Hybridnamic rapid load tests on driven steel pipe piles in sandy ground compared with static load test

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Abstract

Hybridnamic Rapid Load Test (Hybridnamic RLT) and Static Load Test (SLT) were carried out on two identical open-ended steel pipe piles (SPPs), named Piles No. 2 and No. 4, in the Jibanshikenjo test yard at Sashima, Ibaraki Prefecture, Japan. The test pile had an outer diameter of 318.5 mm, a wall thickness of 6.6 mm and an embedment length of 11.0 m. In the RLTs, the classic UnLoading Point Connection (ULPC) method and a new interpretation method: UnLoading Point Connection method invoking Case Method (ULPC_CM) proposed by the authors, were used to obtain "static" load-displacement curves. According to the Japanese RLT standards, the relative loading duration T_r shall be greater than 5. In Pile No. 4, RLTs with T_r = 5 were caried out after SLT. In Pile No. 2, RLTs with T_r = 3 were carried out intentionally prior to SLT. In this paper, test conditions and test results are presented in detail. It will be shown that the static load-displacement curve from the ULPC method overestimates the SLT result, while the static load-displacement curve from the ULPC_CM method conforms to the SLT result well even if T_r decreased to 3.

Keywords: *load-displacement curve; steel pipe pile; static load test; rapid load test; interpretation method*

1. INTRODUCTION

Static Load Test (SLT) is the most reliable method for obtaining the load-displacement relation of a pile. However, SLT requires reaction force devices and loading device, which increases cost and test time. In 2002, Japanese Geotechnical Society (JGS) revised Standards of Japanese Geotechnical Society for Vertical Load Tests of Piles in which Method for Rapid Load Test of Single Piles (JGS1815-2002) [1] was newly added.

In Rapid Load Test (RLT), reaction force devices are not required, and the load is applied to the pile head by dropping a hammer through soft cushions set on the pile head, with a short time and a low cost.

In the current JGS standards, load test with the relative loading duration $T_r = t_L/(2L/c) \geq 5$ (t_L = the loading duration, L = the pile length, c = the propagation speed of longitudinal stress-wave in the pile) is regarded as RLT. As an interpretation method of RLT, the UnLoading Point method (ULP method) [2], which assumes the pile as a rigid mass body, is recommended. Currently, the UnLoading Point Connection method (ULPC), which is an extension of ULP [3], is commonly used. However, Kamei et al. (2022) [4] show that even when $T_r \geq 5$, the soil resistance R_{soil} is overestimated when the pile head acceleration □ is used.

The authors have proposed a new interpretation method, UnLoading Point Connection method invoking Case method (ULPC_CM) [5], for RLT. In the study, with the main purpose of examining the validity of the new interpretation method, comparative tests of RLT and SLT were carried out on two driven steel pipe piles. In the analyses of the RLT signals, two interpretation methods, ULPC and ULPC_CM, were used to obtain the static load-displacement relation

2. OUTLINE OF PILE LOAD TESTS

2.1 Site conditions

Load tests were carried out in Sashima test yard of Jibanshikenjo Co. Ltd., Japan. Figure 1 shows the locations of soil investigations and test piles. One Standard Penetration Test (SPT) and Electric Cone Penetration Tests (CPTs) at just point of test piles were carried out.

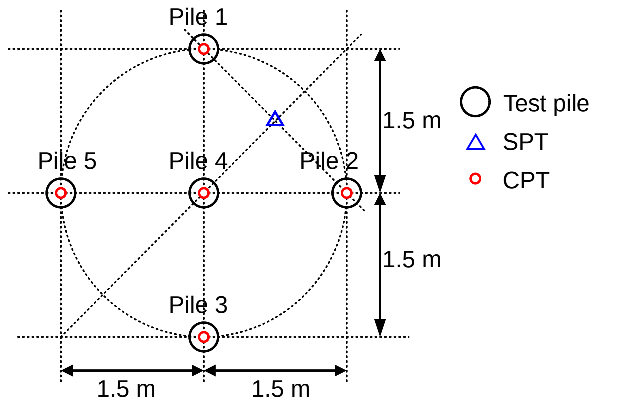

Figure 1. Locations of SPT, CPTs and test piles

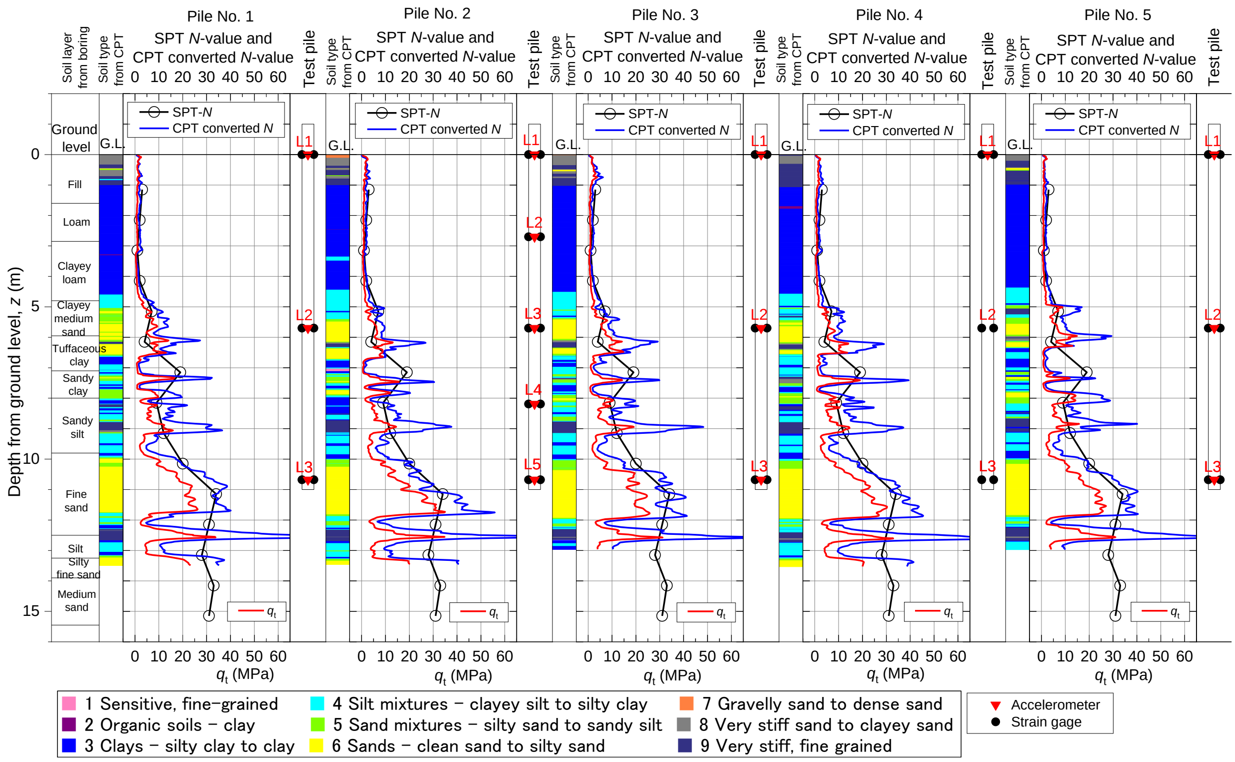

Figure 2. Profiles of soil layers, SPT N-values and CPT q_t, together with instrumented test piles

Figure 2 shows the results of soil investigations, and embedment of the instrumented test piles. N-values from the ground level to a depth z = 5 m are 1 to 3. Below this depth, N-value increases with depth. Below z = 10 m, a sand layer with N = 35 exists. The test piles were driven to z = 11 m. Groundwater table is at z =3.5 m.

It can be seen from the distributions of SPT-N and CPT q_t (cone resistance corrected for pore pressure at filter) that ground conditions are almost uniform in each test pile location.

2.2 Test piles

Table 1 shows the specifications of test steel pipe piles (SPPs). Channel steels were welded on the test SPPs for protecting strain gages and accelerometers. The specifications of the 5 test piles are identical.

Table 1. Specifications of test piles

Item	Value	
	without protection	with protection
Pile length, L (m)	11.8	
Embedment length, L_d (m)	11.0	
Outer diameter, D_o (mm)	318.5	
Inner diameter, D_i (mm)	305.3	
Wall thickness, t_w (mm)	6.6	
Cross-sectional area, A (m^2)	0.00651	0.00926
Young's modulus, E (GPa)	205	
Density, ρ (ton/m^3)	7.81	
Bar wave velocity, c (m/s)	5123	
Mass, m (ton)	0.610	0.819

2.3 Test cases

Table 2 shows the test sequence of each test pile. Dynamic Load Tests (DLTs) were carried out during initial pile driving. After curing period of 1 day, DLTs were carried out again on Pile No. 1 and Pile No. 2 to grasp "set-up" phenomena. RLTs with the relative loading duration Tr = 5 were carried out on Pile No. 1 and Pile No.4, according to the JGS standards in which Tr is required to be ≥ 5. RLTs with Tr = 3 were carried out on Pile No.2 intending the widening of application of RLT. If RLT with shorter Tr is reasonable, it will be possible to apply RLT to piles with longer length and greater bearing capacity using the current RLT equipment.

Table 2. List of test sequence

Pile No.	Driving date (DLT)	Curing (day)	DLT	Curing (day)	Load test		Curing (day)	Load test	
1	2022/05/11	1	2022/05/12	30	RLT (T_r = 5)	2022/06/11	---	---	
2	2022/05/11	1	2022/05/12	33	RLT (T_r = 3)	2022/06/14	184	SLT	2022/12/15
3	2022/05/12	---	---	32	RLT (T_r = 4)	2022/06/13	---	---	
4	2022/05/12	---	---	25	SLT	2022/06/07	8	RLT (T_r = 5)	2022/06/15
5	2022/05/12	---	---	279	SLT	2023/02/15		RLT (under planning)	

3. INTERPRETATION METHODS OF RLT

3.1. ULPC method

The ULPC method is an extension method of UnLoading Point (ULP) method. In ULPC, the pile is treated as a single mass rigid body. To obtain soil resistance R_{soil}, the pile inertial force $R_a = m\alpha$ (m = the pile mass and α = acceleration at pile head) is subtracted from the rapid load F_{rapid}. ULP is the point of R_{soil} at the maximum pile displacement w, where pile velocity v = 0. Hence, R_{soil} at ULP is equal to the static soil resistance R_w. By connecting ULPs from multiple blows, static load-displacement relation is easily obtained.

3.2. ULPC_CM method

The Case method (Raushe et al., 1985) [6] is a method based on one-dimensional stress-wave theory, in which the penetration resistance R_t (= R_{soil}) of a pile during driving.

First, the downward traveling wave F_d and the upward traveling wave F_u are calculated from the measured dynamic signals (axial force F and pile velocity v) by means of Eqs. (1) and (2). Then, by using Eq. (3), the time variation of R_t (= R_{soil}) is obtained (Figure 3).

$$F_{\mathrm{d}}(x_{\mathrm{m}},t) = \frac{F(x_{\mathrm{m}},t) + Z \cdot v(x_{\mathrm{m}},t)}{2} \tag{1}$$

$$F_{\mathrm{u}}(x_{\mathrm{m}},t) = \frac{F(x_{\mathrm{m}},t) - Z \cdot v(x_{\mathrm{m}},t)}{2} \tag{2}$$

$$R_{\mathrm{t}}(x_{\mathrm{m}},t) = F_{\mathrm{d}}\left(x_{\mathrm{m}}, t - \frac{L_{\mathrm{m}}}{c}\right) + F_{\mathrm{u}}\left(x_{\mathrm{m}}, t + \frac{L_{\mathrm{m}}}{c}\right) \tag{3}$$

where,

x: Coordinate along the pile axis (pile head = 0),

x_m: Measurement position,

v: Pile velocity,

L_m: Pile length from measurement position to pile tip,

F: Axial force,

F_d: Downward force wave,

F_u: Upward force wave,

Z: Impedance (=EA/c),

c: Bar wave velocity,

E: Young's modulus of pile,

A: Cross sectional area of pile

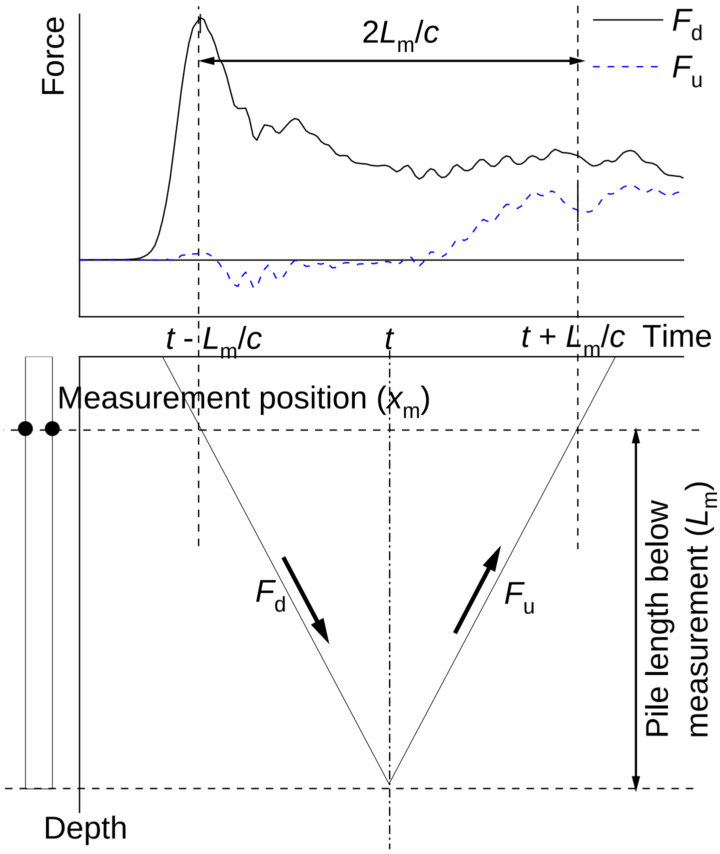

Figure 3. Case method (Raushe et al. 1985) [6].

The Case method evaluates the penetration resistance of the pile during driving, but the load-displacement relationship of the pile cannot be obtained by this method alone. Since the Case method is based on the one-dimensional wave theory, the penetration resistance of the pile can be evaluated correctly regardless of the pile length.

In the proposed ULPC_CM method, multiple blows (rapid load tests) are applied to a pile. The time variation of soil resistance R_{soil} is obtained from the Case method, and the time variation of pile displacement w is directly measured. Hence, $R_{soil} – w$ relation is easily obtained. R_{soil} at the maximum pile displacement can be regarded as the static resistance R_w. Static load-displacement curve is constructed by connecting ULPs from the multiple blows.

As the ULPC_CM method is based on the one-dimensional stress-wave theory, it has the advantage of not requiring correction for pile inertia. Hence, the ULPC_CM method would be applied to RLTs on piles with $T_r < 5$.

4. LOAD TEST RESULTS

4.1. SLT

SLTs were carried on Pile No. 4 and No. 2. The results of SLT will be shown in comparison with the RLT results later.

4.2. RLT (Pile No.4)

In Pile No. 4, RLTs were carried out after SLT. In RLTs, a hammer mass m_h = 3.5 ton was used and 8 blows (RLTs) were applied to the pile with increasing drop height h from 0.03 to 0.83 m. Loading duration t_L was adjusted by changing numbers of Hybridnamic cushions to have $T_r = t_L/(2L/c) \geq 5$.

Figure 4 shows the measured dynamic signals, rapid load F_{rapid}, pile head displacement w, velocity v and acceleration a in the RLT at h = 0.83 m. In the figure, soil resistance R_{soil} (ULPC) from the ULPC method, R_{soil} (ULPC_CM) from the ULPC_CM method are shown together with F_{rapid}. Furthermore, F_d and F_u are also shown.

R_{soil} (ULPC_CM) at the maximum w where v = 0 is defined as the static resistance R_w (R_{ULP}) in a similar way to the ULPC method. Static load-displacement relation can be obtained by connecting R_{ULP} from ULPC_CM from multiple blows (RLTs).

Figure 5 shows the F_{rapid}, R_{soil} (ULPC) and R_w (ULPC) vs w from ULPC method. Figure 6 also shows the F_{rapid}, R_{soil} (ULPC_CM) and R_w (ULPC_CM) vs w from ULPC_CM method.

Comparing Figures 5 and 6, R_{soil} (ULPC) is larger than R_{soil} (ULPC_CM). As Kamei et al. (2022) [4] pointed out, this could be due to the excessive correction of the pile inertial force m□ (where m is the pile mass including channel steel mass).

Figure 7 shows the static load-displacement relations from ULPC and ULPC_CM compared with the SLT result. It is seen from the RLT results that the static soil resistance R_w from ULPC is larger than that from ULPC_CM. The load-displacement relation from ULPC_CM matches with the SLT result very well.

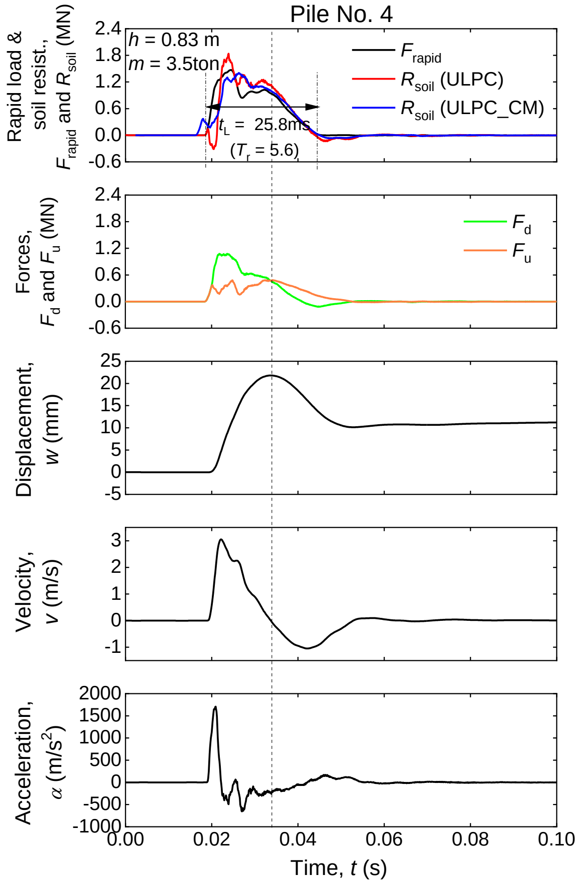

Figure 4. RLT signals (Pile No. 4, h = 0.83 m)

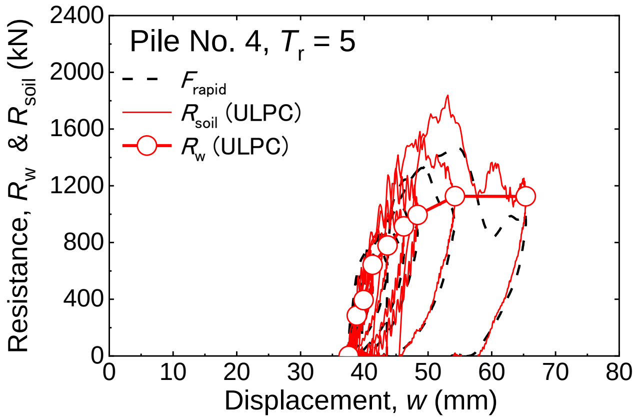

Figure 5. F_{rapid}, R_{soil} and R_w vs w from ULPC (Pile No. 4)

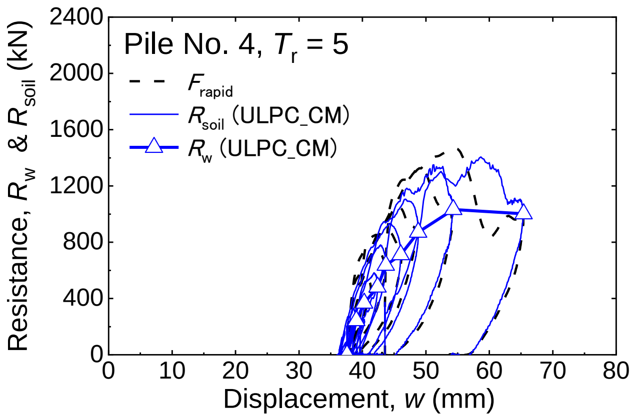

Figure 6. F_{rapid}, R_{soil} and R_{w} vs w from ULPC_CM (Pile No. 4)

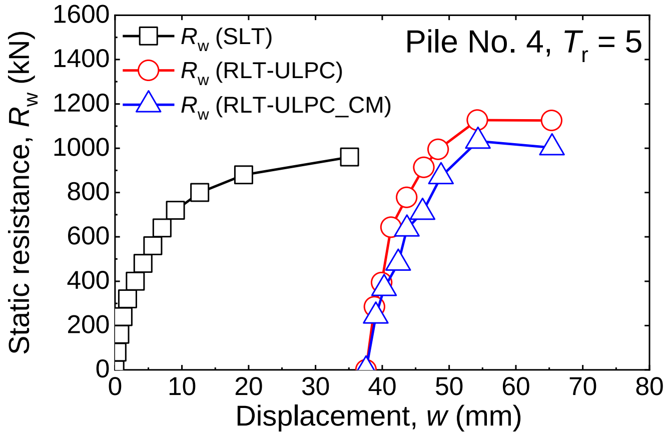

Figure 7. Comparison of load-displacement curves from SLT, RLTs with ULPC and ULPC_CM
(Pile No. 4)

4.3. RLT (Pile No. 2)

In Pile No. 2, SLT was carried out after RLTs. In RLTs, a hammer mass m_{h} = 0.95 ton was used and 12 blows (RLTs) with T_{r} = 3 were applied to the pile with increasing drop height h from 0.02 to 3.84 m.

Figure 8 shows the measured F_{rapid}, w, v and a in the RLT at h = 1.35 m (8th blow) with T_{r} = 3.2. In the figure, R_{soil} (ULPC) and R_{soil} (ULPC_CM) are shown together with F_{rapid}. Furthermore, F_{d} and F_{u} are also shown.

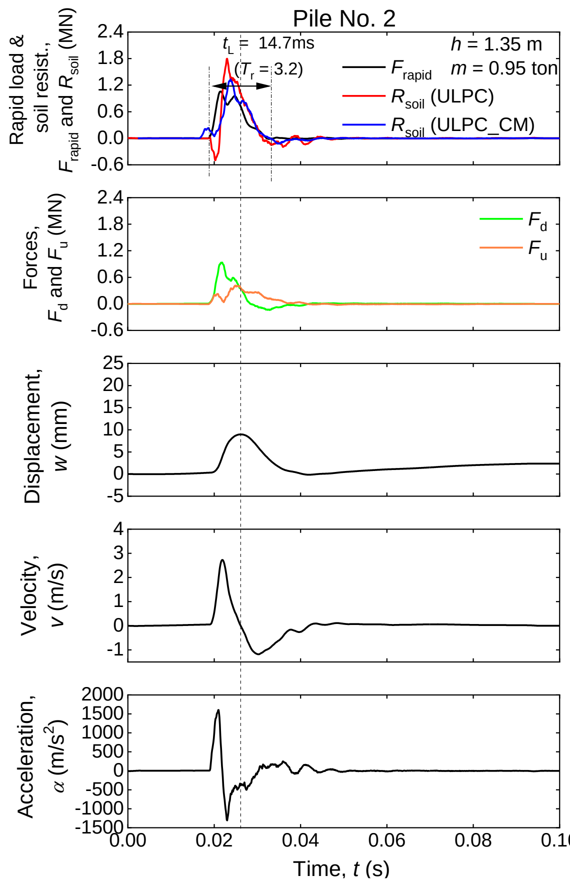

Figure 8. RLT signals (Pile No. 2, h = 1.35 m)

Figure 9 shows the F_{rapid}, R_{soil} (ULPC) and R_w (ULPC) vs w from ULPC. Figure 10 also shows the F_{rapid}, R_{soil} (ULPC_CM) and R_w (ULPC_CM) vs w from ULPC_CM.

Comparing Figures 9 and 10, R_{soil} (ULPC) is much larger than R_{soil} (ULPC_CM). The magnitude of acceleration α at the time instant of maximum pile displacement (ULP) of Pile No. 2 (Figure 8) is much larger than that of Pile No. 4 (Figure 4). Much larger R_{soil} (ULPC) than R_{soil} (ULPC_CM) is caused again by the excessive correction of the pile inertial force $m\alpha$.

Figure 11 shows the static load-displacement relation from ULPC and ULPC_CM compared with SLT result. The load-displacement relation from ULPC_CM matches with the SLT result very well again, even for $T_r \approx 3$.

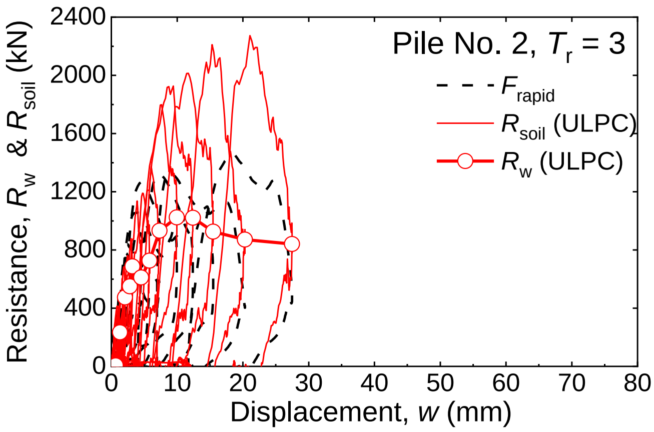

Figure 9. F_{rapid}, R_{soil} and R_w vs w from ULPC (Pile No. 2)

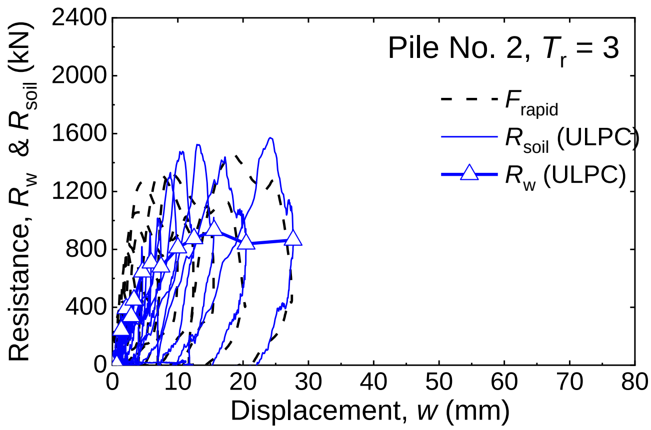

Figure 10. F_{rapid}, R_{soil} and R_w vs w from ULPC_CM (Pile No. 2)

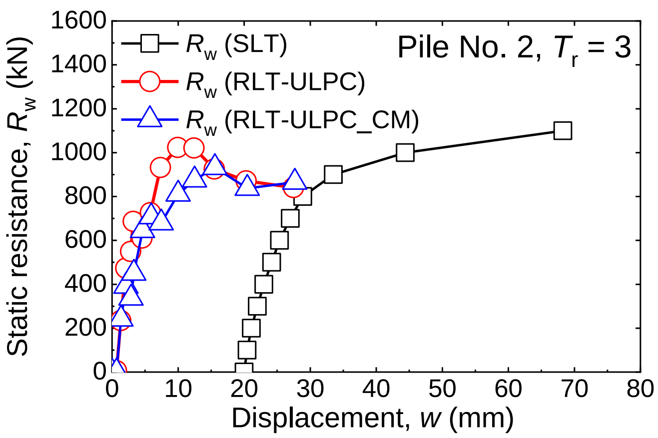

Figure 11. Comparison of load-displacement curves from SLT, RLTs with ULPC and

ULPC_CM (Pile No. 2)

CONCLUSION

In this study, comparative RLTs and SLT were carried out on driven steel pipe piles to examine the validity of the new interpretation method (ULPC_CM).

RLTs with $T_r = 5$ were carried out according to the JGS Standards in which T_r is required to be ≥ 5. Furthermore, RLTs with $T_r = 3$ were carried out with the aim of widening the application of RLT.

The static load-displacement relations from the ULPC_CM method matched with the SLT results very well even in cases of $T_r = 3$, regardless of order of SLT and RLT. In future, a similar comparison between RLTs and SLT with $T_r < 3$ will be needed to discuss the application limit of ULPC_CM method for RLTs with smaller T_r.

It can be said that it is possible to apply the Hybridnamic RLT with ULPC_CM method to piles with longer length and greater bearing capacity using the current RLT equipment.

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