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Static and Hybridnamic rapid load tests on a steel pipe pile in sand ground

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ABSTRACT: Static load test (SLT) and the Hybridnamic rapid load test (RLT) were carried out on an open-ended steel pipe pile (SPP) driven in sandy ground. The Hybridnamic RLT is a kind of falling mass type rapid load test, facilitating quick and efficient execution of multiple blows on a pile. SLT was carried out 25 days after pile driving, and RLT was carried out 8 days after the SLT. Static load-displacement curves were estimated from the RLT using various interpretation methods such as the UnLoading Point Connection (ULPC) method, the ULPC invoking Case method (ULPC_CM), and new methods (calleda *aß* method and *aß*_CM method). Static load-displacement curves from the SLT and the RLT with the various interpretation methods were compared to discuss the applicability of the various interpretation methods.

1 INTRODUCTION

In 2002, the Japanese Geotechnical Society (JGS) revised the standards for Vertical Load Tests -of piles, newly incorporating Method for Rapid Load Test of single piles (JGS1815-2002) (JGS, 2002). Rapid Load Test (RLT) has since gained widespread adoption in Japan due to its standardization. After the standardization of RLT in 2002, the falling mass method has been predominantly utilized in Japan.

This paper presents a case study of a test pile that underwent SLT followed by RLT. Static load-displacement curves were estimated from the RLT with various interpretation methods such as the UnLoading Point Connection (ULPC) method (Kamei et al., 2023), the ULPC invoking Case method (ULPC_CM) (Lin et al., 2023), and new methods called *aß* method and *aß*_CM method that are similar to the method proposed by Brown et al. (2006). In the new interpretation methods, the empirical values of *a* and *ß* are used to obtain the static load-displacement curve. Static load-displacement curves from the SLT and RLT with the various interpretation methods are compared to discuss the applicability of the various interpretation methods.

2 HYBRIDNAMIC RLT DEVICE

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

By changing the stiffness of the cushion system $K_{cushion}$, the hammer mass m_h, falling height of hammer h, loading duration t_L, and maximum rapid load $F_{rapid(max)}$ can be easily controlled.

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In the current JGS standards, a load test with a relative loading duration $T_r = t_L/(2\ L/c) \geq 5$, where L is the pile length and c is bar wave velocity in the pile, is regarded as RLT.

The basic measurement items in the RLT are the rapid load F_{rapid}, acceleration a, 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 strain gages attached to the outer surface of the pile shaft in the cases of SPPs and Pre-stressed concrete (PHC) piles. The acceleration a is measured using two piezoelectric accelerometers attached to the opposite sides of the pile surface. The displacement w is measured using an optical displacement meter placed on the ground surface approximately 20 m from the pile.

Generally, 5 to 7 blows are conducted for each pile within 3 hrs. Hence, the time and cost of RLT using Hybridnamic devices are very effective compared with conventional SLT.

At present, the maximum F_{rapid} is 40 MN using m_h = 140 tons and h = 3.3 m.

3 INTERPRETATION METHODS OF RLT

3.1 ULPC method (Kamei et al., 2022)

The ULPC (UnLoading Point Connection) method (Kamei et al., 2022) is an extension method of the UnLoading Point (ULP) method proposed by Kusakabe & Matsumoto (1995).

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 Figure 1. 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 (Equation 1). The soil resistance R_{soil} is obtained from Equation (2), using the measured F_{rapid} and a. Hence R_{soil} vs w is constructed as shown in Figure 2. The static resistance R_w is then obtained using Equation (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 (Equation 4 and Figure 2).

In Hybridnamic RLT, generally, 5 to 7 blows are applied to the pile, increasing the fall height of the hammer. Hence, several values of R_{ULP} at different displacements w are obtained without determining the value of C. Static load-displacement relation is easily constructed by connecting ULPs from multiple blows (Kamei et al., 2022).

$$F_{rapid} = R_a + R_v + R_w = m\,a + C\,v + R_w \tag{1}$$

$$R_{soil} = F_{rapid} - ma \tag{2}$$

$$R_w = R_{soil} - Cv \tag{3}$$

$$R_{soilatULP} = R_{ULP} = R_w \tag{4}$$

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; a = Pile acceleration; C = Damping constant; v = Pile velocity;

R_{ULP} = ULP resistance (static resistance).

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) employing Equations (5) and (6), respectively. Then, by using Equation (7), the time variation of R_t (= R_{soil}) is obtained (Figure 3).

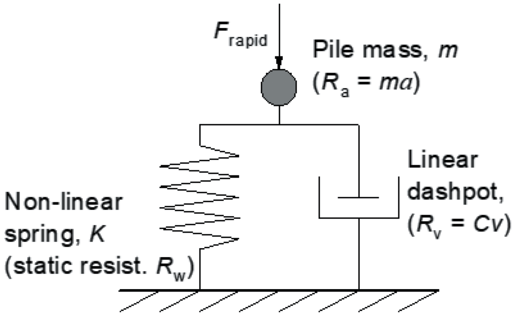

Figure 1. Modeling of pile and soil during RLT (after Middendorp et al. 1992, and Kusakabe & Matsumoto, 1995).

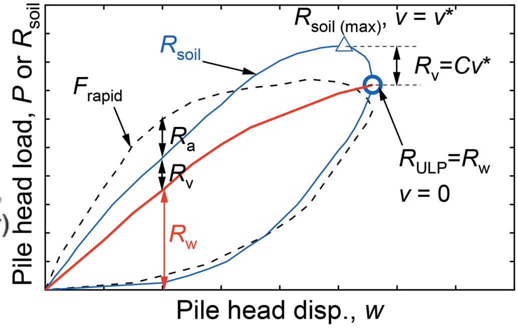

Figure 2. Relationship between load-displacement curve and soil resistance and ULP resistance.

$$F_d(x_m, t) = \frac{F(x_m, t) + Zv(x_m, t)}{2} \tag{5}$$

$$F_u(x_m, t) = \frac{F(x_m, t) - Zv(x_m, t)}{2} \tag{6}$$

$$R_t(x_m, t) = F_d\left(x_m, t - \frac{L_m}{c}\right) + F_u\left(x_m, t + \frac{L_m}{c}\right) \tag{7}$$

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 the pile.

In the Hybridnamic RLT, 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

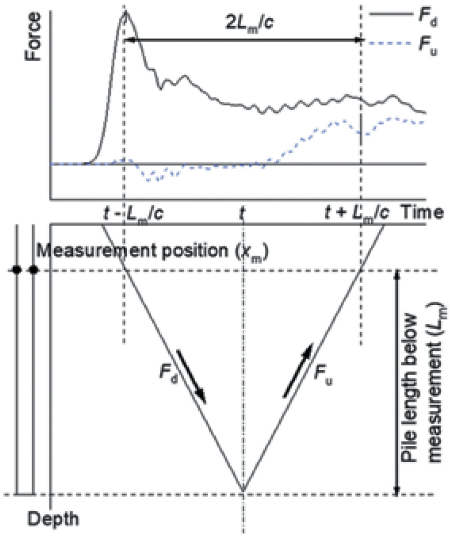

Figure 3. Case method (Raushe et al. 1985).

pile displacement w is directly measured. Hence, the $R_{soil} - w$ relation is easily obtained. R_{soil} at the maximum pile displacement (ULP) can be regarded as the static resistance R_w. Similarly to the ULPC method, a 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 does not require correction for pile inertia R_a.

3.3 αβ method (newly proposed method)

It has been known that the dynamic shaft friction τ_d is generally taken as a non-linear function of velocity, according to Equation (8) where τ_s is static shaft friction, v_0 is a reference velocity (taken for convenience as 1 m/s) and Δv is the relative velocity between the pile and the adjacent soil (Randolph and Deeks, 1992).

$$\tau_d = \tau_s\left[1 + \alpha(\Delta v/v_0)^{\beta}\right] \tag{8}$$

Table 1. Proposed ranges of *a* and *β* (Powell & Brown, 2006).

Originator	Soil type	Index properties (*LL, PL, PI*-%)	α	ß	Test conditions
Randolph & Deeks	Sand	-	0.1	0.2	Summary of previous
(1992)	Clay	-	1.0	0.2	work
Balderas-Meca (2004)	Grimsby glacial till	20-36, 12-18, 7-20	0.9	0.2	Full-scale Statnamic tests
Brown (2004)	Model clay	37, 17, 20	1.26	0.34	Model Statnamic tests
Litkouhi & Poskitt	London clay	70, 27, 43	1.77	0.18	Model pile skin friction
(1980)	Forties clay	38, 20, 18	0.99	0.23	test
	Magnus clay	31, 17, 14	0.86	0.46	

α and β are material-dependent model parameters. The proposed ranges of a and β are shown in Table 1.

Brown (2004) developed a non-linear velocity-dependent analysis method of RLT signals. Equation (9) is the analysis technique to obtain the static soil resistance during the RLT, which is similar to Equation (8). Equation (10) (Brown et al., 2006) is an extension of Equation (9).

$$R_w = \frac{R_{soil}}{1 + \alpha(\Delta v/v_0)^{\beta} - \alpha(\Delta v_{min}/v_0)^{\beta}} \tag{9}$$

$$R_w = \frac{R_{soil}}{1 + \alpha\left(\frac{F_{rapid}}{F_{rapid(max)}}\right)\left(\frac{\Delta v}{v_0}\right)^{\beta} - \alpha\left(\frac{F_{rapid}}{F_{rapid(max)}}\right)\left(\frac{\Delta v_{min}}{v_0}\right)^{\beta}} \tag{10}$$

where R_{soil} = soil resistance (= $F_{rapid} - ma$); Δv = relative velocity between the pile and the adjacent soil; Δv_{min} = velocity of the CRP (Constant Rate of Penetration) pile load test; v_0 = reference velocity (taken for convenience as 1 m/s) and $F_{rapid\ (max)}$ is the maximum value of F_{rapid}.

A new interpretation method is proposed based on Equation (10). Equation (10) supposes that only one RLT (blow) is conducted on the pile like the Statnamic test. As mentioned earlier, several blows (RLTs) are applied to the pile in the Hybridnamic RLT, increasing the hammer drop height. In general, the load-displacement relation of SLT is obtained from the maintained load test when displacement terminates in each load step. Hence Δv_{min} in Equation

(10) can be regarded as zero, and Equation (10) is expressed as Equation (11). When $F_{\mathrm{rapid}} = F_{\mathrm{rapid(max)}}$, Equation (11) is simplified to Equation (12). This is illustrated in Figure 4.

$$R_{\mathrm{w}} = \frac{R_{\mathrm{soil}}}{1 + \alpha\left(F_{\mathrm{rapid}}/F_{\mathrm{rapid(max)}}\right)(\Delta v/v_0)^{\beta}} \tag{11}$$

$$R_{\mathrm{w}} = \frac{R_{\mathrm{soil}}}{1 + \alpha(\Delta v/v_0)^{\beta}} \tag{12}$$

Δv is assumed to be equal to the measured pile velocity because it is not easy to measure the velocity of adjacent soil.

In the Hybridnamic RLT, several blows are applied to the pile head. Hence, several R_{w} is obtained with different pile displacements at different $F_{\mathrm{rapid(max)}}$. A static load-displacement

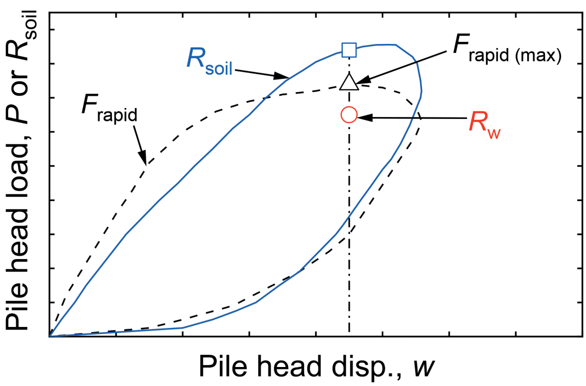

Figure 4. Relationship between forces and pile displacement (F_{rapid}, R_{soil}, and R_{w} vs w).

curve is constructed by connecting these points. This new interpretation method is called the "*aß* method".

3.4 αß_CM method (newly proposed method)

In *aß*_CM method, R_{soil} in Equation (12) is estimated using the Case Method following Lin et al. (2023). Other procedures are the same as *aß* method.

4 PILE LOAD TEST

4.1 Site conditions

Load tests were carried out in the Sashima test yard of Jibanshikenjo Co. Ltd., Japan. Figure 5 shows the results of soil investigations and embedment of the instrumented test pile. The test site is sandy ground. SPT N-values from the ground level to a depth z = 5 m are 1 to 3. Below this depth, the N-value increases with depth. Below z = 10 m, a sand layer with $N \approx$ 33 exists. The test pile was driven to z = 11 m. The groundwater table is at z = 3.5 m.

4.2 Test sequences

Table 2 shows the test sequences.

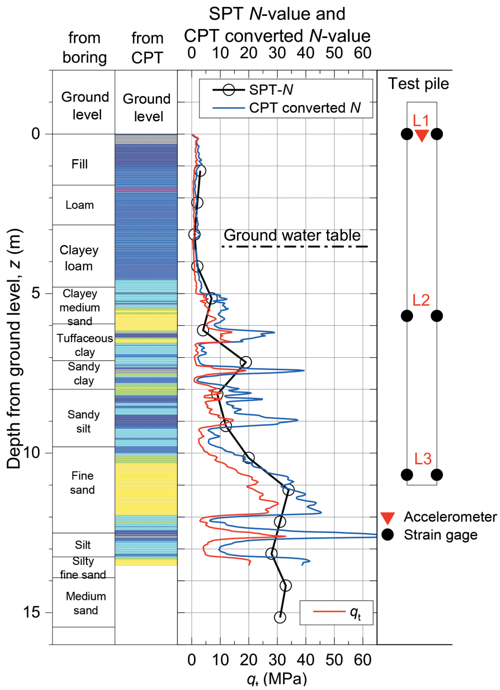

Figure 5. Profiles of soil layers, SPT N-values, and CPT q_t, together with the instrumented test pile.

Table 2. Test sequence.

Driving date (DLT)	Curing (days)	Load test	Curing (days)	Load test
22/05/12	25	SLT	8	RLT (T_r = 5)

Table 3. Specifications of test pile.

Item	Value	
	Original	with protect
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

4.3 *Test pile*

Table 3 shows the specifications of the test pile (SPP). Channel steels were welded on the outer surface of the test pile to protect strain gages and accelerometers. The test pile specifications with steel protection were used in interpretations of RLT signals.

5 TEST RESULTS

5.1 *SLT*

The step-loading SLT was carried out. The holding time of each load step was 30 minutes. The SLT result is later shown in comparison with the RLT results.

5.2 *RLT*

In RLTs, a hammer mass m_h = 3.5 ton was used, and 8 blows (RLTs) were applied to the pile, increasing drop height h from 0.03 to 0.83 m.

Figure 6 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, R_w ($a\beta$) from $a\beta$ method, and R_w ($a\beta$_CM) from $a\beta$_CM method are shown together with F_{rapid}. F_d and F_u are also shown.

R_{soil} at the maximum displacement w where v = 0 is defined as the static resistance R_w (R_{ULP}) in the ULPC and ULPC_CM method (see the chain dotted line). Static load-displacement relation can be obtained by connecting R_{ULP} from ULPC and ULPC_CM, respectively, from multiple blows (RLTs).

R_w ($a\beta$ method) and R_w ($a\beta$_CM) at the $F_{rapid(max)}$ are defined as the static resistance in these methods (see the dashed line). Static load-displacement relation can be obtained by connecting R_w from multiple blows.

Figure 7 shows the static load-displacement relations from ULPC, ULPC_CM, $a\beta$ method, and $a\beta$_CM compared with the SLT result. It is seen from the RLT results that the static soil resistance R_w from ULPC and $a\beta$ method is larger than that from ULPC_CM and $a\beta$_CM, respectively. The load-displacement relations from ULPC_CM and $a\beta$_CM match with the

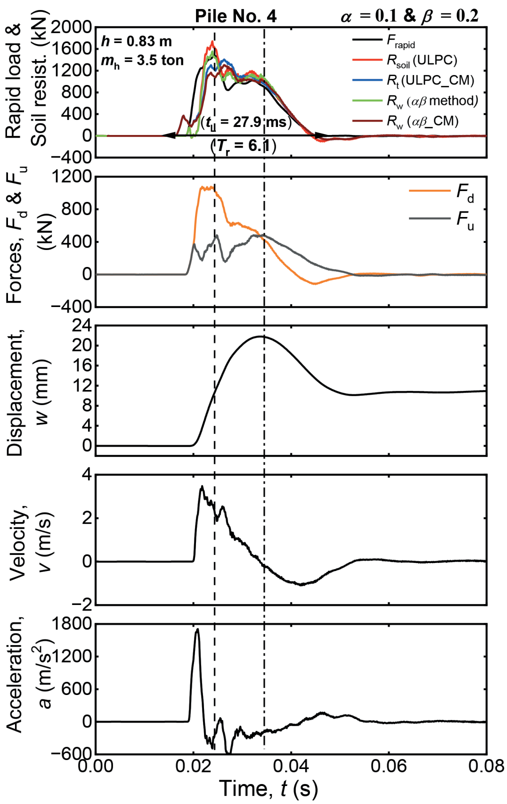

Figure 6. RLT signals (h = 0.83 m).

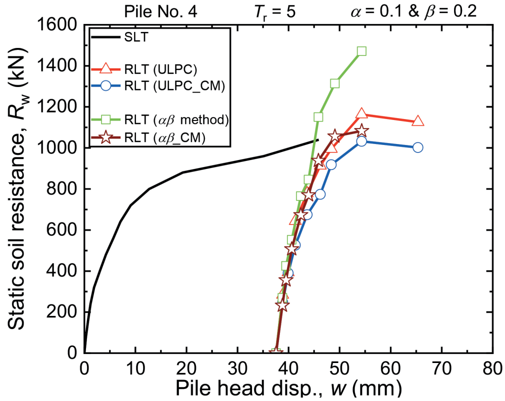

Figure 7. Comparison of load-displacement curve from SLT and RLTs.

SLT result well. In this particular case of the sandy ground, the static load-displacement curve from *aß*_CM with a = 0.1 is the best estimation for the SLT result.

6 CONCLUSION

Comparative SLT and RLT were carried out on a steel pipe pile driven into the sandy ground to examine the validity of the new interpretation methods, *aß* method and *aß*_CM method.

The static load-displacement curve (R_w vs w) from the *aß* method largely overestimated the SLT result. The R_w vs w from the ULPC method slightly overestimated the SLT result. In the *aß* method and the ULPC method, the soil resistance R_{soil} is estimated using the rigid single mass modeling of the pile ($R_{soil} = F_{rapid} - ma$).

The R_w vs w from the ULPC_CM and *aß*_CM method match with the SLT result. In these methods, R_{soil} is estimated using the CASE method based on the one-dimensional stress-wave theory. The R_w vs w from the *aß*_CM method assuming a = 0.1, matches best the SLT result.

In the interpretation methods, multiple blows (RLTs) on a pile are necessary. The Hybridnamic RLT devices developed by Jibanshikenjo Co. Ltd. are very useful in this aspect.

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