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Soon Hoe Chew,[1] Lam Siang Chuah,[2] Hui Hock Tan,[2] and Zi Xun Eng[2]

A Comparison Study for Static and Statnamic Load Tests on Two Instrumented Piles in Southeast Asia

Citation

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ABSTRACT

The statnamic load test (STN) has gained popularity as an alternative pile load testing method in Southeast Asia compared with the conventional static load test (SLT). Owing to the local geological conditions and regulation requirements, drilled shafts in Malaysia and Singapore are basically designed to pass through a layer of soft soil at the upper part of the pile and then socketed into the stiff residual soil/old alluvium/weathered rock. Thus, these piles mobilize relatively higher skin friction near the bottom of the pile with a strong end-bearing component. The rate effect of friction piles under rapid loading that is usually exhibited in stiff clay is found to be insignificant, which allows the unloading point method to work reasonably well to derive the static-equivalent capacity of the pile. Furthermore, the test load usually is still much lower than the real ultimate capacity. Thus, the load-settlement response obtained from the STN is basically identical to the SLT response without any further correlation. To date,

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[1]University of Singapore, Dept. of Civil and Environmental Engineering, 21 Lower Kent Ridge Rd., 119077, Singapore http://orcid.org/0000-0001-9354-3044

[2]Geonamics (M) Sdn. Bhd. No 6, Lot 25, Jalan Udang Harimau 1, Medan Niaga Kepong, 51200, Kuala Lumpur, Malaysia L. S. C. http://orcid.org/0000-0003-0948-6927, H. H. T. http://orcid.org/0000-0001-7775-3877, Z. X. E. http://orcid.org/0000-0003-1686-3049

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there are limited case references on correlation work for these kind of piles. Therefore, we performed a comparison study to evaluate the SLT and STN on two instrumented piles that were installed within a similar soil profile but different in working load, diameter, and length. In this comparison study, the load-settlement behavior and load-transfer curve were evaluated. The correlation between the two tests was found to be excellent in terms of specific settlement values at a specific load, normalized load-settlement response, and normalized load-transfer curve. The normalized load-settlement and normalized load-transfer curve were found to be consistent between the SLT and STN. Hence, it could be concluded that the STN provided a good alternative for a conventional SLT, at least for this category of drilled shafts.

Keywords

statnamic load test, static load test, correlation, case study, rapid load test, drilled shaft

Introduction

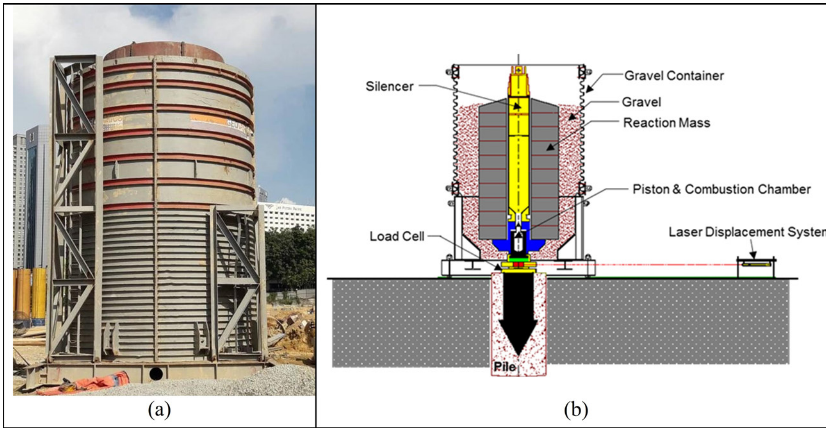
Pile testing is a critical step in verifying design parameters as well as evaluating pile performance. Piles are conventionally tested using static means such as kentledge blocks, steel plates, or reaction-tensioned piles. These conventional tests are also known as a maintained load test. Over the last three decades, driven by productivity gain, the rapid load test (RLT) has been developed [1]. One form of RLT, the statnamic load test (STN), has gained popularity over the years, first in the United States, Canada, and Japan and now in Southeast Asia.

OVERVIEW OF STATNAMIC LOAD TEST

The high cost and large amount of time involved in setting up and conducting a static load test (SLT), particularly with high-capacity drilled shafts or bored piles, have prompted a search for alternative methods of load testing that might be more efficient and cost-effective [2,3]. With this, the STN has been innovatively introduced with a relatively fast setup and small reaction mass compared with the conventional SLT. As shown in **Fig. 1**, the STN launches a reaction mass from the pile head with fast-expanding and high-pressure gases in a confined cylinder. The high-pressure gases are produced by the burning of a solid propellant fuel within the piston cylinder assembly. Typically, the reaction mass is accelerated upward at 20 *g*; thus, a downward force in the order of 20 times the reaction mass will be generated. Therefore, the required reaction mass is only 5 % of the static mass equivalent to the final test load. This salient feature of STN has become one of the key advantages over the conventional SLT. It saves the required amount of reaction mass in the pile load test and hence time and effort in setting up.

In an STN, the actual load on the pile is monitored by using a calibrated load cell placed on the pile top. The pile top displacement is monitored by using a laser assembly. With these two direct measurements (i.e., load and displacement), the load-settlement relation of the test pile can be derived similar to the SLT.

FIG. 1 The statnamic load test: (a) typical field setup and (b) schematic diagram.



The loading duration of the downward force in the STN is typically about 100 to 250 ms, which is considered a relatively long duration in terms of wave propagation. As a result, the pile reacts as a rigid body without the influence of stress wave propagation within the pile. Thus, the soil-pile interaction is considered as consisting of inertial effect and damping only. This can then be used to derive the static-equivalent capacity of the pile. The unloading point method (UPM) is a common approach in Malaysia and Singapore used to derive this capacity. However, its possible derivation from the STN is always hampered by uncertainties about the interpretation of the test results, the effect of the loading rate, etc. Hence, a correlation is required to compare the results of the STN and SLT.

CORRELATION OF STATNAMIC LOAD TEST

To date, while there are some publications of correlation between the STN and SLT in the United States, Japan, and Europe [4,5], there are very few references to these tests in Southeast Asia. In the last 30 years, the development of infrastructures in Southeast Asia has been rapid, especially in Malaysia and Singapore. Hence, there were an ample number of piles constructed and tested. A growing number of these tests used the STN method. Many technical reports were produced to compare the results of the STN and SLT by both testing companies and independent third-party consultants [6–13]. Most of these reports verified that the static-equivalent load-settlement curve obtained from the STN in Malaysia and Singapore compared well with the load-settlement curve from the SLT. These included both land piles and marine piles. All of these test piles as well as others in Malaysia and Singapore have special characteristics. The piles were designed to pass through a layer of soft soil (soft clay or loose sand) at the upper part of the pile and then penetrated stiff soil/residual soil/weathered rock at the bottom part of the pile. They were typically socketed into hard rock or slightly weathered rock. The pile capacity was derived by mobilizing the skin friction at the bottom portion of the pile and end bearing as required. According to the reported test results, the settlement of piles subjected to up to three times the "designed working load" is almost the same as measured during static-maintained load tests.

Most, if not all, piles in Malaysia and Singapore usually have much higher skin friction at the bottom part of the pile and a strong end-bearing component. This is different from other parts of the world, where piles may include much more friction, as in a stiff clay layer. As a result, the load-settlement responses are relatively sharp, and the unloading point (UP) is very close to the peak dynamic force. The UP is the point in the load-settlement curve at which the settlement value is at its maximum and the velocity value is zero. In this situation, the rate effect (mainly for stiff-clay friction piles) is found to be insignificant, and the load-settlement response obtained from UPM is basically identical to the response in the SLT without any further correction. This paper aims to summarize the key findings of these reports and provide a comprehensive case study on the comparison between the SLT and STN in a situation in which piles derive their main capacity from high skin friction at the bottom portion of the pile or the end-bearing component, or both.

Project Background

In conjunction with a building construction project in Putrajaya, Malaysia, there were several STNs and SLTs conducted on the bored piles. Two adjacent instrumented bored piles with similar soil profiles were tested with the SLT and STN in this comparison study. The SLT was performed on Test Pile 1 (TP1), whereas the STN was performed on Test Pile 2 (TP2). The location of the pile tests is shown in Fig. 2.

SOIL PROFILES

The properties and installation details of these test piles are summarized in Table 1. Boreholes ABH-13 and ABH-8 were the nearest boreholes to TP1 and TP2, respectively. The soil profiles for ABH-8 and ABH-13 were superimposed with the SPT N value and shown in Fig. 3. The cutoff level was about 6 to 7 m from the pile top. It can be seen that the major part of the frictional capacity of these two piles was likely to be contributed by the similar layer of soil—"stiff and hard sandy SILT" with SPT N = 30–50. Both piles were further socketed into 3 to 8 m of weathered and fractured schist. Thus, the soil profiles for these two piles could be taken as similar to some degree.

INSTRUMENTATION PLAN

To monitor the mobilization of skin friction and end bearing during the load test, both test piles were instrumented with strain gages in the reinforcement steel cage

FIG. 2 The location of the statnamic load test and static load test.

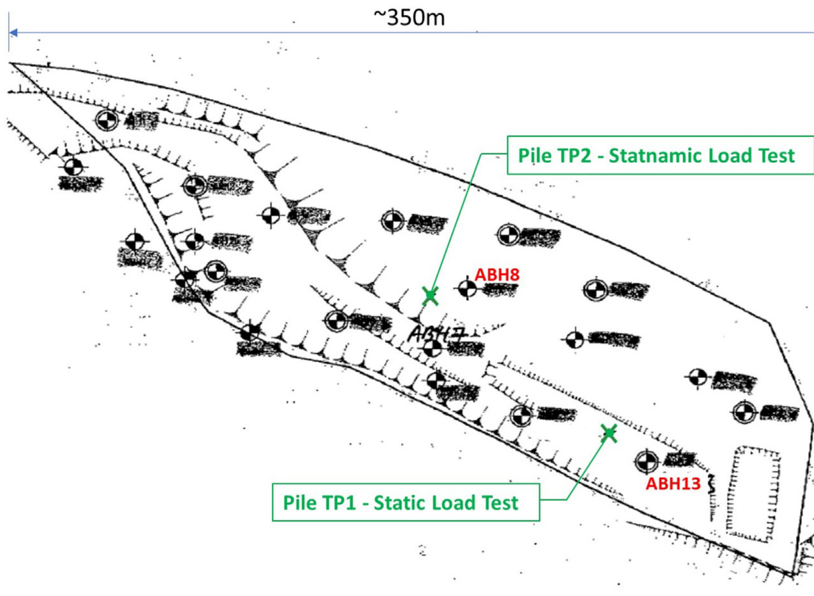
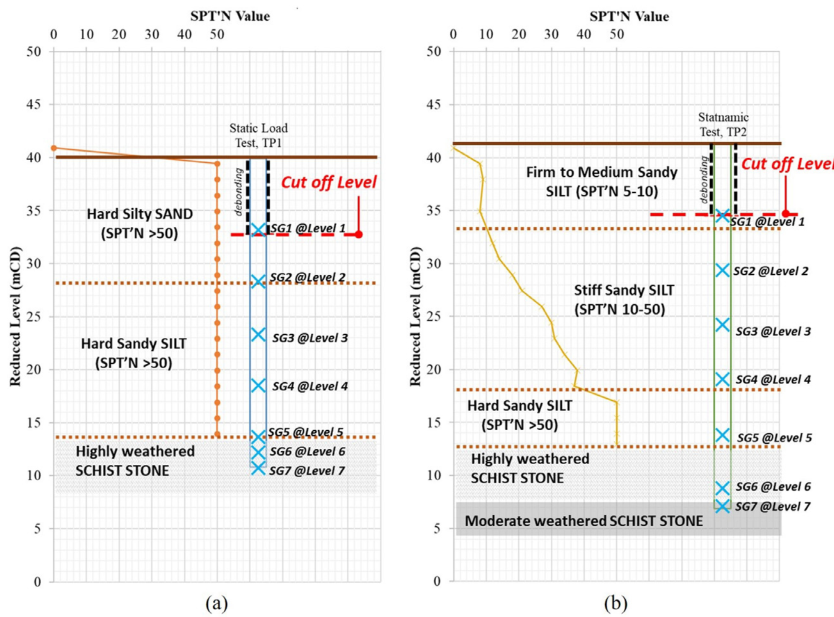


TABLE 1 Summary information of test piles.

Details	Test Pile 1	Test Pile 2
Type	Bored	Bored
Diameter (mm)	1200	1000
Length (m)	29.10	34.50
Design working load (kN)	12,900	9,000
Instrumentation of strain gages over pile length?	Yes	Yes
Testing method	Static load test	Statnamic load test

at seven levels of depth. The location of the installed strain gages in both test piles is shown together with the soil profiles in Fig. 3. There were four cycles of SLT and one cycle of STN conducted on TP1 and TP2, respectively. In both tests, the strain readings were recorded and subsequently converted to the corresponding mobilized force during the pile load tests. The pile section above the designed cutoff level was debonded during the pile construction so that the design working load tested represented the working piles. As a result, the strain gage at Level 1 was taken as the same load at the pile top. The strain gage at Level 7 represented the end-bearing load.

FIG. 3 The soil profiles and SPT N value for borehole (a) ABH-13 and (b) ABH-8.



Results of Pile Load Tests

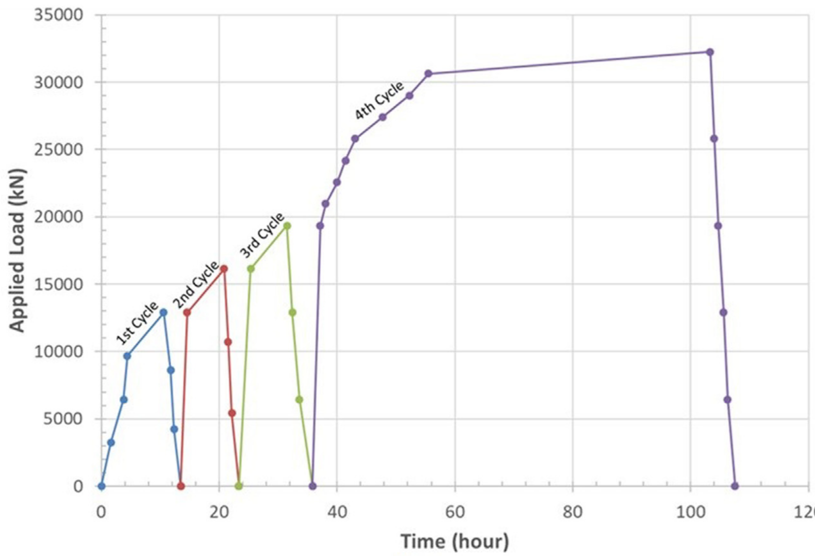
This section presents the test results obtained from the SLT and STN. The load-settlement response and the measured load transfer via strain gages are reported accordingly.

LOAD RESPONSE

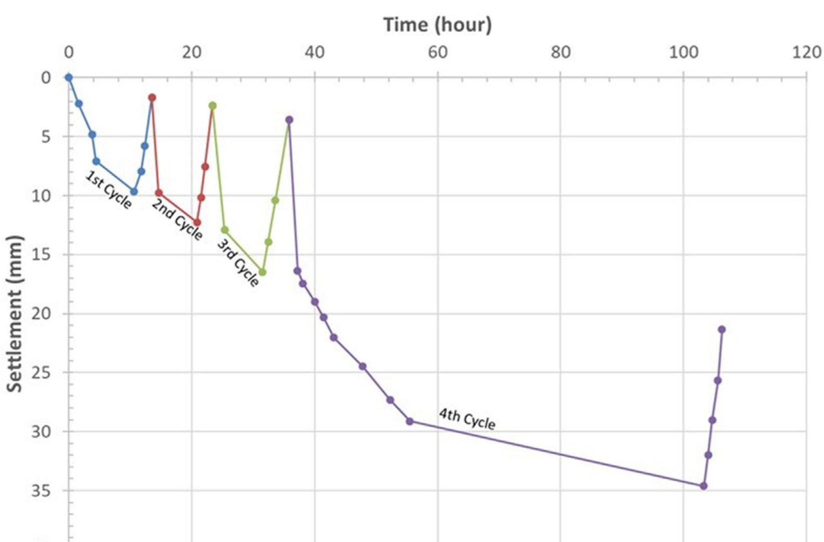
During the SLT, TP1 was subjected to four cycles of loading and unloading stages. The load and settlement at the pile top during the SLT are shown in Fig. 4. It can be seen that the settlement at the top of TP1 shows the typical behavior of the pile-soil interaction. The total duration of the SLT was approximately 107 h.

During the STN, the displacement and acceleration at the top of TP2 were directly measured over time, as shown in Fig. 5. At the beginning of the STN, the pile top was displaced downward rapidly until a time shortly after the maximum applied test load. The pile rebounded in the later unloading stage. It also can be seen that the pile was subjected to several acceleration and deceleration cycles in the loading and unloading stage until the pile became stable and achieved equilibrium. The total duration of the STN cycles was approximately 250 ms.

FIG. 4 The direct measurement in the static load test: (a) load and (b) pile top settlement.



(a)



(b)

LOAD-SETTLEMENT RESPONSE

Fig. 6 and Fig. 7 show the four cycles of static load-settlement curves obtained from the SLT for TP1 and the single cycle of the STN for TP2, respectively. For the SLT,

FIG. 5 The direct measurement in the statnamic load test: (a) load, (b) pile top displacement, and (c) pile top acceleration.

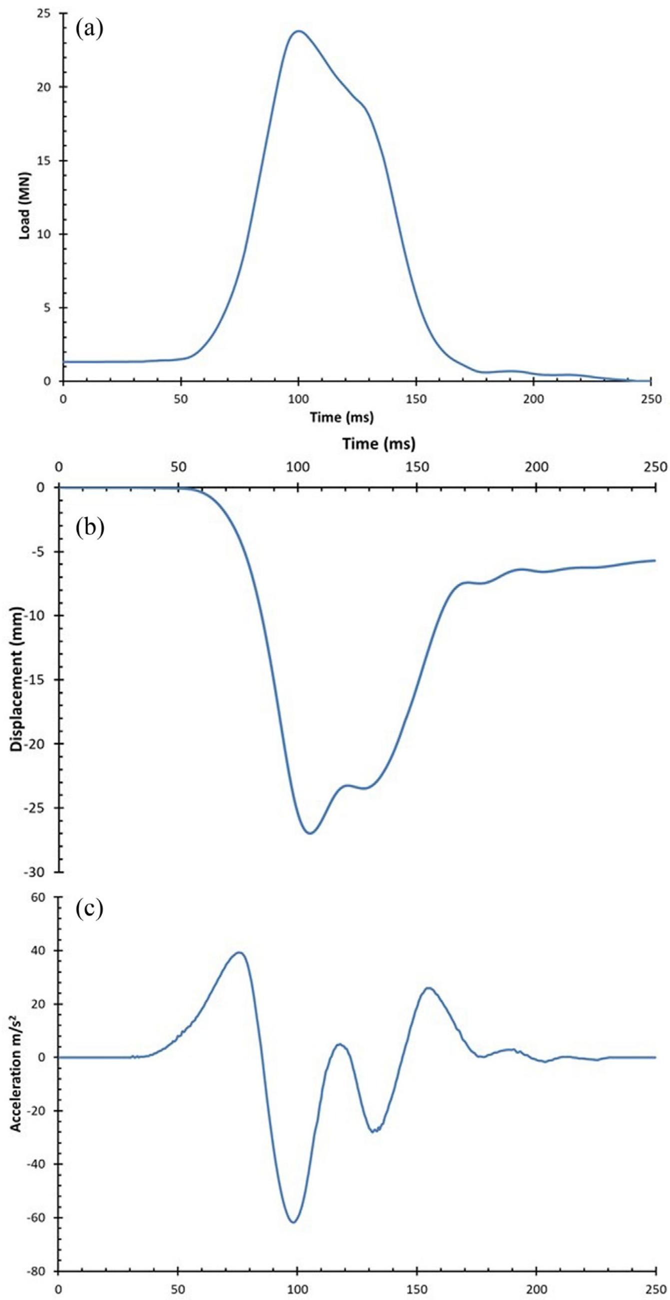


FIG. 6 The static load test on Test Pile 1.

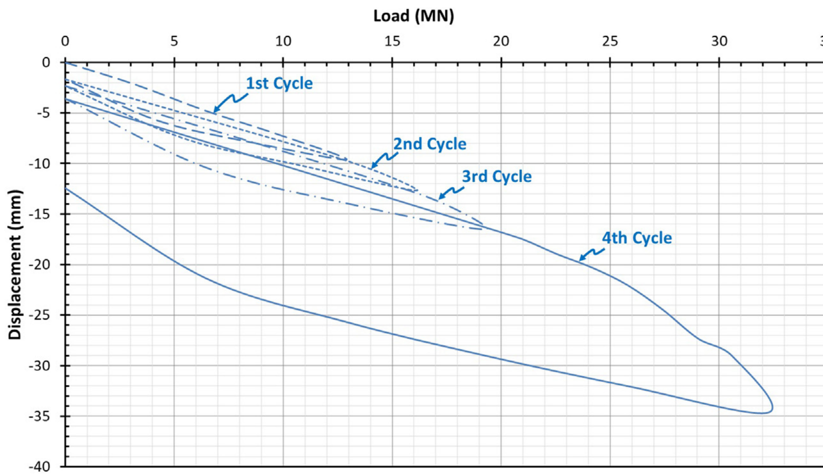
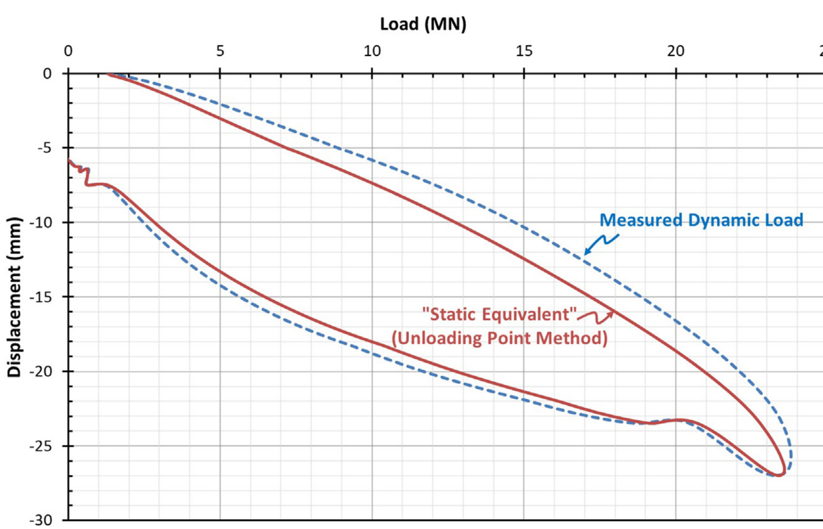


FIG. 7 The statnamic load test on Test Pile 2.



the load-settlement curve generally followed the typical soil-pile behavior in four continuous loading and unloading cycles. The maximum settlement of 34.63 mm was registered at a maximum load of 32,250 kN (WL = 12,900 kN) in the SLT. After the unloading stage, the final residual settlement was 12.42 mm.

For the STN, the load-settlement curve also illustrated a typical soil-pile behavior similar to the SLT. It was noted that the load measurement in the STN was a dynamic load. The UPM was adopted to derive the static-equivalent load-settlement response from the test results. The detail of the UPM methodology can be found elsewhere [13,14]. As shown in Fig. 7, the solid line is the derived static equivalent for the STN. The maximum static resistance and settlement were registered at 23,420 kN (WL = 9,000 kN) and 26.99 mm, respectively. The subsequent unloading stage in the STN yielded a residual settlement of 5.70 mm.

LOAD-TRANSFER CURVES

By measuring the strain readings at different depths in the pile, the distribution of the mobilized friction over the pile length can be computed as a load-transfer curve. Table 2 and Table 3 show the values of the mobilized load at various depths for the

TABLE 2 Load transfer for static load test (Test Pile 1).

Reference	Depth (m)	Load Transferred (kN)			
		1.0 × WL	1.5 × WL	2.0 × WL	2.5 × WL
Pile Top	0.00	12,900	19,350	25,800	32,250
Level 1	−6.70	12,900	19,350	25,800	32,250
Level 2	−11.58	11,133	18,726	25,569	31,188
Level 3	−16.45	5,447	8,713	12,888	17,382
Level 4	−21.33	2,983	4,416	6,767	9,652
Level 5	−26.20	502	409	822	1,643
Level 6	−27.63	278	157	315	716
Level 7	−29.05	32	274	532	849

Note: WL = working load.

TABLE 3 Load transfer for statnamic load test (Test Pile 2).

Reference	Depth (m)	Load Transferred (kN)				
		1.0 × WL	1.5 × WL	2.0 × WL	2.5 × WL	2.6 × WL
Pile Top	0.00	9,000	13,570	18,320	22,520	23,420
Level 1	−6.86	9,000	13,570	18,320	22,520	23,420
Level 2	−12.03	8,650	12,680	17,070	20,890	21,830
Level 3	−17.20	6,790	10,460	14,580	18,540	19,570
Level 4	−22.36	5,070	7,470	10,800	13,930	14,640
Level 5	−27.53	3,250	3,820	6,410	8,400	8,600
Level 6	−32.70	1,110	2,100	3,280	4,490	4,970
Level 7	−34.35	480	700	1,020	1,950	2,230

Note: WL = working load.

SLT and STN, respectively. The load-transfer curves for the SLT and STN are plotted in Fig. 8 with dotted lines and solid lines, respectively. In each case, the load-transfer curves at 1.0, 1.5, 2.0, and 2.5× the WL are plotted together in Fig. 8. Fig. 8 clearly demonstrates that the load-transfer curves of both tests were very similar in nature.

It is observed that the top 12 m of TP1 (i.e., the SLT) and 7 m of TP2 (i.e., the STN) were debonded and hence have the same load as the pile top. In general, it can be seen that most of the shaft friction mobilized was from the bottom portion of the pile. There was very little end-bearing capacity mobilized in both cases.

Discussion

This section discusses the comparison study based on the results of these two test piles (i.e., the STN and SLT), especially for the settlement value at a specific load, the normalized load-settlement response curve, and the normalized load transfer curves.

THE SETTLEMENT VALUE AT A SPECIFIC LOAD

For the comparison study, the load-settlement behavior measured in all four cycles of the conventional SLT, as well as the static equivalent from the STN, are plotted in Fig. 9. It can be seen that the load-settlement responses were very similar. Both tests yielded very similar stiffness, which was expected because both piles were

FIG. 8 The load-transfer curves of the static and statnamic load tests.

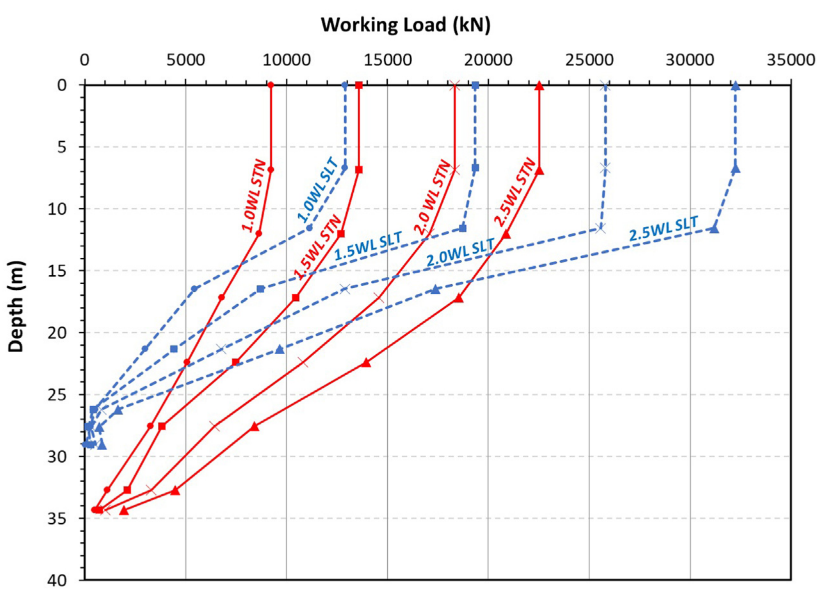
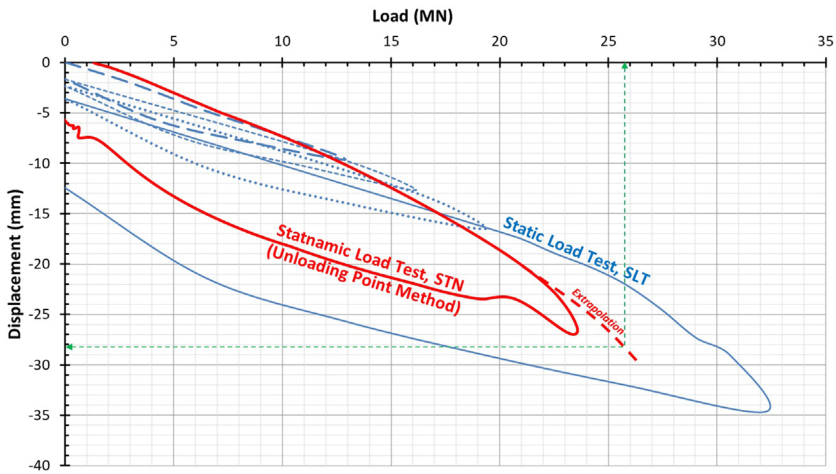


FIG. 9 The load-settlement responses of static and statnamic load tests.



basically terminated on the thick layer of hard soil/weathered rock with N > 50. It should be noted that the two piles did not have the same diameter and were not in exactly the same soil profile.

Interestingly, at a relatively low loading level (i.e., < 15 MN), the settlement value for the two piles was found to be very close. The difference of settlement between these two piles only became large at > 15 MN loading level. Table 4 summarizes the settlement values at various specific loads in the SLT and STN. It can be seen that at the lower loading level (i.e., < 15 MN), both piles experienced almost the same amount of settlement with the STN (TP2), consistently about 0.5 mm less than the SLT (TP1).

It is worth noting that TP2 (STN), being a smaller-diameter pile (i.e., 1.0 m), is installed within a soil profile that is weaker than that in TP1 (SLT) (1.2 m). Hence,

TABLE 4 Comparison of settlement values at specific loads.

Pile Testing Method	Pile Diameter (mm)	WL (MN)	Cycle	Normalized Settlement (Settlement/Pile Diameter) (%)			
				1.0 × WL	1.5 × WL	2.0 × WL	2.5 × WL
SLT(TP1)	1,200	12.9	1	0.80	—	—	—
			3	—	1.37	—	—
			4	—	—	1.84	2.88
STN(TP2)	1,000	9.0	1	0.65	1.08	1.60	2.28
Difference (Δ = STN − SLT)				−0.15	−0.29	−0.24	−0.60

Note: SLT = static load test; STN = statnamic load test; TP1 = Test Pile 1; TP2 = Test Pile 2; WL = working load.

as the load increased, TP2 should have settled more than TP1. This speculation was confirmed with the results shown in Table 5. As the load increased from 18 to 22.5 to 25.8 MN, the settlement for the STN pile was found to be 1.00, 3.89, and 6.17 mm respectively, more than that of the SLT pile. Hence, the overall load-settlement response of the static equivalent from the STN compared very well with the conventional SLT.

NORMALIZED LOAD-SETTLEMENT RESPONSE

To compare the load-settlement curves for the two test piles with different diameters and working loads, each measured load was normalized by each design working load, and each measured settlement was normalized by each pile diameter. With these normalized parameters, Fig. 10 plots the normalized load-settlement response for both test piles with the STN and SLT. Similarly, Fig. 10 demonstrates that the normalized load-settlement response of the conventional SLT results and the static equivalent of the STN results were very close to one another.

Table 4 shows the normalized settlement at various normalized loads for both the SLT and STN. This result indicates that when the pile was loaded long before the failure load (< 2.0 WL), the magnitude of settlement was about 1 %–2 % of the pile diameter for both piles. At this loading level, the differences between the SLT and STN were found to be well within 0.15 % to 0.25 %. However, when both piles were loaded nearer to failure at about 2.5× WL, the settlement was at the approximate 2.2 %–2.8% pile diameter. The difference between the SLT and STN increased to approximately 0.6 % in this respect. This implies that the STN correlates to the SLT.

NORMALIZED LOAD-TRANSFER CURVES

To compare the load-transfer curves for the two test piles with different diameters and working loads, each measured load was normalized by its respective design working load, and each depth was normalized by its respective pile length. With these normalized parameters, Fig. 11 is reproduced from Fig. 8 to illustrate the

TABLE 5 Comparison of normalized settlement values at specific normalized loads.

Pile Testing Method	Pile Diameter (mm)	WL (MN)	Cycle	Settlement at Specific Load (mm)				
				9 MN	12.9 MN	18 MN	22.5 MN	25.8 MN
SLT (TP1)	1,200	12.9	1	6.92	9.63	–	–	–
			3	–	–	14.99	–	–
			4	–	–	–	18.92	22.03
STN (TP2)	1,000	9.0	1	6.47	9.10	15.99	22.81	28.20 (extrapolated)
Difference (Δ = STN – SLT)				−0.45	−0.53	+1.00	+3.89	+6.17

Note: SLT = static load test; STN = statnamic load test; TP1 = Test Pile 1; TP2 = Test Pile 2; WL = working load.

FIG. 10 The normalized load-settlement responses of the static and statnamic load tests.

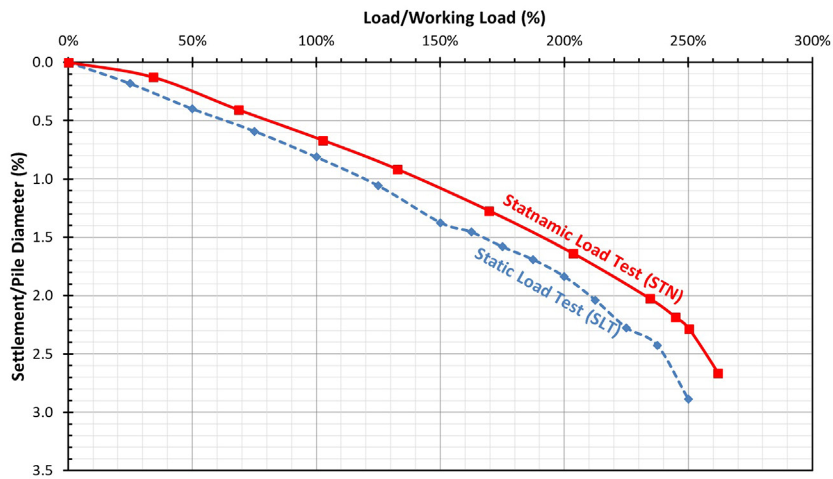
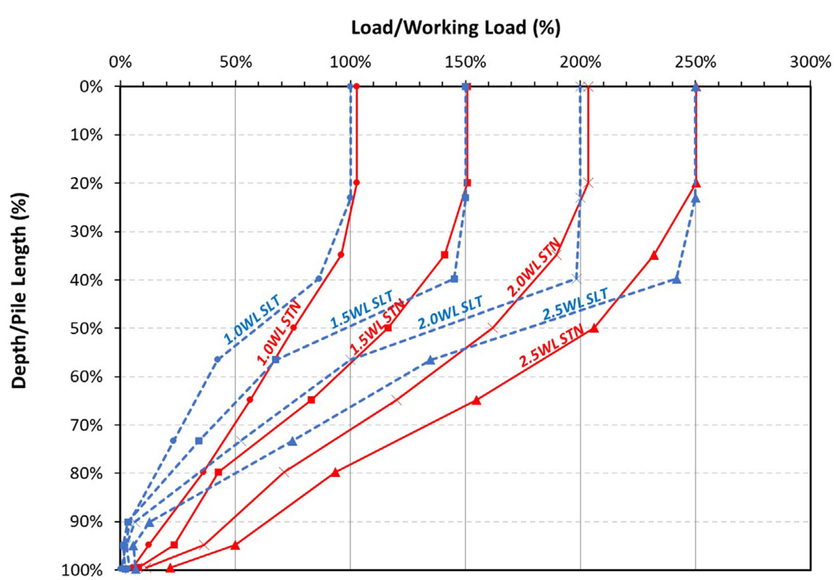


FIG. 11 The normalized load-settlement responses of the static and statnamic load tests.



normalized load-transfer curves for both tests. In this plot, the dotted lines and solid lines represent the load-transfer curves for the SLT and STN, respectively. Based on these normalized load-transfer curves at 1.0, 1.5, 2.0, and 2.5× WL, both tests showed almost identical load-transfer patterns at all load test levels except at 2.5×, owing to the slight variation in the soil profile. Hence, this normalized plot provided additional evidence to show that the STN could be compatible with the SLT.

Conclusion

This comparison study verifies that the STN can yield results that are compatible with those obtained from the conventional SLT and provides additional support for the correlation of the STN to the SLT. It is noted that TP1 (i.e., SLT) and TP2 (i.e., STN) do not have the same working load, pile length, or pile diameter. Furthermore, these two piles were installed into similar, but not exactly the same, soil profiles. However, within the similar soil stratigraphy, the correlation between the SLT and STN was found to be reasonably good in terms of specific settlement values at a specific load, normalized load-settlement response, and normalized load-transfer curve, where each settlement was normalized by its respective pile diameter, each load was normalized by its respective working load, and each depth was normalized by its respective pile length. Last, it should be noted that this comparison study was done on two piles socketed into a stiff layer of soil/weathered rock, which allowed the UPM to work reasonably well to derive the static-equivalent capacity of the pile in this project. Hence, it can be concluded that the STN can be taken as a good alternative for the conventional SLT, at least for similar types of drilled shafts in Southeast Asia.

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