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Comparisons of rapid load test, dynamic load test, and static load test on piles in clayey ground in Thailand

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ABSTRACT: In Thailand, a static load test (SLT) or dynamic load test (DLT) is employed to obtain the bearing characteristics of a pile. Due to the lack of capable DLT signal interpreters, it is widely believed that SLT is the most reliable method to obtain the load-displacement behavior of a pile. However, SLT requires a high cost and a long testing period. Therefore, pile design has been mainly based on empirical equations and soil information from borehole investigation without any load test by adopting excessive design requirements, i.e., high factors of safety. In this paper, case studies comparing SLT, DLT, and rapid load test (RLT) on a bored pile and a spun concrete pile at different sites are presented and discussed. The Hybridnamic device, a falling-mass type RLT device, was used. The test piles were installed in Bangkok subsoil conditions of clayey ground. New interpretation methods of RLT signals, $\alpha\beta$ method and $\alpha\beta$_CM, were used to interpret the RLT signals. The static load-displacement curves derived from the RLT are compared with those from DLT and SLT. The validity of RLT was examined through comparisons of load tests on the piles. The case studies presented in this paper encourage the use of RLT for the construction and quality control of constructed piles in Thailand.

KEYWORDS: Rapid load test, concrete pile, clay ground, load-displacement curve, interpretation method.

1 INTRODUCTION

In Thailand, a static load test (SLT) or dynamic load test (DLT) is employed to obtain the bearing characteristics of a pile. Static load test (SLT) is the most reliable method for determining the load-displacement relation of a pile. SLT requires reaction force and loading devices, which increases cost and test time. Due to the lack of a capable dynamic load test result interpreter, it is widely believed that the static load test is the most reliable method to obtain the load-displacement behavior of a pile. Therefore, pile design has been mainly based on empirical equations and soil information from borehole investigation without any load test by adopting excessive design requirements, i.e., a high factor of safety.

To overcome the above situation, rapid load test methods have been used. 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, in a short time and at a low cost. In the current Japan Geotechnical Society (JGS) standards (2002), the load test with the relative loading duration $T_r = t_L/(2L/c) = 5$ (t_L = the loading duration, L = the pile length, c = the propagation speed of longitudinal stress wave in a pile) is regarded as RLT.

Hybridnamic RLT was conducted on a cast-in-place concrete pile and a spun concrete pile at site A (STS company test yard) and site B (MRT purple line), respectively, in Bangkok, Thailand. The validity of the Hybridnamic RLT method to estimate piles' static behaviors is examined by comparing the results from SLT, DLT and RLT.

2 HYBRIDNAMIC RLT DEVICE

Jibanshikenjo Co. Ltd. has developed several Hybridnamic test devices since 2003. Figure 1 shows a Hybridnamic test device 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 on the pile head via the specially designed cushion to apply rapid 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. 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. 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

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 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 (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.

(a) Hybridnamic test device.

(b) Specially designed cushion.

Figure 1. Hybridnamic test device and specially designed cushion.

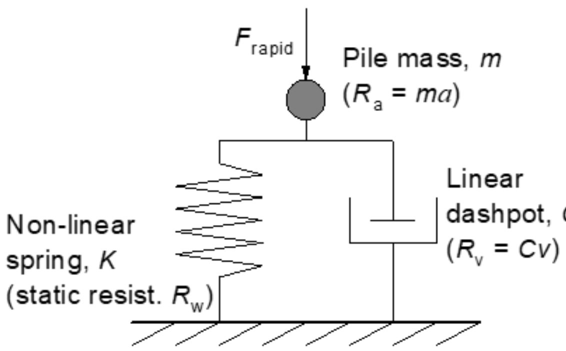

Figure 2. Modeling of pile and soil during RLT (after Middendorp et al. 1992, and Kusakabe and Matsumoto, 1995).

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 3).

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

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

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

$$R_{soil} \text{ at ULP} = R_{ULP} = R_w \tag{4}$$

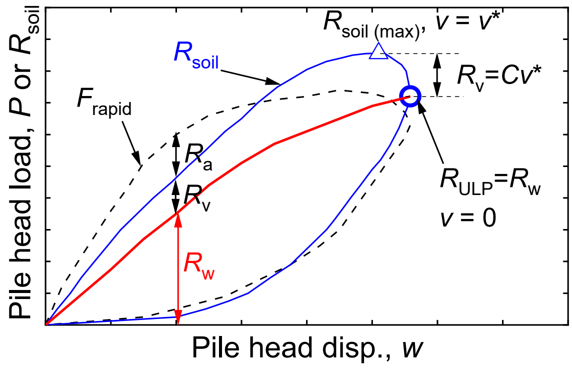

Figure 3. F_{rapid}, R_{soil} and R_w vs w, and ULP.

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. The Static load-displacement relation is easily constructed by connecting ULPs from multiple blows (Kamei et al., 2022).

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

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

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

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

where x = Coordinate along the pile axis (pile head = 0), x_m = Measurement position, L_m = Pile length from measurement position to pile tip, 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 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. Similar 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-dim. stress-wave theory, it does not require correction for pile inertia R_a.

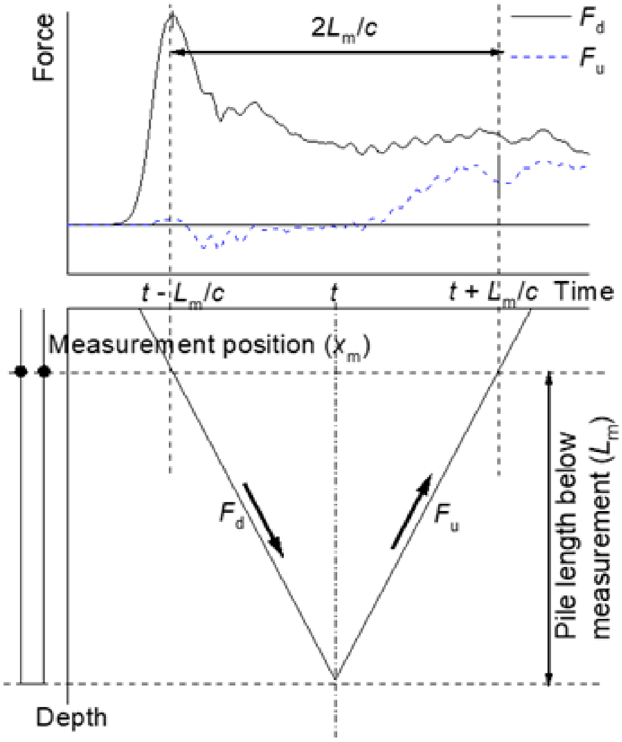

Figure 4. Case method (Raushe et al. 1985).

3.3 *αβ 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).

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

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	0.1	0.2	Summary of previous work
	Clay	1.0	0.2	
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	1.77	0.18	Model pile skin friction test
	Forties clay	0.99	0.23	
	Magnus clay	0.86	0.46	

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).

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

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

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

where R_{soil} = soil resistance (= $F_{rapid} - ma$), Δv_{min} = velocity of the CRP (Constant Rate of Penetration) pile test, $F_{rapid\ (max)}$ is the maximum value of F_{rapid}.

A new interpretation method is proposed based on Equation (10). Equation (10) supposes that only one RLT is conducted on the pile, like the Statnamic test. As mentioned earlier, several blows (RLTs) are applied to the pile in the Hybridnamic RLT by increasing the hammer drop height. In general, the load-displacement relation of SLT is obtained from the maintained load test when displacement is terminated in each load step. Hence, Δv_{min} in Equation (10) can be regarded as zero, and Eq. (10) is expressed as Equation (11).

When F_{rapid} = $F_{rapid(max)}$, Equation (11) is simplified to Equation (12). This is illustrated in Figure 5.

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

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

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

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

3.4 *αβ_CM method*

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

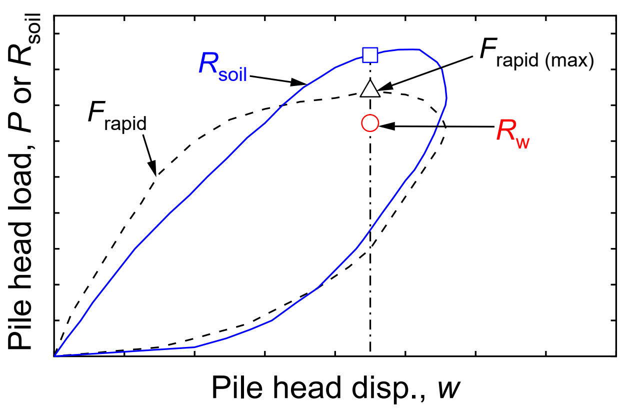

Figure 5. F_{rapid}, R_{soil}, and R_w vs w.

4 PILE LOAD TESTS

4.1 *Load tests at STS test yard (Site A)*

The tests were conducted on a cast-in-place concrete pile at the STS test yard in Bangkok, Thailand. SLTs, DLT, and RLTs were carried out on the pile.

4.1.1 *Site conditions*

Figure 6 shows the profiles of soil layers, SPT *N*-values, cone resistance corrected for pore pressure at filter q_t, and the instrumented test pile. The SPT *N*-values are lower than 20 to a depth of 17 m and about 24 from 20 m in depth *z*.

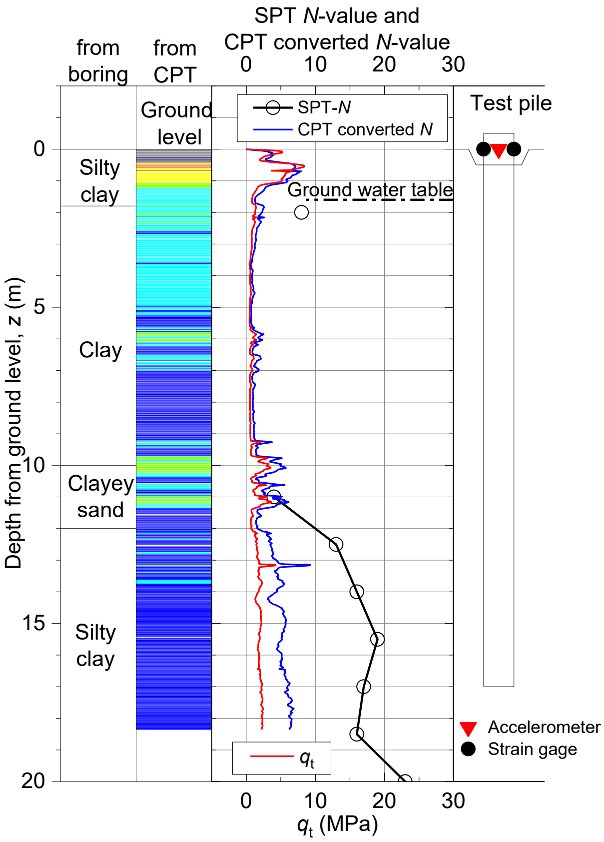

Figure 6. Profiles of soil layers, SPT *N*-values, CPT q_t, and instrumented test pile.

4.1.2 *Test pile*

Table 2 shows the specifications of the cast-in-place concrete pile.

Table 2. Specifications of cast-in-place concrete test pile.

Item	Value
Pile length, L (m)	17.5
Embedment length, L_d (m)	17
Outer diameter, D_o (mm)	350
Cross-sectional area, A (m^2)	0.0962
Young's modulus, E (GPa)	34.656
Density, ρ (ton/m^3)	2.40
Bar wave velocity, c (m/s)	3800
Mass, m (ton)	4.040

4.1.3 *Test sequences*

Table 3 shows the test sequence of the test pile.

4.1.4 *Test results*

The step-loading SLTs were carried out. In DLT, Wave Matching Analysis (WMA) using CAPWAP was conducted to obtain a static load-displacement curve of the test pile. RLTs were carried out three times with different hammer masses m_h and drop heights *h,* as shown in Table 3.

Table 3. Test sequences.

Date	Elapsed time (day)	Type of load test	Descriptions
2023-08-07	0		Pile installation
2023-09-04	28	SLT 1st	No. of cycles = 1, Step load test
2023-10-27	81	DLT	m_h = 4 tons, h = 0.8 m
2023-12-19	134	RLT 1st	m_h = 4 tons, 8 blows, h = 0.09 – 1.20 m, $T_r \geq 5$
2023-12-23	138	SLT 2nd	No. of cycle = 1, Step load test
2024-02-02	179	RLT 2nd	m_h = 8 tons, 4 blows, h = 1.00 – 2.35 m, $T_r \geq 5$
2024-02-23	200	RLT 3rd	m_h = 12 tons, 7 blows, h = 0.06 – 0.96 m, $T_r \geq 5$

The results of SLTs and DLT are shown in comparison with the RLT results.

The measured test signals are interpreted using the ULPC, ULPC_CM, $\alpha\beta$ method, and $\alpha\beta$_CM.

In $\alpha\beta$ method and $\alpha\beta$_CM, the empirical parameters α and β need to be determined. In practice, grounds consist of multiple soil layers having different thicknesses. Each soil layers have different values of α and β. However, a unique set of α and β is employed in the signal interpretation. Hence, a weighted average value of α, α_{avg}, along the pile embedment length was used in the analysis with a constant value of $\beta = 0.2$ as shown in Table 4. Here, L_i and α_i are the thickness and α of soil layer *i*, respectively.

Table 4. Weighted average value of α, α_{avg}.

No	Type of soil	Top (m)	Bot. (m)	Thick., L_i (m)	α_i	$L_i\ \alpha_i$ (m)
1	Silty CLAY	0	1.8	1.8	0.7	1.26
2	CLAY	1.8	10.0	8.2	0.9	7.38
3	Clayey SAND	10.0	12.0	2.0	0.5	1.00
4	Silty CLAY	12.0	17.0 (Pile tip)	5.0	0.7	3.50
				ΣL_i = 17 m	α_{avg} = 0.77	$\Sigma L_i\ \alpha_i$ 13.14 m

Figure 7 shows the measured dynamic signals, rapid load F_{rapid}, pile head displacement *w*, velocity *v* and acceleration *a*, in the first RLT at h = 1.20 m. In the figure, soil resistance R_{soil} (ULPC) from the ULPC method, R_{soil} (ULPC_CM) from the ULPC_CM method, R_w ($\alpha\beta$ method) from $\alpha\beta$ method and R_w ($\alpha\beta$_CM) from $\alpha\beta$_CM method are shown together with F_{rapid}. F_d and F_u are also shown.

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

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

Figure 8 shows the static load-displacement curves from ULPC, ULPC_CM, $\alpha\beta$ and $\alpha\beta$_CM methods compared with the SLT and DLT results. In the figure, the curves from the 1st, 2nd, and 3rd RLTs are shown.

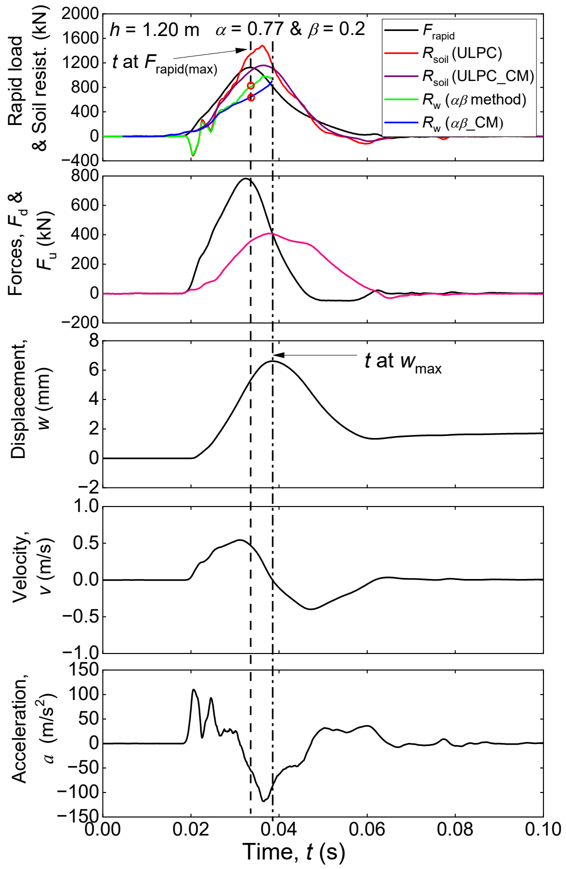

Figure 7. RLT signals (h = 1.20 m, the first RLT).

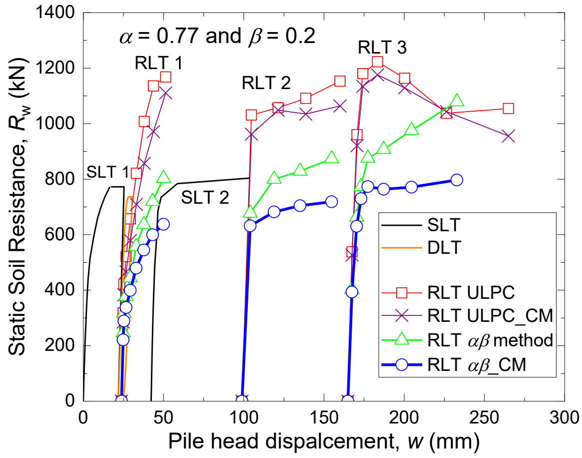

Figure 8. R_w vs w curve from SLTs, DLT, and RLTs.

The RLT results show that the static soil resistance R_w from ULPC and ULPC_CM is much larger than that from SLTs. It can be said that ULPC and ULPC_CM are not applied to piles in clayey ground. R_w from $\alpha\beta$ method continues to increase after the yield load without showing the ultimate resistance.. Please remember that the soil resistance R_{soil} is estimated using the rigid single mass modeling of the pile ($R_{soil} = F_{rapid} - ma$) in the $\alpha\beta$ method, whereas R_{soil} is estimated using the CASE method based on the one-dimensional stress-wave theory in the $\alpha\beta$_CM. When the drop height of the hammer is increased after the yielding of the pile, the accelerations along the pile become largely non-uniform, and the use of acceleration at the pile head leads to the overestimation of R_{soil}, as pointed out by Kamei et al. (2022). This is also valid for the difference between ULPC and ULPC_CM.

Meanwhile, although the load-displacement curves from $\alpha\beta$_CM slightly underestimate the SLT results, the curves from $\alpha\beta$_CM show ultimate resistance states and match the SLT results reasonably.

4.2 *Load tests at MRT purple line (Site B)*

The tests were conducted on a spun concrete pile at the MRT purple line project site.

4.2.1 *Site conditions*

Figure 9 shows the profiles of soil layers, SPT N-values, and the instrumented test pile. Soil layers to the depth of the pile tip are clay or silty clay layers.

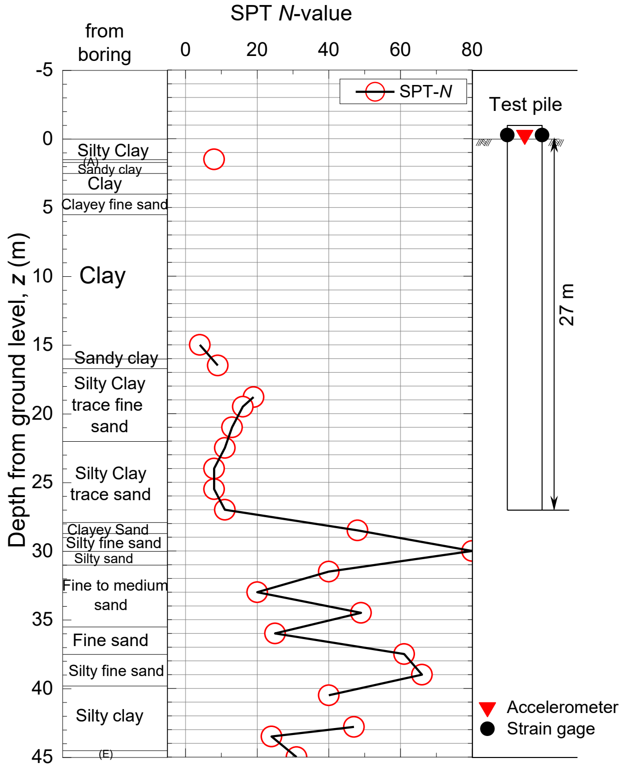

Figure 9. Profiles of soil layers, SPT N-values, and instrumented test pile in Site B.

Table 5. Specifications of spun concrete test pile in Site B.

Item	w/o inner concrete	w/ inner concrete (top 3 m)
Length, L (m)	28	28
Embedment length, L_d (m)	27	27
Outer diameter, D_o (mm)	500	500
Inner diameter, D_i (mm)	320	0
Wall thickness, t_w (mm)	90	250
Cross-sectional area, A (m^2)	0.1159	0.1963
Young's modulus, E (GPa)	44.1	44.1
Density, ρ (ton/m^3)	2.50	2.5
Mass, m (ton)	8.1147	8.428
Longitudinal wave velocity, c (m/s)	4200	4200
Impedance, Z (kN•s/m)	1217.0	2061.7
Pile length below meas. point, L_m (m)	27.3	27.3

4.2.2 *Test pile*

Table 5 shows the specifications of the spun concrete pile. The test pile was driven with a drop hammer until the pile tip reached a depth of 27 m.

4.2.3 *Test sequences*

Table 6 shows the test sequence of the test pile.

4.2.4 *Test results*

As described earlier, in $\alpha\beta$ method and $\alpha\beta$_CM, the empirical parameters α and β need to be determined. Hence, a weighted average value of α, α_{avg}, along the pile embedment length was again used in the analysis with a constant value of $\beta = 0.2$ as shown in Table 7.

Table 6. Test sequences in Site B.

Date	Elapsed time (day)	Type of load test	
2024-09-28	0	Initial driving	Pile installation
2024-11-02	35	SLT	No. of cycle = 2, Maintained load test
2024-11-28	61	DLT	m_h = 12-ton, h = 0.9 m
2024-12-04	67	RLT	m_h = 12-ton, 5 blows, h = 0.22 m - 1.21 m

Table 7. Weighted average value of α, α_{avg} in Site B.

No	Type of Soil	Top (m)	Bot. (m)	Thick L_i (m)	α_i	$L_i\ \alpha_i$ (m)
1	Silty CLAY (Fill)	0	1.5	1.5	0.7	1.05
2	Clayey SAND loose (SC, Fill)	1.5	1.7	0.2	0.5	0.1
3	Sandy CLAY, medium stiff (CL)	1.7	2.5	0.8	0.6	0.48
4	CLAY, trace sand, soft (CH)	2.5	4.0	1.5	0.9	1.35
5	Clayey fine SAND, very loose (SC)	4.0	5.5	1.5	0.5	0.75
6	CLAY, trace fine sand, very soft to soft (CH)	5.5	16.0	10.5	0.9	9.45
7	Sandy CLAY, trace to some gravel, medium stiff (CL)	16.0	16.7	0.7	0.6	0.42
8	Silty CLAY, trace fine sand, stiff (CH)	16.7	22.0	5.3	0.7	3.71
9	Silty CLAY, trace sand, stiff (CH)	22.0	27.0 (Tip)	5.0	0.7	3.5
				ΣL_i 27 m	α_{avg} 0.77	$\Sigma L_i\ \alpha_i$ 20.81 m

Figure 10 shows the static load-displacement curves from $\alpha\beta$ method and $\alpha\beta$_CM method compared with the SLT result. Re-strike tests were carried out prior to the SLT. Pile penetration of 22 mm was caused by the re-strike tests. The results from ULPC and ULPC_CM are omitted in this figure because these methods largely overestimated the SLT result, similarly to the results at Site A.

Loading to the ultimate state was not conducted in the SLT and RLT. R_{soil} from $\alpha\beta$ method based on the rigid pile modeling is similar to that from the CASE method below the yield pile load. The load-displacement curves from $\alpha\beta$ method and $\alpha\beta$_CM method are good estimates for the SLT result.

5 CONCLUDING REMARKS

In this study, comparative SLTs, DLTs, and RLTs were carried out on a cast-in-place concrete pile and a spun concrete pile at different sites of clay ground to examine the validity of the new interpretation methods, $\alpha\beta$ method, and $\alpha\beta$_CM method.

The static load-displacement curves (R_w vs w) from the ULPC and ULPC_CM largely overestimate the SLT result, indicating that these methods cannot be applied to piles in clayey ground.

In the newly proposed methods, a concept of weighted average value α_{avg} of α was introduced because most grounds consist of multiple soil layers. The R_w vs w from the $\alpha\beta$ method and $\alpha\beta$_CM were reasonable estimates for the SLT results. However, R_w vs w from $\alpha\beta$_CM was closer to the SLT results. The soil resistance R_{soil} is estimated using the rigid single mass modeling of the pile ($R_{soil} = F_{rapid} - ma$) in the $\alpha\beta$ method, whereas R_{soil} is estimated using the CASE method based on the one-dimensional stress-wave theory in $\alpha\beta$_CM method. As Kamei et al. (2022) pointed out, the rigid single mass modeling of the pile leads to the excessive correction of the pile inertial force ma resulting in the overestimation of R_{soil}, especially after the yielding of the pile.

The parameters α and β are empirical values. The authors will carry out more comparative SLT and RLT to accumulate reliable values of α and β for various soil types.

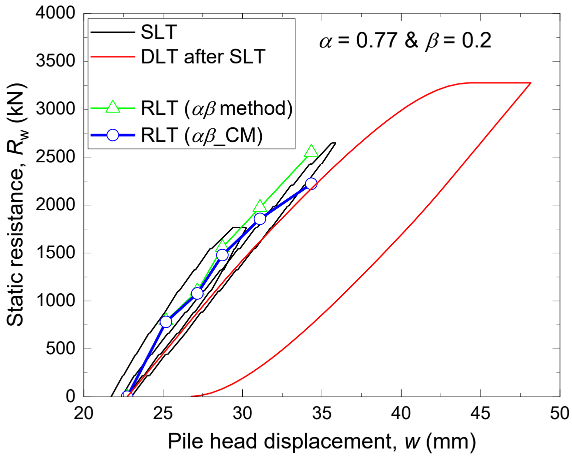

Figure 10. R_w vs w curve from SLT and RLTs in Site B.

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