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A new interpretation method of rapid pile load testing: verification through comparison with static load test

Une nouvelle méthode d'interprétation des essais rapides de charge sur pieux: vérification par comparaison avec un essai de charge statique

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ABSTRACT: Hybridnamic Rapid Load Test (Hybridnamic RLT) and Static Load Test (SLT) were carried out on three identical open-ended steel pipe piles (SPPs), named Piles No. 2, No. 4 and No. 5, in the Jibanshikenjo test yard at Sashima, Ibaraki Prefecture, Japan. The test piles 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 $T_r = t_L/(2L/c)$ (t_L is loading duration, L is pile length, c is bar wave velocity in the pile) 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 Pile No. 5, RLTs with $T_r = 3$ were caried out after SLT. In this paper, test conditions and test results are presented in detail. It will be shown that the static load-displacement curves from the ULPC method overestimate the SLT results, while the static load-displacement curves from the ULPC_CM method conform to the SLT results well even if T_r decreased to 3.

RÉSUMÉ: Des tests de charge rapide Hybridnamic (Hybridnamic RLT) et des tests de charge statique (SLT) ont été réalisés sur trois pieux en acier à extrémité ouverte identiques (SPP), nommés Pieux n°2, n°4 et n°5, dans la cour d'essai de Jibanshikenjo à Sashima, préfecture d'Ibaraki, au Japon. Les pieux d'essai avaient un diamètre extérieur de 318,5 mm, une épaisseur de paroi de 6,6 mm et une longueur d'enfouissement de 11,0 m. Dans les RLT, la méthode classique de Connexion du Point de Déchargement (ULPC) ainsi qu'une nouvelle méthode d'interprétation, la méthode de Connexion du Point de Déchargement invoquant la Méthode de Case (ULPC_CM) proposée par les auteurs, ont été utilisées pour obtenir des courbes de charge-déplacement "statiques". Conformément aux normes japonaises en matière de RLT, la durée relative de chargement T_r doit être supérieure à 5. Dans le Pieu n°4, des RLT avec $T_r = 5$ ont été effectués après le SLT. Dans le Pieu n°2, des RLT avec $T_r = 3$ ont été intentionnellement réalisés avant le SLT. Dans le Pieu n°5, des RLT avec $T_r = 3$ ont été effectués après le SLT. Dans cet article, les conditions d'essai et les résultats sont présentés en détail. Il sera démontré que les courbes de charge-déplacement statiques obtenues par la méthode ULPC surestiment les résultats du SLT, tandis que les courbes de charge-déplacement statiques obtenues par la méthode ULPC_CM sont en bonne concordance avec les résultats du SLT, même lorsque T_r est réduit à 3.

Keywords: Rapid load test; static load test; steel pipe pile; interpretation method; case study.

1 INTRODUCTION

The first standards for the method for Rapid Load Test (RLT) of single piles were published in 2002 (JGS, 2002). In the standards, load test with relative loading duration $T_r \geqq 5$ is defined as RLT, because it is thought that the wave propagation phenomena can be negligible. In the conventional interpretation method, UnLoading Point Connection method (ULPC), the pile body is modelled as a rigid single mass.

Aiming at widening the range of application of RLT, a new signal interpretation method, the

UnLoading Point Connection method invoking Case method (ULPC_CM) was proposed (Lin et al., 2023).

In this study, RLTs were carried out on three steel pipe piles (SPPs) with different relative loading durations, T_r = 5 and 3. Furthermore, Static Load Test (SLT) and RLT were carried out in different order. Load-displacement curves obtained from SLT and RLT using two interpretation methods, ULPC and ULPC_CM, were compared to examine the advantages and reliability of the new interpretation method over the conventional ULPC method.

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 arrangements of soil investigations and test piles. One Standard Penetration Test (SPT) and Electric Cone Penetration Tests (CPTs) were carried out at just points of test piles.

Figure 2 shows the results of soil investigations, and embedment of the instrumented test piles. SPT 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 $N \approx 33$ 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 similar in each test pile location.

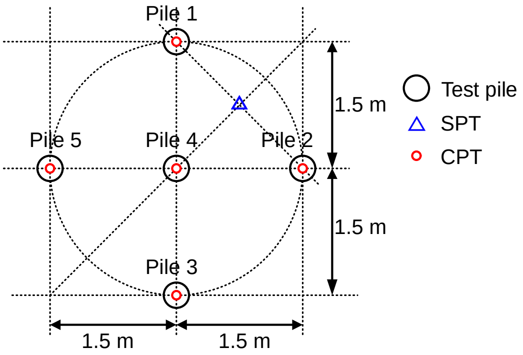

Figure 1. Locations of SPT, CPTs and test piles.

2.2 Test piles

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

Table 1. Specifications of test piles.

Item	Value	
	Original	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

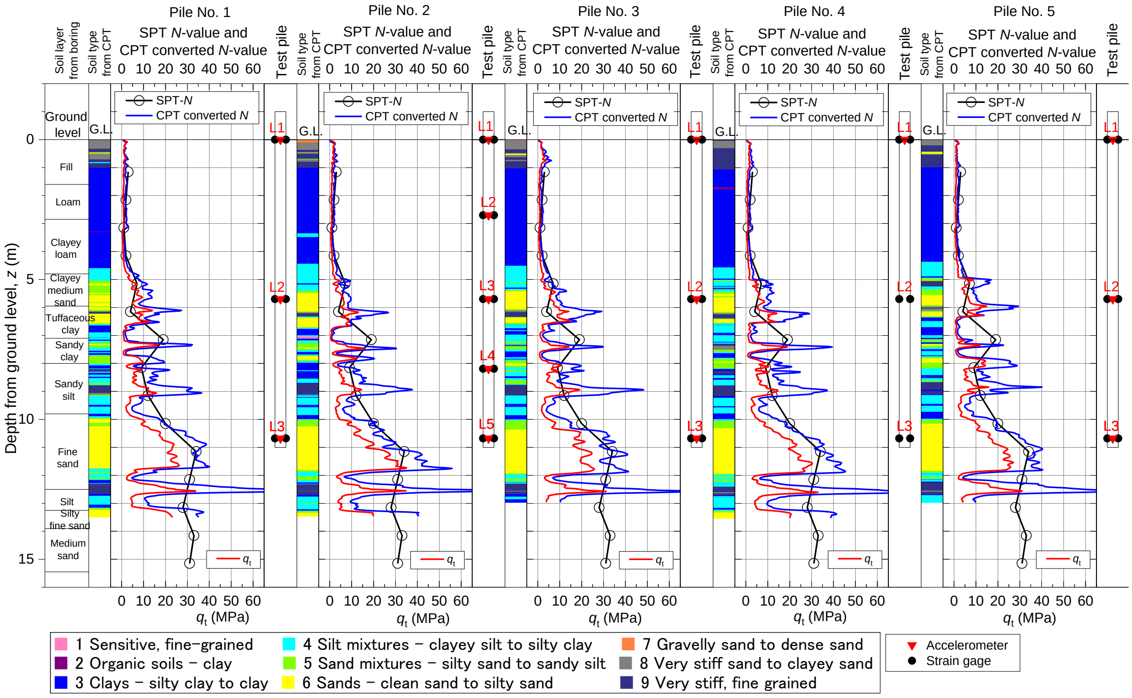

Figure 2. Profiles of soil layers, SPT N-values and CPT q_t, together with instrumented test piles.

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	140	RLT (T_r = 3)	2023/07/05

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 $T_r = t_L/(2L/c) = 5$ (t_L is the loading duration, L is pile length, c is bar wave velocity in the pile) were carried out on Pile No. 1 and Pile No. 4, according to the JGS standards (JGS, 2002) in which $T_r \geqq 5$ is required. RLTs with $T_r = 3$ were carried out on Piles No. 2 and No. 5 intentionally. If RLT with shorter T_r is reasonable, it will be possible to apply RLT to piles with longer length and greater bearing capacity using the current RLT devices.

3 INTERPRETATION METHODS OF RLT

In this section, interpretation methods of RLT signals used in this research are described.

3.1 ULPC method

The ULPC method is an extension method of UnLoading Point (ULP) method. In ULPC, the pile is treated as a rigid single mass. 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 (Lin et al., 2023)

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

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), respectively; then, by using Eq. (3), the time variation of R_t (= R_{soil}) is obtained (Figure 3):

$$F_d(x_m,t) = \frac{F(x_m,t) + Z \bullet v(x_m,t)}{2} \tag{1}$$

$$F_u(x_m,t) = \frac{F(x_m,t) - Z \bullet v(x_m,t)}{2} \tag{2}$$

$$R_t(x_m,t) = F_d\left(x_m, t - \frac{L_m}{c}\right) + F_u\left(x_m, t + \frac{L_m}{c}\right) \tag{3}$$

where, x = coordinate along the pile axis (pile head = 0), x_m = measurement position, L_m = pile length from x_m to pile tip, Z = impedance (=EA/c).

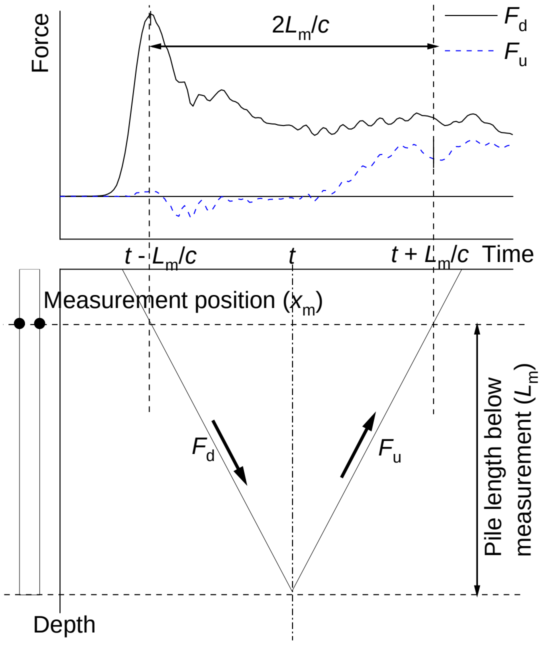

Figure 3. Case method (Raushe et al. 1985).

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 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. Similar to the ULPC method, 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 R_a. Hence, the ULPC_CM method would be applied to RLTs on piles with $T_r < 5$.

4 COMPARISON OF RESULTS OF SLT AND RLT

4.1 SLT

SLTs were carried out on Piles No. 4, No. 2 and No. 5. The results of SLT will be shown in comparison with the RLT results later.

4.2 RLT (Pile No.4, $T_r = 5$)

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 the stiffness of cushion placed on the pile head to have $T_r \geqq 5$.

Figure 4 shows the measured dynamic signals, rapid load F_{rapid}, pile head displacement w, velocity v and acceleration α, in the RLT at h = 0.83 m (8th blow). 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 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.

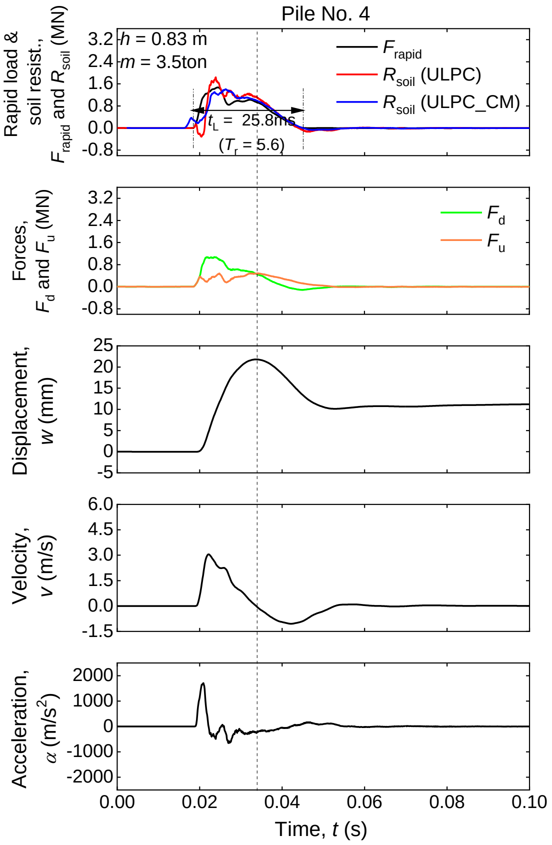

Figure 4. RLT signals (Pile No. 4, h = 0.83 m).

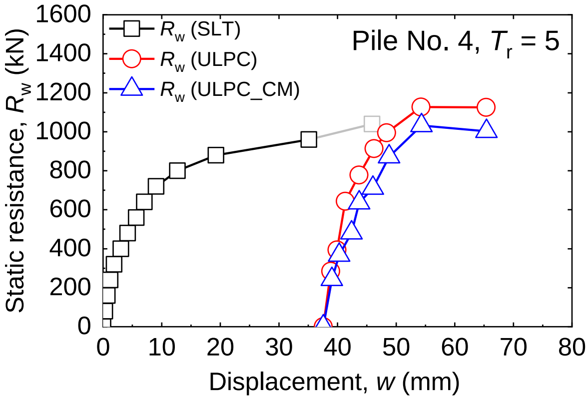

Figure 5. Comparison of load-displacement curves from SLT, RLTs with ULPC and ULPC_CM (Pile No. 4).

4.3 RLT (Pile No.2, $T_r = 3$)

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 6 shows the measured F_{rapid}, w, v and α in the RLT in the 8th blow (h = 1.35 m) 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 7 shows the static load-displacement relations 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 a shorter $T_r \approx 3$.

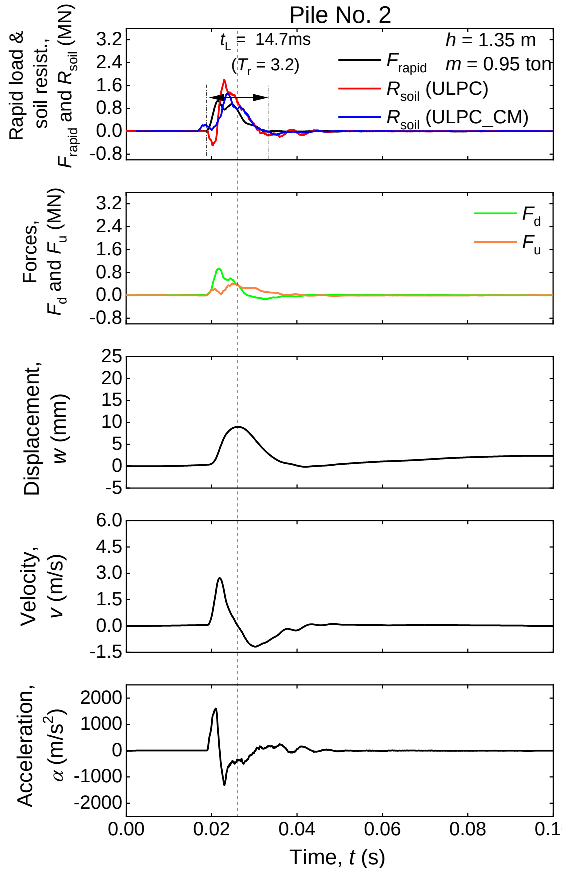

Figure 6. RLT signals (Pile No. 2, h = 1.35 m).

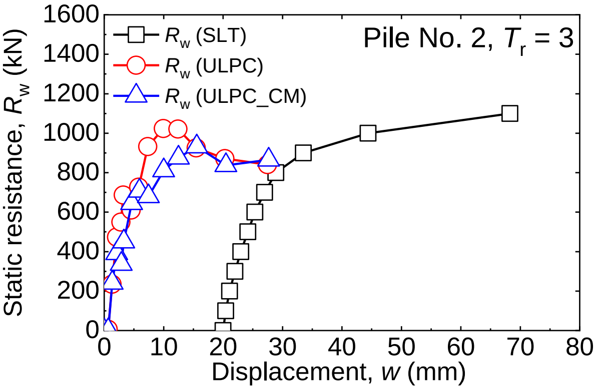

Figure 7. Comparison of load-displacement curves from SLT, RLTs with ULPC and ULPC_CM (Pile No. 2).

4.4 RLT (Pile No.5, T_r = 3)

In Pile No. 5, RLTs were carried out after SLT. In RLTs, a hammer mass m_h = 0.95 ton was used and 13 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 α in the RLT in the 13th blow (h = 3.84 m) with T_r = 3.5.

Figure 9 shows the static load-displacement relations 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 $T_r \approx 3$.

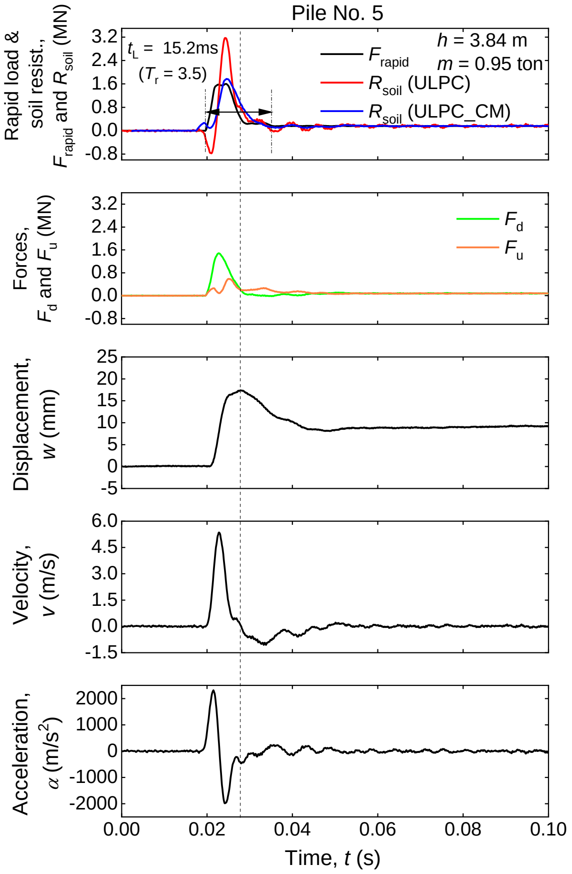

Figure 8. RLT signals (Pile No. 5, h = 3.84 m).

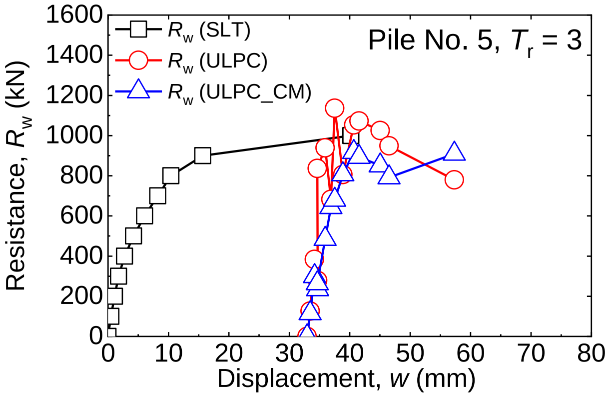

Figure 9. Comparison of load-displacement curves from SLT, RLTs with ULPC and ULPC_CM (Pile No. 5).

4.5 Comparison of results of RLTs having different relative loading durations

Figure 10 shows the comparison of load-displacement curves from SLT and RLTs with ULPC interpretation for the three test piles. ULPC result in case of $T_r = 5$ is consistent with the SLT result. However, the results in cases of $T_r = 3$ fluctuate and overestimate the SLT result. This suggests that ULPC is applicable for RLTs with $T_r \geqq 5$ as specified in the JGS standards.

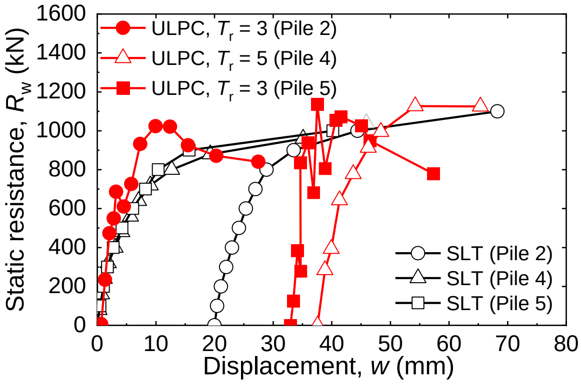

Figure 10. Comparison of load-displacement curves from SLT, RLTs with ULPC.

Figure 11 shows the comparison of load-displacement curves from SLT and RLTs with ULPC_CM interpretation for the three test piles.

Despite a slight underestimation, the load-displacement curves in both cases of $T_r = 3$ and 5 are comparable to the SLT results.

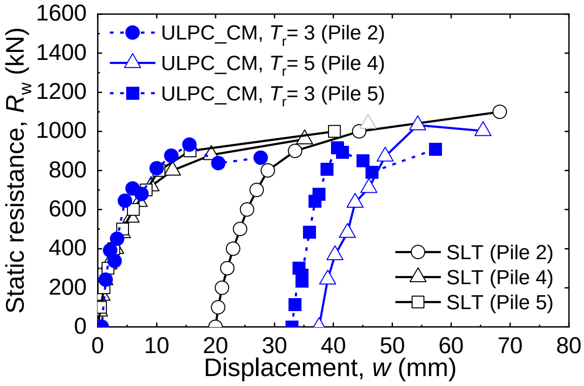

Figure 11. Comparison of load-displacement curves from SLT, RLTs with ULPC_CM.

Figure 12 shows an example of application ranges of RLTs with different T_r in case of m_h = 100 ton and h = 3.00 m. The stiffness of the cushion is varied so that required T_r is satisfied.

With the widened range of application of RLT by decreasing T_r in RLT with ULPC_CM method, it is possible to apply RLTs to a longer and higher capacity pile with the same loading device. On the other hand, it is possible to carry out RLT with the same load by using a lighter hammer, providing a more economical and convenient testing option.

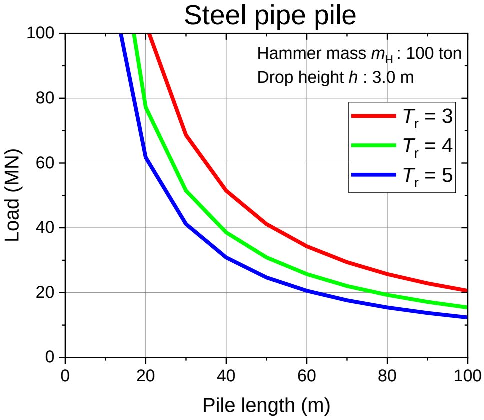

Figure 12. Application ranges of RLTs with different T_r.

5 CONCLUSIONS

In this study, comparative RLTs and SLTs were carried out on driven steel pipe piles to examine the validity of the new interpretation methods: ULPC_CM.

RLTs with $T_r = 5$ were carried out according to the JGS Standards in which T_r is required to be equal or greater than 5. Furthermore, RLTs with $T_r = 3$ were carried out to widen 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.

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

The authors are planning to conduct similar comparisons between RLTs and SLT for different types of piles to examine the applicability of ULPC_CM method in the near future.

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