Comparison of static load test and rapid load test on steel pipe piles in two sites

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ABSTRACT

Two case studies of comparison of the static load test (SLT) and the rapid load test (RLT) on steel pipe piles (SPPs) are presented and discussed in this paper. The Hybridnamic device, a falling-mass type RLT device, was used in both two cases. In Case study 1, an SPP having an outer diameter of 800 mm and a length of 23.8 m was installed in a weathered rock ground using the down-the-hole hammer method (a percussion drilling method). In the RLTs, three accelerometers were attached to the pile at head, intermediate and tip levels. Unloading Point (ULP) Method was used to interpret the RLT signals. Static load-displacement curves derived from the RLTs using three different accelerations α are compared with those from SLTs with the step load method and the continuous load method. An appropriate selection of α is discussed, based on the measured results. In Case study 2, an SPP having an outer diameter of 1000 mm and a length of 15.5 m was installed in a sandstone having SPT *N*-values greater than 50 using a vibro-hammer together with water jetting. Acceleration at the pile head alone was measured in the RLT. Static load-displacement curve derived from the RLT with ULP was comparable with that obtained from the SLT.

Keywords: rapid load test, steel pipe pile, Unloading Point method, pile acceleration, static load test

1 INTRODUCTION

In 2002, Japanese Geotechnical Society (JGS) revised standards for Vertical Load Tests of Piles in which Method for Rapid Load Test of Single Piles (JGS1815-2002) (JGS, 2002) and Method for Dynamic Load Test of Single Piles (JGS1816-2002) were newly added. Rapid load test (RLT) is now widely used in Japan, owing to the standardization of RLT.

Two types of RLT have been developed; launching mass type such as Statnamic (Bermingham and Janes, 1989) and falling mass type such as Dynatest (Gonin. and Leonard, 1984) and Pseudo-static test (Schellingerhout and Revoort 1996). In the launching mass type method, combustion gas pressure is used to apply load on the pile head, while in the falling mass type method, a hammer mass is dropped onto the pile head through a soft cushion placed on the pile head. The falling mass method has been dominantly employed in Japan after the standardization of RLT in 2002, to obtain design parameters for piles at the site, and for quality assessment of the constructed piles.

RLTs can be applied to various types of piles such as steel pipe piles (SPPs), pre-stressed concrete piles (PHC piles), cast-in-situ concrete piles, composite piles of concrete and SPP (SC piles), whereas Dynamic (impact) Load Test (DLT) can be applied to only SPPs and PHC piles. Cast-in-situ concrete piles are likely to be cracked during DLTs, and it is difficult to apply one-dimensional stress theory to SC piles. RLTs have been employed in sites where space and/or testing time for preparation of reaction piles for static load test (SLT) are limited.

Several methods, such as single mass analysis, one dimensional stress-wave analysis and FEM, of interpreting the measured signals of RLTs are given in the test standards to obtain "static" load-displacement relation. Unloading Point (ULP) method is a simplified analysis method based on single mass modelling of pile. One dimensional stress-wave analysis is a rigorous analysis method, and FEM is most rigorous analysis method. In the latter two analysis methods, back-analyses are needed with assuming soil parameters. On the other hand, in ULP method, static load-displacement relationship can be obtained using only the measured dynamic signals.

However, there are few examples of comparison of load-displacement curves obtained from SLT and RLT, although such a comparison was done in Takano and Lin (2019).

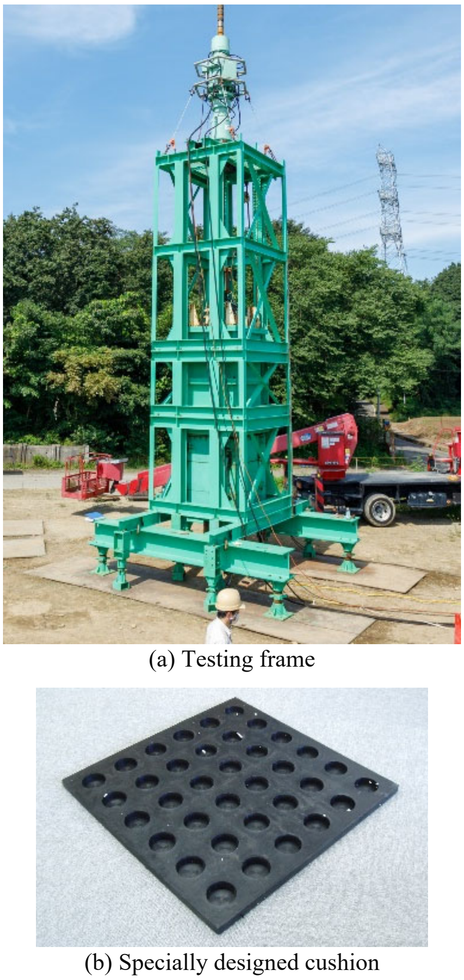
In this paper, case studies at two sites where the same test pile was subjected to SLTs followed by RLTs are presented, and validity of ULP method for deriving "static" load-displacement curve is discussed through comparisons of SLT and RLT results.

2 HYBRIDNAMIC TEST METHOD

2.1 Devices

Jibanshikenjo Co., Ltd. has developed several Hybridnamic test devices since 2003. Fig. 1 shows one of Hybridnamic test devices and a specially designed cushion. Hybridnamic test devices are "falling-mass type", in which a hammer mass in the steel frame is lifted using a hydraulic jack and free-dropped to apply rapid load to the pile head via the specially designed cushion.

By changing combination of stiffness of the cushion system K_{cushon}, hammer mass m_h and falling height of hammer h, loading duration t_L and the maximum rapid load $F_{rapid(max)}$ can be easily controlled. In the current JGS standards, load test with the relative loading duration $T_r = t_L/(2L/c) \geq 5$, where L is the pile length and c is the propagation speed of longitudinal stress-wave in the pile, is regarded as RLT.



(a) Testing frame

(b) Specially designed cushion

Fig. 1. Hybridnamic test device and specially designed cushion.

The performance of Hybridnamic test devices developed so far is shown in Table 1. An appropriate device can be selected according to the required loading conditions. In recent years, very large RLTs with a hammer mass m_h of 180 ton, a maximum fall height of 3 m and a maximum load of 40 MN have been carried out to obtain the load-displacement curves of piles for the foundation of port facilities (Lin et al, 2022).

The basic measurement items in RLT are rapid load F_{rapid}, acceleration α and displacement w at or near the pile head. F_{rapid} is measured using a load cell placed on the pile head beneath the soft cushion or strains gages attached to the outer surface of the pile shaft in cases of SPPs and PHC piles. α is measured using two piezoelectric accelerometers attached on opposite sides of the pile surface. w is measured using an optical displacement meter placed on the ground surface about 20 m away from the pile.

Strains and accelerations are measured at several levels of the pile including underground levels, if necessary.

Testing time for a pile depends on the scale of the loading device and the number of hammer drops (blows). Generally, 5 to 7 blows are conducted for each pile within 3 hours. Hence, time and cost for RLT using the Hybridnamic devices are very effective, compared to the conventional SLT.

Table. 1. Performance of Hybridnamic test devices.

Item	Value
Hammer mass (ton)	1 to 180
Max. fall height of hammer (m)	3 to 6
Maximum load (MN)	1 to 40

N.B. Four Hybridnamic devices are available as of 2020.

2.2 Construction of static load-displacement curve using Unloading Points

The measured dynamic signals of RLTs conducted at the two sites were interpreted based on the ULP method, which is one of the analysis methods specified in the JGS test standards.

In the ULP interpretation method, the pile is assumed to be a rigid body having a mass m supported by a nonlinear spring K and a linear dashpot as shown in Fig. 2. The load on the pile F_{rapid} is resisted by the inertia of the pile R_a, velocity-dependent resistance R_v and the static soil resistance R_w (Eq. (1)). The soil resistance R_{soil} is obtained from Eq. (2), using the measured F_{rapid} and α, and R_{soil} vs w is constructed as shown in Fig. 3. The static resistance R_w is then obtained using Eq. (3), if the damping constant C is determined. The R_{soil} at the maximum displacement point (ULP) is equal to the static resistance R_w because the pile velocity v is regarded as zero at ULP (Eq. (4) and Fig. 3).

When the Hybridnamic test is employed, generally 5 to 7 blows are applied to the pile increasing the fall height of hammer h. Hence, several values of R_{ULP} at different displacements w are obtained without determining the value of C because the pile velocity v is zero at ULP, and R_w vs w ("static" load-displacement curve) is easily obtained by connecting ULPs. This method is named Unloading Point Connection method (ULPC method).

This aspect is one of big advantages of the Hybridnamic test.

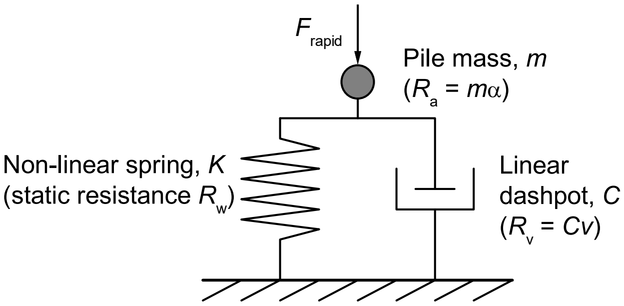


Fig. 2. Modeling of pile and soil during RLT (after Middendorp et al, 1993, and Kusakabe and Matsumoto, 1995).

$$F_{\text{rapid}} = R_a + R_v + R_w = m\,\alpha + C\,v + R_w \qquad (1)$$

$$R_{\text{soil}} = F_{\text{rapid}} - m\alpha \qquad (2)$$

$$R_w = R_{\text{soil}} - Cv \qquad (3)$$

$$R_{\text{soil at ULP}} = R_{\text{ULP}} = R_w \qquad (4)$$

where, F_{rapid} = Rapid load, R_a = Inertial force of pile, R_v = Dynamic resistance component of soil, R_w = Static resistance component, m = Pile mass, α = Pile acceleration, C = Damping constant, v = Pile velocity and R_{ULP} = ULP resistance (static resistance).

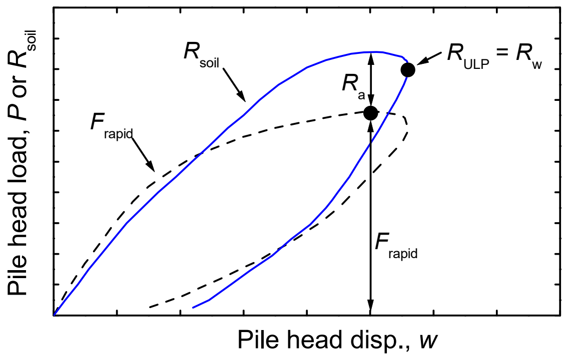


Fig. 3. Relationship between load-displacement curve and soil resistance and ULP resistance.

3 TEST RESULTS

Results of two case studies are presented and discussed in this section.

3.1 Case study 1

3.1.1 Test site

Test site was located in Okayama Prefecture, Japan.

The profiles of soil layer and SPT N-values are shown in Fig. 4, together with the final seating of the test pile. The bearing stratum is the weathered or weakly weathered rocks having N-values greater 50 below a depth z = 20 m. Rock Quality Designation of the bearing stratum is 21-38%.

3.1.2 Test pile and test sequences

In this experimental work, SLT and RLT were carried out to obtain the load-displacement relationship of an SPP installed in the bearing stratum, and to examine the validity of the analysis method of RLT signals to derive the load-displacement relation.

SLT was carried out 29 days after pile installation, and RLTs were carried out on the same pile 90 days after the SLT.

The specifications of the test pile (designated as Pile No. 1) are shown in Table 2. The test pile was an SPP and was constructed using the down-the-hole hammer method.

Two strain gages and two accelerometers were attached near the pile head (Level 1: L1), and strain gages were instrumented at L2, L3 and L4. Furthermore, accelerometers were instrumented at L3 and L4. The outer surface of the pile section in the weathered rock between L3 and L4 was coated by a friction reduction material except for the upper 0.8 m section from the pile tip, to ensure that the load on the pile head was sufficiently transferred to the pile tip.

Table 2. Specifications of the test pile Case study 1.

Item	value
Length, L (m)	24.8
Outer diameter, D_o (mm)	800
Inner diameter, D_i (mm)	772
Wall thickness, t_w (mm)	14
Cross-sectional area, A (m^2)	0.0346
Cross-sectional area, A (m^2)†	0.0376
Young's modulus, E (kPa)	2.00×10^8
Density, ρ (ton/m^3)	7.85
Mass, m (ton)	7.032
Longitudinal wave velocity, c (m/s)	5048

†: including steel protection cover for strain gages.

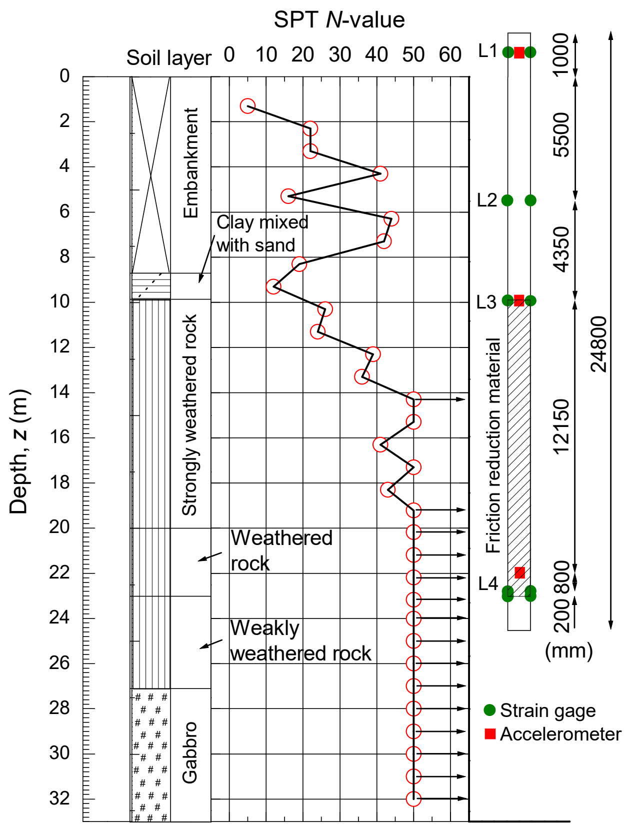


Fig. 4. Profiles of soil layers and SPT N-values, together with the test pile No. 1.

3.1.3 Comparison of SLT and RLT results

Fig. 5 shows the loading sequences of the SLTs. First, the step load test was conducted, and then the continuous load test was conducted. The maximum load in the continuous load test was the same as that in the step load test.

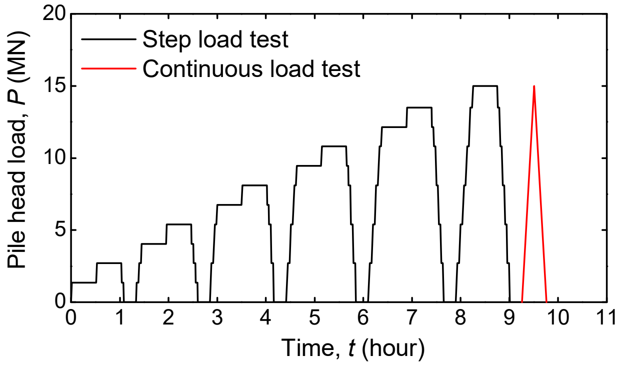


Fig. 5. Loading sequences in SLTs.

Fig. 6 shows the load *P*-displacement *w* relationships obtained from the SLTs. As seen from Fig. 6, displacement due to consolidation or creep of the ground was very small during the load holding duration. It is noticed that *P* vs *w* in the continuous load test was very similar to that in the 6th (last) load step in the step load test, even though the time for reaching the maximum load was 6 minutes in the continuous load test. At the maximum load of 15 MN, the maximum displacement was 72.0 mm and the residual displacement was 20.5 mm in the step load test, and the maximum displacement was 73.3 mm and the residual displacement was 22.3 mm in the continuous load test, showing an elastic response in the continuous load test.

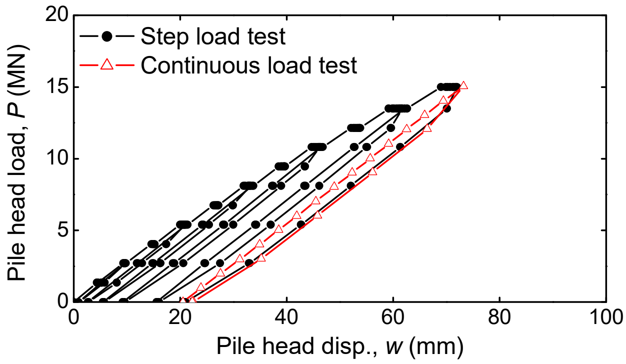


Fig. 6. Load-displacement curves obtain from SLTs.

As mentioned earlier, 90 days after the SLTs, RLTs with a hammer mass m_h of 44 ton were carried out. A total of 7 blows were applied to the pile.

Fig. 7 shows the time histories of F_{rapid}, accelerations, velocities and displacements at L1, L3 and L4 in the last (7th) blow with the maximum hammer fall height of h = 3.0 m.

The velocities and displacements were calculated from single and double integral of the measured accelerations with respect to time, respectively. The pile head displacement thus obtained was almost equal to that measured using the optical displacement meter.

As for the time history of F_{rapid}, the loading duration tt_L at the pile head is 70 ms and the relative loading duration $T_r = t_L/(2L/c)$ is 7.1, which satisfies the test criteria ($5 \leq T_r < 500$).

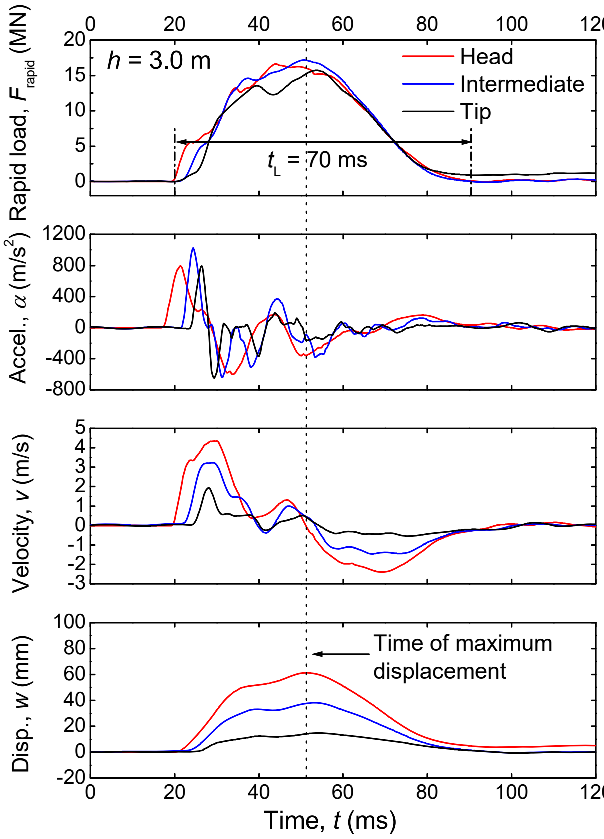


Fig. 7. Measured RLT signals in the last (7th) blow.

The maximum displacement at the pile head is 61.2 mm, while that at the pile tip is 14.8 mm. At the time instant of the maximum pile head displacement, α at the head, intermediate and tip levels are -362 m/s^2, -165 m/s^2, and -85 m/s^2, respectively. At the time instant of the maximum pile head displacement, w at the head, intermediate and tip levels are 61.2 mm, 38.2 mm and 14.8 mm, respectively, resulting in the pile deformation of 46.4 mm. As mentioned earlier, the pile body is assumed as a rigid mass in the simplified method ULP. Hence, an adequate selection of α is investigated.

Three types of ULP analysis method were conducted. In these analyses, the pile inertia, $R_a = m\alpha$, was estimated from 3 different α as shown in Table 3 and the constant pile mass m = 7.032 ton. In Type 1, α at the pile head was used, while in Type 2 the average of α at head, intermediate and tip levels was used. In Type 3, α was assumed to be zero. Type 1 is the normal analysis prescribed in the JGS standards. Type 3 is an extreme case where the pile inertia is neglected.

Table 3. Relationship between inertial force assumptions and static resistance.

Type	Acceleration used for analysis	R_{ULP} at h = 3.0 m (MN)	Ratio of R_{ULP} to Type 2
1	Pile head acceleration	18.58	1.06
2	Average value of accelerations at 3 levels	17.47	1.00
3	Acceleration = 0	16.03	0.92

Fig. 8 shows R_{soil} vs w at the pile head from Type 2 analysis, and the connection of R_{ULP} is the derived static load-displacement curve of the pile.

In Fig. 9, R_{ULP} vs w from the 3 types of analysis of RLTs and the SLTs are shown. It is reasonable to compare the results of RLTs with the result of continuous load test because the continuous load test was carried out immediately before RLTs. It is seen that R_{ULP} vs w from Type 2 matches best with that measured in the continuous load test. R_{ULP} in the last (7th) blow from Type 1 analysis is 6% higher than that from Type 2 analysis, and R_{ULP} from Type 3 analysis is 8% smaller than that from Type 2 analysis (Fig. 9 and Table 3). Although R_{ULP} vs w from Type 3 in which R_a is ignored gives a safe side result, it could be practically used for design purpose.

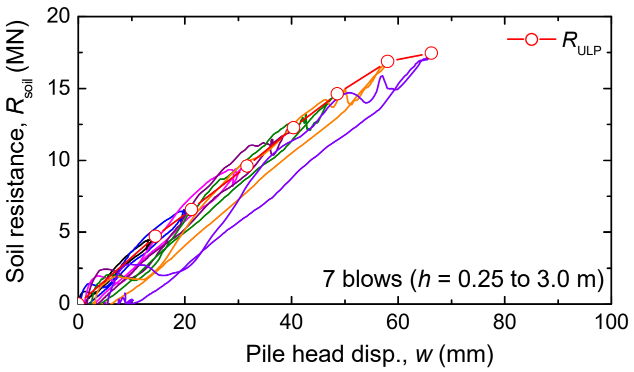


Fig. 8. Soil resistance vs. pile displacement in Type 2.

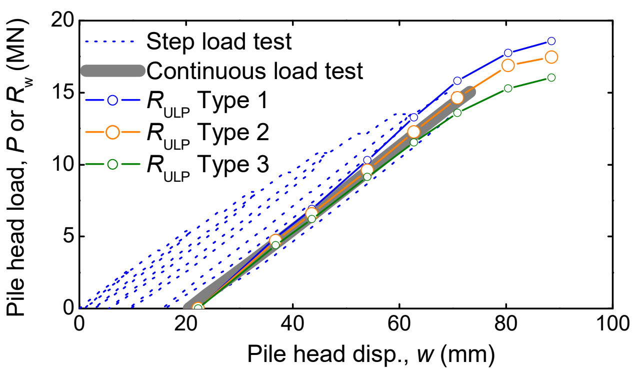


Fig. 9. Comparison of load-displacement curves from SLTs and RLTs.

3.2 Case study 2

This test was carried out to confirm the bearing capacity of an SPP for a steel-pipe-sheet-pile well foundation adopted in a highway bridge construction work in Shimane Prefecture, Japan (see Fig. 10).

Fig. 10. Load tests conducted at the construction site.

3.2.1 Test site

The profiles of soil layers and SPT N-values are shown in Fig. 10, together with the final seating of the test pile. The bearing stratum is the sandstone layer with N-values over 50. The bearing stratum is mainly composed of fine-grained sand and silt, and it is weathered to a sediment-like state with a low cohesion. The test pile was embedded about 4.2 m into the sandstone layer where N-values are greater than 50.

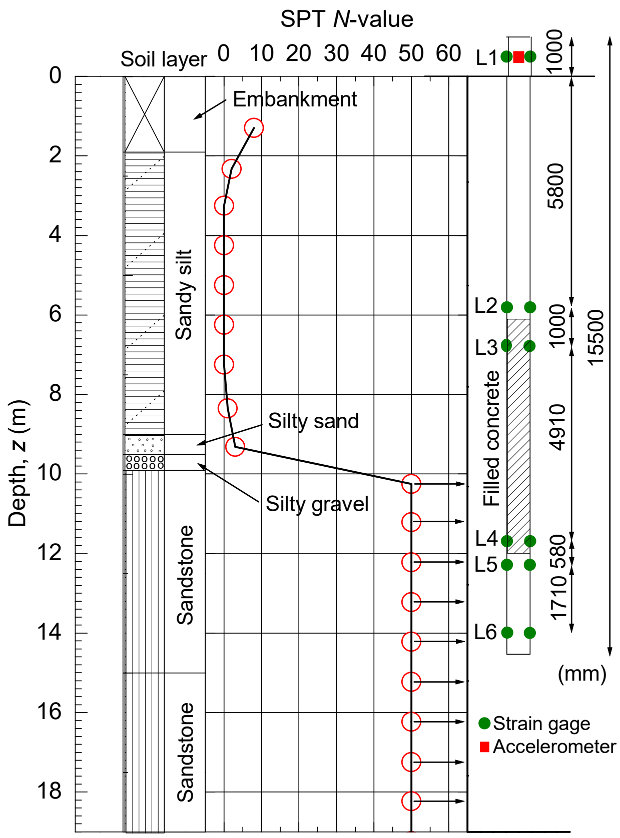


Fig. 11. Profiles of soil layers and SPT N-values, together with the test pile No. 2.

3.2.2 Test pile

The test pile (designated as Pile No. 2) was constructed separately within the steel-pipe-sheet-pile well foundation for the purpose of obtaining basic design parameters of a single SPP, which were further used for design of the whole foundation structure.

Table 4. Specifications of the test pile Case study 2.

Item	value
Length, L (m)	15.5
Outer diameter, D_o (mm)	1000
Inner diameter, D_i (mm)	972
Wall thickness, t_w (mm)	14
Cross-sectional area, A (m^2)	0.0434
Cross-sectional area, A (m^2)†	0.0474
Young's modulus, E (kPa)	2.10×10^8
Density, ρ (ton/m^3)	7.85
Mass, m (ton)	5.77
Longitudinal wave velocity, c (m/s)	5172
Cross-sectional area of inner concrete, A_c (m^2)	0.742
Length of inner concrete, L_c (m)	5.9
Density of inner concrete, ρ_c (ton/m^3)	2.4
Mass of inner concrete, m_c (ton)	10.51

†: including steel protection cover for strain gages.

The specifications of the test pile are shown in Table 4. The test pile was constructed using a vibro-hammer together with water jetting, and concrete was cast inside the steel pipe pile after the pile installation.

The test pile was equipped with two strain gages and two accelerometers near the pile head (Level 1: L1), and 5 pairs of strain gages were attached to the underground pile section at L2 – L6 (see Fig. 11).

3.2.3 Comparison of RLT and SLT results

SLT with step loading was carried out on the test pile 28 days after the pile installation, and RLTs were carried out on the same pile 48 days after the SLT.

Loading sequence in the SLT is shown in Fig. 12, in which 5 load steps were applied.

In RLTs, 8 blows were applied to the pile with a hammer mass m_h of 22 ton, increasing h from 0.25 to 2.2 m.

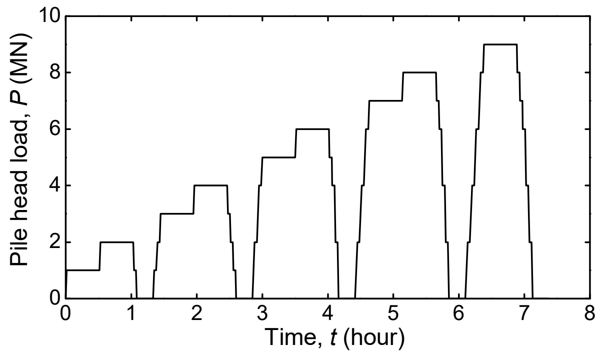


Fig. 12. Loading sequences in SLT.

Fig. 13 shows the time histories of rapid loads measured at different pile levels (L1–L6) in the last (8th) blow with h = 2.2 m. As mentioned earlier, acceleration was measured near the pile head (L1) only. The rapid load at L6 is 67% of the pile head load at L1. The loading duration t_L at the pile head is 59 ms and the relative loading duration T_r is 9.8 which satisfies the test criteria sufficiently.

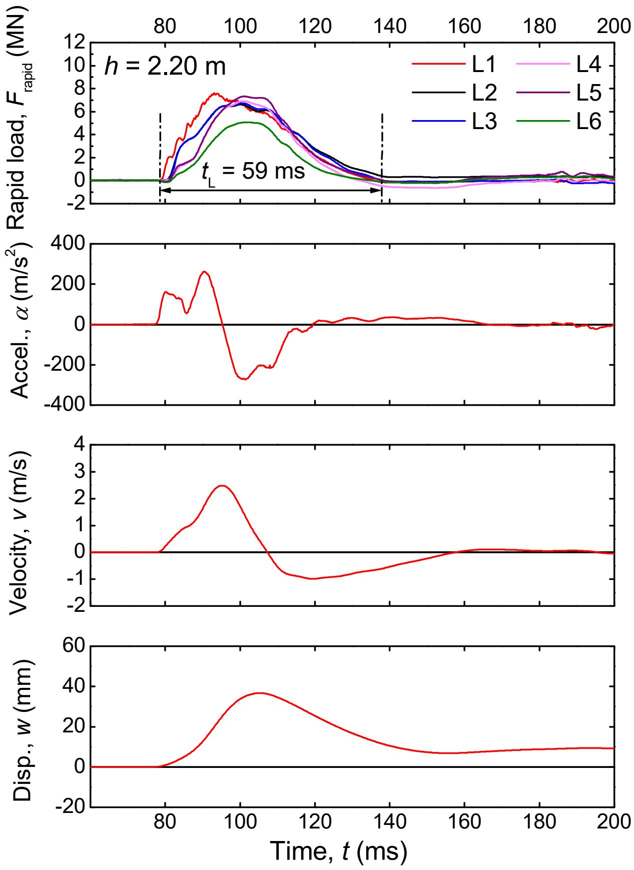


Fig. 13. Rapid load test signals.

Fig. 14 shows the pile head load in SLT and the soil resistance R_{soil} obtained from RLTs against the pile head displacement w. In the ULP analyses of RLTs, the pile mass m was the sum of the SPP and the concrete filled inside the SPP, and the inertial force R_a was calculated using α measured at the pile head.

In SLT, the maximum pile head displacement was 86.5 mm and the residual displacement was 59.7 mm after loading up to 9 MN. The "static" load-displacement curve from RLTs (connection of R_{ULP} from 8 blows) is almost equal to that measured in the last (5th) load step in SLT (see Fig. 15).

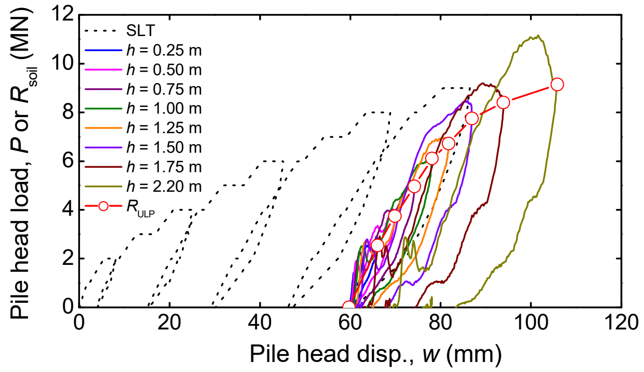


Fig. 14. Soil resistance vs. pile head displacement.

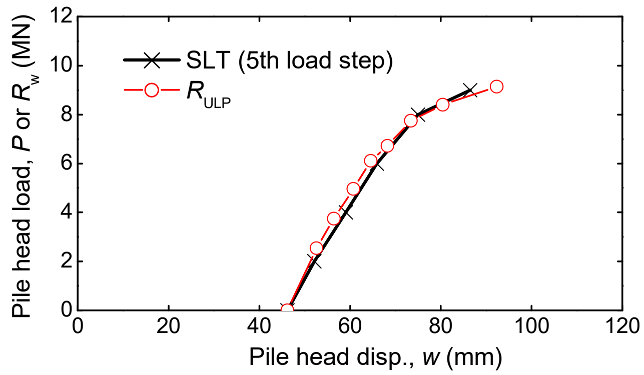


Fig. 15. Comparison of load-displacement curves from SLT and RLTs.

A possible reason for the good matching between the results of SLT and RLTs is a large value of the relative loading time T_r = 9.8 in this Case study 2. Please remember that T_r = 7.1 in Case study 1 (see Fig. 7).

Another possible reason is the amount of elastic deformation of the pile during the RLT.

The displacement of the pile head during the load test is the sum of the elastic deformation of the pile and displacement of the pile tip. If the pile tip were fixed and a rapid load is applied to the pile head, displacements of the pile head and the pile tip will be different largely, and the accelerations in the pile generated at different levels will also be different. As mentioned earlier, the pile is assumed as a rigid single mass in ULP method

Let us look back the measured signals (Fig. 7) in Case study 1. The maximum values of rapid forces F_{rapid} at the head, intermediate and the tip levels are almost equal, whereas the measured accelerations and displacements at time of the maximum pile head displacement were different between the head, intermediate and tip levels. The displacement at the pile tip was fairly small compared to that at the pile head. These facts indicate that the pile was a nearly end-bearing pile, as intended. Remember here that Pile No. 1 was coated with friction reduction material (see Fig. 4).

On the other hand, the rapid load at L6 (near pile tip) is 67% of the pile head load at L1 in Case study 2 (see Fig. 13), suggesting that relatively large shaft resistance acts.

Table 5 shows the maximum pile head displacement w_{max} and residual displacement w_{res} in the last blow in Case study 1 and Case study 2.

In Case study 1, w_{max} in the 7th blow was 61.2 mm and w_{res} was 4 mm, and the ratio w_{res}/w_{max} was 6.5 %. On the other hand, in Case study 2, w_{max} and w_{res} in the 8th blow were 37.1 mm and 10 mm, respectively, resulting in w_{res}/w_{max} = 26.9 %.

The above results suggest that the pile in Case study 2 behaved like a rigid mass more, compared to the pile in Case study 1, although only the pile head acceleration was measured in Case study 2.

Table 5. Maximum displacement and residual displacement at pile head.

Case Study	Blow No.	Max. fall height, h (m)	Maximum pile head disp., w_{max} (mm)	Pile head residual disp., w_{res} (mm)	w_{res}/w_{max} (%)
1	7	3.0	61.2	4	6.5
2	8	2.2	37.1	10	26.9

4 CONCLUSIONS

In this paper, comparative tests of SLTs and RLTs on SPPs were carried out at two different sites. One of the test piles was coated with friction reduction material to realize a nearly end-bearing pile.

The conclusions obtained from the comparative tests are as follows:

1) In Case study 1 (Pile No. 1) where the pile was a nearly end-bearing pile and the pile did not reach yield or ultimate state, the accelerations α measured at the head, intermediate and tip levels were different; the magnitude of α at the pile head was largest followed by α at the intermediate and the tip levels. Relative loading duration T_r was 7.1 which satisfied the test criteria (5 ≤ T_r < 500). The pile resistance R_{ULP} estimated from ULP method using α at the pile head overestimated the static resistance obtained from SLT. R_{ULP} estimated ignoring the pile inertia (α = 0) underestimated the static resistance. Derived static load-displacement curve constructed by connecting R_{ULP} points estimated using the average of α at the three pile levels matched well with the SLT result.

2) In Case study 2 (Pile No. 2) where T_r = 9.8 and the pile reached the ultimate state, derived static load-displacement curve constructed by connecting R_{ULP} points estimated using α at the pile head matched well with the SLT result.

3) Length of Pile No. 1 and Pile No. 2 were 24.8 m and 15.5 m, respectively. The maximum pile head displacement w_{max} of Pile No. 1 and Pile No. 2 during the last blow of RLTs were 61.2 mm and 37.1 mm, with residual displacement w_{res} of 4 mm and 10

mm, respectively. This result suggests that Pile No. 2 behaved like a rigid mass more, compared to Pile No. 1. The corresponding w_{res}/w_{max} of Pile No. 1 and Pile No. 2 were 6.5% and 26.9%, respectively. w_{res}/w_{max} may be a parameter whether ULP analysis can be applied or not.

4) The above results indicate that it is insufficient to define RLT by using T_r alone. Elastic deformation of the pile body and residual displacement of the pile also would be parameters to define RLT where single mass modeling can be employed.

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