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Special Contribution

Rapid Load Test on a Gyropress Steel Pipe Pile for Design Purpose

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Reiki Bridge, an old bridge in Gunma Prefecture, Japan, was rebuilt in 2022. Steel pipe piles (SPPs) constructed using the Gyropress Method were used for the pile foundations of the abutments of the new bridge. The piles were designed preliminarily based on the empirical equations specified in Guidelines for design and construction of Gyropress steel pipe piles retaining walls. However, as the number of applications of Gyropress pile is not enough so far, the Hybridnamic rapid load test was carried out on one of the constructed piles for the purpose of pile design.

Keywords: Gyropsess pile, design, load-displacement relation, rapid load test, case study

1. Introduction

Reiki Bridge crossing Name-kawa River in Gunma Prefecture, Japan was replaced by a new bridge in 2022 [1]. The old Reiki Bridge (Fig. 1a), a two-span rolled steel beams and reinforced concrete slab bridge, had a span length of 28.09 m and a width of 3.7 m. The width of the new bridge (Fig. 1b), a single-span simple beam composite floor bridge with a span length of 26.90 m, was widened to 7.5 m to accommodate increased traffic. The old bridge's pier foundation was removed, making the river's flow smooth and mitigating the risk of floods.

Steel pipe piles (SPPs) were adopted for the foundations of the abutments of the new bridge. Because of narrow site conditions, limited access (as shown in Fig. 1a and 1b), mitigation of noise and vibration, and shortening of the construction period, Gyropress Method (Rotary Cutting Press-in Method) was employed to construct the SPPs. In the Gyropress Method, an open-ended steel pipe pile with cutting bits at the pile tip is pressed into the ground with rotation as shown in Fig. 2. The piles were designed preliminarily based on the empirical equations specified in Guidelines for design and construction of Gyropress steel pipe piles retaining walls (IPA, 2014) [2]. However, as the number of applications of Gyropress pile is not enough so far, it was determined to carry out a load test on the constructed pile.

Fig. 1a The old Reiki bridge

Fig. 1b The new Reiki bridge

The constraints of the narrow space made the conventional static load test (SLT) impractical. And, the construction period needed to be shortened. Hence, the Hybridnamic Rapid Load Test (Hybridnamic RLT) (Kamei et al., 2022) [3] was carried out on one of the constructed SPPs to obtain “static” load-displacement curve. The Hybridnamic RLT requires less space and test period, compared with SLT.

2 Outline of Rapid Load Test

2.1 Site condition

Fig. 3 shows the results of borehole investigations and the embedment of the instrumented test pile. Beneath the top filled layer, there exists a very hard gravel layer with SPT *N*-values ≥ 50. Because the borehole terminated at a depth of 10 m, the soil layer below this depth was assumed to be a gravel layer similar to the shallower gravel layer.

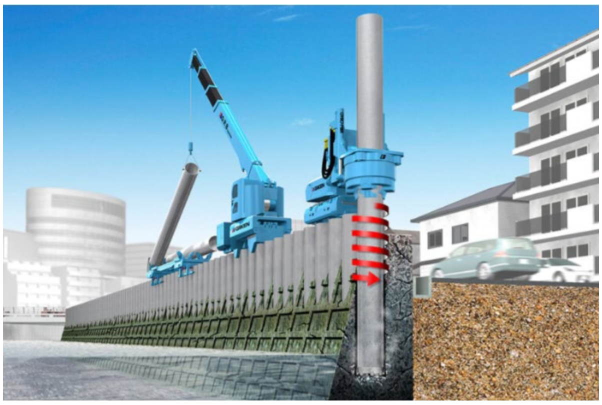

Fig. 2 GYRO PILER™ (https://www.giken.com/en/solutions/gyro/)

2.2 Pile specifications

Table 1 shows the specifications of the test steel pipe pile (SPP). The SPP was installed using the Gyropress Method. The test pile was instrumented with two pairs of strain gages and accelerometers near the pile head for the Hybridnamic RLT (see Fig. 3).

Table 1. Specifications of test piles

Item	Value
Pile length, L (m)	15.0
Embedment length, L_d (m)	14.0
Outer diameter, D_o (mm)	1200
Inner diameter, D_i (mm)	1176
Wall thickness, t_w (mm)	12.0
Cross-sectional area, A (m^2)	0.045
Young's modulus, E (GPa)	206.8
Density, ρ (ton/m^3)	7.88
Bar wave velocity, c (m/s)	5123
Mass, m (ton)	4.94

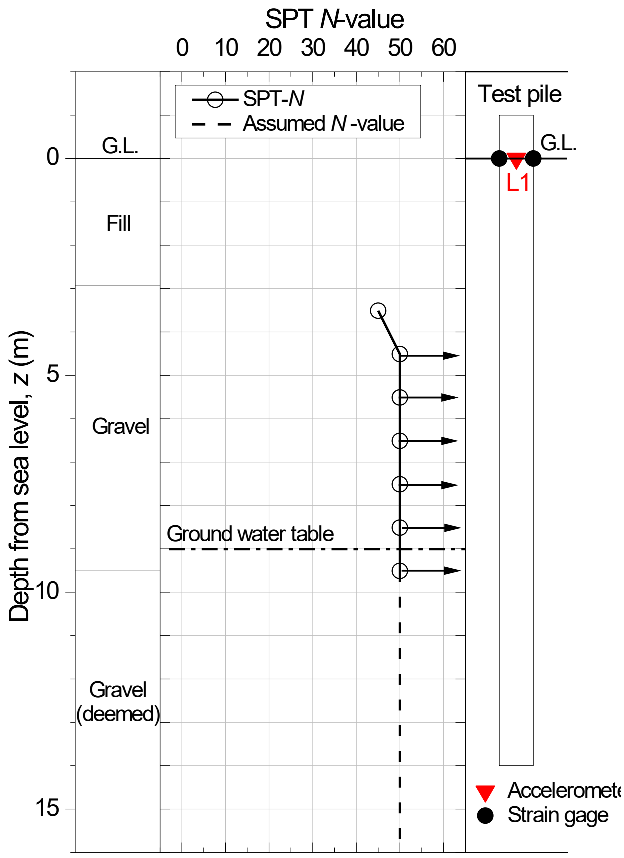

Fig. 3 Profiles of soil layers and SPT *N*-values

2.3 Preliminary pile design

Table 2 lists the design working loads on the pile, the factor of safety and the corresponding required pile capacity. The action of the reaction mass caused during loading is about 5g. Hence, weight of the reaction mass is about 20% of the planned maximum load. An advantage of the Statnamic test is the high loading capacity which can be as high as 60 MN. However, repeated loading is difficult in the Statnamic test.

The ultimate bearing capacity of the pile was preliminarily calculated using the empirical formulas listed in Table 3.

Using N = 50, the following values of ultimate resistance were roughly obtained:

q_d = 2400 kPa, total tip resistance Q_d = 2714 kN
f_s = 100 kPa, total shaft resistance Q_s = 2740 kN
Total pile capacity $Q = Q_d + Q_s$ = 5454 kN

Table 2. Design loads, factor of safety and required pile capacity

State	Working load	Factor of safety	Required pile capacity
Usual	1305 kN	3	3915 kN
L1 earthquake	1440 kN	2	2880 kN

While the estimated total pile capacity sufficiently exceeds the required capacity, the limited number of Gyropress pile applications raises concerns about the reliability of empirical formulas used to estimate tip and shaft resistance. Hence, it was determined to carry out a load test on one of the constructed piles. As mentioned earlier, the narrow site conditions rendered the conventional SLT impractical. For these reasons, it was determined to carry out the Hybridnamic RLT to confirm that the pile has a bearing capacity greater than 3915 kN.

3. Interpretation Methods of RLT Signals

3.1 ULPC method

The ULPC (UnLoading Point Connection) method (Kamei et al., 2022) [3] is an extension method of UnLoading Point (ULP) method. In the Hybridnamic RLT, generally, 5 to 7 blows are applied to the pile with increasing the fall height of hammer *h*. In each blow, the time variation of the soil resistance $R_{soil}(t)$ is obtained using Eq. (1).

$$R_{soil}(t) = F_{rapid}(t) - M\alpha(t) \qquad (1)$$

where F_{rapid} is the measured applied force, α is the measured pile head acceleration and *M* is the pile mass.

R_{soil} contains dynamic soil resistance depending on the pile penetration velocity $v(t)$. At the maximum pile displacement (UnLoading Point, ULP), the pile velocity v = 0. Hence, R_{soil} at ULT is thought to be the static soil resistance. By connecting ULPs from multiple blows, static load-displacement relation is easily constructed.

3.2 ULPC_CM method

The Case method (Raushe et al., 1985) [4] 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) using of Eq. (2) and Eq. (3), respectively. Then, by using Eq. (4), the time variation of $R_t(t)$ (= $R_{soil}(t)$) is obtained (Fig. 4).

$$F_d(x_m,t) = \frac{F(x_m,t) + Z \cdot v(x_m,t)}{2} \qquad (2)$$

$$F_u(x_m,t) = \frac{F(x_m,t) - Z \cdot v(x_m,t)}{2} \qquad (3)$$

$$R_t(x_m,t) = F_d\left(x_m, t - \frac{L_m}{c}\right) + F_u\left(x_m, t + \frac{L_m}{c}\right) \qquad (4)$$

Table 3. Empirical formulas to estimate tip and shaft resistance (IPA, 2014)

Soil type	Tip resistance q_d (kPa)	Shaft resistance f_s (kPa)
Sand	60 *N* (≤ 2,400 kPa)	2 *N* (≤ 100 kPa)
Gravel		

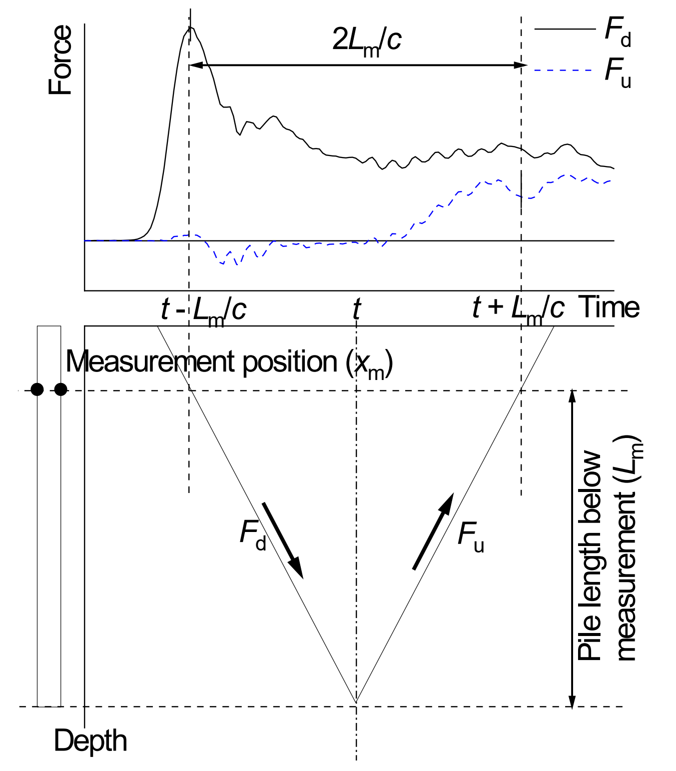

Fig. 4 Case method (Raushe et al. 1985)

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, *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 pile.

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, 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 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 relative loading duration $T_r = t_L/(2L/c) < 5$ (t_L is the loading duration).

4 Rapid load test at the site

4.1 Outline of RLT

Fig. 5 is the Hybridnamic RLT device used at the site. As seen from the figure, the usual reaction system such as reaction piles and rection beams are not required and the testing space is very narrow.

Fig. 5 Hybridnamic RLT device used in the site

RLTs were carried out using the device with a hammer mass m_h = 9.5 tons. A total of 6 blows (RLTs) were applied to the pile with increasing drop height h from 0.30 to 1.80 m. The target maximum load was 4083 kN which was greater than the required pile capacity of 3915 kN. The test was completed within 3 days including preparation, testing and dismounting of the device.

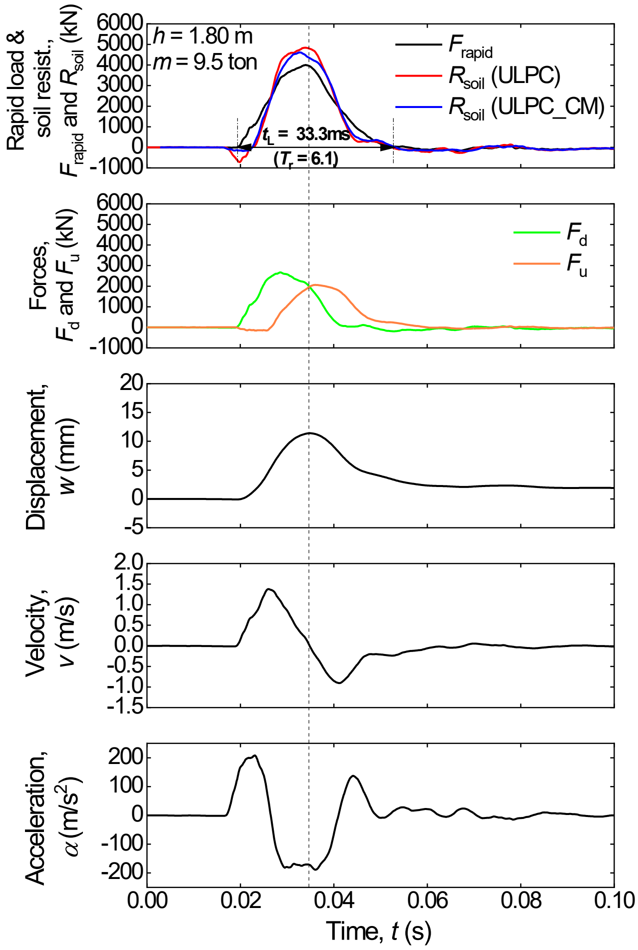

Fig. 6 RLT signals (h = 1.80 m)

4.2 Test results

The measured test signals were interpreted using two methods, ULPC and ULPC_CM. Fig. 6 shows the measured dynamic signals, rapid load F_{rapid}, pile head displacement w, velocity v and acceleration α, in the RLT at h = 1.80 m. In the figure, soil resistance R_{soil} (ULPC) from the ULPC method and R_{soil} (ULPC_CM) from the ULPC_CM method are shown together with F_{rapid}. Furthermore, F_d and F_u are also shown.

Fig. 7 shows the F_{rapid}, R_{soil} (ULPC) and R_w (ULPC) vs w from the ULPC method.

Fig. 8 also shows the F_{rapid}, R_{soil} (ULPC_CM) and R_w (ULPC_CM) vs w from the ULPC_CM method.

Fig. 9 shows the static load-displacement relations from ULPC and ULPC_CM. The 2 curves match quite well up to 6 mm displacement, but start to show some deviation as the displacement increases from 6 mm. Until the 3rd blow the pile head accelerations were relatively small. Hence the 2 curves match well. After the 4th blow large pile head upward (negative) acceleration was generated resulting in an overestimation of R_{soil} when ULPC interpretation method is employed. On the other hand, as mentioned earlier, because 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. Therefore ULPC_CM is more reliable than ULPC.

Both of the result from each interpretation method satisfied the required capacity. The initial pile head stiffness K_h from each interpretation was almost same, K_h = 501 MN/m.

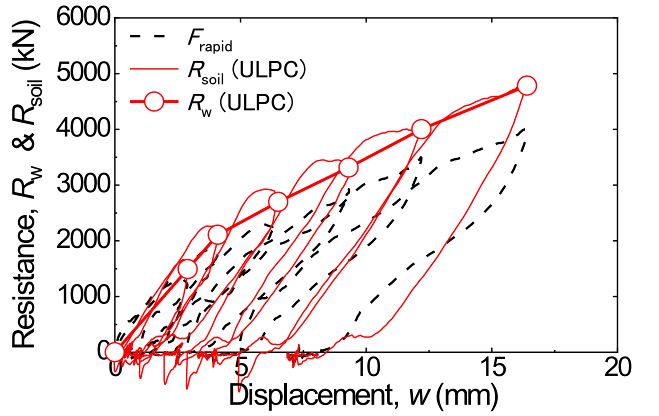

Fig. 7 F_{rapid}, R_{soil} and R_w vs w from ULPC

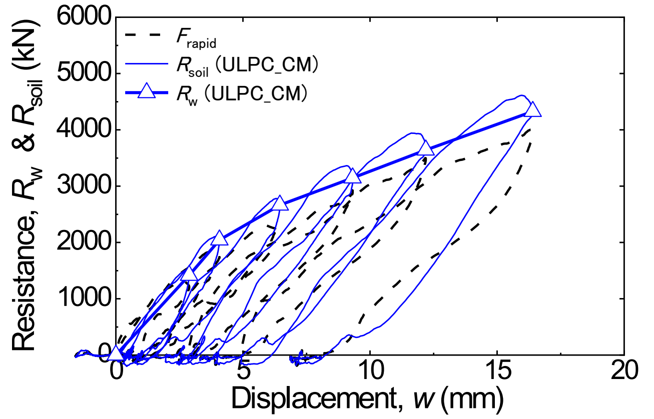

Fig. 8 F_{rapid}, R_{soil} and R_w vs w from ULPC_CM

5 Concluding Remark

Due to the low reliability of the empirical formulas for estimating tip and shaft resistance, RLT was carried out to confirm the required capacity of SPPs constructed using the Gyropress Method.

In this study, load-displacement relations of the pile were obtained from RLT with two interpretation methods, ULPC (the current JGS method) and ULPC_CM (a new and more reliable method). The load-displacement curves from both interpretation methods exceeded the required pile capacity with a pile head displacement of about 14 mm.

It is emphasized that the Hybridnamic rapid load testing was used as a reliable design tool.

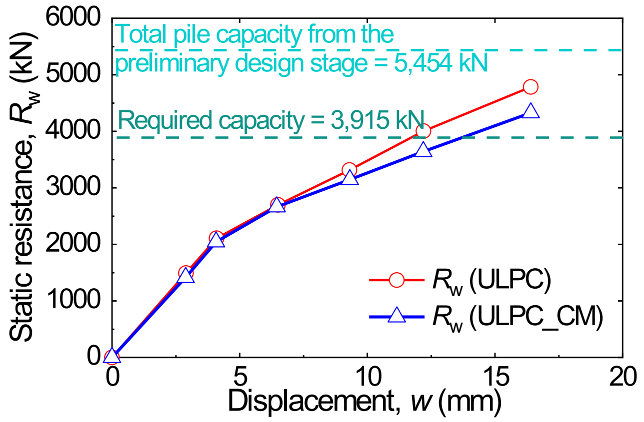

Fig. 9 Comparison of load-displacement curves from RLTs with ULPC and ULPC_CM

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◆ A brief CV of Prof. Tatsunori Matsumoto

Tatsunori Matsumoto obtained his Bachelor of Engineering and Master of Science from Kanazawa University, Japan. He joined the Department of Civil Engineering of Kanazawa University in 1981 as research associate. He became an Associate Professor in 1991 and promoted to a Professor from August in 1999. He retired from Kanazawa University in 2021 and became Emeritus Professor.

He retains an active involvement in research into pile dynamics and deformation of pile foundations including piled rafts subjected to load combinations. He has published more than 200 technical papers including more than 60 Journal papers.

He was the Chairman of IS-Kanazawa 2012: The 9th International Conference on Testing and Design Methods for Deep Foundations held in Kanazawa, Japan, from 18 to 20 September, 2012. He was Vice-President Asia of IPA from 2019 to 2024.