Calibration Test Results of Rapid Load Test on Bored Piles Embedded in Sedimentary Rock Formation in Singapore

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ABSTRACT

In Singapore's local practices, the results of RLT are typically interpreted by the Unloading Point Method (UPM) to subtract the inertia and damping effects, and deriving the equivalent static load displacement curves. However, there are concerns on the reliability of equivalent static pile behaviour derived from RLT to represent pile behaviour under static load, in view of the significant differences in loading duration. In view of this concern, the local Building & Construction Authority (BCA) of Singapore has requested that each project that intend to adopt RLT as part of the pile load test regime shall have at least one calibration test performed on the same site in similar ground conditions to demonstrate the reliability of equivalent static pile response derived from RLT, and to establish "Correction Factor" if any. Correction Factor is typically derived by methodology outlined in Annex A of ISO 22477-10:2016. This paper presents the results of correlation tests of cast in-situ bored piles embedded in Sedimentary Rock Formation (locally named as Jurong Formation) found in west southern side of Singapore Island. The comparisons of RLT and conventional results are discussed from the aspects of load displacement response and axial load distribution characteristics. At the end of the paper, the significant influence of percentage of end bearing contribution on correlation factor is highlighted.

Keywords: rapid load test, full-scale tests, correlation tests, rate effects

1 INTRODUCTION

Rapid Load Test (RLT), a pseudo-static load testing method, has gained its popularity and becoming more widely-used in Asia, particularly in Singapore in the recent years, as an alternative to the conventional static load testing method, for assessing the axial static behaviour of piles. This is due to the numerous benefits RLT has over other conventional test method (Bamrumrong, et al., 2019; Brown, 2004; Chew et al., 2015; Holscher et al., 2012; Middendorp, 2000). Comparing to conventional static test method, RLT has significant saving in time, cost and less labor intensive, requires much lesser space for test setup. On the other hand, the characteristics of RLT with longer loading duration compared to high strain Pile Dynamic Test has eliminated the influence of stress wave propagation phenomenon and simplify the interpretation procedure of RLT results.

Unloading Point Method (UPM) is the most commonly adopted interpretation method of RLT results. Numerous methods of subtracting damping effects by taking reference at "Unloading Point" has been proposed and discussed (Middendorp et al., 1992; Brown et al., 2006; Chew et al. 2015; Kusakabe and Matsumoto, 1995; Holscher et al., 2012). In general, this method initiates the interpretation by first subtracting the inertial effect assuming rigid body pile acceleration, followed by determining the Unloading Point where maximum displacement takes place with zero velocity. Theoretically, damping effect is zero at the point of zero velocity. Therefore, Unloading Point can be taken as the point where resistance is purely contributed by displacement dependent component, and hence the equivalent "static" response. For this paper, method illustrated in EN ISO 22477-10 for multiple cycle RLT tests was adopted, where the equivalent static load displacement curve is derived by joining the Unloading Point of consecutive cycles of RLT tests, fit into a hyperbolic function (Holscher et al., 2012).

Several researchers including Brown (1994), Brown et al. (2012), McVay et al. (2003), Rajagopal et al. (2012) and Wood (2003) have reported that RLT derived results are practically comparable with the static tests behaviour for sands and gravel. Brown and Hyde (2008) concluded based on their study that this method seems to be adequate for coarse-grained soils but poorly predicts the static pile resistance in fine-grained soils. Meanwhile, Holscher et al. (2012) conducted a study on the influence of loading rate and excess pore pressures during RLT and commented that RLT can overestimate static capacity due to rate effects for piles in medium to fine sands. Paikowsky (2006) recommended rate effect factor of 0.96 and 0.91 for piles in rock and sand respectively, while reduces to 0.69 and 0.65 in fine grained soils for silt and clay respectively,

Despite of the available publications to date, the influence of rate effects on interpreted static pile behaviour from RLT is still a debatable subject. Therefore, it is still a good engineering practice to perform a site-specific calibration or validation test to evaluate the reliability of static pile response derived from RLT and establish the site-specific correction factor (Weaver and Rollins, 2010; Holscher et al., 2012; Chew et al., 2015).

In view of this concern, the local Building & Construction Authority of Singapore has recently formulated a guideline requiring each project that intends to adopt RLT as a replacement to conventional static test to have at least one calibration test in the same site with similar ground and pile embedment conditions, on pile constructed by same method.

This paper presents the results of 3 calibration tests carried out in western part of Singapore Island. Each pile was subjected to RLT followed by conventional static Kentledge test and the results from both tests were compared and discussed.

2 GEOLOGICAL CONDITIONS AND TEST PILES DESCRIPTIONS

2.1 Geological condition

The test site was located in the west region of Singapore, which is made up of Jurong Formation. The formation was reported to have undergone extensive weathering due to humid tropical climate. At the test site, the ground profile comprised dominantly of reddish brown or greyish sandy Silt (residual soils and completely weathered layers), underlain by undulating bedrock consists of interbedded Sandstone and Siltstone.

Figure 1 plots the SPT N profiles versus depth of test piles. In general, the SPT N values increase with depth. Sandy Silt or Silt with N > 100 was encountered at depth 10m to 20m below ground. Fine contents (Silt & Clay) of this soil layer were between 60% to more than 95%. RQD of the underlying Sandstone and Siltstone bedrocks was ~ 25% with Unconfined Compressive Strength (UCS) of about 20MPa to 40MPa.

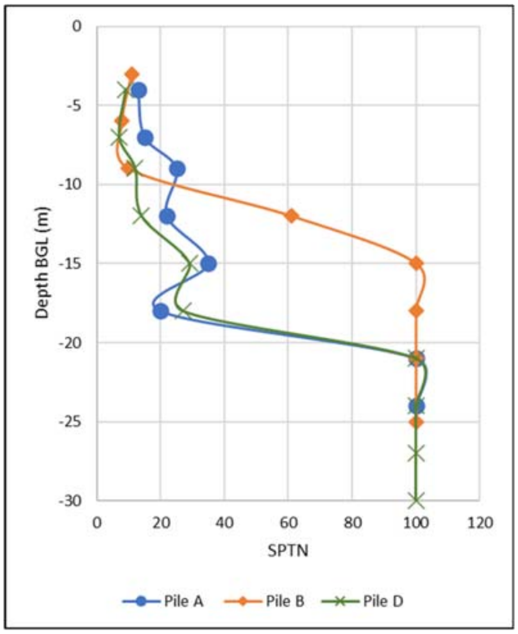

Fig. 1. SPT N profile versus depth

2.2 Test pile description

Three number cast in-situ bored piles were tested with rapid load test followed by conventional Kentledge static test. Pile diameters varied from 600 mm to 1000 mm. Pile A was 0.9m socketed into Sandstone bedrock. Pile B and Pile C were terminated in hard greyish sandy Silt or Silt with SPT N > 100. Test pile details are presented in Table 1. All test piles were instrumented with resistance type strain gauges for the measurements of axial loads along pile shaft during RLT and conventional static tests. Sampling rate of the resistance type strain gauges was 4000Hz. Loading durations of RLT were in the range of 71ms to 92ms, with Wave Number not less than 10. The wave Number have satisfied the criteria set in EN ISO 22477-10 for a valid RLT.

Table 1. Test pile summary.

Test ID	Pile A	Pile B	Pile D
Pile Dia.(mm)	600	1000	600
Pile Length (m)	27.2	24.2	29.9
Pile Toe Embedment	0.9m into Sandstone / Siltstone,	9.4m into SPTN > 100	4.9m into SPTN > 100
Calculated Total Pile Resistance (kN)	6.6	20.7	6.4
Rapid Loading Duration (ms)	71	92	77
Wave Number	10	15.2	10

2.3 Rapid Load Test Setup

The rapid load test was conducted by hydraulic assisted self-lifting impact hammer with customized rubber cushion. Figure 2 shows the test setup and Figure 3 plots a typical impulse load exerted by the test setup on pile head.

Fig. 2. Rapid load test impact hammer.

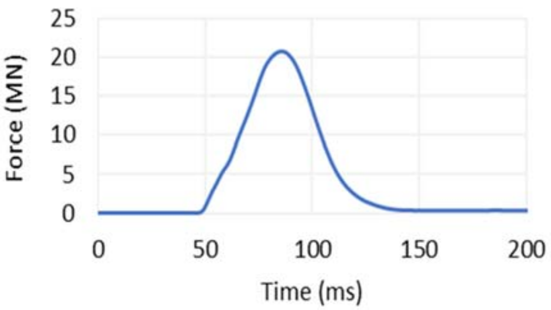

Fig. 3. Typical impulse load patent exerted on pile head

3 RESULTS AND DISCUSSIONS

The Rapid Load Test (RLT) results were analyzed by Unloading Point Method (UPM) for multiple cycles test outlined in EN ISO 22477-10 Appendix A.

3.1 Comparison of Static Load Displacement Responses

Figure 4 to Figure 6 plot the multiple cycles RLT load displacement response with the interpreted equivalent static load displacement curve. All 3 tests exhibit increase in pile head settlements with consecutive rapid load cycles, in conjunction with the increase in peak rapid load. Peak RLT load (after subtraction of inertia effect) of the last load cycle was approximately 3 times of the designed pile working capacity. The rapid load displacement response of Pile B was “narrower” compared to Pile A and Pile C, infers that the influence of damping effects on rapid load response of Pile B was lesser.

From the interpreted equivalent static load displacement curves, ultimate pile capacity was not achieved in all tests.

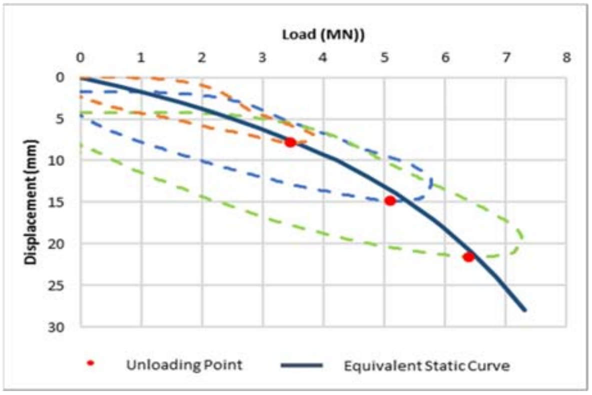

Fig. 4. RLT Results and interpreted equivalent static curve of Pile A

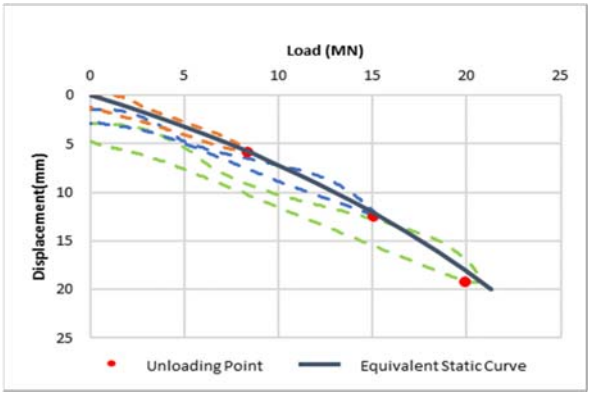

Fig. 5. RLT Results and interpreted equivalent static curve of Pile B

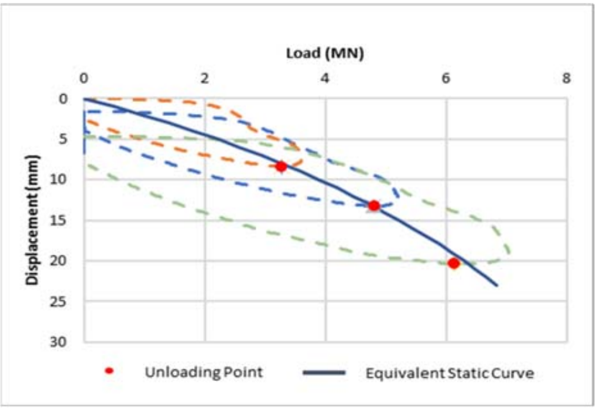

Fig. 6. RLT Results and interpreted equivalent static curve of Pile C

Conventional static tests by Kentledge method were carried out for all test piles after the rapid load tests, and compared with the equivalent static load displacement interpreted from RLT in Figure 7 to Figure 9.

For Test A and Test B, the conventional static test results were virtually matched with the interpreted equivalent static response from RLT. In both tests, the static pile response was mainly within the elastic zone and no signs of approaching the ultimate pile capacity.

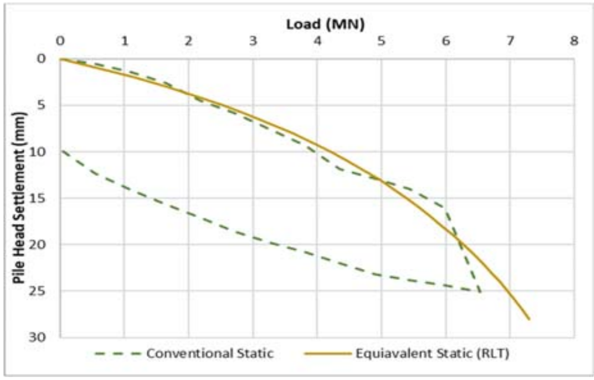

Fig. 7. Comparison of conventional static and equivalent static (RLT) load displacement response for Pile A

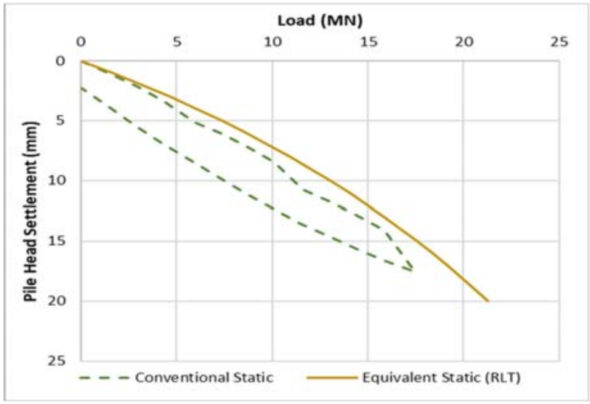

Fig. 8. Comparison of conventional static and equivalent static (RLT) load displacement response for Pile B

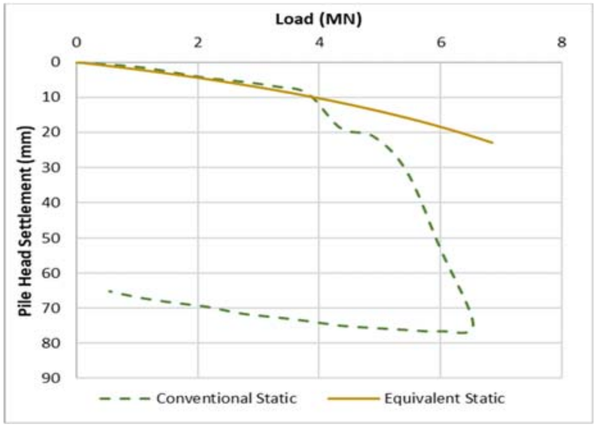

Fig. 9. Comparison of conventional static and equivalent static (RLT) load displacement response for Pile C

However, for Pile C, though the load displacement curve of conventional static test matched reasonably well with the equivalent static response derived from RLT, both curves start to deviate after static load of ~4MN. In conventional static test, a clear yield point was observed at static load of ~ 4MN. Beyond this yield point, pile head settlement increased rapidly from ~10mm to ~74mm with the increase in static test load from ~4MN to ~6.5MN, signaling the full mobilization of shaft resistance and substantial engagement of end bearing beyond the yield point. On the other hands, equivalent static response derived from RLT showed virtually elastic behaviour up to the maximum test load of > 6.5MN without any sign of yielding.

3.2 Axial Load Distribution Along Pile Shaft

Figure 10 to Figure 12 plot the load distributions along pile shaft of RLT and conventional static test for Pile A, B and C, at various static test load. The figures clearly show the axial load distributions along pile shaft were practically identical for both RLT (after subtraction of inertial effect for RLT load) and conventional static tests. These observations imply that the mobilized shaft resistance and end bearing in both RLT and conventional static tests are practically comparable. The same observations were also made for Pile C (Figure 12) despite of the significant differences in load displacement behaviour of RLT and conventional static tests (Figure 9). The results appear to suggest that correction is not required on the recorded shaft resistance and end bearing interpreted from RLT despite of its stiffer load displacement response compared to conventional static test. However, further studies are needed to include wider range of ground conditions such as soft clayey soils where higher material damping behaviour is anticipated.

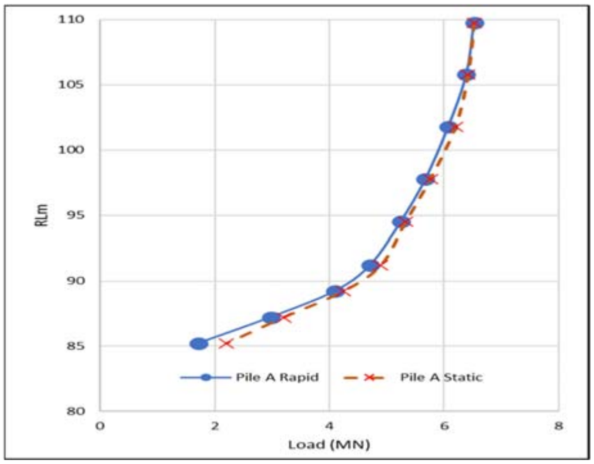

Fig. 10. Axial Lod Distribution Curve of Pile A

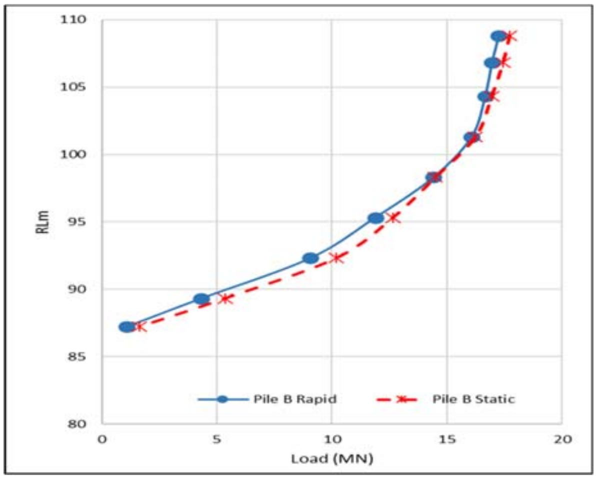

Fig. 11. Axial Lod Distribution Curve of Pile B

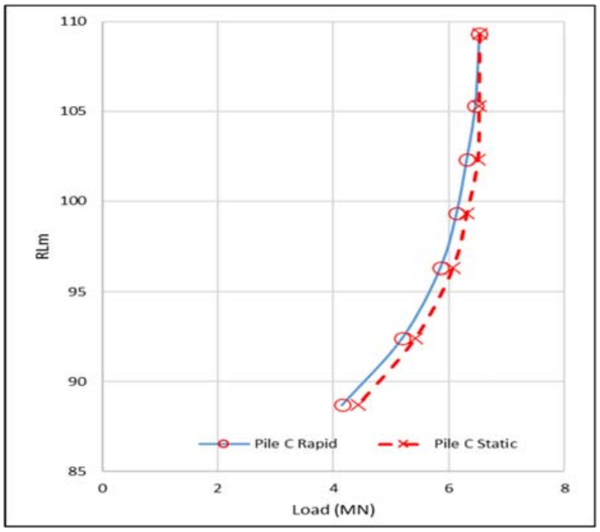

Fig. 12. Axial Lod Distribution Curve of Pile C

From Figure 10, end bearing contribution of rock socketed Pile A was ~ 20% of total pile resistance at maximum static test load, with maximum mobilized unit end bearing of 4500kPa. Pile B terminated in hard soils with SPTN > 100 was predominantly a friction pile with contribution of end bearing not more than 10% of total pile resistance (Figure 11). For Pile C, the contribution of end bearing was less than 10% but was increasing after the yield point of ~4MN, to more than 30% of total pile resistance at maximum static test load of ~6.5MN. The maximum mobilized unit end bearing of Pile C was 6000kPa opposed to merely 200kPa of Pile B.

Deducing from the observations, the significant differences in matching quality of RLT and conventional static test results of Pile B and Pile C terminated in hard sandy Silt or Silt with SPTN > 100 could be related to the contribution of end bearing to total pile resistance. End bearing could be relatively more susceptible to rate effects compared to shaft resistance. Hence, the deviation between RLT and conventional static test grows with the increase in end bearing contribution. For rock socketed Pile A, similar behaviour was not observed, which is tally with findings by other researches that correction factors for piles in rock or sandy soils were close to unity (Paikowsky, 2006).

3.3 Correction Factor

Correction factor, η is defined by Eq. 1, where R_{RLT} = equivalent static resistance derived from Unloading Point of RLT, R_{SLT} = measured static resistance in corresponding conventional static test at the same pile head settlement.

$$\eta = \frac{R_{RLT}}{R_{SLT}} \qquad (1)$$

For Pile A and Pile B, the Correction Factor η were essentially = 1.0 in view of the practically good agreement between RLT and conventional static results. For Pile C, the calculated Correction Factor η are plotted in Figure 13, versus percentage of end bearing contribution.

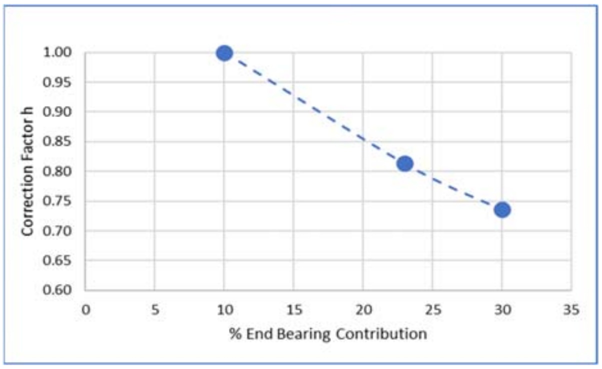

Fig. 13. Correction Factor for Pile C

Figure 13 clearly shows that the Correction Factor is not a constant, and appears to display clear relationship with percentage of end bearing contribution. The calculated Correction factor were decreasing from 1.0 to 0.7 with the increase in end bearing contribution from less than 10% to 30%. The findings fit well with the results of Pile B with end bearing contribution not more than 10% throughout the test, and resulted in Correction factor = 1.0. The calculated Correction Factor of 0.7 at maximum test load reasonably tally with recommendations by Paikowsky, 2006.

In the light of these observations, percentage of end bearing contribution appears a crucial parameter to be considered in the interpretation of RLT results and determination of suitable Correction Factor, especially for piles terminated in fine grained soils. It seems that end bearing could be the major source of rate effects observed in RLT, while rate effect of shaft resistance appears negligible.

However, it shall be commented that Correction factor could be varies depending on site geology, pile construction method, and etc. Therefore, a site-specific function of Correction Factor should be defined for each individual project.

4 CONCLUSIONS

This paper presented calibration test results of 3 nos. of cast in-situ bored piles in western side of Singapore Island. From the presented results, for rock socketed pile, equivalent static pile response derived from RLT matched reasonably well with the results of conventional static test with Correction factor close to unity. For piles terminated in hard fine grain soils with SOTN > 100, the Correction Factor display clear relationship with the percentage of end bearing contribution to total pile resistance, with Correction factor dropping from 1.0 to 0.7 with the increase in end bearing contribution from less than 10% to more than 30%. End bearing appears to be the main sources contributing to the observed rate effects while rate effects of shaft resistance seem negligible.

In the light of the observations from these test results, for piles terminated in fine grain soils, percentage of end bearing contributions appears a crucial parameter to be considered in the interpretation of RLT results and selection of appropriate Correction Factor. For industry practice, it is advisable to carry out calibration tests to establish site specific relationship of Correction Factor, especially for piles terminated in fine grain soils.

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