CORRELATING RAPID AND STATIC LOAD TEST RESULTS OF BORED PILES IN SINGAPORE

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ABSTRACT

Rapid Load Test (RLT) has become a common and standard method of testing in Singapore for bored pile as it is generally easier and faster to set-up than conventional Static Load Test, and is less complex to analyse than Dynamic Load Test. Recently Singapore is seeing greater use of Rapid Load Test for verification of pile design parameters and pile geotechnical capacity, in ultimate load tests, as well as, for verification of pile head settlement criteria in working load tests. This paper summarizes results of many correlation tests conducted on bored pile, where both static load test and rapid load test were conducted, for high-rise buildings developed by public housing agency, Housing & Development Board (HDB), Singapore. Based on tests carried out in HDB projects, Rapid Load Test generally provides good correlation with Static Load Test in various soil types in Singapore. This paper focus on the correlation between Rapid Load test and Static Load Test especially in pile head load-settlement behaviour, mobilized skin friction and mobilized end bearing.

Keywords: Rapid Load Test, StatRapid Test, Static Test, Correlation, Pile Head Settlement, Skin Friction, End Bearing

1. INTRODUCTION

With limited land and dense population in Singapore, Housing & Development Board (HDB) has been building taller and taller residential blocks which require deeper and larger diameter bored piles as foundation system. To ensure that the constructed piles are able to safely support the design load, certain percentage of these piles have to be verified by pile load tests – both ultimate load test to verify the design parameters and geotechnical capacity, and working load test to verify that the piles satisfy the pile settlement criteria. Traditionally, these pile load tests are carried out using Static Load Test method such as Kentledge test where concrete blocks are stacked to build up the required test load. Sometimes the concrete blocks stacking can be as high as 20 m depending on the load required (see Figure 1). This method requires extensive manpower, large temporary working space and footprint, and is very time consuming. Furthermore, it poses safety risks for the workers such as falling from height or being hit by toppling of these heavy concrete blocks.

Figure 1. Massive Kentledge Test by Stacking Concrete Blocks

To increase productivity and enhance construction safety, HDB introduced Rapid Load Test (RLT) technology, as an alternative solution which does not require stacking of heavy concrete blocks. There are two types of RLT, commonly known as Statnamic and StatRapid. The Statnamic works by the rapid burning of a fuel that produces gas in a pressure chamber (Middendorp, 1993). This gas accelerates a reaction mass upwards at a maximum peak acceleration of about 20 times gravity which in turn imparts a downward load on the test pile. Thus only 5% of the reaction mass used during static testing is required to produce the same test load (Middendorp, 2000). The load duration is normally regulated to about 200 milliseconds or up to 40 times greater than that for a dynamic test, hence minimizing the generation of tensile stresses for piles (Nishimura & Matsumoto 1995, Middendorp & Bielefeld 1995). This method becomes very popular in USA, Japan, Canada, Netherlands, Germany and Malaysia over the years.

Another type of RLT, StatRapid Test, is developed based on the similar concept; but instead of using fuel combustion, the compression load is generated by dropping a modular weight onto a soft spring system, thus generating a downward decelerating force of about 20 times of its gravity (Chew et al., 2015). The typical set-up of StatRapid is shown in Figure 2. Given this advancement in technology, pile testing can now be done faster, safer and requires less space.

Figure 2. StatRapid System for Rapid Load Testing of Piles at Punggol C36 Project

2. STATRAPID TEST AND ITS INTREPRETATION IN SINGAPORE

The StatRapid system consists of a lifting and guidance frame, a modular drop mass (allowing for a mass up to 40 or 100 tonnes), a catch mechanism and a modular soft spring system (see Figure 3). The duration of the load application and the maximum load level can be adjusted by varying the drop mass weight, the spring stiffness and the lifting height. The system is hydraulically operated and has sensors for a proper vertical and stable position. It should be noted that the dead weight of the drop mass can also be used for the first (static) loading cycle. The catch mechanism catches the drop mass after bouncing up from the soft springs. This allows for successive multiple-cycle testing with varying loads similar to multiple-cycle static load testing.

The pile head settlement and acceleration are measured at the pile top and recorded. For measurement of load, two to three load cells, instead of one big load cell, are placed at the pile top in StatRapid system as the pile diameter are sometimes more than 1,5 m in Singapore.

Rapid load test can be viewed as a pseudo-static load application. Thus, after the load application, it is necessary to derive an **equivalent static** load-settlement curve from the Rapid Load Test data by eliminating rate effect, inertia effect and damping effect (Hyde & Brown, n.a.). The most common form of analysis currently used is the Unloading Point Method (UPM) (Kusakabe & Matsumoto 1995; Nishimura and Matsumoto, 1995) which takes into account both velocity dependent soil viscous damping and acceleration dependent pile inertia. However, this method assumes the soil viscous damping is linear with velocity. It was reported that the UPM method generally provides a good correlation with static tests for sands and gravels (Brown 1994, McVay et al. 2003, Wood 2003) where rate and viscous damping is negligible, it may over predict pile capacities by up to 50% for clay soils (Holeyman et al. 2000). However, in Singapore, our piles are designed such that the pile head settlement is limited to 15 mm at 1.5 times of working load, or 25 mm at 2 times of working load. This pile settlement requirement results in piles being mostly socketed into firm soil or rock for some penetration length where skin fiction is the major component under 1.5 or 2 times of working load. Most of these pile are socketed in dense to hard sandy or silty soil, as Singapore does not have thick layer of stiff clay formation. Hence, rate and viscous damping effect on such piles is negligible (Chew et al., 2015, Chew et al., 2017).

Note: Working Load is equivalent to Characteristic Load in EC7.

Figure 3. StatRapid Modular Spring System (Middendorp & Verbeek, 2012).

3. TYPICAL STATRAPID TEST AND ITS CORRELATION WITH STATIC TEST-PUNGGOL EAST C36 CASE STUDY

A typical HDB housing project at Punggol East C36 site is described and discussed as an example of the application of Rapid Load Test in Singapore. In this project, correlation test with static load test is carried out as required by the local authority.

Bored piles with various lengths and diameters are installed for the construction of high-rise public housing in Punggol East (C36). The bore logs and the logs from pile installation record indicate that the soil profile consists mainly of sand, high in silt content up to and beyond the pile toe level. The top 25m is interlayered with one or two clayey-silt layers.

For the purpose of the study, two working piles have been tested by both Kentledge and StatRapid method. The pile specifications are shown in Table 1.

Table 1. Test Pile Specifications for C36

Test Pile Number	Diameter (mm)	Length (m)	Working Load (tons)
7C47-1	600	51.0	212
G74-5	800	46.2	377

Pile 7C47-1 was tested with Kentledge system and subsequently StatRapid test. Pile G47-5 was tested with StatRapid first and then subsequently Kentledge system.

3.1 Results and Analysis

Table 2 and 3 summarize the settlement results of these two test piles. The settlements results from StatRapid test correlates very well with settlement results from Kentledge test. The sequence of test on the same test pile has appeared to have no significant influence to pile settlement results at this particular site.

Table 2. Settlement results from Kentledge and StatRapid on Pile 7C47-1

Times of Working Load	Settlement from Kentledge Test - Scale Rule (mm)	Settlement from Kentledge Test – Dial Gauge (mm)	Settlement from StatRapid (mm)
1xWL(2.1MN)	2.75	3.15	2.90
2xWL(4.2MN)	7.00	6.82	6.60

Table 3. Settlement results from Kentledge and StatRapid on Pile G74-5

Times of Working Load	Settlement from Kentledge-Scale Rule (mm)	Settlement from Kentledge–Dial Gauge (mm)	Settlement from StatRapid (mm)
1xWL (3.8MN)	4.75	4.87	4.20
2xWL (7.5MN)	10.00	10.58	10.00

The typical soil profile and the typical load-transfer curve for the project C36 are shown in Figure 4a and 4b respectively. As the soil profile at this particular site is mostly sandy, Unloading Point Method is appropriate. Furthermore, it can be seen that even at 2 times of working load, the major contributor of the pile capacity is still the skin friction, and the end bearing is hardy mobilized. This explained why that the settlement at 2 times of working load is still small. Hence, the loading rate effect is NOT significant, and hence, the correlation between the static load test and StatRapid test is so good, and the sequence of loading has no effect, and the residual settlement is very small. It is essentially an "elastic pile behavior". Most of the Singapore piles are indeed in this condition.

4. COMPILATION OF CORRELATION TEST RESULTS

Given that Rapid Load Test is relatively new in Singapore, in the last ten years, HDB conducted a study to correlate the results of RLT against Static Load Test to establish the reliability of RLT before being used to replace Static Load Test at HDB sites to a larger extent.

A total of 14 correlation tests have been performed at the 11 different HDB sites in this study. This correlation tests were done either on the same test pile or two similar piles adjacent to each other. In this paper, only correlation tests whereby the same pile is tested by both methods (Static Load Test and RLT) are presented.

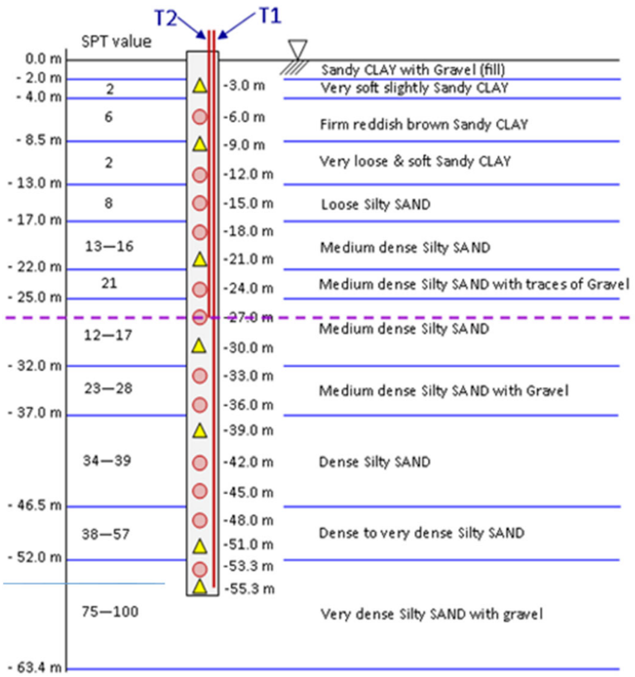

Figure 4a. Typical soil profile at the project site.

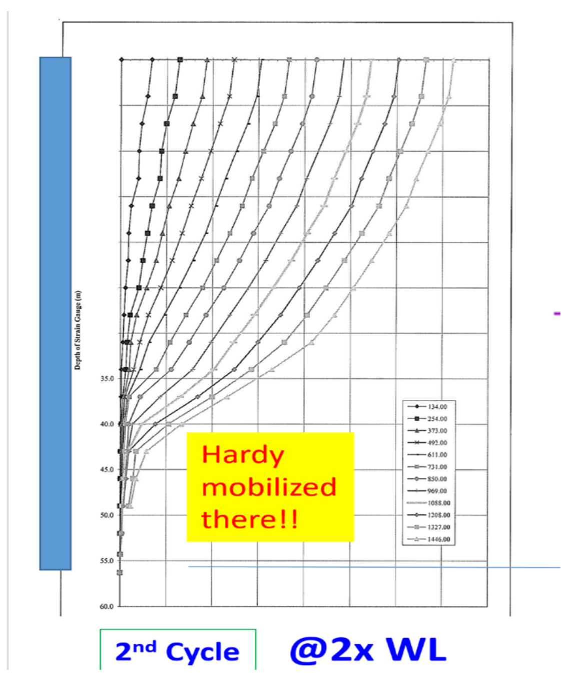

Figure 4b. Typical load-transfer curve at the project site at Punggol East C36.

Regarding the sequence of test (i.e. static first or StatRapid first), eight (8) number of the correlation tests began with Kentledge followed by StatRapid method, and another 6 numbers of the correlation tests began with StatRapid and then followed by Kentledge method.

The correlation test pile diameter is between 600mm to 1000mm. Pile penetration length varies from 15m in Tampines site to 51m in Punggol East site. For instrumented Ultimate Load Test (ULT), the pile is tested to 3 times working load. For Working Load Test (WLT), the pile is tested to 2 times of working load. Table 4 summarizes the location and soil profile where correlation tests have been conducted.

Table 4. Correlation Test Location and Soil Profile

Location	Type of Test	Test ID	Predominant Soil Profile	Pile toe Soil/Rock (N=SPT)
(A) Kentledge → StatRapid Test				
Punggol East C36	WLT1 (7C47/1)	L	Silty sand (OA)	Very dense silty sand (N=100)
Yishun N5C6-7	ULT6	A	Sandy silt (BTG)	Very dense silty sand (N=100)
Sembawang N3C7	ULT2	G	Sandy silt (BTG)	GIII granite
Bukit Batok N4C5-7	ULT10	B	Sandy silt (JF) Sandy clay (JF)	SIV siltstone SIV mudstone
Dawson C4	ULT6	C	Sandy silt (JF)	Very hard sandy Silt (N= 100)
Sembawang N1C6	ULT1	D	Sandy silt (BTG)	Hard sandy silt (N=100)
Sembawang N1C12	ULT5	E	Sandy silt (BTG)	GIII granite
Tampines N6C2A	ULT7	F	Sandy clay (OA)	Hard sandy clay (N=60+)
(B) StatRapid → Kentledge Test				
Punggol East C36	WLT2 (G74/5)	M	Silty sand (OA)	Very dense silty sand (N=100)
Sembawang N1C1	ULT-2	H	Sandy silt (BTG)	GIII granite
Sembawang N1C1	WLT- (G46-1)	N	Sandy silt (BTG)	GIII granite
Tampines N6C2B	ULT3	I	Sandy clay (OA)	Hard sandy clay (N=60+)
Bidadari C6 C7	ULT2	J	Silty/grained sand (OA)	Very dense silty/grained sand (N=100)
Bidadari C6 C7	ULT12	K	Silty/grained sand (OA)	Very dense silty/grained sand (N=100)

Note: OA = Old Alluvium Formation
BTG = Bukit Timah Granite Formation
JF = Jurong Formation

4.1 Load-Settlement Behavior of Working Load Tests (WLT)

The pile top settlement of Static Load Test is the average of strain gauge reading and scale rule measurement. The settlement of StatRapid is obtained from the accelerometer and optical measuring device (Reyca). The settlement data of these correlation tests were compiled and shown in Figure 5 (at 1 time of working load), and in Figure 6 (at two times of working load). In these plots, the residual settlement of the first loading cycle is neglected as it is generally very small (less than 2 mm).

It is noted that all the correlation test results satisfy local pile design requirement (i.e. CP4) in terms of pile settlement criteria. That is the allowable maximum pile top settlements of 25mm at two times of working load.

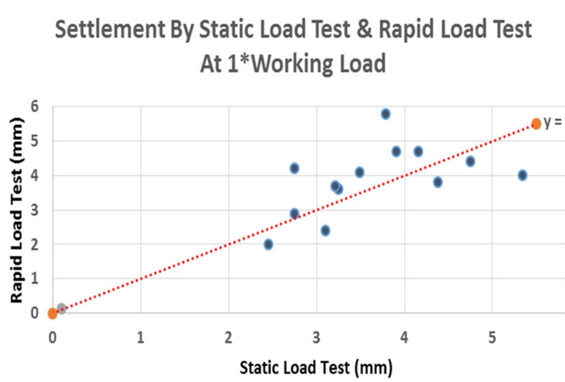

Figure 5- Settlement comparison between Static test and Rapid Test at 1x Working Load.

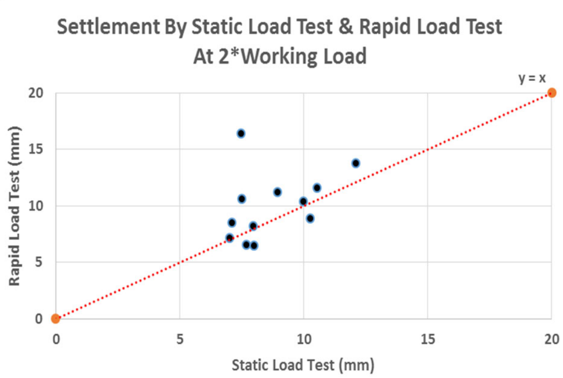

Figure 6- Settlement comparison between Static test and Rapid Test at 2x Working Load.

4.2 Load-Settlement Behavior of Ultimate Load Tests (ULT)

As the sequence of the correlation test begins with one method (say Kentledge) followed by the second method (say StatRapid method), there might be residual settlements upon unloading of the first method. Hence, it is necessary to account for the residual settlement when comparing the settlement values by the two methods, especially for ultimate load test (ULT) when the load is near to the failure load. Also, it is more meaningful to compare the settlement of the second method when it was loaded beyond the "maximum previous load" of the previous cycles (of the first method load).

Figures 5 and 6 shows the settlements by StatRapid method vs Static Load Test method <u>without</u> including residual settlements or "virgin" settlements up to 2 times of working load. The results show that the settlements are almost near the linearity plot, or in other words, settlements by RLT method is almost the same as those by Static method. The difference in settlements is generally 2mm or less. This indicates that the pile was still within their elastic range and the residual settlement from the first method was very small.

For ULT test, it is common to test the pile till three times of working load or to real failure. Figure 7 shows the settlements by StatRapid method vs Static Load Test method at three times working load. In this case, proper account for the residual settlements is needed. Figure 7 shows that the settlements by StatRapid (inclusive residual settlement) still correlates very well with settlements by Static Load Test.

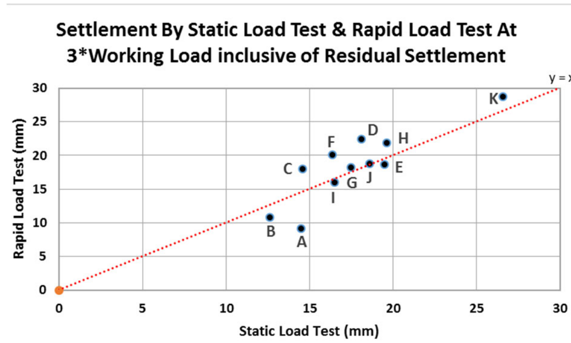

Figure 7- Settlement comparison between Static test and Rapid Test at 3 x Working Load with residual settlement accounted

4.3 Mobilized Skin Friction and End Bearing Obtained from Instrumented Ultimate Load Test

The graph of mobilized skin friction obtained by Kentledge and StatRapid tests are very closely related at one, two and three times of working load as shown in Figure 8.

A series of strain gauges (arranged at full bridge using 120 Ohm resistance type strain gauges) were installed at various depth of the pile shaft. Mobilized skin friction were calculated from the two adjacent strain gauges at various load steps, with correction to the equivalent static load. Figure 8 reveals that the mobilized skin friction obtained by RLT at various depth of the pile is almost identical to that of Static Load Test.

Mobilized unit end bearing was also obtained from the bottom most strain gauges with correction to the depth of embedment below that. Figure 9 shows the unit end bearing results of both static and StatRapid test. Figure 9 also shows close resemblance between the Static Load Test and RLT results. It should be noted that this may not be the ultimate unit end bearing, as the pile toe bearing may not be fully mobilized at this load level.

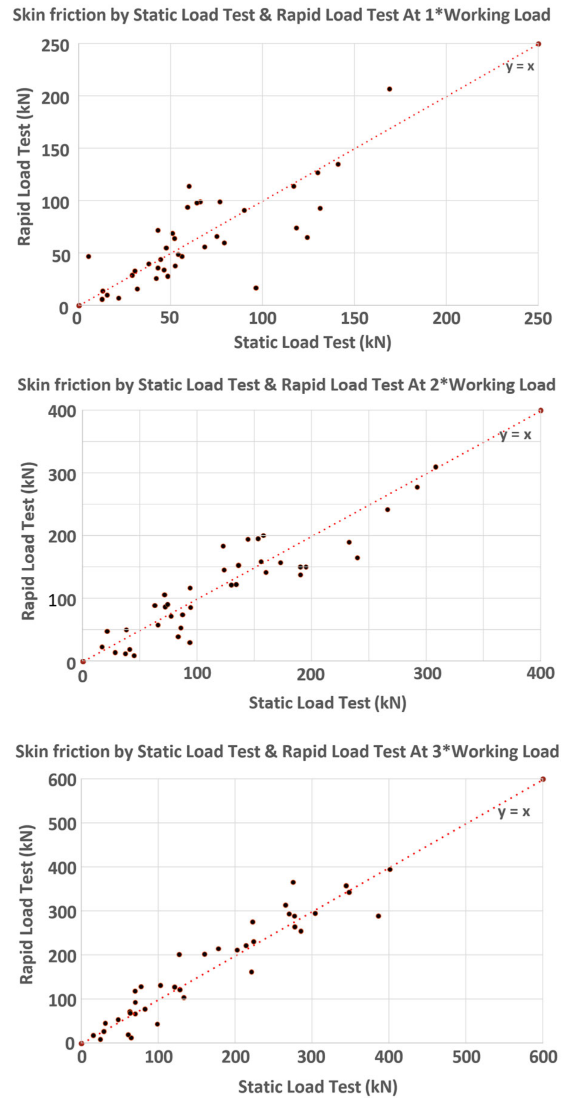

Figure 8. Correlation of Mobilized Skin Friction Obtained by Static Load Test and Rapid Load Test at One, Two and Three Times of Working Load

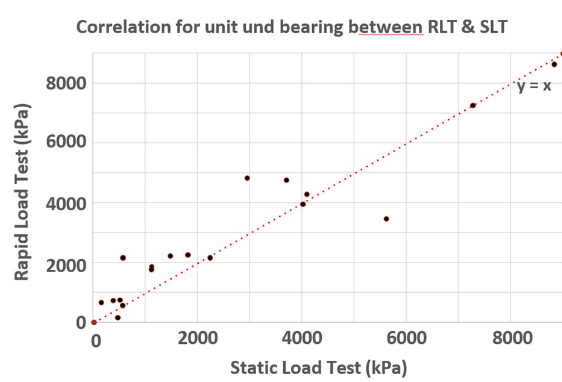

Figure 9. Correlation of Mobilized Unit End Bearing Obtained by Static Load Test and Rapid Load Test at Three Times of Working Load

5. CONCLUSION

Rapid Load Test offers potential time, space, materials and manpower saving. In addition to increased productivity, RLT also enhances construction safety as it does not require stacking of heavy concrete blocks, minimizing the risk of falling from height and being hit by toppling heavy concrete blocks. Hence, RLT can be an alternative to the conventional static load test.

Given that RLT is relatively new in Singapore, HDB conducted a study to correlate the results of RLT against Static Load Test to establish the reliability of RLT before being used to replace Static Load Test. Two aspects were particular interested: (a) settlement comparison for Working Load Tests, and (b) comparison of unit skin friction and unit end baring for Ultimate Load Tests.

The study shows that at 1 time and 2 times of working load, the settlement obtained from StatRapid Test is very close to that of Static Load Test, irrespectively of the sequence of the test methods. For unit skin friction and unit end bearing comparison, at three times of working load, the comparison between the two methods are also very good.

The correlation tests performed at various HDB sites in Singapore proved that Rapid Load Test can provide a faster and reliable alternative to Static Load Test to (a) verify that the pile settlement performance is indeed satisfactory (by Working Load Test), and (b) verify the pile design parameters and pile geotechnical capacity (by Ultimate Load Test).

REFERENCES

Brown, D.A. (1994). Evaluation of static capacity of deep foundations from Statnamic testing. Geotechnical Testing Journal, ASTM, Vol. 17, No. 4, pp. 403–414.

Chew, S.H.; Middendorp, P.; Bakker J.; Chua G., (2015) Recent advances of rapid load testing in Asia and Europe, Procedings XVI European Conference on Soil Mechanics and Geotechnical Engineering, Edinburgh, Scotland, ISBN 978-0-7277-6067-8 , P.2909-2914 ,

Chew, S.H. & Middendorp, P. & Bakker, J. & Chuah, G. (2017) The application of Rapid Load Testing in Singapore, Conference: DFI-PFSF Piled Foundations and Ground Improvement Technology Conference, At Melbourne, , .

Holeyman, A.E., Maertens, J., Huybrechts, N. and Legrand, C. (2000). Results of an international pile dynamic testing prediction event. Proc. 6th Int. Conf. on the Application of Stress Wave Theory to Piles, Sao Paulo, pp. 725–732.

Kusakabe, O. and Matsumoto, T. (1995). Statnamic tests of Shonan test program with review of signal interpretation. Proc. 1st Int. Statnamic Seminar, Vancouver, pp. 113–122.

McVay, M.C., Kuo, C.L. and Guisinger, A.L. 2003. Calibrating resistance factor in the load and resistance factor design of Statnamic load testing. Research Report 4910-4504-823-12, Contract BC354, RPWO#42. University of Florida, Florida Department of Transportation.

Middendorp, P. (1993). First experiences with Statnamic load testing of foundation piles in Europe. Proc. 2nd, Int. Geotechnical Seminar on Deep Foundations on Bored and Auger Piles, Ghent, pp. 265–272.

Middendorp, P. (2000). Statnamic the engineering of art. Proc. 6th Int. Conf. on the Application of Stress Wave Theory to Piles, Sao Paulo, pp. 551–561.

Middendorp, P. and Bielefeld, M.W. (1995). Statnamic load testing and the influence of stress wave phenomena. Proc. 1st Int. Statnamic Seminar, Vancouver, pp. 207–220.

Nishimura, S. and Matsumoto, T. (1995). Wave propagation analysis during Statnamic loading of a steel pipe. Proc. of 1st Int. Statnamic Seminar, Vancouver, pp. 23–33.

Wood, T. (2003). An investigation into the validation of pile performance using Statnamic tests. MSc Thesis, Imperial College, UK.