Use of press-in piling data for construction on the Moon: Estimating subsurface information and pile capacity

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ABSTRACT

The construction projects on the earth basically proceed through the phases of “investigation”, “design”, “construction work” and “service & maintenance” in a one-way manner. Following this process will not always be the most reasonable option, because the actual ground conditions encountered in the phase of “construction work” sometimes differ from those captured in the phase of “investigation”, mainly due to the limitation of information obtained in this phase. In the construction projects on the Moon, this issue will be more eminent, because the information obtained in the phase of “investigation” will be even more limited. In the press-in method, the subsurface information and the pile capacity can be estimated from the piling data, and this information will be utilized for securing the rationality of the construction process on the Moon. However, the conditions on the Moon are different from those on the earth, and the applicability of the press-in method and the estimation methods to such conditions are unknown. This paper investigates the applicability of the press-in method and the estimation methods to the dense ground consisting of granular materials with scarce water. Full-scale field tests were conducted, where a small-diameter pipe pile was installed by the Rotary Cutting Press-in (RCP) without water and the static loading tests were carried out to identify the vertical and horizontal capacity of the RCP piles. The piling data were used to estimate the subsurface information and the pile capacity, and the estimated results were compared with the information obtained by the subsurface investigation and the loading tests.

Key words: *Rotary Cutting Press-in, Use of piling data, Subsurface information, Pile capacity*

1. Background and objectives

A construction project usually proceeds through the phases of “investigation”, “design”, “construction work” and “service & maintenance”. In the construction project on the Moon, the information from the “investigation” (subsurface information) may be limited. With regard to the construction of structures with piles or sheet piles, the subsurface information could be even more limited, because the investigation in deeper underground is more difficult.

There are various pile installation methods for constructing the structures with piles. In the press-in method, a pile is gripped at the “Chuck” of a press-in machine as shown in **Fig. 1**, and a hydraulic pressure is used to statically install the pile into the ground. The reaction force to prevent the press-in machine from moving is secured by clamping the previously installed piles and using their pull-out resistance. The press-in machine and other related devices (power unit, crane and pile transporter) are equipped with a self-walking function on the head of the pile wall, allowing the installation to be completed in the space above the pile, as shown in **Fig. 2**.

These characteristics make the above-ground technology effective for low-vibration, low-noise construction, and construction under constrained conditions such as narrow areas, slopes, and above water. For construction on the Moon, the construction principle of not relying on heavy objects to secure the reaction force is thought to be an advantage in its ability to cope with low gravity.

The press-in method has several penetration techniques that can be applied to a wide range of ground conditions. The applicability to hard ground conditions including bedrock is assured by the "Press-in with Auger" (PA) method, in which steel sheet piles are installed into the ground using an auger, and the "Rotating Cutting Press-in" (RCP) method, where a steel pipe pile with cutting teeth on its base is rotated and pushed into the ground while water is injected in its base. This will be another advantage for the construction on the Moon, where hard ground conditions are expected.

In the press-in method, the piling data (information obtained during piling, such as press-in force and torque) can be obtained for all the piles. By processing the piling data appropriately, it can be applied to multiple applications as shown in **Fig. 3** (Ishihara et al., 2008), and is expected to be utilized for rationalizing the construction process (i.e. the process including the phases of "investigation", "design", "construction work" and "service & maintenance") of structures with piles (Suzuki & Ishihara, 2019). If these technologies are applied to the construction projects on the Moon, a rational construction process could be realized even under conditions where information from the "investigation" is limited. Specifically, as shown in the left hand side cycle of **Fig. 4**, the main process could be as follows: (1) the "design" of structures is roughly implemented based on the limited information in the "investigation", (2) the piling work is conducted in "construction work" while yielding the estimated subsurface information and pile capacity, (3) the information in the "investigation" is supplemented by the estimated information obtained in "construction work", and the content of the "design" is validated and updated based on the estimated information in "construction work". In addition, as shown in the right hand side cycle of **Fig. 4**, the press-in machine used for the construction process in the left hand side cycle of the figure could also be applied to conducting a static loading test, to obtain information of the performance of the pressed-in piles on the Moon.

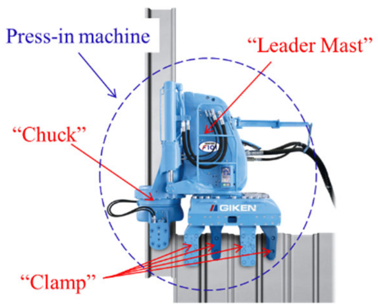


Fig. 1 Typical structure of press-in machine

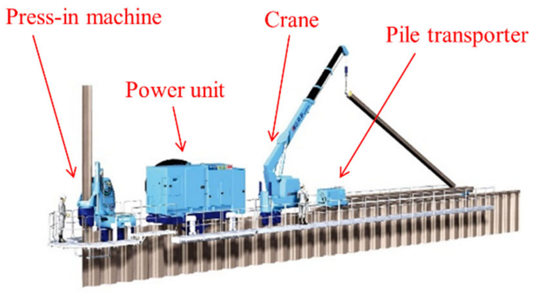


Fig. 2 Press-in piling system with spatial efficiency

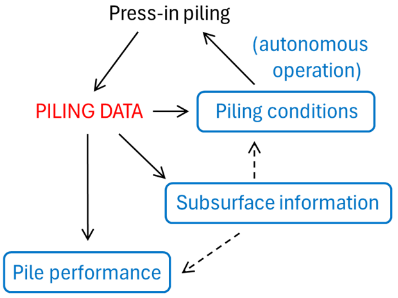


Fig. 3 Use of press-in piling data

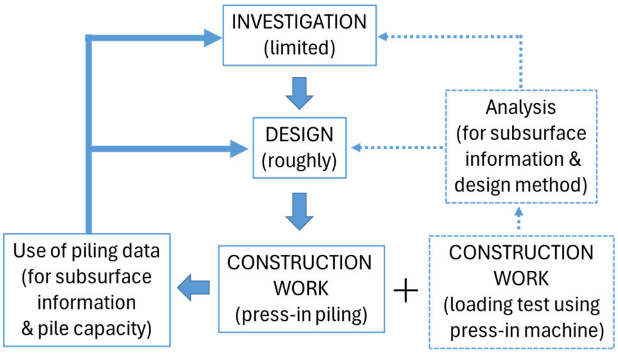


Fig. 4 Proposed construction process on the Moon using information during construction work

The authors have been working on ensuring the applicability of these processes to the construction projects on the Moon. The RCP method has been chosen as a penetration technique, taking its advantage of applicability to wider ground conditions. On the other hand, one of the constraints in the construction work on the Moon is the low availability of water. This constraint may be critical to the RCP installation, where water injection is standardly adopted in the construction projects on the Earth. In addition, according to Heiken et al. (1991), the surface of the Moon is covered with a dense sandy material called “regolith”, which may increase the installation resistance of the pile. The feasibility of the RCP installation without water into such a ground and the validity of the estimated subsurface information and pile capacity from the piling data obtained in such conditions are unknown.

Based on these backgrounds, this study aims to (1) confirm if open-ended and closed-ended pipe piles can be successfully installed by the RCP without water into a dense sandy ground, and (2) assess the validity of subsurface information and pile capacity estimated from the piling data obtained under such conditions.

2. Methods of field test

The field test was conducted using a small-diameter pipe pile and a press-in machine that can install the pile by the RCP. The test site was selected from among GIKEN’s testing sites, where the ground conditions were relatively closer to those of the regolith layer of the Moon. The site profile captured by the Standard Penetration Test (SPT) is shown in **Fig. 5**. The ground is composed of dense sand and gravel, and the groundwater table is approximately 7 m below the surface.

The test cases are shown in **Table 1**. A total of 10 tests were conducted. The J2203 test series were designed to confirm the possibility and obtain the basic information of the RCP installation without water, using closed-ended and open-ended piles. The J2301 test series were intended to investigate the effect of the load limit adopted during the RCP installation, using an open-ended pile.

The procedures in each test were as follows. (1) The reaction piles were installed by the RCP. (2) The press-in machine was positioned on the reaction pile wall. (3) The test pile was installed by the RCP. (4) The static loading test was conducted either vertically or horizontally. (5) The test pile was extracted.

In the J2203 test series, the Cone Penetration Test (CPT) was conducted after the extraction of the test pile and the reaction piles, at the positions near where the test piles were installed and extracted. In the J2301 test series, the CPT was conducted at the center of the position of the test pile prior to the installation of each test pile.

The test layout is shown in **Fig. 6**. A pile wall consisting of pipe piles with an outer diameter (D_o) being a typical value in the RCP on the Earth (1000 mm) was used as a reaction wall. The test pile was installed by the RCP on both sides of the reaction wall. The situation of the RCP installation is shown in **Fig. 7**.

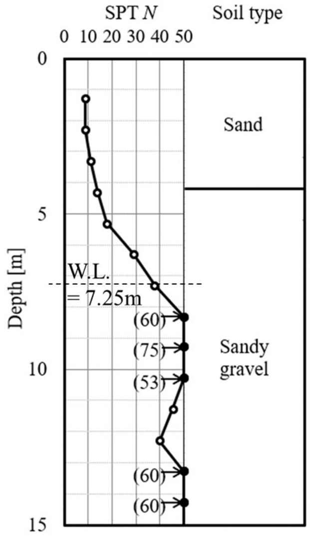


Fig. 5 Site profile of field test

Table 1 Test cases

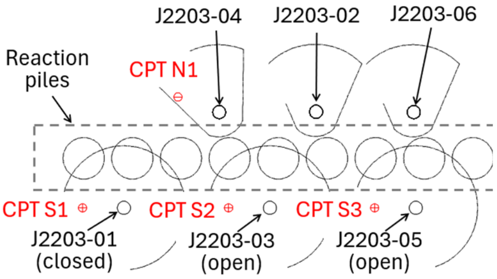
Test case	Pile	Q'_{UL} [kN]	Loading test
J2203-01	Closed	200	Vertical
J2203-02	Closed	200	Horizontal
J2203-03	Open	200	Vertical
J2203-04	Open	200	Horizontal
J2203-05	Open	200	Vertical
J2203-06	Open	200	Horizontal
J2301-01	Open	100	Vertical
J2301-02	Open	None	Vertical
J2301-03-2	Open	100	Horizontal
J2301-04	Open	None	Horizontal

Two types of test piles were used as shown in **Fig. 8**: a closed-ended and an open-ended pipe pile. The closed-ended pile had an outer and an inner diameter (D_o and D_i) of 318.5 mm and 297.9 mm, respectively. The pile base was closed with a steel circular plate. Inside the pile, thermocouples for measuring the temperature were attached at three locations: the base plate, and 0.25 m and 1.5 m from the pile base. On the other hand, the open-ended pile had the same D_o and D_i as the closed-ended pile. A base ring with 6 cutting teeth was welded to the pile base. The outer and inner diameters of the base ring (D_{bo} and D_{bi}) were 318.5 mm and 258.5 mm, respectively.

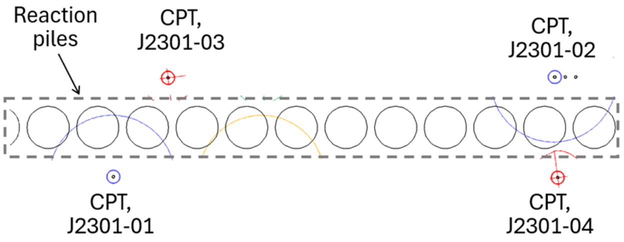
The RCP installation was performed using a dedicated press-in machine (F401). This press-in machine is designed for pipe piles with D_o of about 1000 mm, but it can be applied to small-diameter pipe piles by using an attachment. The press-in force (Q'), torque (T'), and penetration depth (z) were obtained by an automatic measuring system installed in the press-in machine. In the tests using the open-ended pile, a wire-type stroke sensor was fixed near the pile head and a weight attached to the end of the wire was placed on the surface of the soil inside the pile, to obtain the inner soil length.

The press-in conditions are shown in **Table 2**. In "surged installation" (or "installation with surging"), the pile is installed by repeating the cycles of penetration and extraction. In each cycle, the penetration distance (l_d) is greater than the extraction distance (l_u). On the other hand, "monotonic installation" does not involve extraction. In some tests, an upper limit of press-in force (Q'_{UL}) was adopted, and the pile was extracted by l_u every time Q' reached Q'_{UL}. This meant that the surged installation was conducted in a displacement-controlled manner when $Q' < Q'_{UL}$ and in a load-controlled manner otherwise.

Vertical or horizontal static loading tests were conducted based on two types of loading methods: using a hydraulic jack or a press-in machine. In this paper, these two types are treated identically, since the loading test results obtained by them were confirmed to be consistent



(a) J2203 test series



(b) J2301 test series

Fig. 6 Test layout

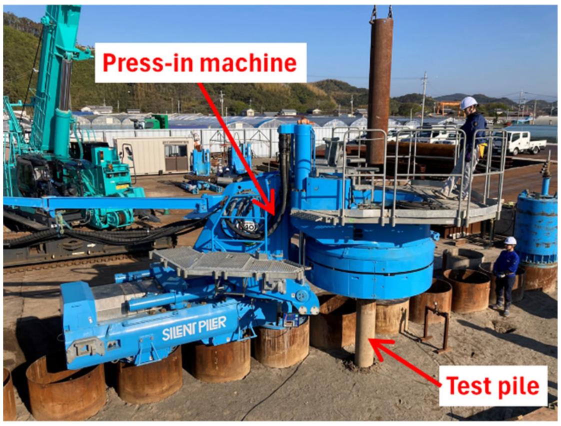
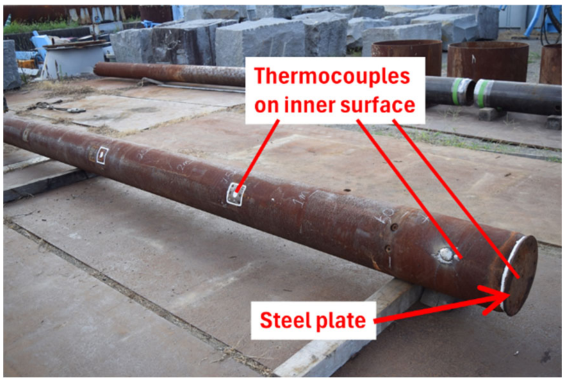


Fig. 7 Situation of RCP installation



(a) Closed-ended pipe pile

(b) Open-ended pipe pile

Fig. 8 Test piles

Table 2 Press-in conditions

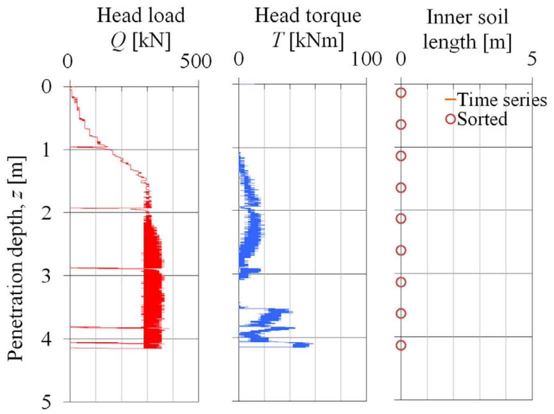
Test case	l_d	l_u	v_d	v_u	v_r	Q'_{UL}
	[mm]		[mm/s]			[kN]
J2203-01	-	-	12	-	83	200
J2203-02	-	-	12	-	83	200
J2203-03	-	-	12	-	83	200
J2203-04	-	-	12	-	83	200
J2203-05	-	-	12	-	83	200
J2203-06	-	-	12	-	83	200
J2301-01	200	50	12	12	83	100
J2301-02	200	50	12	12	83	None
J2301-03-2	200	50	12	12	83	100
J2301-04	200	50	12	12	83	None

(Ishihara et al., 2024). The time from the end of installation to the start of the loading test (curing period, t_{LT}) was 7 days in all the tests. The loading height in the horizontal loading test was 0.15 m above the ground surface.

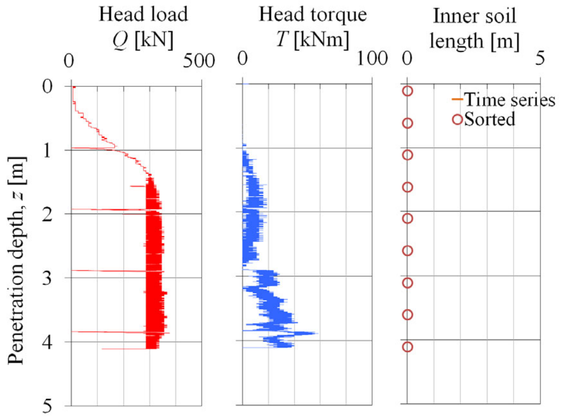
3. Results of field test

Typical results of the RCP installation without water injection are shown in **Fig. 9**. Both the open- and closed-ended piles were successfully installed down to a penetration depth of 4 m. The head load (Q) and head torque (T), which were obtained by considering the effects of the weight of the Chuk and mechanical friction, were similar to those estimated from the results of subsurface investigation (SPT) based on the methods of Okada & Ishihara (2012), as shown in **Fig. 10**. The plugging condition during the installation of the open-ended pile, which can be judged by the Incremental Filling Ratio ($IFR = \delta h_{sc} / \delta z$) where δh_{sc} and δz are the incremental inner soil length and the incremental penetration depth, shifted from fully unplugged to almost fully plugged as z increased.

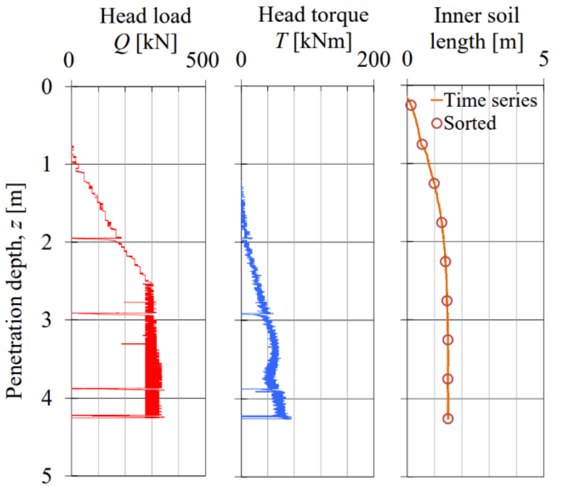
Fig. 11 shows the variation of z and pile temperature (T_p) with time during the RCP installation. The increase in T_p at the pile base occurred earlier than that on the pile shaft, and T_p became the highest at the pile base. This would be suggesting that the increase in T_p was caused mainly by the friction at the pile base rather than on the pile shaft. T_p increased to around 650 °C in J2203-01 and to around 800 °C in J2203-02. After the extraction of the test pile in J2203-02, the pile body near the pile base was observed to have been damaged. The damage was thought to be attributed to the reduction of the strength of the pile body, as a result of the high temperature of the pile during the RCP installation. **Fig. 12** shows the effect of the temperature of a steel material SN490B, which is similar to the material of the test pile in this study (STK490), on its stress-strain relationship (Hirashima, 2007). The strength of the steel material decreases significantly at high temperatures, with a yield strength of 150 N/mm^2 (=



(a) J2203-01 (closed-ended, Q'_{UL} = 200 kN)

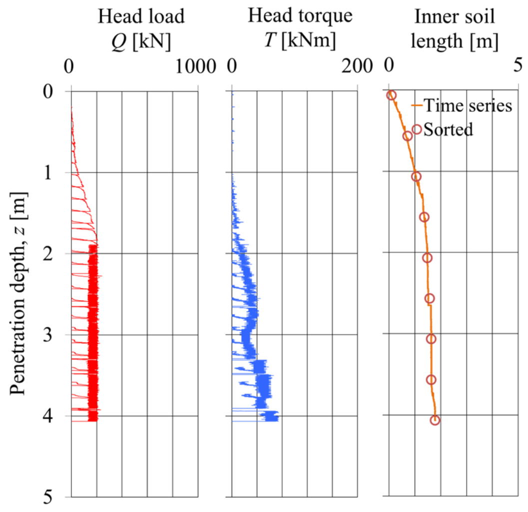


(b) J2203-02 (closed-ended, Q'_{UL} = 200 kN)

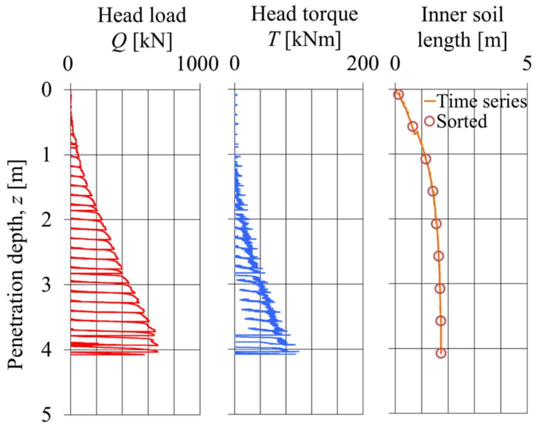


(c) J2203-03 (open-ended, Q'_{UL} = 200 kN)

Fig. 9 Piling data obtained in RCP installation without water



(d) J2301-01 (open-ended, Q'_{UL} = 100 kN)



(e) J2301-02 (open-ended, without Q'_{UL})

Fig. 9 (continued) Piling data obtained in RCP installation without water

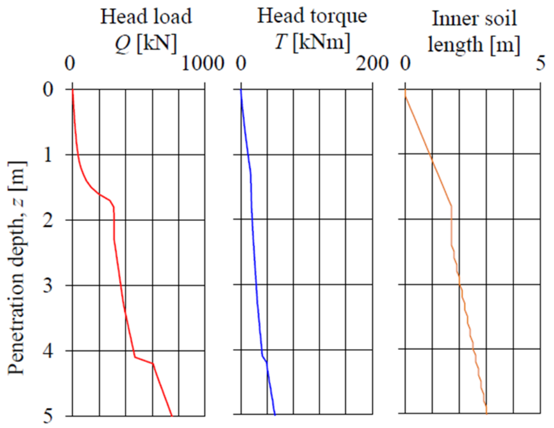
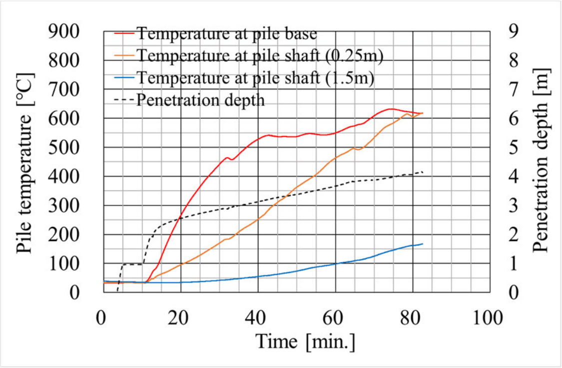
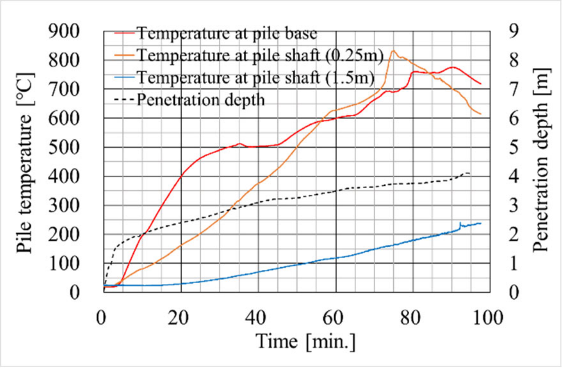


Fig. 10 Piling data estimated from SPT results



(a) J2203-01



(b) J2203-02

Fig. 11 Time variation of pile temperature during RCP installation without water

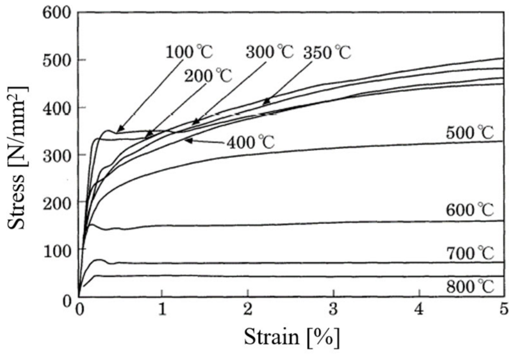
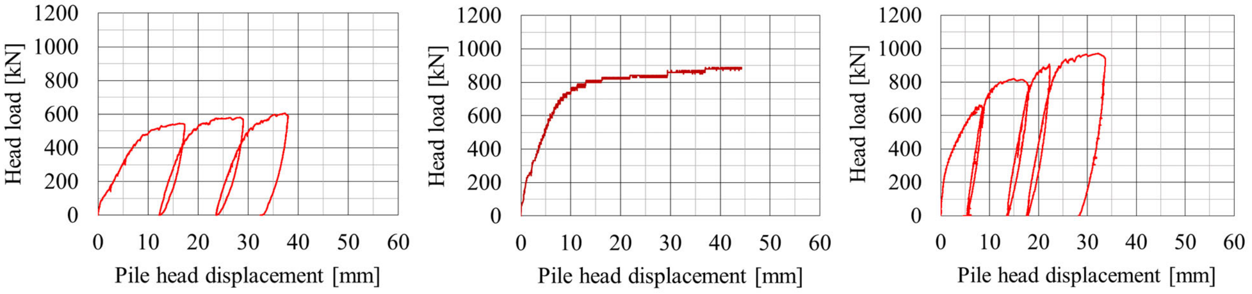


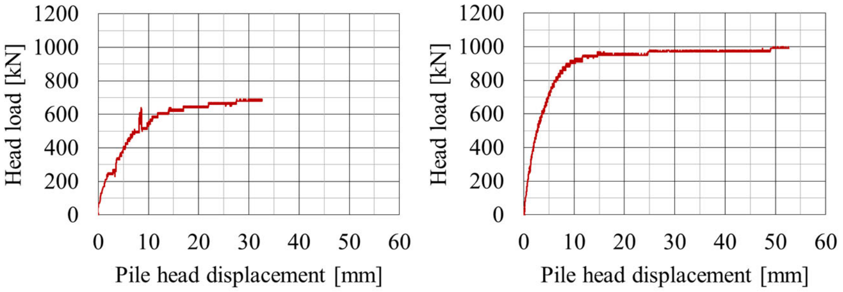
Fig. 12 Temperature effect on stress-strain relationship of SN490B (after Hirashima, 2007)

150 MPa) at 600 °C and 40 N/mm^2 (= 40 MPa) at 800 °C. In J2203-01 and J2203-02, the torsional stress of the pile body inferred from the torque values during the RCP installation was about 60 MPa. This value is lower than the pile strength at 600 °C (experienced in J2203-01) and higher than that at 800 °C (experienced in J2203-02).

The results of the vertical loading test are shown in **Fig. 13**. The vertical capacity (Q_{f}) obtained in each test, if defined as the load applied when the pile head displacement reaches 1/10 of D_{o}, is summarized in **Fig. 13** as well. According to the results of the J2203 test series,



(a) J2203-01 (b) J2203-03 (c) J2203-05



(d) J2301-01 (e) J2301-02

Test case	Pile	Measured vertical capacity, Q_f [kN]
J2203-01	Closed	581
J2203-03	Open	870
J2203-05	Open	970
J2301-01	Open	680
J2301-02	Open	980

(f) Measured vertical capacity

Fig. 13 Results of vertical loading test

Q_f of the closed-ended pile was smaller than that of the open-ended pile. This is contradictory to the general understanding that the closed-ended pile shows higher vertical capacity than the open-ended pile. One of the possible causes was thought to be the difference in the ground conditions. However, little difference was confirmed by the results of CPT, as shown in **Fig. 14**. Investigating the possibility of other causes, such as the installation effect, remains an issue. On the other hand, according to the results of the J2301 test series, Q_f was smaller in the test with the load limit. This suggests that Q_f can vary depending on the magnitude of the load during the RCP installation even under the same ground conditions.

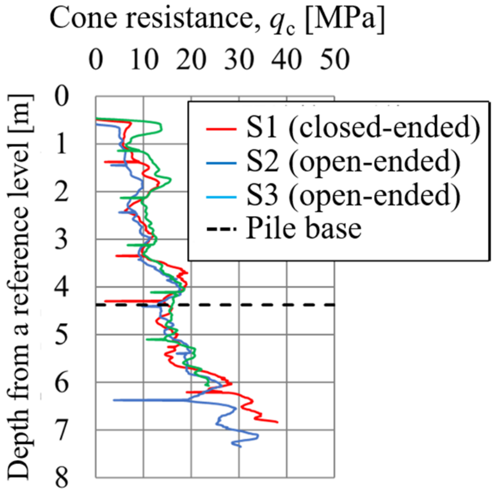
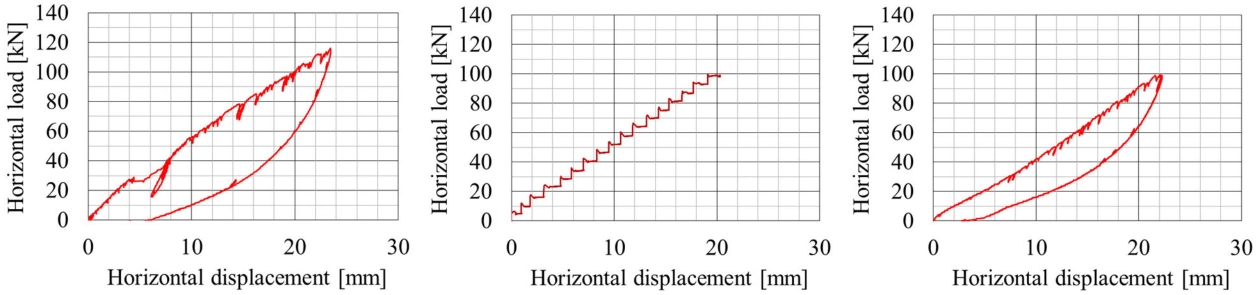
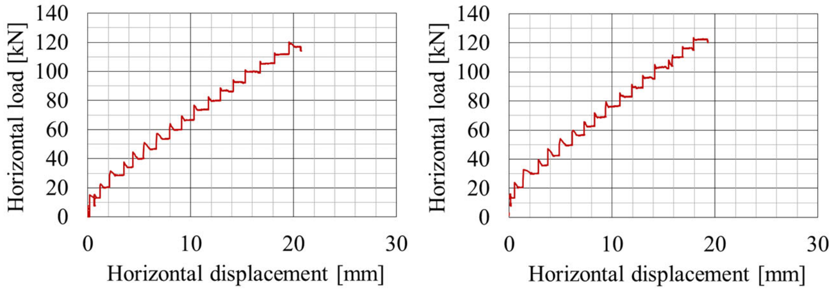


Fig. 14 Comparison of CPT results at several positions

The results of the horizontal loading test are shown in **Fig. 15**, where the horizontal axis represents the horizontal displacement at the loading height. The horizontal capacity (P_f) obtained in each test, if defined as the load applied when the horizontal displacement of the pile at the loading height reaches 15 mm, is summarized in **Fig. 15** as well. According to the results of the J2203 test series, P_f of the closed-ended pile was similar to (slightly greater than) that of the open-ended pile. On the other hand, the results of J2301 test series showed that P_f was little influenced by the load limit. The reason for the minimal influence of the load limit on P_f would be as follows. P_f will be dependent more on the horizontal resistance of the soil at shallower depths than that at deeper depths. At shallow depths, the load limit did not work because the head load required for installation was smaller than the load limit.



(a) J2203-02 (b) J2203-04 (c) J2203-06



(d) J2301-03-2 (e) J2301-04

Test case	Pile	Measured horizontal capacity, P_f [kN]
J2203-02	Closed	78
J2203-04	Open	75
J2203-06	Open	65
J2301-03-2	Open	93
J2301-04	Open	103

(f) Measured horizontal capacity

Fig. 15 Results of horizontal loading test

4. Verification of subsurface information and pile capacity estimated from press-in piling data

4.1. Estimation method

The process of estimating the subsurface information and pile capacity from the piling data obtained during the RCP installation consists of four steps (Ishihara, 2023), as illustrated in **Fig. 16**.

Step 1 estimates the base resistance (Q_b) and base torque (T_b) from the head load (Q) and head torque (T), considering the pile-soil interaction during installation.

In Step 2, the Specific Energy (*SE*) consumed at the pile base is estimated from Q_b and T_b obtained in Step 1, taking into account the effects of the load limit during installation and the plugging condition.

In Step 3, the cone resistance (q_c) and sleeve friction (f_s) of CPT and the *N* value (*N*) of SPT are estimated by assuming a proportional relationship between the *SE* in the RCP (SE_{RCP}) and the *SE* in CPT or SPT (SE_{CPT} or SE_{SPT}), by expanding the existing knowledge on the correlation between the unconfined compressive strength of a rock and the *SE* required for drilling the rock (Hughes, 1972; Li & Itakura, 2012).

In Step 4a, the base capacity (Q_{bf}) is estimated by inputting the subsurface information obtained in Step 3 (q_c and *N*) and Q_b obtained in Step 2 to a newly proposed capacity estimation method. In this method, the plugging condition is estimated by considering the installation resistance and the subsurface information.

In Step 4b, the shaft capacity (Q_{sf}) is estimated by inputting *N* obtained in Step 3 to another capacity estimation method. This method uses the conventional SPT-based methods, with the value of its parameter adjusted for the RCP piles.

In Step 4c, the horizontal capacity (P_f) is estimated from the *N* obtained in Step 3, by using a conventional

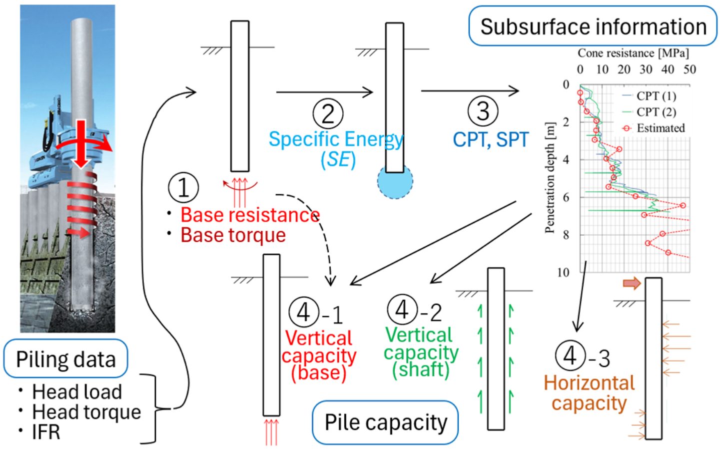


Fig. 16 Estimation process for subsurface information and pile capacity

SPT-based method that is based on the Winkler idealization of soils (e.g. Yamagata et al., 1969). In our research, the spring stiffness of the soil was assumed to show elastic and perfectly plastic behavior, with the yielding stress being equal to the passive earth pressure.

4.2. Comparison of measured and estimated results

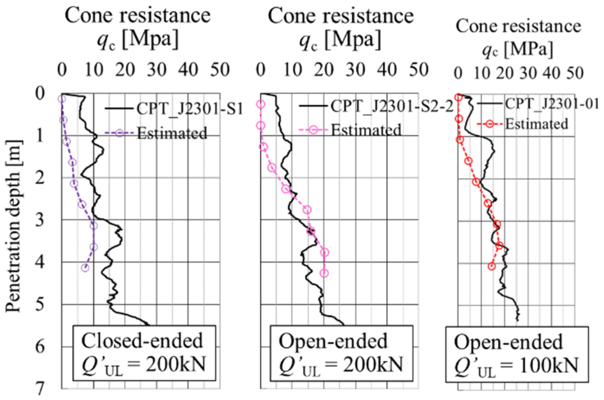
Figs. 17(a,b) show a comparison of the q_c values measured by the CPT and those estimated from the piling data in the J2203 test series. The estimated q_c values of the open-ended piles agreed well with the measured q_c values. The estimated q_c values of the closed-ended piles were smaller than those of the open-ended piles, and were smaller than the measured q_c values.

Figs. 17(c-f) show a comparison of the q_c values measured by the CPT and those estimated from the piling data in the J2301 test series. The estimated q_c values in the tests with the load limit were smaller than those in the tests without the load limit. The measured q_c values fell in between the estimated q_c values in the tests with and without the load limit.

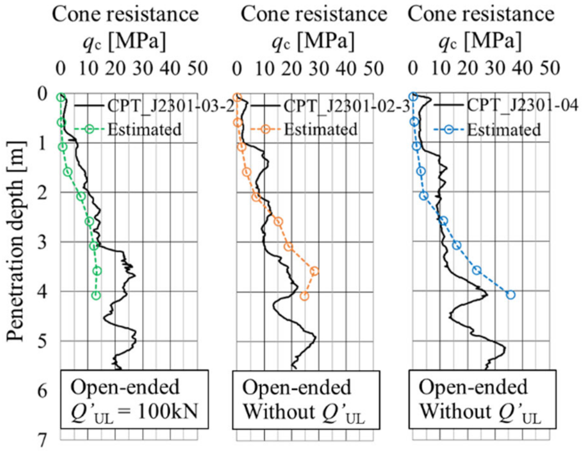
Fig. 18(a) shows a comparison of the Q_f values measured in the vertical loading tests and those estimated from the piling data. The estimated Q_f values showed a linear correlation with the measured Q_f values. Specifically, the estimated values were comparable to or smaller than the measured values, regardless of the pile type (open- or closed- ended) or the extent of the load limit.

By the way, as discussed in Section 3, the Q_f values measured in the loading tests were greater in those using the open-ended piles than in the tests using the closed-ended piles, and this was caused not by the difference in the initial ground conditions but presumably by the installation effect. The linear correlation between the estimated and the measured Q_f values regardless of the pile type, as confirmed in **Fig. 18(a)**, suggests that the installation effect on Q_f was appropriately considered in the estimation.

Fig. 18(b) shows a comparison of the P_f values measured in the horizontal loading tests and those estimated from the piling data. The estimated P_f values were smaller than the measured P_f values by around half, regardless of the pile type or the extent of the load limit. Considering that the extent of underestimation in the q_c values was not so significant (as previously shown in **Fig.**



(a) J2203-01 (b) J2203-03 (c) J2301-01



(d) J2301-03 (e) J2301-02 (f) J2301-04

Fig. 17 Comparing measured and estimated cone resistance

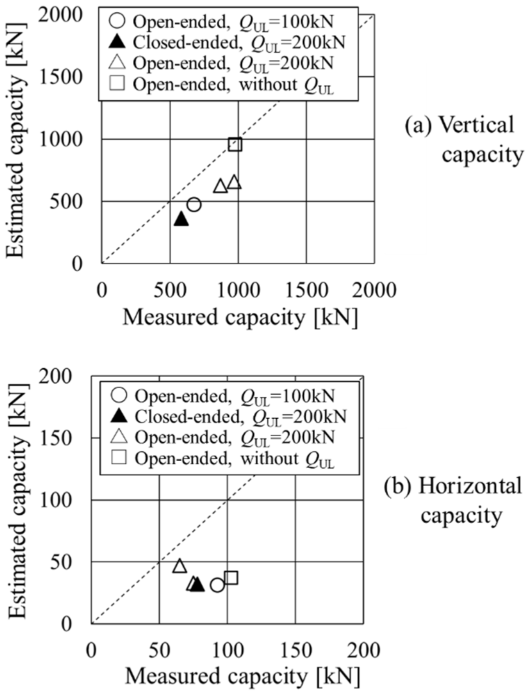


Fig. 18 Comparison of measured and estimated capacity

17), the underestimating trend in P_f is likely due to the underestimating nature of the estimation method that combines the Winkler's idealization of soils and the elastic - perfectly plastic modelling of soils, as has been pointed out by other researchers such as Matsumaru et al. (2019).

5. Conclusions

A full-scale field test using a press-in machine was conducted at a test site where the ground conditions were relatively similar to those on the Moon, to investigate the feasibility of pile installation by the Rotary Cutting Press-in (RCP) method without water and to confirm the validity of the subsurface information and pile capacity estimated from the piling data obtained under such conditions. The following findings were obtained.

An open-ended or a closed-ended pile with the outer diameter of 318.5 mm was successfully installed into dense sandy ground above the water level, by the RCP method without water. The head load and head torque required for the RCP installation were similar to those estimated from the SPT results. On the other hand, in one of the tests, the pile was damaged due to an increase in the temperature of the pile body.

The subsurface information (CPT q_c and SPT N) estimated from the piling data was influenced by the pile type (closed-ended or open-ended) or the extent of the load limit. This influence did not cause a significant difference between the estimated and measured results.

The vertical capacity estimated from the piling data was comparable to or slightly smaller than that obtained in the vertical loading tests. The correlation between the estimated and the measured values was linear.

The horizontal capacity estimated from the piling data was smaller by half than that obtained in the horizontal loading tests. This was attributed to the underestimating nature of the estimation method that combines the Winkler's idealization of soils and the elastic - perfectly plastic modelling of soils.

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