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Hybridnamic rapid load testing with UnLoading Point Connection method invoking Case method

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ABSTRACT: The Hybridnamic testing is a kind of falling-mass type rapid load test (RLT), by which several blows on a pile can be conducted easily and quickly. Hence, static load-displacement curve is constructed by connecting UnLoading Point (ULP) loads. This procedure is called UnLoading Point Connection (ULPC) method. ULP method or ULPC method is employed for cases of the relative loading duration $T_r = t_L/(2L/c)$ greater than 5, where t_L is loading duration, L is pile length and c is bar wave velocity. ULPC with Case method (ULPC_CM) is proposed in this paper so that RLT can be employed even in cases of T_r less than 5. A case study was carried out to demonstrate the applicability of ULPC_CM. Load-displacement curves from the ULPC_CM interpretation of RLT signals having smaller T_r less than 5 were comparable to the conventional static load test result.

1 INTRODUCTION

Twenty years have passed since the rapid loading test (RLT) of piles were newly added to the Japan Geotechnical Society (JGS) standard (JGS1815-2002). After 2002, most of the RLTs in Japan are conducted using the falling-mass method with a soft-cushion placed on the pile head. In line with this, the number of loading cycles has also changed from one loading of the maximum planned load to multiple loading with the hammer drop height being raised in stages. Therefore, the interpretation method has shifted from the UnLoading Point (ULP) method to the UnLoading Point Connection (ULPC) method (Kamei et al. 2022), which provides a static load-displacement relationship simply by connecting the ULPs without the need to obtain the damping constant C required in the ULP method.

As a result of the widespread use of the ULPC method as an interpretation method for rapid loading tests, some cases have emerged that pose challenges for the analysis of single mass model method in which the entire pile length is considered as a rigid body.

In this paper, as a new interpretation method to address these issues, the ULPC method invoking the Case method (ULPC_CM) is proposed.

2 HYBRIDNAMIC RAPID LOAD TEST DEVICES

Jibanshikenjo Co. Ltd. has developed several Hybridnamic test devices since 2003. The 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 to apply rapid load to the pile head via a specially designed cushion on the pile head. By changing combination of stiffness of the cushion system K_{cushon}, hammer mass m_h and falling height of hammer h, loading duration t_L

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and the maximum rapid load $F_{rapid(max)}$ can be easily controlled. In the current JGS standards, load test with the relative loading duration $T_r = t_L/(2L/c) \geq 5$, where L is the pile length and c is the bar wave velocity in the pile, is regarded as RLT.

3 UNLOADING POINT CONNECTION METHOD WITH CASE METHOD (ULPC_CM)

Middendorp et al. (1992) treated the pile as a rigid mass during RLT assuming that the effects of wave propagation phenomena in the pile body are negligible. When a dynamic load F_{rapid} is applied to the pile, the static soil resistance R_w and dynamic soil resistance R_v act on the pile. These relationships are expressed in Equations 1 and 2, and Figures 1 and 2.

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

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

$$R_w = R_{soil} - \ C\ v \tag{3}$$

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

where, F_{rapid} = Rapid load, R_a = Inertial force of pile, R_v = Dynamic soil resistance, R_w = Static soil resistance, m = Pile mass, α = Pile acceleration, C = Damping constant, v = Pile velocity, R_{ULP} = ULP resistance (static soil resistance).

At the maximum displacement w_{max} (called UnLoading Point, ULP) the pile velocity v is 0, hence R_{soil} is equal to R_w (R_{ULP}) as Equation 4.

In the Hybridnamic RLT, the hammer drop height h is increased in stages, and the pile is loaded multiple times. In each blow, ULP load and the corresponding displacement are obtained. Therefore, by simply connecting the ULPs, the R_w - w relationship can be easily obtained without the estimation of C.

Kamei et al. (2022) point out that even if $T_r \geq 5$, there are cases where assumption of rigid mass modeling of a pile may not be adequate. To overcome this situation, Kamei et al. (2023, in press) proposes Segmental UnLoading Point Connection (SULPC) method. The SULPC method can be employed in case that the pile is instrumented with strain gages and accelerometers at several levels of the pile.

In many cases, however, dynamic signals are measured only near the pile head. Hence, a new interpretation method is proposed, in which the ULPC method (Kamei et al. 2022) and the Case method (Raushe et al. 1985) are combined as described below.

The Case method is a method based on one-dimensional stress-wave theory, in which the soil resistance R_t (= R_{soil}) of a pile during driving, and the static soil resistance R_s (= R_w) are obtained using an empirical coefficient called the J_c-factor.

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) (Equations 5 and 6). Then, using Equation 7, the time variation of the penetration resistance R_t of the pile is obtained (Figure 3).

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

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

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

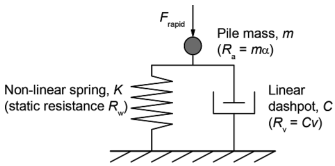

Figure 1. Modeling of pile and soil during RLT (after Middendorp et al. 1992, and Kusakabe and Matsumoto, 1995).

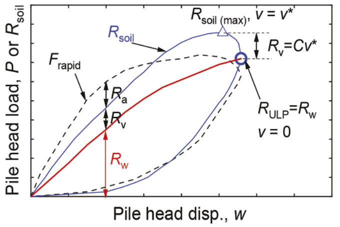

Figure 2. Relationship between load-displacement curve and soil resistance and ULP resistance.

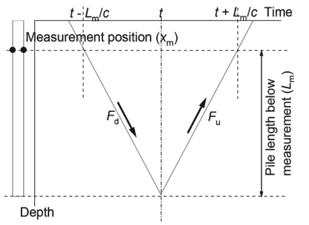

Figure 3. Case method (Raushe et al. 1985).

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, Z: Impedance ($=EA/c$), F: Axial force, F_d: Downward force wave, F_u: Upward force wave, c: Bar wave velocity, E: Young's modulus of pile material, A: Cross sectional area of pile

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 (ULP) 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 CASE STUDY

4.1 *Test description*

The test site was in Ibaraki Prefecture, Japan. The profile of SPT-N values is shown in Figure 4, together with pile embedment. The test pile was a steel pipe pile (SPP) having the specifications listed in Table 1. The pile was constructed using the inner excavation method. Two strain gages and two accelerometers were attached near the pile head.

Static load test (SLT) with 5-step maintained load was carried out 29 days after the pile construction. RLTs using the Hybridnamic test device with a hammer mass of 23 ton was carried out 112 days after the SLT.

4.2 *Test results*

Figure 5 shows the measured dynamic signals in the RLT with $T_r = 3$. In the figure, soil resistance $R_{soil\ (ULP)}$ from the ULP method and $R_{soil\ (Case)}$ from the Case method are also shown. $R_{soil\ (ULP)}$ and $R_{soil\ (Case)}$ at the time of maximum displacement are the static soil resistance R_w from both methods.

By connecting R_w from the all blows, pile head load P_h vs pile head displacement w_h are obtained as shown in Figure 6. P_h vs w_h from both ULPC and ULPC_CM are comparable with the SLT result when $T_r = 5$. However, as T_r decreases, the results from ULPC overestimate the SLT result, while the results from the ULPC_CM are still comparable with the SLT result.

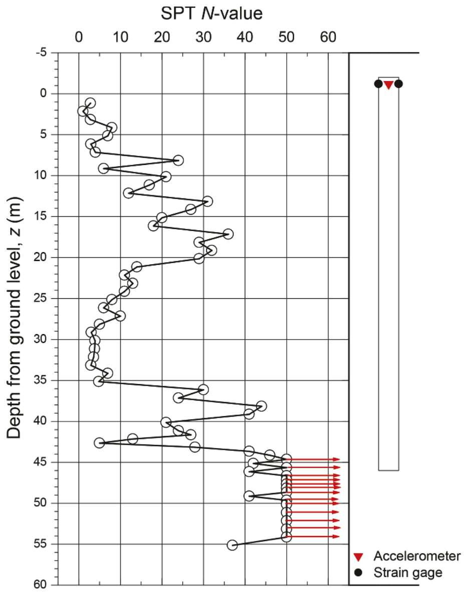

Figure 4. Profile of SPT-N values, together with pile seating.

Table 1. Specifications of the test pile.

Item	Value
Length, L (m)	48.0
Outer diameter, D_o (mm)	800
Inner diameter, D_i (mm)	750
Wall thickness, t_w (mm)	25
Cross-sectional area, A (m^2)	0.0609
Young's modulus, E (kPa)	2.00×10^8
Density, ρ (ton/m^3)	7.85
Mass, m (ton)	22.314
Bar wave velocity, c (m/s)	5133

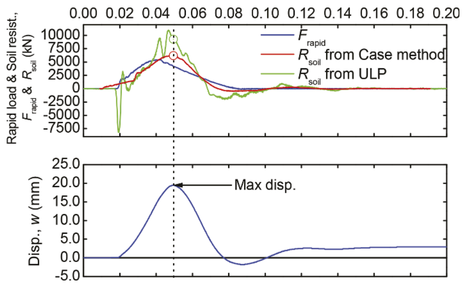

Figure 5. RLT signals (T_r = 3, h = 1.0 m).

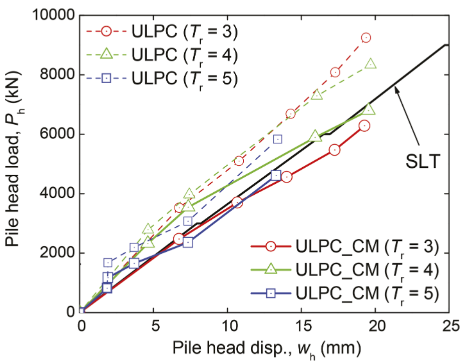

Figure 6. Comparison of load-displacement curves from SLT, RLTs with ULPC and ULPC_CM.

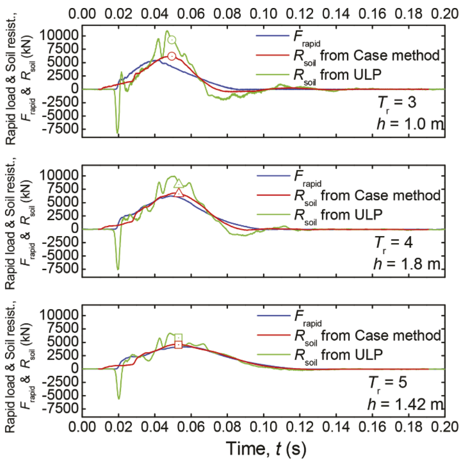

Figure 7. RLT signals (T_r = 3~5).

As shown in Figure 7, for T_r = 5, there is no significant difference between $R_{soil\ (Case)}$ and $R_{soil\ (ULP)}$; as T_r decreases to 4 and 3, the difference between $R_{soil\ (Case)}$ and $R_{soil\ (ULP)}$ increases. The results in Figures 6 and 7 indicate that the ULPC_CM method has a potential applicability to RLTs with $T_r < 3$.

5 CONCLUSIONS

A new interpretation method, ULPC_CM, of RLT signals was proposed in this paper. The load-displacement relations of an SPP from RLTs with the ULPC_CM interpretation were comparable with the SLT result until T_r was decreased to 3.

The loading in this test was within the range of reloading. In future, similar comparison between RLTs and SLT will be needed to examine the applicability of the ULPC_CM to obtain the load-displacement relation of a pile to the ultimate load. Furthermore, conduction of RLTs with $T_r < 3$ will be needed to discuss the application limit of ULPC_CM method for RLTs with smaller T_r.

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