Rapid load test on high bearing capacity piles

Miyasaka, T.
Jibanshikenjo Co., Ltd., Tokyo, Japan
Kuwabara, F.
Nippon Institute of Technology, Saitama, Japan
Likins, G.
Pile Dynamics, Inc., Ohio, USA
Rausche, F.
GRL Engineers, Inc., Ohio, USA

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ABSTRACT: Currently, plenty of High Bearing Capacity Piles have been installed in Japan. In most cases, the pre-cast high strength (up to 120 MPa) concrete piles with cylindrical cross-section are used. Pre-cast piles are installed in a predrilled hole, in which an enlarged cement slurry base was constructed previously. The void between the soil and pile is also filled with cement slurry, so that these piles have large bearing capacity. For lack of other proper quality control methods for checking the soundness of enlarged base and surrounding solidified material, the Rapid Load Test has been used as the most popular alternative for static pile load test to ensure the high bearing capacity of the piles, because of its cost effectiveness and quick set-up capability.

In this paper, a study on a Rapid Load Test applied to a typical High Bearing Capacity Pile is reported. The installation method of the typical High Bearing Capacity Pile is explained. A newly developed Rapid Load Testing system is introduced. A case study describes how this new Rapid Load Test was conducted two months later after Static Pile Load Testing. The Unloading Point Method was applied to interpret the test results. Moreover, signal-matching analysis with CAPWAP was also conducted to obtain independent verification of total capacity and to estimate shaft resistance and end bearing components. Finally, the difference between the various test methods and results are examined, an optimum range of the total number of loading cycles for Hybridnamic Test is suggested, and a practical method to prepare Static Load-Displacement Curve is proposed in this paper.

1 INTRODUCTION

Recently many High Bearing Capacity Piles have been installed in Japan. Generally, a pre-cast cylindrical pile is inserted into a predrilled hole with an enlarged cement slurry base. This pile achieves extremely high end bearing capacity due to the enlarged base. Similarly, to increase the skin frictional capacity of the piles, cement slurry is also filled along the pile shaft. Due to lack of other suitable construction quality control methods for checking the soundness of the enlarged base and surrounding solidified material during the installation, Rapid Load Test becomes the most cost effective and economical method to ensure the high bearing capacity of this pile type.

Up to 2004, three types of Rapid Load Test method have been available: Dynatest (Gonin et al 1984), Statnamic Test (Bermingham & Janes 1989) and Pseudo Static Test (Schellingerhout & Revoort 1999). Dynatest and Pseudo Static Test employ a falling hammer mass with relatively soft spring attached, while Statnamic utilizes the reaction force of gas pressure of launching the mass to prolong the duration of loading time on the pile top.

The Statnamic Test was first introduced in 1992 into Japan. The Rapid Load Testing has been standardized and incorporated in Standards of Japanese Geotechnical Society (JGS) for Vertical Load Test of Piles in 2002. Nevertheless due to the relatively high cost and long preparation time of Statnamic, the test is very seldom adopted these days. Less expensive and quicker tests are desirable.

In this paper, a method of a Rapid Load Test applied to the above mentioned typical High Bearing Capacity Pile with ultimate capacity generally larger than 10 MN is reported. A newly developed Rapid Load Testing system called "Hybridnamic Test", which focus on large pile permanent displacement, is introduced. A case study describes how this new Rapid Load Test was conducted. After fully mobilizing the soil resistance, the Unloading Point Method (Middendorp et al 1992) was applied to interpret the test results. Moreover, signal-matching analysis with CAPWAP (Rausche et al 1972) was also conducted to obtain independent verification of the total ultimate capacity and to separate shaft resistance and end bearing components. Finally, the difference between the results obtained from static load test and Hybridnamic load test is examined, an optimum range of the total number of loading cycles for Hybridnamic Test is suggested, and a practical method to prepare Static Load-Displacement Curve is proposed in this paper.

2 HYBRIDNAMIC TEST

2.1 Hybridnamic test equipment

The newly developed Loading system is called ‘‘Hybridnamic’’ because it uses a newly developed Hybridnamic cushion as shown in Figure 1, which consists of elastomer, metal, and air cell. The leaking of the compressed air causes the longer duration during the loading process. A comparison of load duration between Statnamic and Hybridnamic Test is shown in Figure 2. It reveals that the applied force pulse is significantly longer than the typical Statnamic pulse. Furthermore, the negative air pressure generated during unloading reduces the rebound of the ram. A further advantage is the adjustment ability of the cushion spring constant through the series and/or parallel assembly. The above features make the pile load test with arbitrary loading duration between Dynamic Load Test and Rapid Load Test possible. Generally it is obvious that sufficient permanent pile top displacement is required to fully mobilize the soil resistance. To ensure this point, various types of test equipment are available at present, corresponding to various test loads (i.e. from 200 kN through 35 MN).

Figure 1. Hybridnamic Cushion.

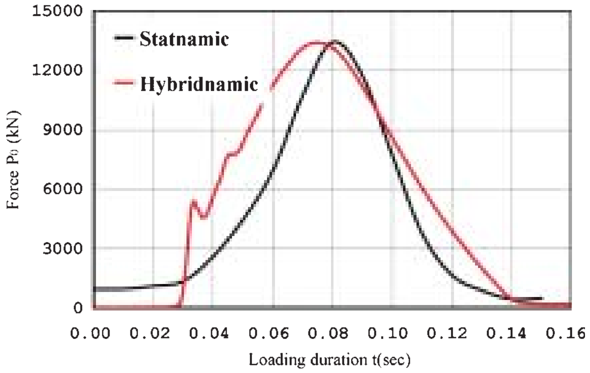

Figure 2. Comparison of load duration between Statnamic Test and Hybridnamic Test.

2.2 Hybridnamic test case study

In this case study, the heavy-duty testing equipment shown in Figure 3 was used. This equipment consists of a ram with a mass of 45 tons, a stacked cushion with spring constant of 87.0 MN/m and with dimension of 1.5×1.5×0.5 m, and a 10.0 m high frame, which allows for up to a 3.0 m ram drop. Thus, this testing equipment is capable of conducting a test with relatively long load duration of up to 72 ms. This long duration is equivalent to the time that stress-wave requires to travel 7.2 times up and down along the shaft of a typical 20 m long pile. The relevant details of this case history test are shown in Table 1.

2.3 Test pile and boring log

The test pile is composed of an upper steel pipe pile, a middle steel and concrete composite pile, a lower pre-cast high strength concrete pile, and a cement-enlarged base. Pile specification is given in Table 2.

Soil stratigraphy consists of a 6 m thick cohesive ground surface layer, followed by a 4 m thick sand layer and a 1.5 m thick silt layer, and then sandy soil beyond. Boring log and test pile profiles are shown in Figure 4. Pile tip is located in a fine sand stratum with *N* value of 35.

2.4 Testing procedures

The pile was first subjected to Static Pile Load Test 3 months after installation. The Static Load Test result as shown in Figure 6 indicates that the pile reached the yield point at a load of 4.5 MN with a displacement of

Figure 3. Hybridnamic Test Equipment (45t Ram Type).

Table 1. Relevant points of the case history test

Pile Length	Wave Speed	Travel Round	Load Duration	Ram Mass	Cushion Spring
(m)	(m/s)		(ms)	(kg)	(kN/m)
20	4 ,000	7.2	72	45,000	87,000

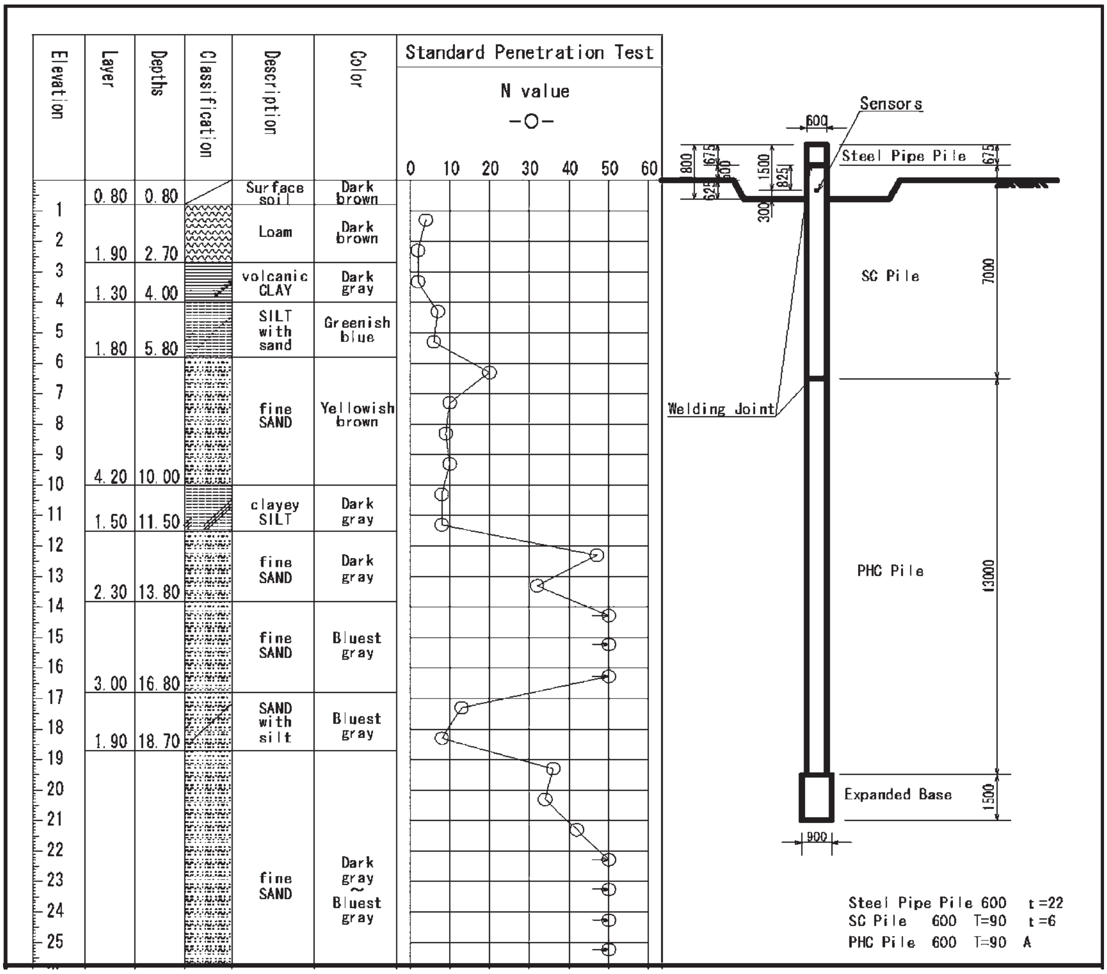

Figure 4. Boring log and test pile profile.

Table 2. Test pile specification

Dia. (mm)	Type	Thickness (mm)	Length (m)	Installation Method
600	SPP	22	0.675	Welded afterward
600	SC	90(6+84)	7.0	Center Boring Method
600	PHC	90	11.5	
900	Enlarged Base	NA	1.5	Pressurized Cement Jetted

Table 3. Summary of Static Load Test results

Yield Resistance		Ultimate Resistance		Pile-Soil Stiffness
Load (kN)	Top Disp. (mm)	Load (kN)	Top Disp. (mm)	Ko (kN/mm)
4,500	12	5,775	60	400

Table 4. Maximum Hybridnamic Test loads

Drop Height (cm)	Cushion Deformation (cm)	Applied Force (kN)
50	7.7	6,270
100	10.7	8,870

12 mm at the pile head, and then reached the ultimate point (where the pile top displacement reached 10% of pile diameter) at a load of 5.8 MN with a displacement of 60 mm measured at the pile head. Initial settlement stiffness at the pile head was 0.4 MN/mm. The summary of test results is shown in Table 3.

The Rapid Load Test was conducted 8 weeks after the Static Load Test was finished. The ram was dropped from 0.5 m and 1.0 m. Maximum applied forces achieved were 6.3 MN and 8.9 MN respectively, as shown in Table 4.

Measuring sensors consisted of two strain gages, two accelerometers and one permanent displacement device. Velocity and displacement waveforms were integrated from measured acceleration, and force waveform was derived from the measured strain and pile section properties.

2.5 *Test result*

Force waveforms obtained from the 0.5 m and 1.0 m drops are shown in Figure 5. Loading duration for the 0.5 m drop was 70 ms, and duration for the 1.0 m drop was 74 ms. Both loading durations are very close to the equipment specifications of Table 1. The time for

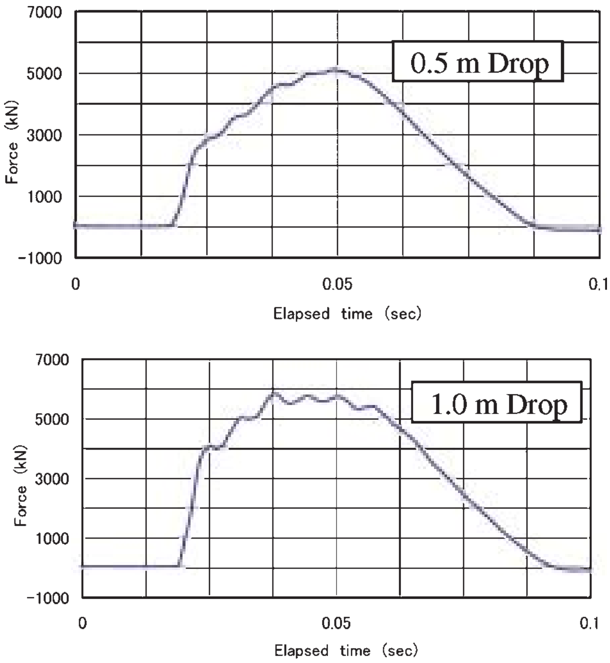

Figure 5. Force waveforms obtained from 0.5 m and 1.0 m drop test respectively.

stress wave to travel one round along the test pile is around 10 ms. According to Japanese Code standardized by JGS for Rapid Load Test, a minimum loading duration which is longer than the time that stress wave requires to travel 5 times down and up the test pile shaft is required. It is obvious that the loading duration in this test (7 times) meets above requirement.

In addition, the shape of the waveform from the 0.5 m drop varies from the shape of the waveform from the 1.0 m drop. Generally the waveforms obtained from different drop heights show similar trends even though the magnitudes are different with each other.

Comparing the force waveforms in Figure 5, obviously the peak of the form of the 1.0 m drop is more flat than that of the 0.5 m drop. The waveform of the 1.0 m- drop suggests that the bearing capacity of the test pile has reached its ultimate state.

In Figure 5, the number of higher frequency wave components for the 0.5 m drop is about 4, while that for the 1.0 m drop is 7. These higher frequency waves are around 130–140 Hz. This frequency is close to the frequency for a stress wave to travel one round along the test pile shaft. These components may come from ground motion.

3 INTERPRETATIONS

3.1 *Estimation of static ultimate soil resistance*

The estimation of soil resistance is made by the conventional Unloading Point Method. Both the force-displacement (F) and soil resistance-displacement (R) relationships are shown in Figure 6. Force is directly measured during the

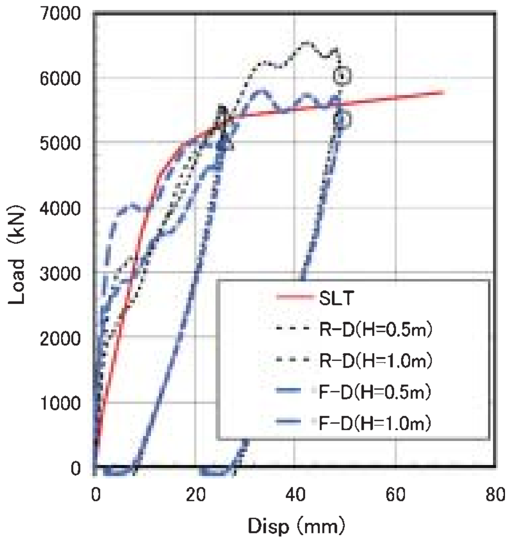

Figure 6. Estimation of soil resistance by conventional Unloading Point Method.

Hybridnamic Test. Static soil resistance R'_{soil} is calculated by the following equation.

$$R_{soil} = F_{soil} - M \cdot \alpha$$

$$R'_{soil} = R_{soil} - C \cdot v$$

where,
R_{soil} : soil resistance
F_{hyb} : measured force
M : concentrated mass
a : acceleration
R'_{soil} : static soil resistance
C : damping factor
v : velocity

At Unloading point, velocity is zero (v = 0), so there is no rate effect, and Rsoil = R′soil.

The soil resistance at the Unloading Point for 0.5 m drop is 5400 kN, whereas that for 1.0 m drop is 6000 kN. The permanent pile top displacement is 8 mm and 28 mm respectively for the 0.5 m drop and the 1.0 m drop. Comparing the Hybridnamic results with the Static Load Test, i.e. 5775 kN, the estimation precision is 93% and 104% respectively for 0.5 m drop and 1.0 m drop. These results indicate that the soil resistance at 0.5 m drop was not fully mobilized, and that the soil resistance at 1.0 m drop was fully mobilized. The overestimated soil resistance at 1.0 m drop is attributed to the over evaluation of the term for inertial force. In other words, the directly measured pile top acceleration cannot represent the average acceleration along the full length of the test pile.

3.2 *Signal Matching Analysis*

The CAPWAP program was used to conduct signal – matching analysis of the measured waveform. Two different pile models were used for data analysis, one with an enlarged base model (A-model) and the other without enlarged base model (B-model) were used. Signal matching results of force and upward traveling wave at pile top for 0.5 m drop and 1.0 m are shown in Figure 7a and Figure 7b, respectively. Despite the different models were used, not so much difference can be seen from these figures. It is possible that the material strength of enlarged base is relatively weak in comparison to strength of pre-cast concrete pile, so the impedance is similar.

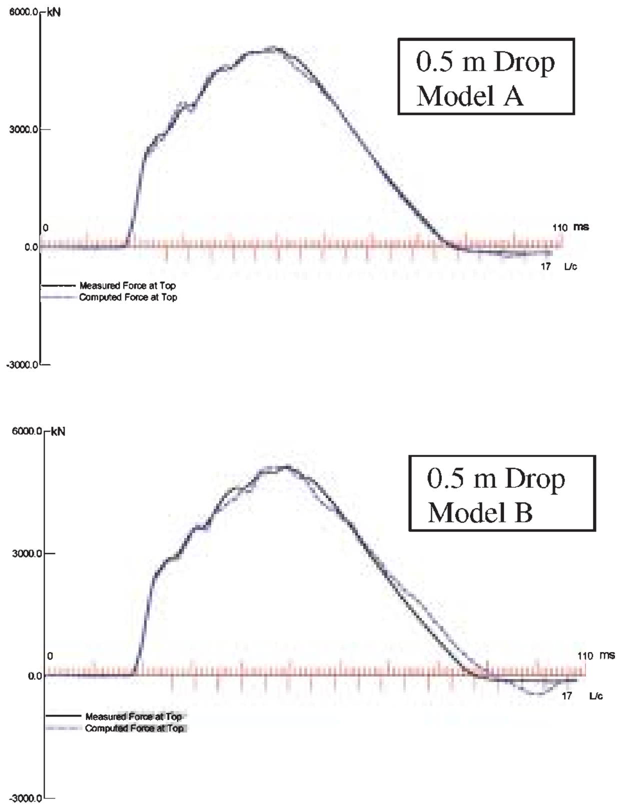

Figure 7a. Signal matching results of force at pile top for 0.5 m drop.

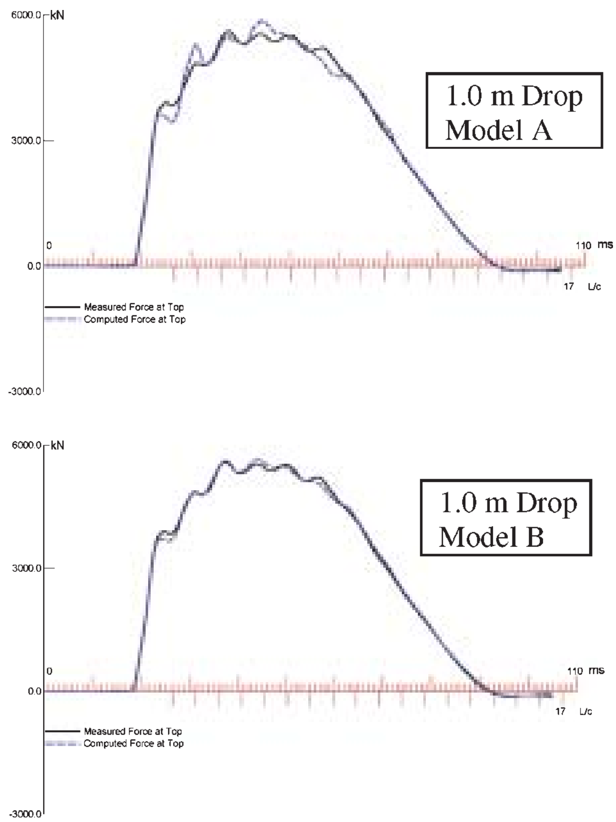

Figure 7b. Signal matching results of force at pile top for 1.0 m drop.

The load–displacement curve obtained from both Static Load Test and CAPWAP signal matching are shown in Figure 8. The initial settlement stiffness obtained from the Static Load Test is 400 kN/mm whereas that obtained from the signal matching result is 200 kN/mm.

The static soil resistance obtained from the 0.5 m drop is 5380 kN, while that from 1.0 m drop is 5762 kN. Comparing the results of the Static Load Test, i.e. 5775 kN, the estimation precision is 93% and 99% respectively for 0.5 m drop and 1.0 m drop.

In addition, the wave speed obtained from signal matching analysis is 4060 m/sec. This value is very close to the assumed wave speed described in Table 1.

3.3 Preparation of static load–displacement relationship

A practical method to prepare Static Load-Displacement is proposed in this study. The detailed procedures are described below.

1. Plot the initial slope of the Load–Displacement curve obtained from first drop.
2. Plot the load and displacement obtained at the Unloading Point.
3. Plot the load of the Fully Mobilized Unloading Point at the displacement of D/10.
4. Complete the curve based on Weibull's Formula.

The Static Load–Displacement Curves prepared based on the above proposed method are shown in Figure 9. The curves apparently fit well with the measured curve obtained from Static Load Test.

The axial force distributions along the pile obtained from signal matching, based on different pile models for 1.0 m drop, are shown in Figure 10. The distribution obtained based on the B-model pile shows that axial force is much closer to that

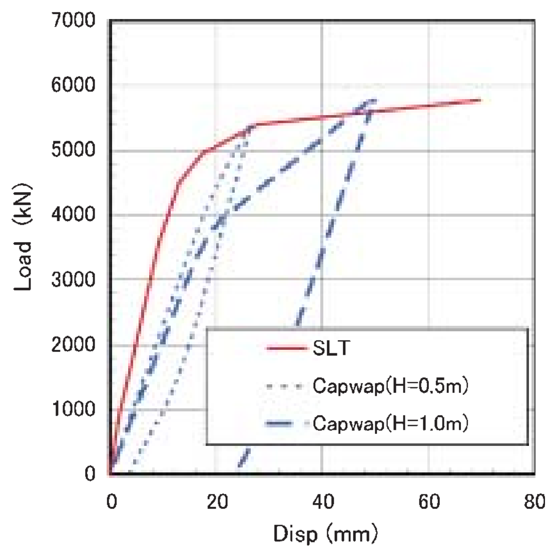

Figure 8. Load–Displacement curve obtained from Static Load Test and signal matching.

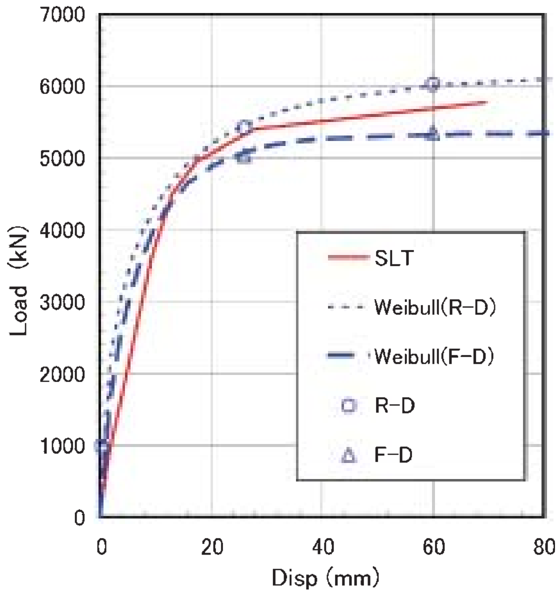

Figure 9. Static Load–Displacement curve prepared based on proposed method.

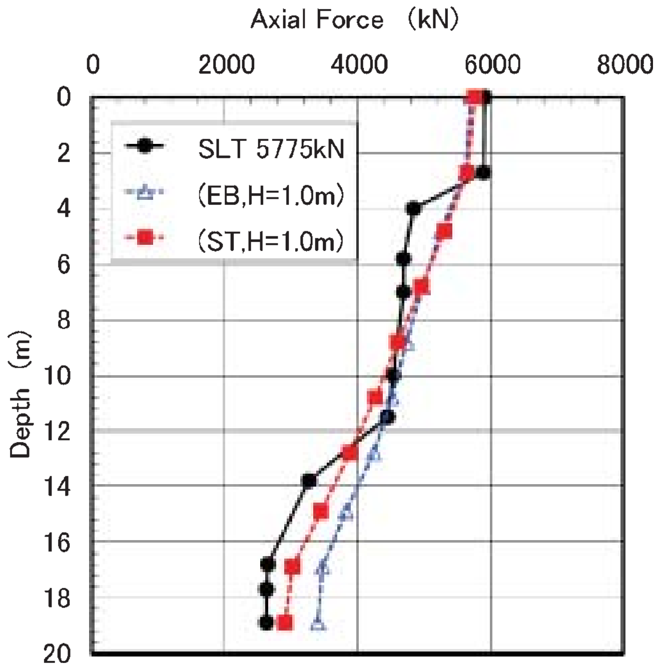

Figure 10. Axial force distributions along the pile.

obtained from the Static Load Test than that obtained based on the A-model pile.

4 CONCLUSIONS

Comparison of the Hybridnamic Test with a Static Load Test and conventional CAPWAP analysis are summarized below:

1. Loading duration was as long as 7 rounds along the pile shaft. (i.e. $N_w = 7$)
2. The permanent displacement which exceeded D/30 allows pile-soil resistance to be fully mobilized.
3. Both estimated ultimate soil resistances based on Fully Mobilized Unloading Method and Signal Matching Analysis are very close to the static ultimate bearing capacity of pile obtained from a Static Load Test.
4. The solution based on the CAPWAP signal matching analysis for the 1.0 m drop offers the best estimation of the pile ultimate bearing capacity.
5. In case that permanent displacement is not large enough to fully mobilize the soil resistance, the ultimate pile static bearing capacity could be either underestimated or overestimated by the Unloading Point Method.
6. To access Ultimate Soil Resistance of High Bearing Capacity pile, following the rule of thumb, pile should have sufficient material strength until soil resistance is fully mobilized, otherwise the Ultimate Bearing Capacity would be limited by the pile's material strength.
7. Excessive dropping cycles may cause driving effect that would increase the base resistance as the soil is compacted from previous impacts, resulting in overestimation of ultimate pile static bearing capacity, or require significant pile displacement to achieve for non-tested piles.
8. Base on authors' experience, it is recommend that the number of loading cycles should not exceed 3 cycles before the soil resistance reaches the yield point of the Load-Displacement curve, and should not exceed 2 cycles after the soil resistance is fully mobilized. The optimum range of the total number of loading cycles is suggested to be 3 to 5.
9. A practical method to prepare Static Load-Displacement curve is proposed in this study. The Static Load-Displacement curves prepared based on the proposed method fit well with the measured curve obtained from the Static Load Test.

REFERENCES

Bermingham, P., Janes, M., (1989), "Innovative Approach to Load Testing of High Capacity Piles", Proc. of the International Conference on Piling and Deep Foundations, London, pp.409–413.

Gonin, H., Coelus, G., and Leonard, M., (1984), "Theory and Performance of a New Dynamic Method of Pile Testing", Proc. of 2nd International Conference on the Application of Stress Wave Theory to Piles, Stockholm, pp.403–410.

Japanese Geotechnical Society, (2002), "JGS Standards 1815", "Standards for Vertical Load Test of Piles, Method for Rapid Load Test of Single Piles", pp.171–222.

Japan Patent Office, (2008), "Patent Number 4068030", "Rapid Pile Load Test Equipment".

Middendorp, P., Bermingham, P., Kuiper, B., (1992), "Statnamic load testing of foundation piles", The 4th International Conference on the Application of Stress Wave Theory to Piles, Sao Paulo.

Rausche, F., Moses, F., and Goble, G., (1972), "Soil resistance predictions from Pile Dynamics," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 98, No. SM9.

Schellingerhout, A.J.G., Revoort, E., (1996), "Pseudo Static Pile Load Tester", Proc. of 5th International Conference on the Application of Stress Wave Theory to Piles, Orlando, pp.1031–1037.