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Static load-displacement curves of steel pipe piles installed in sandy ground from static load test and rapid load test with different interpretation methods

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ABSTRACT: Static load test (SLT) and the Hybridnamic rapid load test (RLT) were carried out on two steel pipe piles (SPPs) in sandy ground. One of the test piles had a length L of 11.8 m, an outer diameter D_o of 318.5 mm, and an inner diameter D_i of 305.3 mm. The other test pile had L = 48 m, D_o = 800 mm, and D_i = 750 mm. Static load-displacement curves were estimated from the RLT using different interpretation methods such as the UnLoading Point Connection (ULPC) method, the ULPC invoking Case method (ULPC_CM), and new methods (called $\alpha\beta$ method and $\alpha\beta$_CM method). In the new interpretation methods, the empirical values of α and β are used to obtain the static load-displacement curve. Static load-displacement curves from the SLT and the RLT with the different interpretation methods were compared. The curves from ULPC_CM and $\alpha\beta$_CM methods were closer to the SLT results for the test piles in sandy ground. It is demonstrated that the Hybridnamic RLT is a reliable alternative to the conventional SLT.

KEYWORDS: Load-displacement curve, pile, rapid load test, static load test, interpretation method.

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, a load test with a relative loading duration $T_r \geq 5$ is defined as RLT. This standardization led to the widespread use of RLT in Japan. Since 2002, the falling mass type RLT method has been widely used. RLTs apply to various pile types, including steel pipe piles (SPPs), pre-stressed concrete piles (PHC piles), cast-in-situ concrete piles, and composite piles of concrete and SPP (SC piles). RLTs have been employed at sites where space and /or testing time for the preparation of reaction piles for static load tests are constrained.

The test standards offer several methods for interpreting RLT signals to derive a "static" load-displacement relationship. This paper presents a case study where short and long SPPs underwent SLT followed by RLT in a test site. Static load-displacement curves were estimated from the RLT using different 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 $\alpha\beta$ method and $\alpha\beta$_CM method, which are similar to that proposed by Brown et al. (2004). In the new interpretation methods, the empirical values of α and β are used to obtain the static load-displacement curve. Static load-displacement curves from the SLT and RLT using different 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. Figure 1 shows (a) a Hybridnamic test device and (b) 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 on the pile head via a specially designed cushion to apply rapid load.

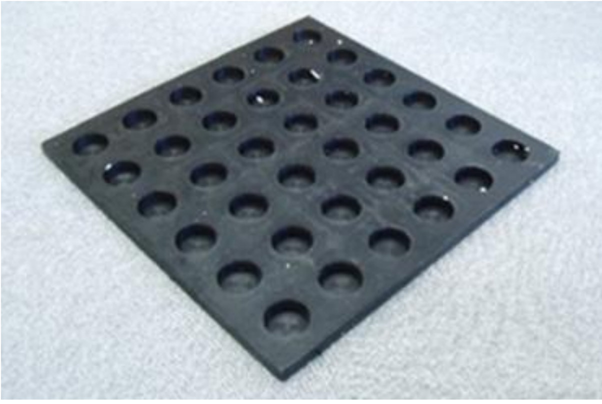
By changing the stiffness of the cushion system $K_{cushion}$, the hammer mass m_h, and falling height of hammer h, loading duration t_L, and maximum rapid load $F_{rapid(max)}$ can be easily controlled. In the current JGS standards, a load test with a relative loading duration $T_r = t_L/(2L/c) \geq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

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. The acceleration a is measured using two accelerometers attached to the opposite sides of the pile surface. The displacement w is measured using an optical displacement meter set on the ground surface approximately 10 m from the pile.

The testing time for a pile depends on the scale of the loading device and several hammer drops (blows). 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.

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

(a) Hybridnamic test device.



(b) Specially designed cushion.

Figure 1. Hybridnamic test device and specially designed cushion.

3 INTERPRETATION METHODS OF RLT

Interpretation methods of RLT signals used in this paper are described below.

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 and 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 2. 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 3. The R_{soil} at the maximum displacement point (ULP) is equal to the static resistance R_w because the pile velocity v is zero at ULP (Equation (4) and Figure 3).

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 the damping constant C. The Static load-displacement relation is easily constructed by connecting ULPs from multiple blows.

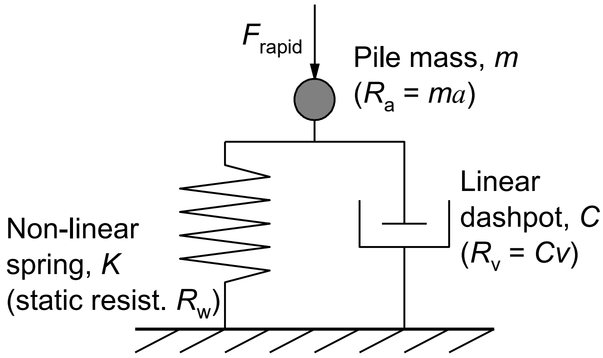


Figure 2. Modeling of pile and soil during RLT (Middendorp et al., 1993, and Kusakabe and Matsumoto, 1995).

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

$$R_{soil} = F_{rapid} - ma \quad (2)$$

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

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

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).

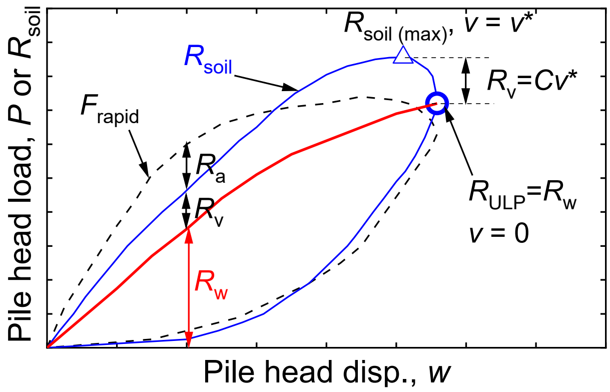


Figure 3. Relationship between F_{rapid}, R_{soil}, and R_w vs w, and ULP.

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 time variation of 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 Equation (5) and Equation (6), respectively. Then, by using Equation (7), the time variation of R_t (= R_{soil}) is obtained (Figure 4).

$$F_d(x_m,t) = \frac{F(x_m,t) + Z \bullet v(x_m,t)}{2} \quad (5)$$

$$F_u(x_m,t) = \frac{F(x_m,t) - Z \bullet v(x_m,t)}{2} \quad (6)$$

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

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.

The time variation of R_{soil} is obtained from the Case method, and the time variation of pile displacement w is directly measured. Hence, the $R_{soil} - w$ relation is easily obtained. R_{soil} at the maximum pile displacement can be regarded as the R_w. Similarly to the ULPC method, a static load-displacement curve is constructed by connecting ULPs from 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. Hence, the ULPC_CM method would be applied to RLTs on piles with relative loading duration $T_r < 5$, although further research is needed for the minimum requirement for T_r.

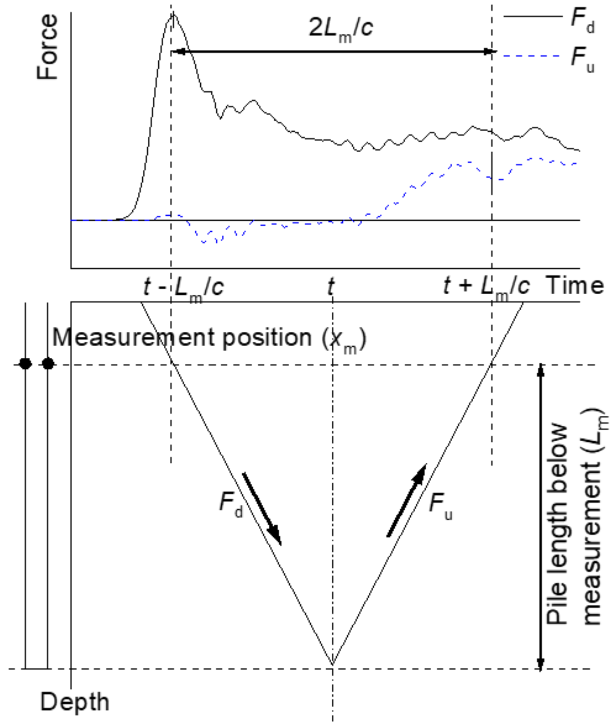


Figure 4. Case method (Raushe et al. 1985).

3.3 *Method by Brown et al. (2004)*

It has been known that the dynamic 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).

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

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

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

Originator	Soil type	α	β	Test conditions
Randolph & Deeks (1992)	Sand Clay	0.1 1.0	0.2 0.2	Summary of previous work
Balderas-Meca (2004)	Grimsby glacial till	0.9	0.2	Full-scale Statnamic tests
Brown (2004)	Model clay	1.26	0.34	Model Statnamic tests
Litkouhi & Poskitt (1980)	London clay Forties clay Magnus clay	1.77 0.99 0.86	0.18 0.23 0.46	Model pile skin friction test

Brown et al. (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 based on Equation (8).

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

where R_{soil} = soil resistance (= $F_{rapid} - ma$), m = pile mass, Δv_{min} = velocity of the Constant Rate of Penetration pile test, v_0 = reference velocity (taken for convenience as 1 m/s).

Equation (10) (Brown et al., 2006) is the extension of Equation (9).

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

where $F_{rapid\,(max)}$ is the maximum value of F_{rapid}.

3.4 *Proposal of new methods (αβ method and αβ_CM method)*

Equation (10) supposes that only one RLT is conducted on the pile, like the Statnamic test. As mentioned earlier, several blows (RLTs) are applied to the pile in the Hybridnamic RLT with increasing the hammer drop height. 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 $F_{rapid} = F_{rapid(max)}$, Equation (11) is simplified to Equation (12). In the proposed method of Equation (12), Δv is assumed to be equal to the measured pile velocity because it is not easy to measure the velocity of the adjacent soil on sites. This is illustrated in Figure 5.

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

$$R_w = \frac{R_{soil}}{1 + \alpha \left(\frac{\Delta v}{v_0} \right)^{\beta}} \qquad (12)$$

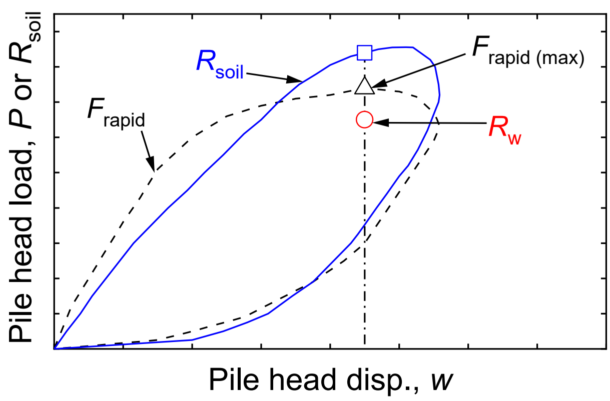


Figure 5. Relationship between F_{rapid}, R_{soil}, and R_w vs w.

In the Hybridnamic RLT, several blows are applied to the pile head. Hence, several R_w values are obtained with different pile displacements at different maximum rapid force $F_{rapid(max)}$. A static load-displacement curve is constructed by connecting these points. This interpretation method is called the "$\alpha\beta$ method".

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

4 OUTLINE OF PILE LOAD TESTS

4.1 *Site conditions*

Load tests were carried out in the Sashima test yard of Jibanshikenjo Co. Ltd., Japan. Standard Penetration Tests (SPTs) were carried out near the test piles.

Figure 6 displays the results of soil investigations and the embedment of the instrumented test piles. The test ground is sandy. SPT N-values from ground level down to a depth of 5 m range from 1 to 3. Below this depth, the N-value increases with depth. At more than 10 m deep, there is a sand layer with $N \approx 33$. The short test pile was driven to 11 m using a drop hammer. Below 45 m, a gravel soil layer with $N = 50$ is present. The long test pile was installed to 46 m using a pre-boring method. The groundwater table is located at 3.5 m depth.

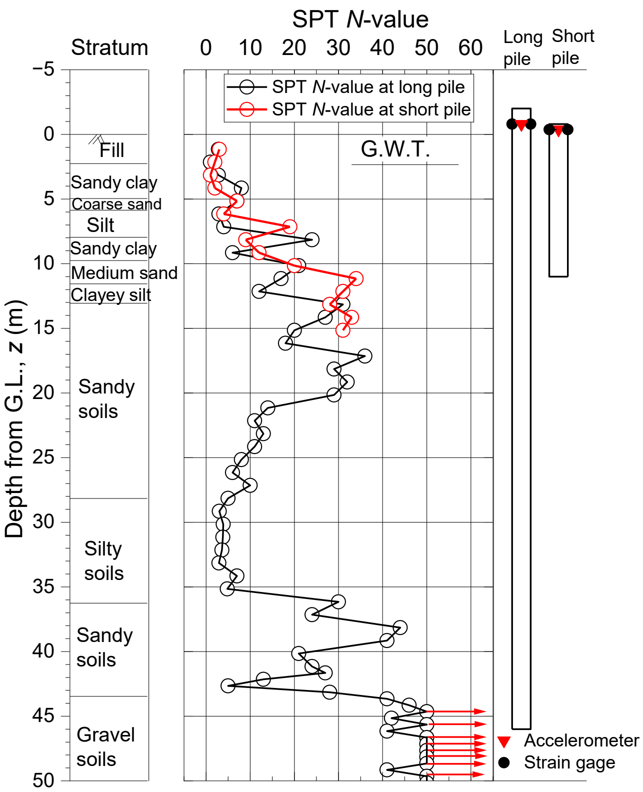


Figure 6. Profiles of soil layers, SPT N-values, and test piles.

4.2 *Test piles*

Table 2 shows the specifications of short and long test piles of steel pipe piles (SPPs). In the short pile, 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 the interpretations of RLTs.

Table 2. Specifications of test piles.

Item	Value	
	Short pile	Long pile
Pile length, L (m)	11.8	48
Embedment length, L_d (m)	11	46
Outer diameter, D_o (mm)	318.5	800
Inner diameter, D_i (mm)	305.3	750
Wall thickness, t_w (mm)	6.6	25
Cross-sectional area, A (m^2)	0.00651 0.00926 †	0.061
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 †	22.821

† : with protection steel

4.3 *Test sequence*

Table 3 shows the test sequence of each test pile.

Table 3. List of test sequences.

	Test type	Short pile	Long pile
Driving date		2022/05/12	2021/04/07
Curing (day)		25	29
Load test	SLT	2022/06/07	2021/05/06
Curing (day)		8	929
Load test	RLT	2022/06/15	2025/03/12

5 TEST RESULTS

5.1 *Static Load Test (SLT)*

The step-loading SLT was performed on both short and long piles. Each load step was maintained for 30 minutes. The SLT results are later compared to the RLT results.

5.2 *Test results of short pile*

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

Figure 7 shows the measured dynamic signals 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 ($\alpha\beta$) from $\alpha\beta$ method, and R_w ($\alpha\beta$_CM) from $\alpha\beta$_CM method are shown together with F_{rapid}. Furthermore, F_d and F_u are shown. In $\alpha\beta$ method and $\alpha\beta$_CM method, $\alpha = 0.1$ and $\beta = 0.2$ were assumed according to Randolph and Deeks (1992) (also see Table 1 in this paper) because the test site is sandy ground.

R_{soil} at the maximum pile head displacement w, where v = 0 (at the chain dotted line), is defined as the static resistance R_w (R_{ULP}) in the ULPC and ULPC_CM method.

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

Figure 8 shows the static load-displacement relations from ULPC, ULPC_CM, $\alpha\beta$ method, and $\alpha\beta$_CM compared with the SLT result. It is seen from the RLT results that the static soil resistance R_w from $\alpha\beta$ method is considerably larger than those from other methods, and R_w from ULPC is slightly larger than those from ULPC_CM and $\alpha\beta$_CM. The load-displacement curves from ULPC_CM and $\alpha\beta$_CM match the SLT result well. In this particular case of the sandy ground, the static load-displacement curve from $\alpha\beta$_CM with α = 0.1 is the best estimation for the SLT result.

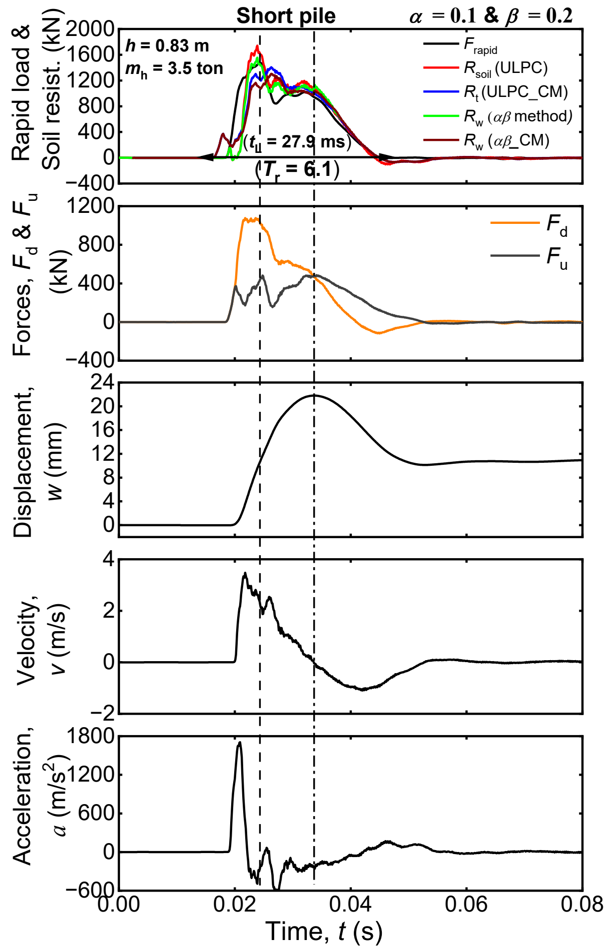


Figure 7. RLT signals of the short pile (h = 0.83 m).

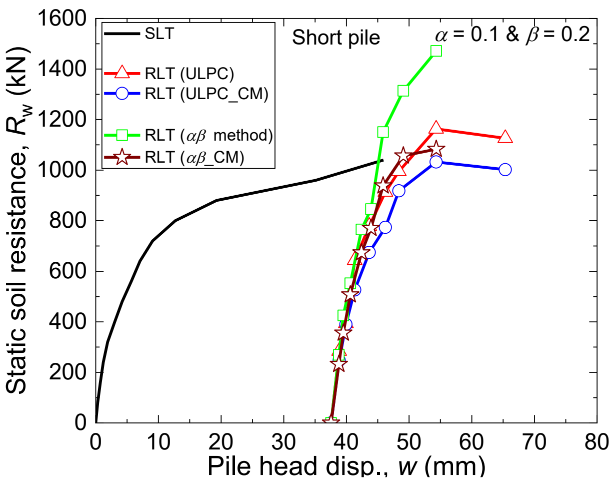


Figure 8. R_w vs w of the short pile from SLT and RLTs.

5.3 *Test results of long pile*

In RLT, a hammer mass m_h = 70 tons was used, and 7 blows (RLTs) were applied to the pile with increasing h from 0.01 to 2.5 m.

Figure 9 shows the measured dynamic signals. Figure 10 shows the static load-displacement relations from RLT and SLT. It is seen from the RLT results that the static soil resistance R_w from ULPC and $\alpha\beta$ method is larger than those from ULPC_CM and $\alpha\beta$_CM. The load-displacement curves from ULPC_CM and $\alpha\beta$_CM match the SLT result very well.

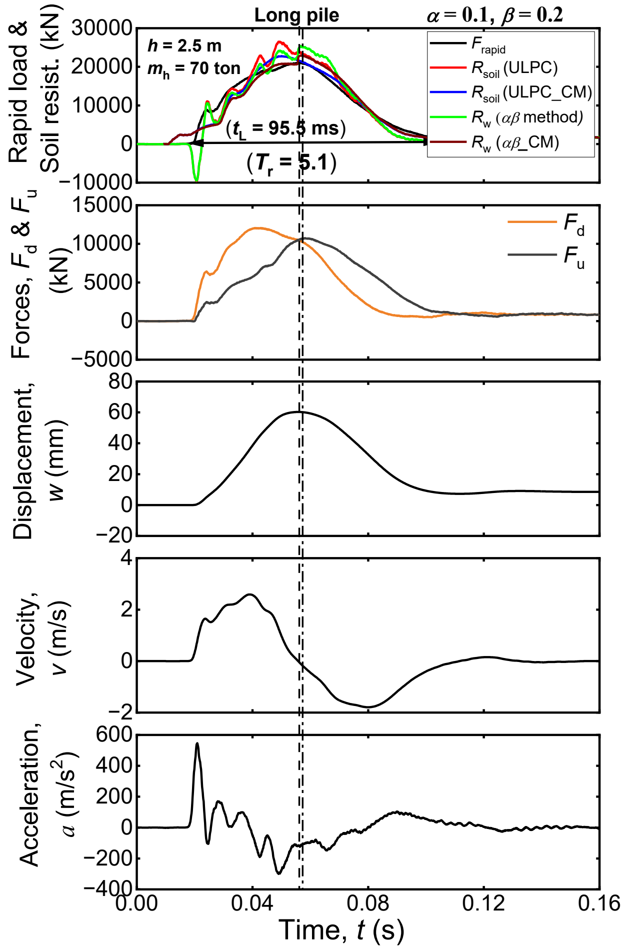


Figure 9. RLT signals of the long pile (h = 2.50 m).

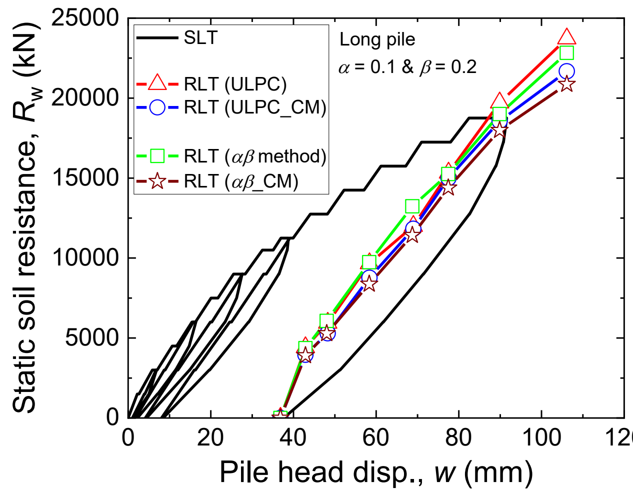


Figure 10. R_w vs w of the long pile from SLT and RLTs.

6 SENSITIVITY ANALYSIS

The empirical value α influences static soil resistance, while another empirical value β has less influence on static soil resistance.

Figures 11 and 12 show the influence of α on the static load-displacement curves, with β set constant as 0.2. As expected, as α increases, the static soil resistance decreases. In this particular case of the sandy ground, the static load-displacement curve from $\alpha\beta$_CM with α = 0.1 is the best estimation for the SLT result in both the short and long piles, regardless of pile installation method.

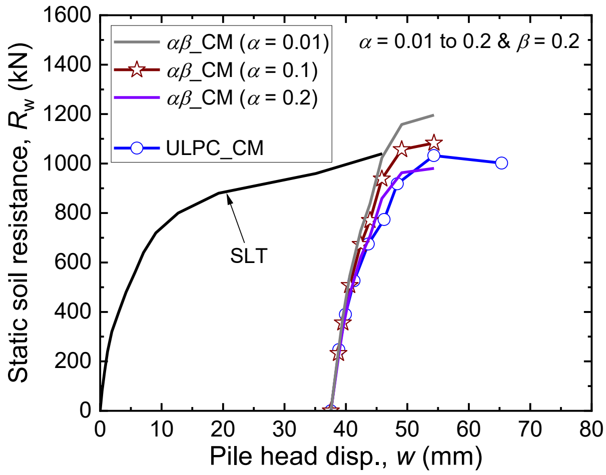


Figure 11. Influence of α (short pile).

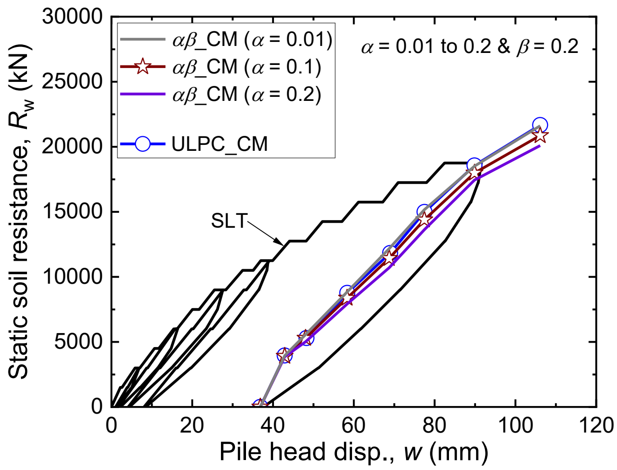


Figure 12. Influence of α (long pile).

7 CONCLUSIONS

In this study, comparative SLT and RLT were carried out on short and long steel pipe piles installed in the sandy ground to examine the validity of the new interpretation methods, $\alpha\beta$ method, and $\alpha\beta$_CM method. The short pile was driven using a drop hammer, while the long pile was installed using a pre-boring method.

The static load-displacement curves from the ULPC and $\alpha\beta$ method overestimate the SLT result. In the ULPC and the $\alpha\beta$ 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 $\alpha\beta$_CM method match with the SLT results. 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 $\alpha\beta$_CM method, assuming α = 0.1, matches best the SLT result in both the short and the long piles in the sandy ground in this research.

The sensitivity analysis was carried out to investigate the influence of α on the static load-displacement curve. In this particular case of the sandy ground, the static load-displacement curve from $\alpha\beta$_CM with α = 0.1 is the best estimation for the SLT result in both the short and long piles, regardless of pile installation method.

8 REFERENCES

Balderas-Meca, J. 2004. Rate effects in rapid loading of clay soils. PhD Thesis, University of Sheffield, UK.

Brown, M.J. 2004. The rapid load testing of piles in fine-grained soils. Ph.D. thesis, Univ. of Sheffield, Sheffield, U.K.

Brown, M.J., Anderson, W.F., and Hyde, A.F.L. 2006. Analysis of rapid load test on instrumented bored pile in clay. *Géotechnique* 56(9), 627–638. https://doi.org/10.1680/geot.2006.56.9.627

Japanese Geotechnical Society (JGS) 2002. JGS 1815-2002 Method for Rapid Load Test of Single Piles.

Kamei, S., Lin, S., Yamamoto, I., and Matsumoto, T. 2023. Hybridnamic rapid load testing with an extended interpretation method of dynamic signals. *Proc. 17th ARC on SMGE,* Nur-Sultan,1420-1424.

Kamei, S., Takano, K., and Fujita, T. 2022. Comparison of static load test and rapid load test on steel pipe piles in two sites. *Proc. the 11th Int. Conf. on Stress Wave Theory and Design and Testing Methods for Deep Foundations,* The Netherlands, DOI/10.5281/zenodo.7148489.

Kusakabe, O., and Matsumoto, T. 1995. Statnamic tests of Shonan test program with a review of signal interpretation. *Proc. 1st Int. Statnamic Seminar*, Vancouver, Canada, 113-122.

Lin, S., Kamei, S., Yamamoto, I., and Matsumoto, T. 2023. Hybridnamic rapid load testing with UnLoading Point Connection method invoking Case method. *Proc. 17th ARC on SMGE*, 1425-1429.

Litkouhi, S., and Poskitt, T.J. 1980. Damping constants for pile driveability calculations. *Geotechnique* 30(1), 77-86.

Middendorp, P., Bermingham, P., and Kuiper B. 1993. Statnamic testing of foundation pile. *Proc. 4th Int. Conf. on Application of Stress-Wave Theory to Piles*, The Hague, 585-588.

Powell, J.J.M., and Brown, M.J. 2006. Statnamic pile testing for foundation re-use. *Proc. Int. Conf. on the Re-use of Foundations for Urban Sites*, IHS BRE Press, Bracknell, UK, 223-236.

Randolph, M.F., and Deeks, A.J. 1992. Dynamic and static soil models for axial response. *Proc. 4th Int. Conf. on the Application of Stress Wave Theory to Piles*, Balkema, Netherlands, 3-14.

Raushe, F., Goble, G., and Likins, G.E.Jr. 1985. Dynamic determination of pile capacity. *ASCE Jour. Geotech. Div.*, 111(3), 367-383.