Rapid load test on a press-in steel pipe pile with Gyropress Method for confirmation of design bearing capacity

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ABSTRACT

Reiki bridge, an old bridge in Gunma Prefecture, Japan was rebuilt in 2022. Steel pipe piles (SPPs) were used for the pile foundations of the abutments of the new bridge. At the site, a sand-gravel layer exists from 4 m depth with STP-*N* values greater than 50. The piles were designed preliminarily based on the empirical equations specified in Guidelines for design and construction of Gyropress steel pipe piles retaining walls. SPPs having an outer diameter of 1200 mm, an inner diameter of 1176 mm, a total length of 15.0 m, and an embedment length of 14.0 m were adopted for the pile foundations. The Hybridnamic rapid load tests (RLTs) were carried out on one of the constructed SPPs to confirm the required design bearing capacity. Two interpretation methods as UnLoading Point Connection method (ULPC) and UnLoading Point Connection method invoking the Case method (ULPC_CM) were used to obtain "static" load-displacement relations of the pile. The load-displacement curves from both interpretation methods exceeded the required pile capacity with a pile head displacement of about 16 mm.

Key words: *Rapid load test, Press-in steel pipe pile, Gyropress, Gravel ground, Case study*

1. Introduction

Reiki Bridge crossing Name-kawa River in Gunma Prefecture, Japan was replaced by a new bridge in 2022. 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, having a span length of 26.90 m was widened to 7.5 m to accommodate for increased traffic. The pier foundation of the old bridge was removed, which makes the flow of the river smooth and mitigates 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) (GIKEN, 2023) 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. 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). 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) 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.

Comparisons of static load *P*-displacement *w* curves derived from RLT and directly obtained from SLT were carried out on piles in sandy grounds (Hoshino et al., 2012; Kamei et al., 2022; Lin et al., 2023b). These comparative studies showed that *P*-*w* curve derived from RLT and that from SLT were almost similar.

2. Out line of rapid load test

2.1. Site condition

Fig. 2 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.

The test pile was instrumented with two pairs of strain gages and accelerometers near the pile head for the Hybridnamic RLT.

2.2. Pile specifications

Table 1 shows the specifications of the test steel pipe pile (SPP). The SPP was installed using the Gyropress Method.

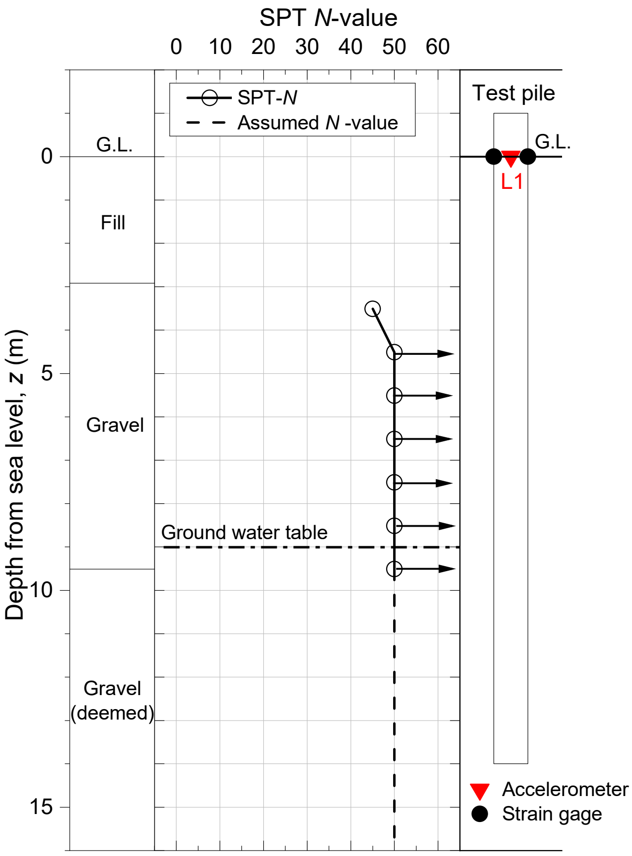

Fig. 2 Profiles of soil layers and SPT *N*-values

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

2.3. Preliminary pile design

Table 2 lists the design working load on the pile, the factor of safety and the corresponding required pile capacity.

Table 2. Design load, 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

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

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		

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

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 Rapid load test

Interpretation methods of RLT signals used in this research are described.

3.1. ULPC method

The ULPC (UnLoading Point Connection) method (Kamei et al., 2022) is an extension method of 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 **Fig. 3** 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 (**Eq. (1)**). The soil resistance R_{soil} is obtained from **Eq. (2)**, using the measured F_{rapid} and α, and R_{soil} vs w is constructed as shown in **Fig. 4**. The static resistance R_w is then obtained using **Eq. (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 (**Eq. (4)** and **Fig. 4**).

In ULPC, generally, 5 to 7 blows are applied to the pile with increasing the fall height of hammer h. Hence, several values of R_{ULP} at different displacements w are obtained without determining the value of C because the pile velocity v is zero at ULP. By connecting ULPs from multiple blows, static load-displacement relation is easily constructed (Kamei et al., 2022).

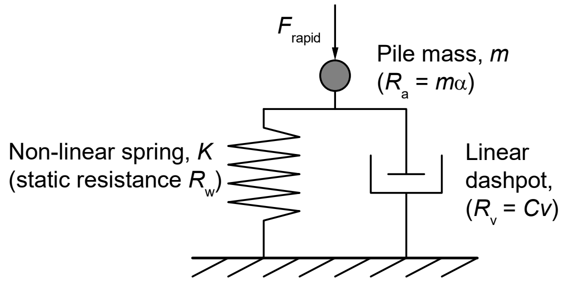

Fig. 3 Modeling of pile and soil during RLT (after Middendorp et al, 1993, and Kusakabe and Matsumoto, 1995)

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

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

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

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

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,
α = Pile acceleration,
C = Damping constant,
v = Pile velocity and
R_{ULP} = ULP resistance (static resistance).

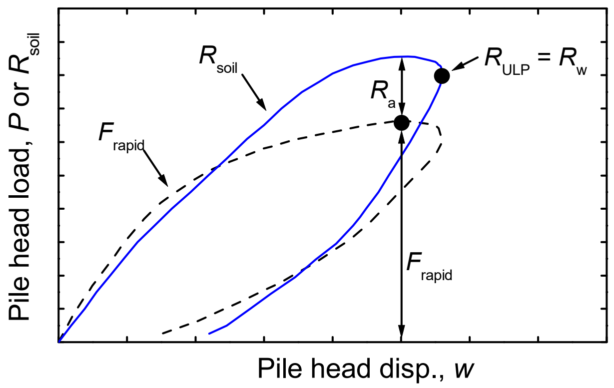

Fig. 4 Relationship between load-displacement curve and soil resistance and ULP resistance

3.2. ULPC_CM method (Lin et al., 2023a)

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) by means of **Eq. (5)** and **Eq. (6)**, respectively. Then, by using **Eq. (7)**, the time variation of R_t (= R_{soil}) is obtained (**Fig. 5**).

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

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

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

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 pile

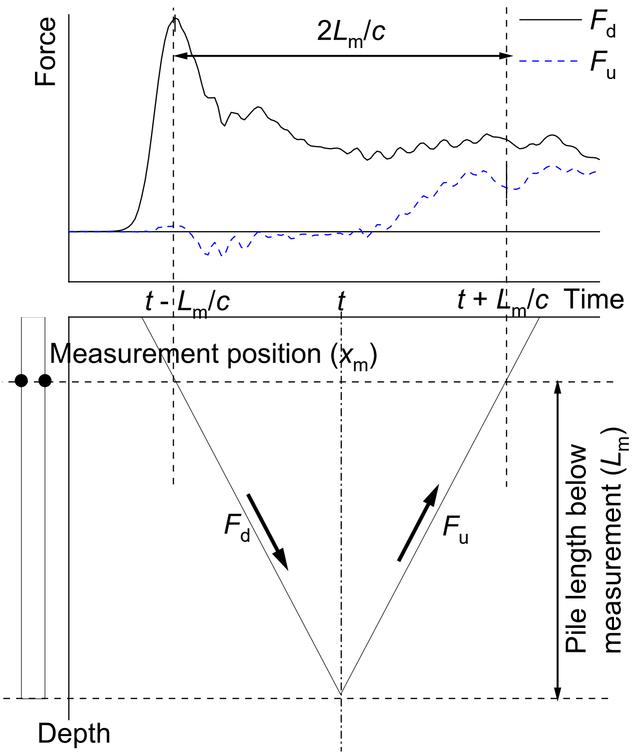

Fig. 5 Case method (Raushe et al. 1985)

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, 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. 6 is the Hybridnamic RLT device used at the site. As seen from **Fig. 6**, the usual reaction system such as reaction piles and rection beam is not required and the testing space is very narrow.

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 Hybridnamic RLT device used in the site

4.2. Test results

The measured test signals were interpreted using two methods, ULPC and ULPC_CM. ULPC follows the current RLT standards (JGS, 2002). ULPC_CM was proposed by Lin et al. (2023a), which is based on one-dimensional stress-wave theory, and more reliable.

Fig. 7 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.

R_{soil} (ULPC_CM) at the maximum w where v = 0 is defined as the static resistance R_w (R_{ULP}) in a similar way to the ULPC method. Static load-displacement relation can be obtained by connecting R_{ULP} from ULPC_CM from multiple blows (RLTs).

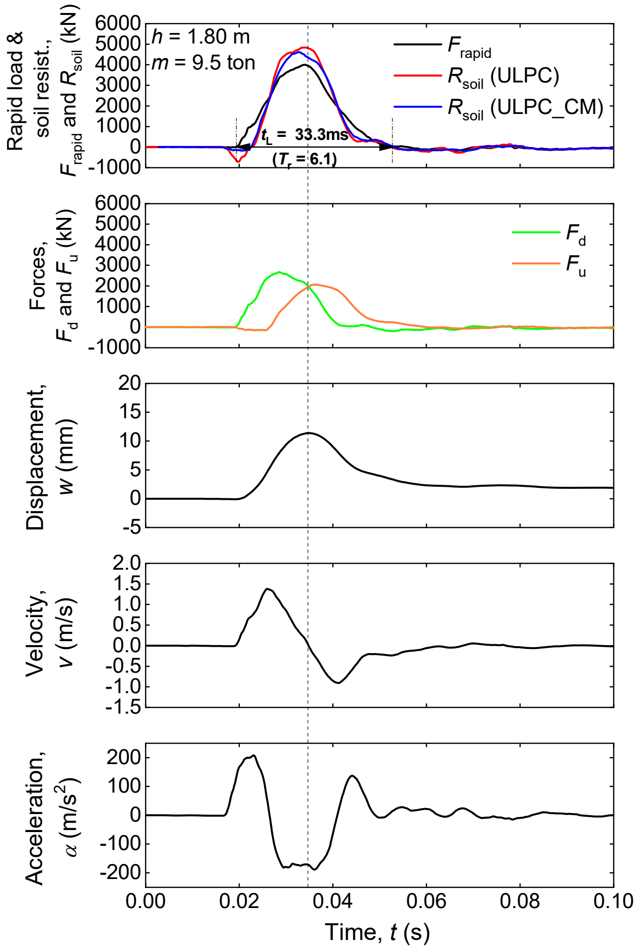

Fig. 7 RLT signals (h = 1.80 m)

Fig. 8 shows the F_{rapid}, R_{soil} (ULPC) and R_w (ULPC) vs w from the ULPC method. **Fig. 9** also shows the F_{rapid}, R_{soil} (ULPC_CM) and R_w (ULPC_CM) vs w from the ULPC_CM method.

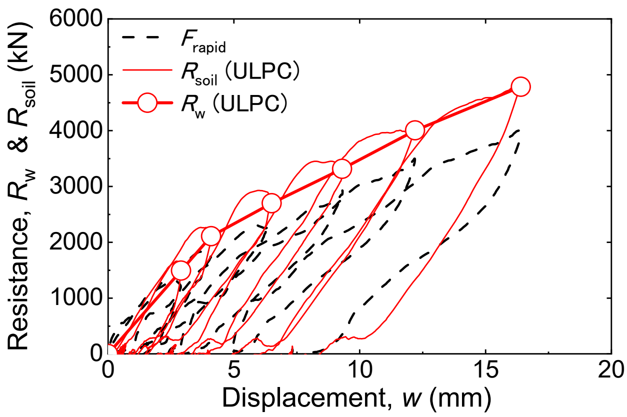

Fig. 8 F_{rapid}, R_{soil} and R_w vs w from ULPC

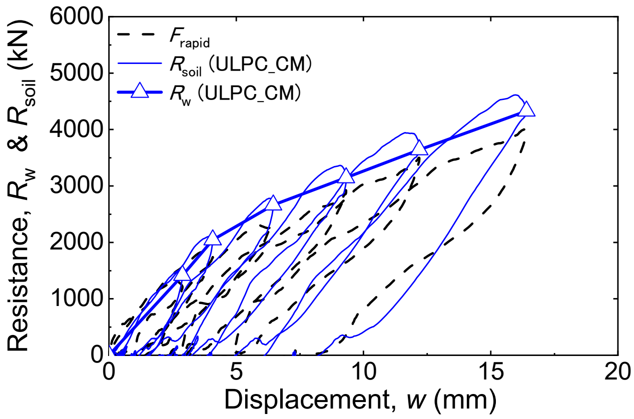

Fig. 9 F_{rapid}, R_{soil} and R_w vs w from ULPC_CM

Fig. 10 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.

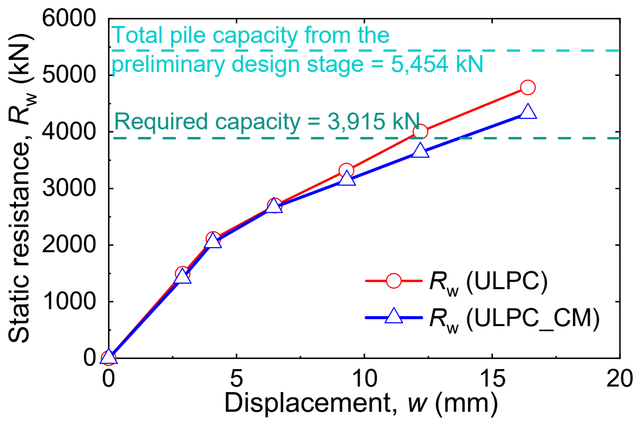

Fig. 10 Comparison of load-displacement curves from RLTs with ULPC and ULPC_CM

5. Concluding remarks

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 the pile head displacement of about 16 mm.

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

6. Acknowledgements

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References

GIKEN, 2023. Rotary Cutting Press-in Method, http://www.giken.com

Hoshino, M., Sato, K., Takano, K., Kamei, S. and Nishimura, S., 2012. A comparison between static load test and rapid load test for a steel pipe pile installed by water jet vibratory technique. *Proc. of the 9th Int. Conf. on Testing and Design Methods for Deep Foundations (IS-Kanazawa 2012)*, Kanazawa, pp.581-585.

International Press-in Association (IPA), 2014. Guidelines for design and construction of steel pipe pile retaining walls constructed using Gyropress Method (in Japanese).

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

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*, Rotterdam, 8p., DOI 10.5281_zenodo.7148489.

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

Lin, S., Kamei, S., Yamamoto, I. and Matsumoto, T., 2023a. Hybridnamic rapid load testing with UnLoading Point Connection method invoking Case method. *Proc. the 17th Asian Regional Conference on Soil Mech. and Geotech. Engineering 2023*, Nur-Sultan, pp.1425-1428.

Lin, S., Watanabe, K., Kamei, S., Yamamoto, I. and Matsumoto, T., 2023b. Comparative static and rapid load tests on steel pipe piles: A case study at Sashima test yard. *Proc. 5th Int. Conf. on Geotechnics for Sustainable Infrastructure Development*, Hanoi, 8p. (to be published).

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, The Netherlands, pp. 581-588.

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