UNDERSTANDING THE TRENDS OF LOAD-SETTLEMENT CURVES OF RAPID LOAD TESTS

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ABSTRACT

The Rapid Load Testing (RLT) of foundation piles has been applied worldwide since 1984. Several international and national codes are available. For checking the performance of piles, they are more economical, faster and environmentally friendly than Static Load Testing (SLT), while yielding good correlations with SLT results through an objective analysis method. In Singapore, most of the foundation piles in Singapore are usually socketed into competent soil material (SPT N>100) or hard rock. In addition to the usual pile bearing capacity with adequate factor of safety, local regulation stipulates that the pile has to satisfy the serviceability criteria, which is pile top settlement less than 15 mm for 1.5 times working load, or less than 25 mm for 2 times working load. To date (January 2022), over one thousand RLT (by StatRapid Load Test method) have been successfully tested in Singapore. It was observed that the load-settlement pattern of the multiple cycles of StatRapid test actually gives useful indication of the performance of the pile – from very elastic behavior to near geotechnical failure case. If the pile is undergoing structure failure (i.e. material yielded or cracked) during the loading stage, the multiple cycle load-settlement result will also show unique patterns. Hence, the StatRapid load-settlement results can also be used to “indicate” the health of the pile. This paper aims to introduce five unique patterns of the StatRapid multiple cycle load-settlement responses, with correlation to their actual pile performance. Actual case studies representing several common scenarios will be presented and discussed.

Keywords: Rapid load test, StatRapid method, multiple load cycle, load-settlement behavior, correlation with Static Load test.

1. INTRODUCTION

Rapid Load Testing (RLT), by which a quasi-static load is applied to a foundation pile, is used increasingly as an alternative to Static Load Testing (SLT) for cast in-situ piles, such as drilled shafts or bored piles. RLT has an advantage over Dynamic Load Test (DLT) in the sense that its interpretation/analysis method is simple and person-independent. There are established methods of such analysis (such as the ASTM D7383, 2008; Dutch Guidelines, 2010; and Eurocode Implementation EN ISO 22477-10, 2016) which yield unique equivalent static results that do not depend on person skill and signal matching. There are no subjective assumptions that are used to interpret the test data (Chew et al, 2015; Verbeek, Tera and Middendorp, 2015; Holeyman et al., 2001).

The analysis technique is simple and straightforward. The most widely applied analysis method for non-cohesive soils is the Unloading Point Method (UPM) 1992 (Middendorp et al., 1992), while for cohesive soils the Sheffield method (SHM) is applied. The details of these interpretations are not further discussed in this paper, but is clearly described by Chew et al. (2017) and Brown and Powell (2013).

These analysis methods make use of the direct measurements of load, settlement and acceleration values to obtain the final equivalent static results. Currently, over one thousand numbers of RLT have been conducted in Singapore (till 2022 January), with over a hundred sets of RLT being correlated against Static load test, across various geological formation in Singapore soil as shown in Figure 1.

A careful study on these StatRapid tests results discovered that there are certain unique patterns of the multiple cycles response of load vs settlement. It was observed that the load-settlement pattern of the multiple cycles of StatRapid test actually gives some indication of the performance of the pile – from very elastic behavior to near geotechnical failure case. Furthermore, this pattern can also indicate the integrity of the pile – i.e. is the pile undergoing structure failure (i.e. material yielded or cracked) during the loading stage. Hence, understanding the pattern of these multiple cycles load-settlement response can be a helpful aid to the quality control and the indication of the "health" of the pile installed on ground.

From this study, it can be seen that five (5) broad categories of this multiple cycle load-settlement pattern can be observed. This paper aims to introduce the five unique patterns of the StatRapid multiple cycle load-settlement responses, their interpretation and correlation to the actual pile performance. Actual case study of each pattern, coupled with associated soil profile and loading history, will be presented and discussed.

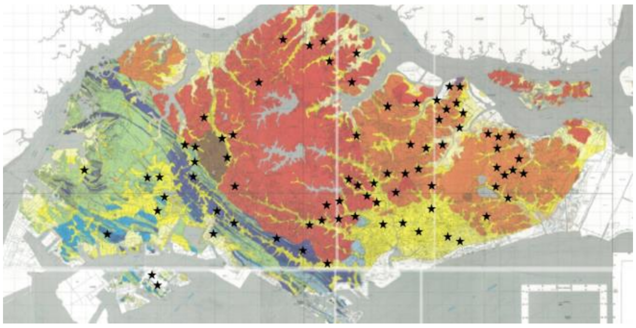

Figure 1. RLT tests (StatRapid Method) correlations in the last 20 year, in Singapore various geological units

2. CLASSIFICATION OF PATTERN OF STATRAPID TEST RESULTS IN SINGAPORE

A large number of deep foundations are designed for high-rise residential use and critical infrastructure development in Singapore over the past 40 years. The local authorities balance both engineering design requirements and public safety requirements. Hence, in additional to the usual pile bearing capacity with adequate factor of safety, local regulation stipulates that the pile has to satisfy the serviceability criteria, which is pile top settlement of less than 15 mm for 1.5 times working load, or less than 25 mm for 2 times working load. These requirements apply regardless of pile sizes. Except that when a very long pile is encountered, some allowance can be given to account for the elastic shortening effect of piles.

It is noted that most of the foundation piles in Singapore are usually toe in into competent soil material (SPT N>100) or hard rock. Furthermore, most of the piles will have sufficient length of pile embedded in stiffer soil such that the shaft friction is the predominant component of the pile capacity especially at the working load range.

Over the years, it was observed that due to the settlement requirements imposed by the serviceability criteria, a majority of piles (around 60% of tested piles) tested at 2 times working load with StatRapid method exhibited mostly elastic pile behaviour with almost predominately shaft friction mobilisation only. Around 30% of piles tested showed some form of shaft friction full mobilisation coupled with partial end bearing mobilisation. Less than around 10% of piles achieved nearly full mobilisation of end bearing at 2 to 2.5 times working load. A very limited number of piles, less than 1%, showed some form of defects in the piles during test.

Based on our experiences, five (5) broad categories of the multiple cycles load-settlement patterns can be observed from the StatRapid test. They are:

- Category 1a- Load-settlement behavior indicates a pure elastic pile behavior with moderate length (<40m).
- Category 1b- Load-settlement behavior indicates elastic pile behavior with long length (>40m).
- Category 2- Load-settlement behavior indicates some partial end bearing mobilization with settlement equals to ~2-5% of pile diameter.
- Category 3- Load-settlement behavior of pile tested to near ultimate capacity (with settlement ~10% of pile diameter)
- Category 4- Load-settlement behavior of pile tested to structural failure

The following sections will discuss these 5 categories with one specific case (at one site) each, showing the StatRapid multiple cycles load-settlement results, as well as the correlation with Static Test. Pile information and soil layering information of these cases will be discussed together with RLT and SLT results.

2.1 Category 1a -- Load-settlement behavior indicates a pure elastic pile behavior with moderate length (<40m)

A pile load test at a construction site for infrastructure development between Ang Mo Kio Avenue 9 and Sg Seletar was selected to illustrate this category of pile behaviour – Case 1a in Site A. The pile selected is labelled as PLT-8.

A Static Load Test (SLT) had been conducted on this test pile, PLT-8, a bored pile with diameter of 1000mm, and length 14.3m, with 2 metres of socketing into strong rock. This test pile is having a design working load of 3.9MN.

The SLT was tested from 28th December 2019 to 2nd January 2020 to up to 4 times of the designed working load. There was a residual settlement of 1.00mm upon unloading of the load after 4th cycle of loading. Subsequently, the RLT was conducted on 23rd March 2021 for up to 4 times the working load.

The multiple cycle StatRapid test results is shown in Figure 2. The clear feature of this case is that the rapid load-settlement curve for each loading cycle is very sharp and the unloading point is coinciding with the peak loading point for each cycle.

The equivalent static load-settlement curve was obtained from Unloading Point Method (UPM) of RLT interpretation, and shown in Figure 3, together with Static Load Test (SLT) results. It can be seen that this equivalent static load-settlement behaviour is almost a straight line, signifying that it is a “pure” elastic pile behaviour, even at 4 times working load. The settlement values for both SLT and RLT tests are shown in Table 1.

Table 1- Settlement (mm) for SLT and RLT for test pile PLT-8 in Case 1a (Site A)

	1xWL	1.5xWL	3xWL	4xWL
SLT	1.75	2.75	6.00	8.50
RLT	1.90	2.80	5.90	7.80
RLT (@ pre-loading point)	--	--	--	8.80

It is noted that the equivalent static curve is plotted after taking into account the residual settlement of the static load cycles. At the unloading point (i.e. 4x WL), the RLT settlement (8.8 mm) and SLT settlement (8.5 mm) is almost identical.

The performance of this pile is clearly almost “pure” elastic in nature, even up to loading of 4xWL. The pile’s load-settlement results from SLT and RLT compared very well. The soil profile for this case is shown in Figure 4. It is clear that the last 4.5 m of pile socket into very strong soil and competent rock (G(III) with RQD of >85%) provided sufficient amount of shaft friction to the pile under this load.

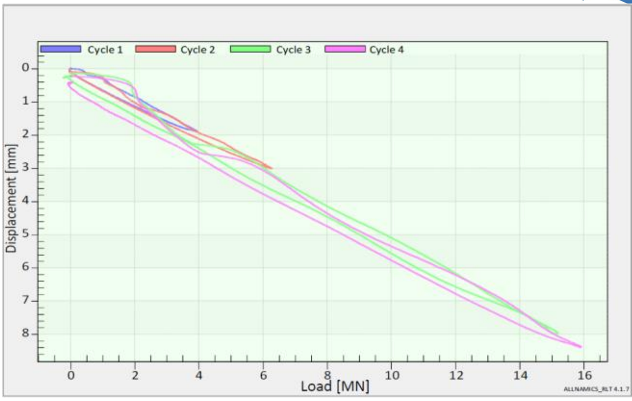

Figure 2. StatRapid multiple cycles load-settlement results for Case 1a (Site A)

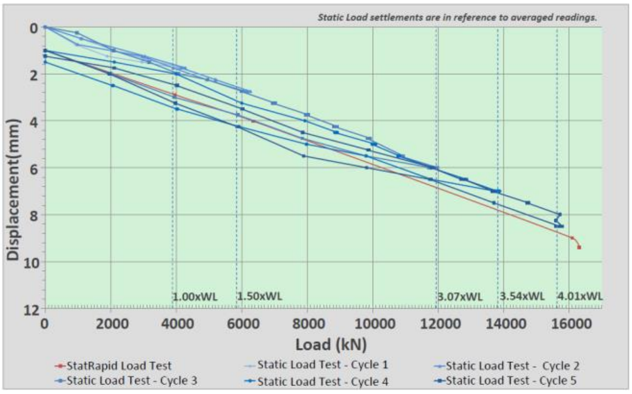

Figure 3. Equivalent Static Load-Settlement curve from RLT (Red line) plotted together with SLT results (blue lines)

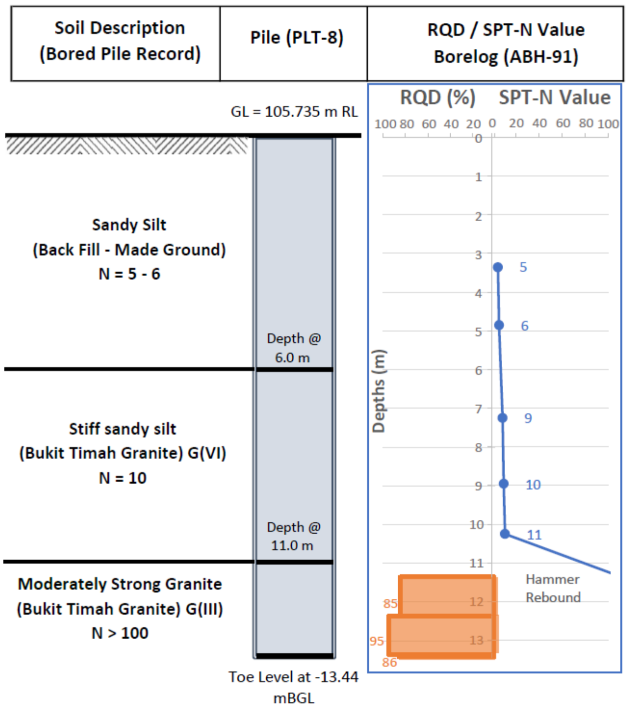

Figure 4. Soil Profile of PLT-8 (for Case 1a, Site A)

2.2 Category 1b -- Load-settlement behavior indicates an elastic pile behavior with long length (>40m)

This is a case similar to Case 1a, but with long pile.

A pile load test at a high-rise residential development site between Upper Serangoon Road and Upper Aljunied Road was selected to illustrate this category of pile behaviour – Case 1b in Site B. The pile selected is labelled as WLT-1.

A Static Load Test (SLT) had been conducted on this test pile, WLT-1, a bored pile with diameter of 1500mm, and length 50.2m, with over 30 m of socketing into competent soil (SPT N>50). This test pile is having a design working load of 14.0MN.

The SLT was tested from 30th August to 3rd September 2018 to up to 2.2 times of the designed working load. There was a residual settlement of 5.10mm upon unloading of the load after the last cycle of static loading. Subsequently, the RLT was conducted on 20th November 2018 for up to 2.2 times the working load.

The multiple cycle StatRapid test results is shown in Figure 5. The clear feature of this case is that the rapid load-settlement curve for each loading cycle is still very sharp and the unloading point is coinciding with the peak loading point for each cycle. Additional feature of this case is that there is a "spiral" shape in this load-settlement curve. This is because when a pile is very long, and is "rigidly" held at the bottom end; it will tend to vibrate when it was loaded with a relatively small load (w.r.t. its ultimate load). In this case, the pile reaction was almost fully elastic with almost no damping, and the mass (representing the pile) is oscillating on the spring (representing the soil reaction) during loading.

It should also be noted that this shape of the StatRapid load-settlement curve does not affect the interpretation of the "Equivalent Static" results by UPM. As the UPM utilized only the data at the Unloading Point, i.e. the point at the moment of unloading (where pile is at maximum displacement, which remains as sharp as case 1a.

The equivalent static load-settlement curve was obtained from Unloading Point Method (UPM) and shown in Figure 6, together with Static Load Test (SLT) results. It can be seen that this equivalent static load-settlement behaviour is again almost a straight line except toward the end, signifying that it is a "pure" elastic pile behaviour. Except that this time the load is only till 2.2xWL. The settlement values for both SLT and RLT tests are shown in Table 2.

Table 2- Settlement (mm) for SLT and RLT for test pile WLT-1 in Case 1b (Site B)

	1xWL	1.5xWL	2xWL	2.2xWL
SLT	6.29	11.90	15.08	18.61
RLT	7.00	9.90	12.40	13.40
RLT (@ pre-loading point)	--	--	--	18.50

From Figure 6, it is noted that the settlement of RLT at load level less than pre-loading point (due to SLT loading) is slightly smaller than that of the SLT results. This slightly stiffer load-settlement respond is expected for non-virgin loading. However, at the pre-loading point (i.e. @2.2xWL), the settlement of the two methods are almost identical: the RLT settlement is 18.50mm, and the SLT settlement is 18.61mm. This signifies that RLT method compared very well with SLT method, even with this long pile.

This is a case with long piles (>40m), and yet still shows a highly elastic pile behavior. The "spiral" shaped load-settlement curve from RLT suggests that it is a long and yet elastic pile with low level of loading.

The soil profile of this case is shown in Figure 7. It shows that the pile is embedded into relatively stiff/strong soil (N>100) from -15 m to -40 m below ground, with only 15 m of "softer" soil surrounding the pile. The pile behaviour is still elastic in nature during the RLT.

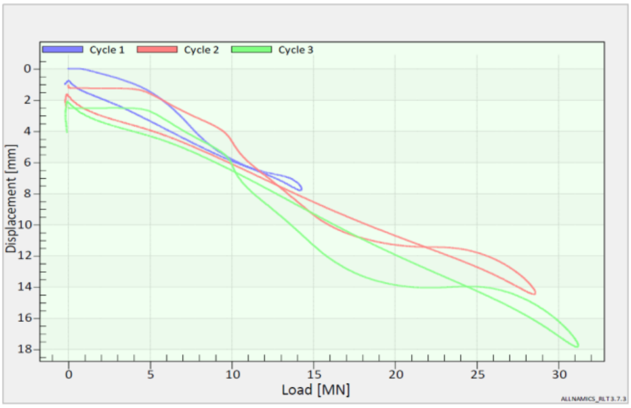

Figure 5. StatRapid multiple cycles load-settlement results for Case 1b (Site B)

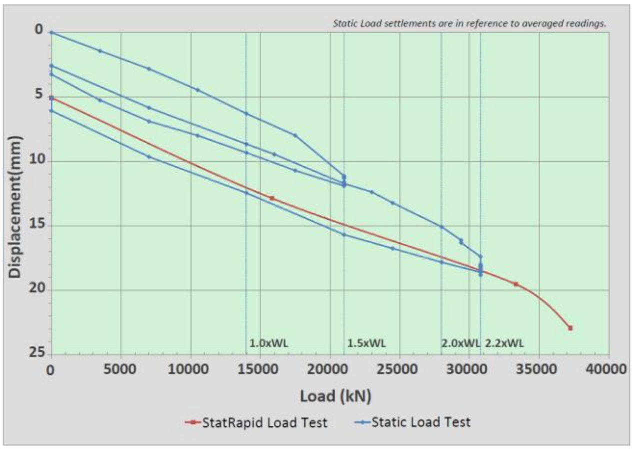

Figure 6. Equivalent Static Load-Settlement curve from RLT (Red line) plotted together with SLT results (blue lines) for Case 1b (Site B)

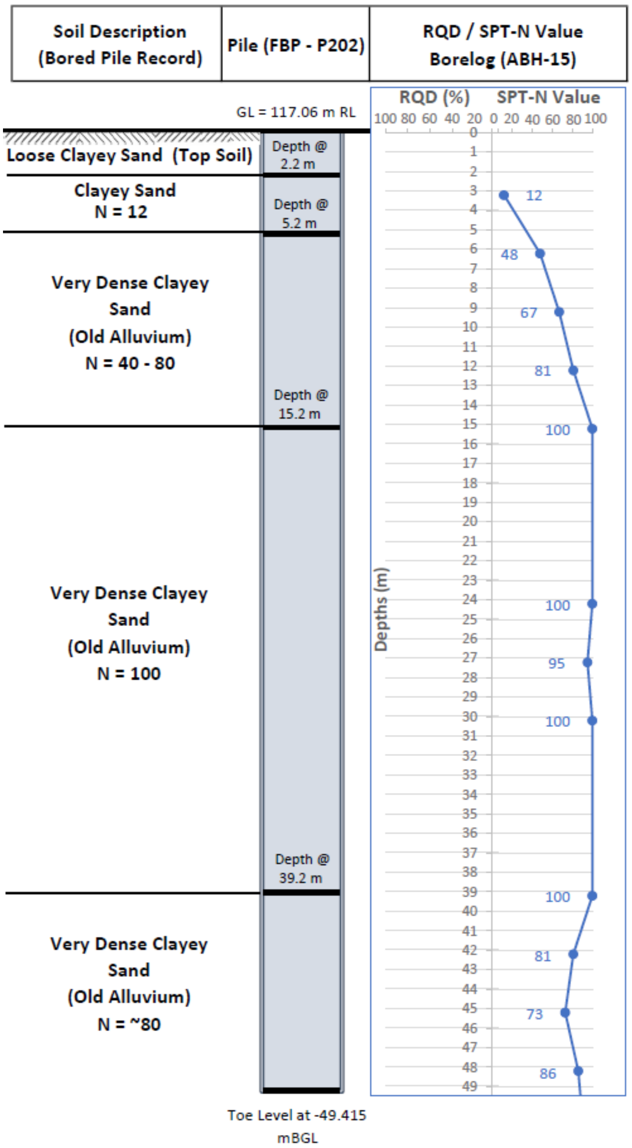

Figure 7. Soil Profile of WLT-1 (for Case1b, Site B)

2.3 Category 2 -- Load-settlement behavior indicates some partial end bearing mobilization with settlement equals to ~2-5% of pile diameter

This case is illustrated by a construction for upgrading works at an educational institute at Tanjong Katong - Case 2 at Site C. A pile load test, labelled as iULT-2, was conducted on a bored pile of 800 mm diameter, with a design working load of 3.33MN. The pile is 44.8m long with around 8m of socketing into competent soil (SPT N>50), and another 2m of socketing into SPT N>100 material.

RLT on iULT-2 was conducted first on 1st August 2018 for up to 3 times the working load. There was a residual settlement of 5.00mm upon unloading. Subsequently, the SLT was conducted (in 1 single cycle) on 7th August till 10th August 2018, till 3 times the working load.

The multiple cycle StatRapid test results are shown in Figure 8. The clear feature of this case is that the rapid load-settlement curve for 3rd and 4th StatRapid cycle is NOT very sharp, and with some "distance" between the Unloading Point (UP) and the Maximum Load Point (Pmax).

The equivalent static load-settlement curve was obtained from Unloading Point Method (UPM), and shown in Figure 9, together with Static Load Test (SLT) results. It can be seen that, in this case, the equivalent static load-settlement curve from RLT and the SLT load-settlement curve show a linear trend at the beginning and followed by a "concave downwards" curve as load increases. This is a general case where partial mobilization of end bearing is taking place as load increased.

The settlement values for both RLT and SLT tests are shown in Table 3.

Table 3- Settlement (mm) for SLT and RLT for test pile iULT-2 in Case 2 (Site C)

	1xWL	2xWL	3xWL
RLT	6.80	13.90	26.90
SLT	3.07	8.41	31.50
SLT (@ pre-loading point)	--	13.41*	36.50

The performance of the pile was still far from ultimate failure state as the settlement at three times working load is only 36 mm, which is only 4.5% of pile diameter.

It can be noted that in this case, as shown in soil profile in Figure 10, there is a layer of stiff clayey soil from -29m to -43 m. A loading rate reduction factor may have to be applied to correlate with the static test results, especially when the applied load is near to 3 times WL in this case. This is in-line with the international experiences for piles installed into stiff clayey soil. However, in Singapore, this geological formation is rather rare. Never-the-less, the load-settlement respond for load less than 2 times WL is still basically elastic, and RLT settlement at up to 2 times WL could be used directly, after adjustment with residual settlement.

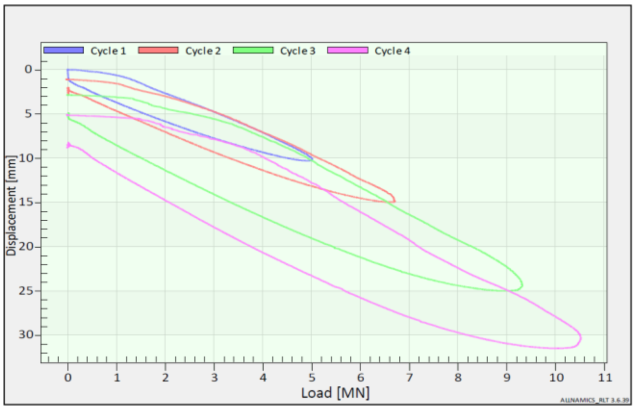

Figure 8. StatRapid multiple cycles load-settlement results for Case 2, Site C.

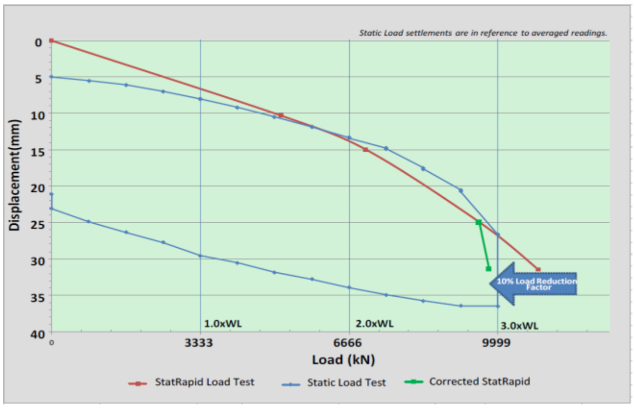

Figure 9. Equivalent Static Load-Settlement curve from RLT (Red line) plotted together with single cycle SLT results (blue lines) for Case 2, Site C.

2.4 Category 3 -- Load-settlement behavior of pile tested to near ultimate capacity (with settlement ~10% of pile diameter

A construction site for high-rise public housing development in Tengah Boulevard/Tengah Drive was selected to illustrate this case- Case 3, Site D. The selected pile was labelled as ULT-11, a bored pile with 800 mm diameter, and a design working load of 3.77MN. This pile is 26.1m long with around 8.3m socketing into SPT N>100 sandy silt material.

A rapid load test using StatRapid method (RLT) was conducted on this test pile on 07th February 2020 for up to 3.5 times the working load. The residual settlement upon removal of the RLT setup was ~105.4mm. Subsequently, static load test (SLT) was conducted from 7th March to 10th March 2020. The SLT test was terminated at 3 times working load due to the excessive settlement (92 mm) that exceeded 10% of pile diameter.

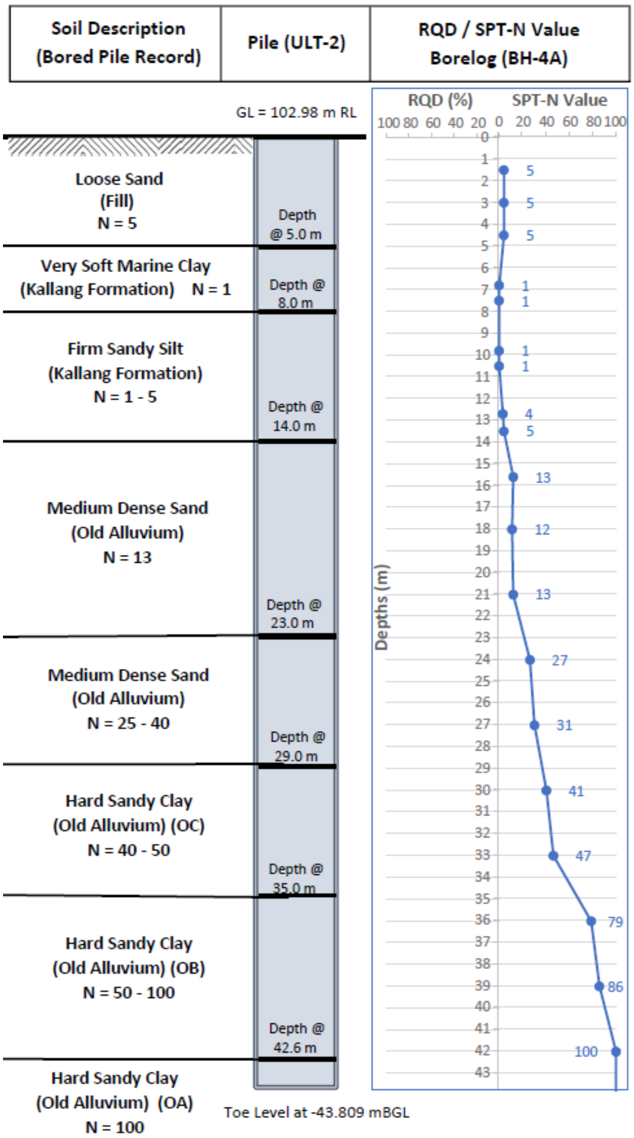

Figure 10. Soil Profile of iULT-2 (for Case 2, Site C)

The multiple cycle StatRapid test results is shown in Figure 11. The clear feature of this case is that while the rapid load-settlement curve for 1st and 2nd cycle are very sharp (i.e. elastic), the load-settlement curve for 3rd and 4th cycle is basically "pregnant" shaped. The Unloading Point (UP) is very far away from the Maximum Load Point (Pmax), and there is a large settlement from Pmax to UP point, signifying that the large un-recoverable settlement of pile at this time. This is corresponding to some sort of "geotechnical failure" near to the pile toe – either soft toe or pile punching – occurring.

The equivalent static load-settlement curve obtained from Unloading Point Method (UPM) is shown in Figure 12, together with Static Load Test (SLT) results. Figure 12a shows the plotting where residual settlement included, while Figure 12b plots the load–settlement curve for both tests as if it is virgin loading.

The settlement values for both SLT and RLT tests are shown in Table 4.

Table 4- Settlement (mm) for SLT and RLT for test pile ULT-11 in Case 3 (Site D)

	1xWL	1.5xWL	3xWL	3.35xWL
RLT	3.00	8.00	72.00	114.5
SLT	2.42	6.62	92.73	--

This pile is considered as “failed” between 3 and 3.35 times of WL. This is easier picked up by the RLT at 3rd cycle, and it is confirmed by the subsequently SLT test till 3 x WL.

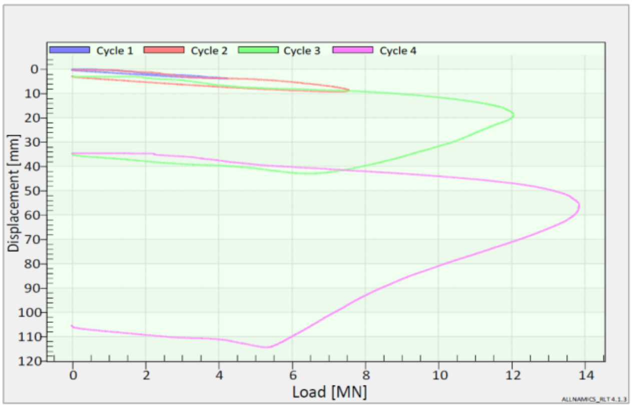

Figure 11. StatRapid multiple cycles load-settlement results for Case 3, Site D.

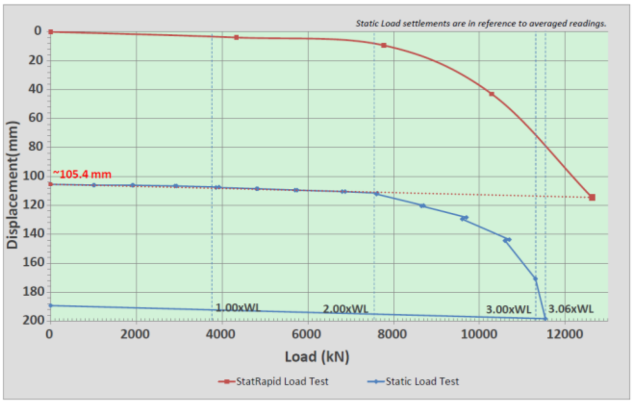

Figure 12a. Equivalent Static Load-Settlement curve from RLT (Red line) plotted together with single cycle SLT results (blue lines) – residual settlement included – for Case 3, Site D

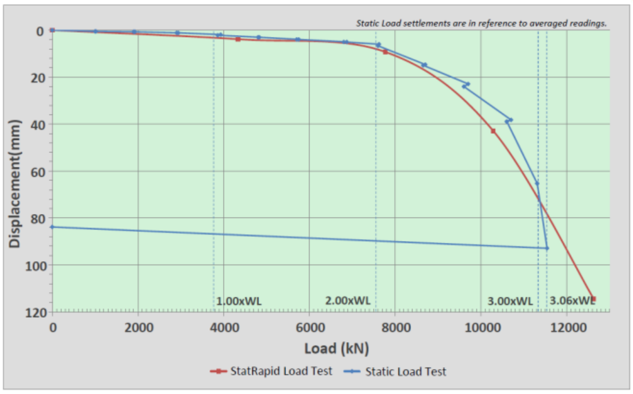

Figure 12b. Equivalent Static Load-Settlement curve from RLT (Red line) plotted together with single cycle SLT results plotted as virgin loading (blue lines) – for Case 3, Site D.

At about 3xWL, the full mobilisation of both shaft friction and end bearing can be envisaged for this pile. However, up till 1.5 times WL, the pile is still considered as satisfactory as the settlement at that load is still <15 mm. The RLT and SLT’s settlement comparison is still very good till a load of 1.5xWL.

Soil profile, as shown in Figure 13, shows that this pile is socketed well into a SPT N>100 material for the last 7m. This will provide sufficient shaft friction for load till about 1.5 x WL. Beyond that, the end bearing started to be mobilised. And somewhere near 3 x WL, end bearing either was mobilised to the ultimate value or due to presence of soft toe, the pile failed.

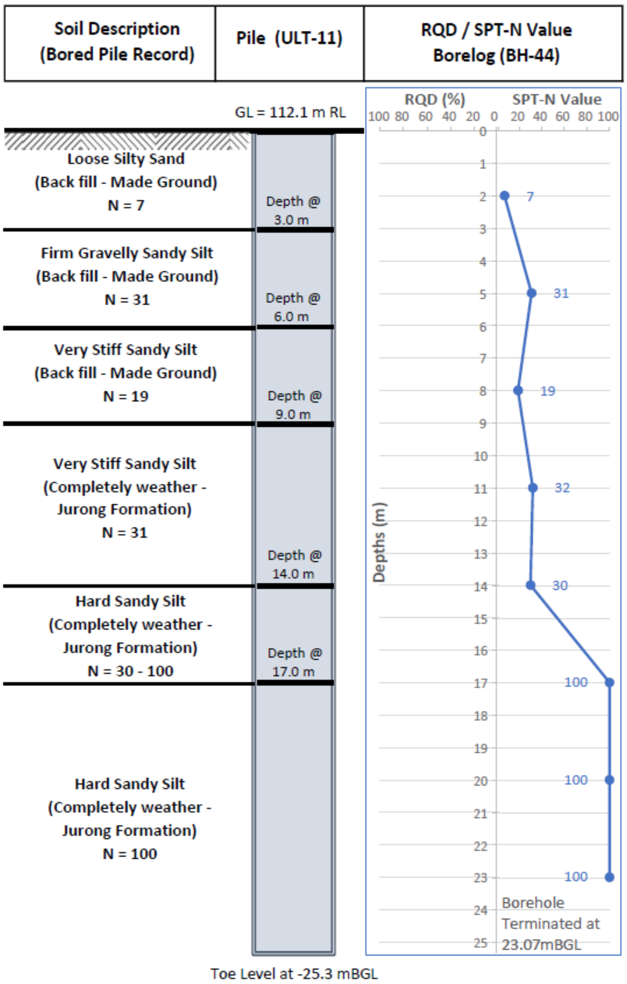

Figure 13. Soil Profile of ULT-11 (for Case 3, Site D)

2.5 Category 4 -- Load-settlement behavior of pile tested to structural failure

These are a few cases that piles were tested using StatRapid method, and exhibit unique shapes which hint at a possible structural failure of the pile. These type of pile tests results is very rare, and constitute less than 1% of all the piles tested so far.

One such case is at the construction of high-rise building in Bukit Batok area (Case 4, Site E). A pile, labelled as P2107, a bored pile with 800 mm diameter, and a design working load of 3.70MN, was subjected to a working load test. This pile is 25.18m long with around 17.2m socketing into SPT N>100 sandy silt material.

RLT test on P2107 was conducted on 8th November 2018, with a test load of up to 2 times WL (7.4 MN). The settlements of the pile from RLT were 11.7mm, and 24.0mm at 1xWL and 2x WL, respectively. As this was a serviceability test pile, there was no subsequent SLT performed on the pile.

During the test, it was noted that the RLT load settlement curve was odd. The first loading cycle and corresponding settlement showed a large pile top settlement at the start of application of the load, and gradually got better. The second cycle RLT seems to perform as expected. The multiple cycle load-settlement curve of this RLT test is shown in Figure 14.

After the test, this observation of a possible structural defect was highlighted to the main contractor. The pile was excavated and a horizontal crack was clearly found just a few metres below the pile top, as shown in Figure 15.

The likely reconstruction of events would be that the crack was formed during the construction of the bored pile, possibly during the extraction of the casing. Hence, during the 1st cycle loading, excessive settlement occurred. However, this crack could have been “closed up” by the loading, and leading to “normal” load – settlement behavior during the 2nd cycle.

However, if this was not detected by this working load test (or called “proof” load test), this pile will have excessive settlement during super-structure building stage, and hence, structure defect will likely to occur. Hence, RLT enables the detection of this kind of structure or material in-perfection of the pile, and can be used as a reliable form of serviceability check of the pile.

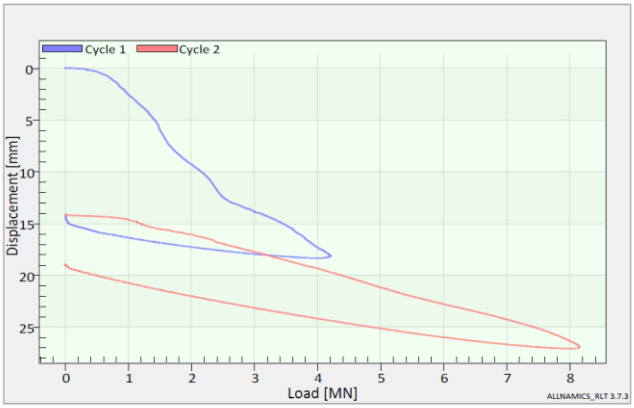

Figure 14. StatRapid multiple cycles load-settlement results for pile P2107 (Case 4, Site E).

Figure 15. Photo of excavated pile head showing the horizontal crack (Case 4, Site E).

5. CONCLUSION

The load-settlement pattern obtained for the multiple cycle StatRapid test reveals the basic nature of the pile behavior. A straight-line load-settlement response indicates that the pile behavior is elastic where pile resistance predominantly comes from shaft friction. A long and rigid pile subjected to relatively small load will see some form of vibration or spiral in load-settlement shape. The “pregnant” shaped load-settlement curve may indicate some partial mobilization of end bearing in addition to almost full mobilization of shaft friction. Finally, if the pile is undergoing some form of soft toe or structural failure, it will show some premature large settlement especially at the early cycles of the multi-cycle RLT.

Understanding the pattern of load-settlement curves of RLT can help to ascertain the satisfactory performance of pile with respect to serviceability criteria, help to identify early mobilization of end bearing and hence, excessive settlement of pile, as well as help pick up structural failure, if there is. In short, it can provide some form of check on the integrity of pile installed and provide additional information on the “health” of installed pile.

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