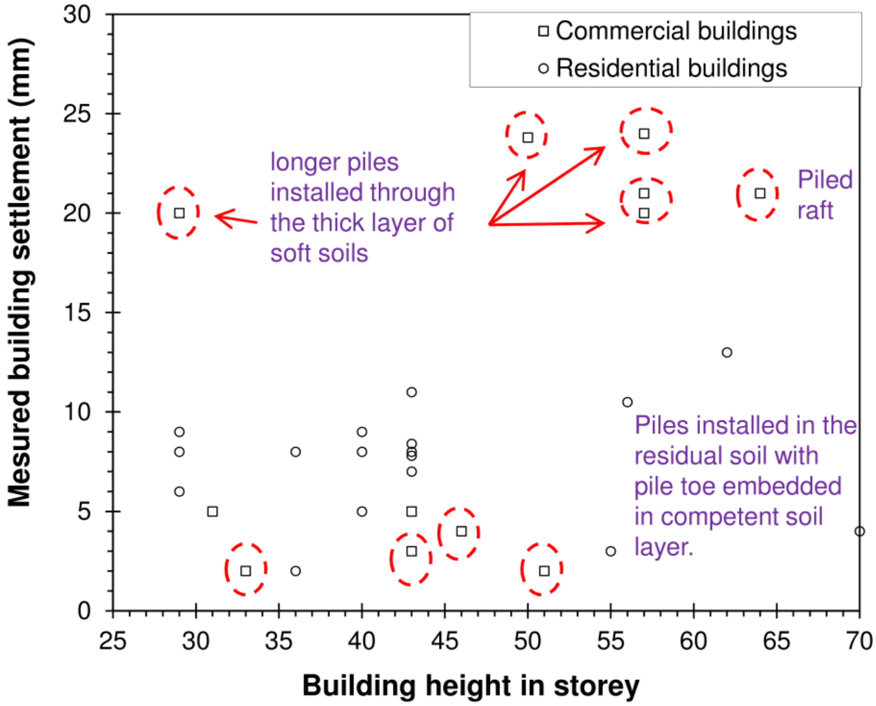

Figure 9 Measured building settlements plotted against building height in storey

These observations suggest that, for piles designed to SS CP4, the measured settlement of buildings supported on piles socketed into competent soil stratum, with SPT N value greater than 100, is likely to be less than 15 mm during the construction due only to the design dead load. For piles installed into competent soil stratum through thick layer of soft soils, the building settlement may be higher due to larger elastic shortening for long piles.

Figure 10 shows the distribution of settlement ratio, defines as the ratio of measured settlement over the allowable settlement, plotted against the height of the building in number of storey. Settlement ratio of 1.0 indicate a perfect match between the measured and allowable settlement. Settlement ratio larger than 1.0 indicates underestimation of building settlement and vice versa. It is obvious from Figure 10 that there is no case involving underestimation of building settlement. There is only one case where the settlement ratio is higher than 0.5. The settlement ratio for this case is 0.7 and this is due to the relatively smaller allowable building settlement of 15 mm. For the remaining cases, the settlement ratio is less than 0.5 with some cases fall below 0.2 indicates gross overestimation of building settlements even though only settlement due to dead load has been measured.

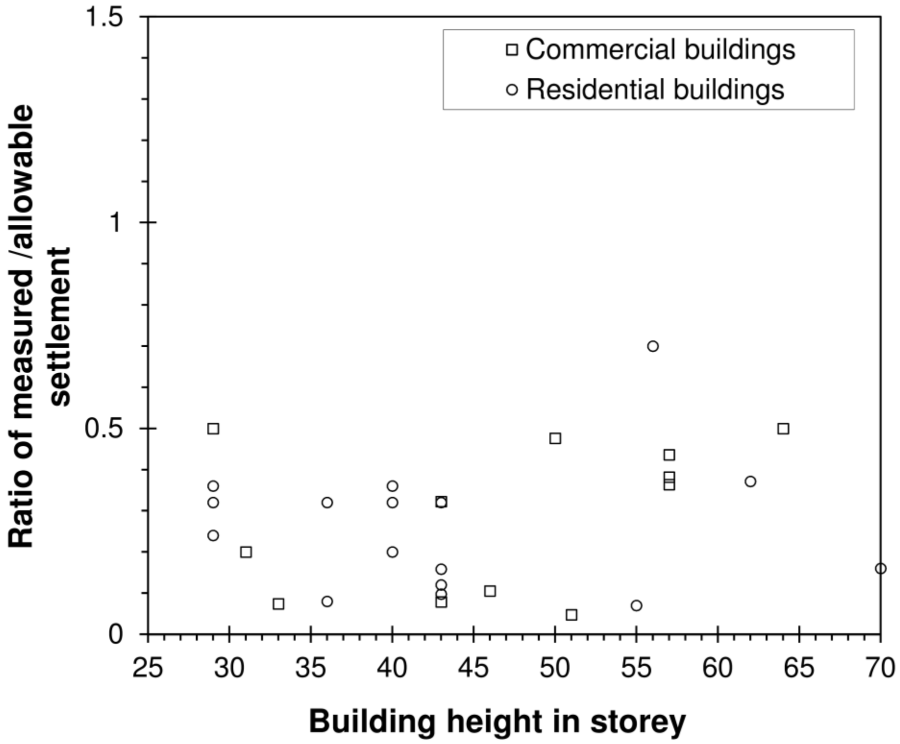

Figure 10 Ratio of measured over allowable building settlement

Prior to the adoption of Eurocode in April 2015, foundations are designed in accordance with SS CP4. In accordance with SS CP4 clause 7.5.4.4, the allowable settlement under pile load test to 1.5 to 2.0 times working load is 15 mm and 25 mm, respectively. In addition, for piles subject to negative skin friction, the acceptable pile settlement at the test load of 1.0 times column load plus 2.0 times negative friction should not exceed 10 mm. In order to comply with the allowable pile settlement values at 1.5 to 2 times working load, designers usually specify pile settlement value of 5 to 10 mm under one time working load.

A quick check of the expected building settlement value can be obtained by multiplying the settlement ratio of 1.5 to 2.0, obtained from Table 7 above, with the commonly adopted pile settlement value of 5 to 10 mm under working load. This will result in estimated building settlement in a range of 7.5 to 20 mm, which is consistent with the range of settlement observed in the 29 case studies presented in Figure 9.

Such observation suggests that in general, for foundation designed in accordance with SS CP4, the observed building settlement value, during construction, is likely to fall within a range of up to 15 mm (for piles in residual soils) and up to 25 mm (for pile installed into competent soil strata through thick layer of soft soils), during construction. Such observation is in line with measured building settlement data for high-rise buildings collected to-date. The settlement requirements in SS CP4 has shaped the foundation design principal in the past and serve the industry well prior to EC era. To ensure the same robustness in the foundation design adopting EC7, the joint BCA/IES/ACES//GEOSS Circular 2016 issued on 22 September 2016 has restated the allowable pile top settlement of 15mm and 25mm for pile tested to 1.5 times and 2 times characteristic load, respectively.

9 CONCLUSION

A strong and stable deep foundation play a key role in ensuring building safety of high-rise buildings. Proper control measures are crucial to ensure a safe and robust design and construction of deep foundation supporting high-rise buildings. This paper attempts to provide a brief state of practice of pile foundation for high-rise buildings in Singapore covering the evolution of design standard, method of pile load test, building control regulations and foundation settlement assessment.

With comprehensive ultimate load tests and working load tests program, the average geotechnical factor of safety required in EC7 design approach will be lower as compared to that required using SS CP4. To ensure the performance of the foundation designed by EC7 is comparable to that obtained from SS CP4, the allowable pile top settlement of 15mm and 25mm at 1.5 times and 2 times characteristic load, respectively shall remain.

For more accurate prediction of building settlement, the results from pile load tests shall be used to calibrate the soil modulus used in the pile settlement computation. For building supported on large pile group, the pile group effect resulting is large building settlement as compared to isolated pile cap shall also be taken into consideration.

10 REFERENCES

Chow, Y.K.,Chew, S.H.,Chow,W.M. Chuah, L.S. 1998. Case Histories of Statnamic Pile Load Test. *Thirteenth Southeast Asian Geotechnical Conference*,Tapei, Taiwan. 479-484

Chew, S.H., Middendorp P., Barker J. and Chuah G. 2017. The application of Rapid Load Testing in Singapore. *DFI-PFSF Piled Foundations and Ground Improvement Technology Con*, Melbourne.

Poulos, H.G. 2006. Pile Group Settlement Estimation – Research to Practice, *GeoShanghai 2006*, New York: American Society of Civil Engineers.

Poulos, H.G, & Davis, E. H. 1980. *Pile Foundation Analysis and Design*, John Wiley & Sons, Inc.

Shirlaw, J. N., Broome, P. B., Chandrasegaran, S., Daley, J., Orihara, K., Raju, G. V. R., Tang, S. K., Wong I. H., Wong K. S., and Yu, K., 2003. The Fort Canning Boulder Bed. *Underground Singapore 2003*. TUCSS Singapore 2003

Tomlinson, M.J. 1994. *Pile Design and Construction Practice*, 4th Ed. E & FN Spon.