Use of Press-in Piling Data for Automatic Operation of Press-in Machines and Estimation of Subsurface Information

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ABSTRACT

The Press-in Method is a piling technique that installs piles with a static jacking force, while gaining a reaction force from previously installed piles. It generates less noise and vibration, and requires less space for construction. Another feature is that it is possible to obtain piling data for each pile. It has been expected that this feature can be utilized as a construction technique supported by ICT (Information and Communication Technology) to enhance the rationality of the design and construction of the structures with piles. This paper summarizes the present situation of two techniques to utilize the press-in piling data, which were registered with NETIS (New Technology Information System) in Japan in 2017. One is the automatic operation of a press-in machine and the other is the estimation of subsurface information.

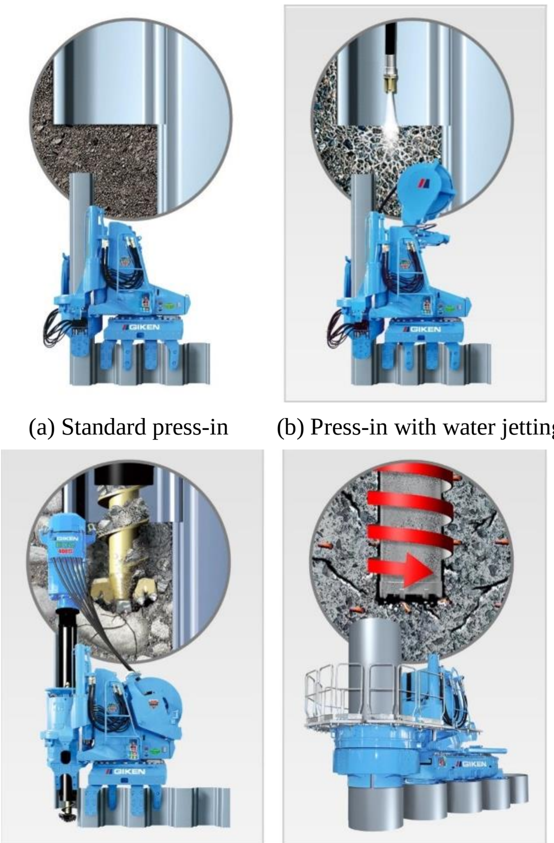
Key words: *Press-in piling data, Automatic operation, Estimation of subsurface information*

1. Introduction

1.1. Outline of the Press-in Method

The Press-in Method is one of the pile jacking methods that use a static jacking force to install piles into the ground. Its environmental impact of noise and vibration is smaller than those of conventional piling methods using drop hammers or vibratory hammers (IPA, 2016). One of the characteristics of the Press-in Method that provides an essential difference from the other pile jacking methods is that a reaction force is secured from the previously installed piles. Therefore, the space for piling and the cost for temporary works can be significantly reduced.

As shown in **Fig. 1**, there are four press-in piling techniques: 'standard press-in' that uses no auxiliary methods, 'press-in with water jetting' in which a high pressure water is discharged at the base of a pile, 'press-in with augering' in which an augering device is used to auger the ground before or at the same time with the installation of a sheet pile, and 'rotary cutting press-in' in which a vertical and a rotational jacking force are applied to a tubular pile with teeth on its base at the same time. Recently, the applicability of the Press-in Method has



(a) Standard press-in (b) Press-in with water jetting (c) Press-in with augering (d) Rotary cutting press-in

Fig. 1 Four press-in piling techniques.

been significantly expanded, especially in response to the development of the latter two press-in techniques. This piling method has been adopted in 37 countries by 2017 (IPA, 2017a).

1.2. Use of press-in piling data

In general, the design and construction of structures with piles are based on the subsurface information that are obtained by interpolating the results of the site investigations carried out separately from each other with the distance of several dozens of meters or about one hundred meters. On the other hand, local variations are often found in the actual ground conditions, such as the inhomogeneity of the soil layers and the existence of weak soils or hard cobbles in the ground. The difference between the prior information and the actual conditions related with the ground is one of the major factors that deteriorate the rationality of the design and construction of structures with piles.

In the Press-in Method, it is possible to obtain piling data for each pile. It has been expected that this feature can be utilized as a construction technique supported by ICT (Information and Communication Technology) to enhance the rationality of the design and construction of the structures with piles (Ishihara, 2008). In fact, the significance of this feature had been recognized since before the establishment of Japan Press-in Association in 1979 (Kitamura, 2018).

The examples of the press-in piling data are a vertical jacking force, a rotational jacking force (or torque), a penetration depth, a time, a rotation number, and so on. **Fig. 2** shows the concept of the use of the press-in piling data. The press-in piling data can be obtained automatically by a system equipped in a press-in machine at a press-in construction site. The obtained piling data are supposed to be utilized in three ways; selecting piling conditions, estimating subsurface information and estimating the performance of piles.

The selection of piling conditions refers to the selection of an adequate press-in technique (standard press-in, press-in with water jetting, press-in with augering or rotary cutting press-in) and the selection of adequate values for press-in conditions such as a rate of penetration or extraction, rotation number, a displacement of penetration or extraction, and so on. An automatic operation of a press-in machine related with this concept has recently been developed, which is reported in Section 2 in this paper.

The estimation of subsurface information refers to the estimation of information related with the ground at the base of a pile which is being pressed-in. The examples of the estimated information are q_c and f_s of CPT (Cone Penetration Test), soil type and N value of SPT (Standard Penetration Test). It is expected to improve the reliability of the termination control of the press-in piling work and to provide an objective material for judging the necessity of adopting another press-in technique or modifying the embedment depth of piles. Technical Committee 2 in IPA finalized a technical material on this issue in 2017 (IPA, 2017b). The third section of this paper summarizes this issue.

In the estimation of the performance of piles, it is expected that a capacity or a stiffness of a pile in a vertical or a horizontal direction is estimated from the piling data. This will make it possible to assure the quality of each pile while mitigating the impact of additional time and cost required for confirming the performance of piles based on the conventional load testing methods.

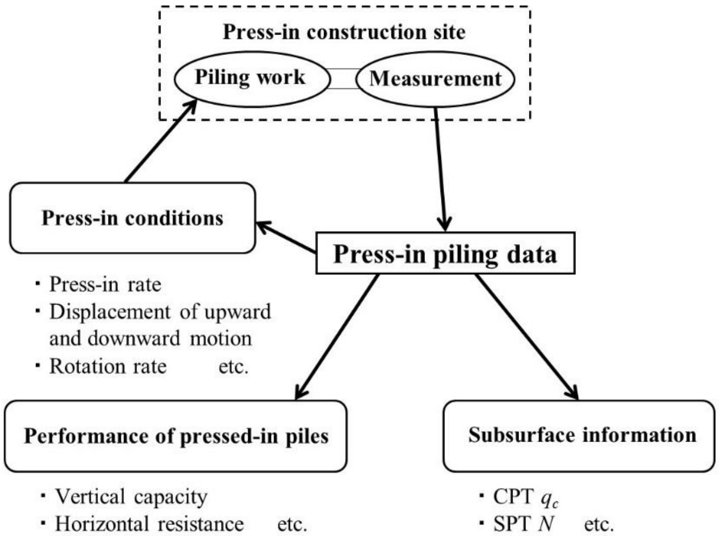


Fig. 2 Concept of the use of the press-in piling data.

1.3. Objectives of this paper

As a construction technique supported by ICT, this paper introduces two techniques of utilizing the press-in piling data, which were developed recently and registered with NETIS (New Technology Information System) in Japan in 2017. One is the automatic operation of a press-in machine and the other is the estimation of subsurface information.

2. Automatic operation based on press-in piling data

2.1. Outline of the automatic operation of press-in machines

When operating a press-in machine, the values of the press-in parameters such as the rate of penetration and extraction, the displacement of penetration and extraction, the flowrate of the water jet, the rotation number of the auger head and so on are controlled so that the resistance acting on the pile being pressed-in can be maintained to be sufficiently smaller than the sum of the reaction forces such as the pull-out resistance of the previously installed piles, the weight of the press-in machine and so on. There has been existing a technique of the automatic operation of the press-in machine, in which the values of all the press-in parameters have to be determined by the operators themselves. In other words, in this existing automatic operation technique, a press-in machine functions automatically as specified by an operator. Expecting that the process of determining and specifying the values of the press-in parameters can also be automated by utilizing the information estimated from the press-in piling data, the collection of the piling data at construction sites were started extensively in 2007, and much effort has been made by mechanical and electrical engineers in Giken to develop a program for this new automatic operation since then. As a result, a system for this new automatic operation applicable to press-in with augering has been put into trial use at several construction sites since 2013.

The comparison of the above-mentioned existing automatic operation and the new automatic operation is shown in **Fig. 3**. In the new automatic operation, press-in piling data such as the penetration depth, the vertical and rotational jacking force and the inclination of the press-in machine are utilized to estimate the piling state (the state of interlocking with the previously installed pile, the extent of plugging inside a casing of the augering device, and so on) and the ground condition at the pile base (SPT *N* for soils or the unconfined compressive strength for rocks). The methods and the results of estimating the ground condition are explained in sections **3.2.** and **3.3.** Based on the estimated information, adequate values for the press-in parameters are determined and fed back to the press-in machine. On the other hand, by setting the upper limit for some of the press-in parameters or for the inclination of the press-in machine, it is possible to control the press-in machine to conduct the piling work

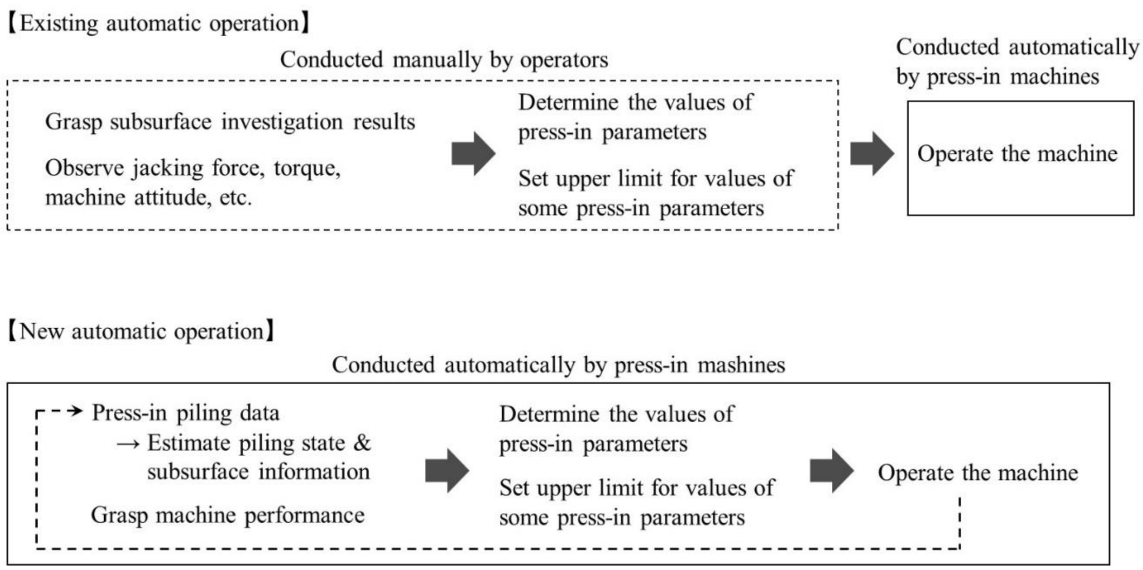


Fig. 3 Concept of the use of the press-in piling data.

within the possible maximal reaction force. As a result, the efficiency of the piling work can be improved while the accuracy of the piling work are secured.

2.2. Case study

A piling work was carried out at a test site in Kochi, Japan, in which both the existing and the new automatic operations were adopted. The site profile is shown in **Fig. 4**, which is typical for the piling work by press-in with augering. The ground of the test site is hard with the converted SPT *N* (**Eq. (1)**) greater than 75, which means that press-in with augering associated with the pre-augering process is the suitable technique (IPA, 2016). On the other hand, the ground is highly layered and contains cobble stones. This requires frequent change in the values of the press-in parameters.

$$N = 50 \times \frac{0.3}{\delta z_{SPT,50}} \tag{1}$$

where $\delta z_{SPT,50}$ is the penetration depth of the SPT sampler in meters, in response to the blow count of 50 (JGS, 2013).

In general, there are two different sets of procedures in press-in with augering (IPA, 2016). One is a simultaneous augering to install a pile together with an augering device, which is applicable to the grounds with the converted SPT *N* smaller than 75. The other is the combination of a pre-augering and a simultaneous augering, in which the simultaneous augering is conducted after the ground is pre-augered by using the same augering device as used in the above-mentioned process of simultaneous augering.

Fig. 5 is the comparison of the modes of the penetration rate during the pre-augering process, in which the penetration rate is higher if the mode of the penetration rate is larger. In the existing automatic operation, the mode of the penetration rate was determined as ‘two’ consistently with depth, with which the piling can be completed down to the designated depth. Therefore, the standard mode of the penetration rate was maintained throughout a single pre-augering process. On the other hand, in the new automatic operation, the mode of the penetration rate frequently varied with depth. Similar trends were found in other press-in parameters as well. As a result, as shown in **Fig. 6**, the duration of a single pre-augering process operated by the new automatic operation system was reduced by approximately 30% from that operated by the existing automatic operation system.

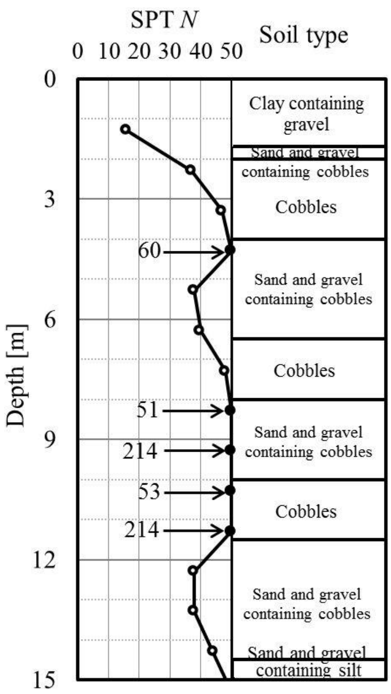


Fig. 4 Site profile in the case study on automatic operation.

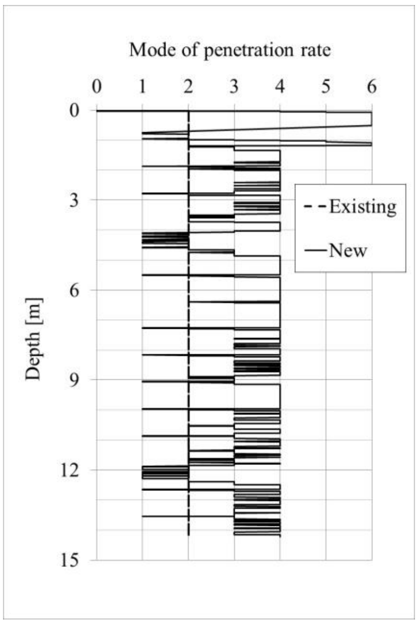


Fig. 5 Variation of the mode of the penetration rate.

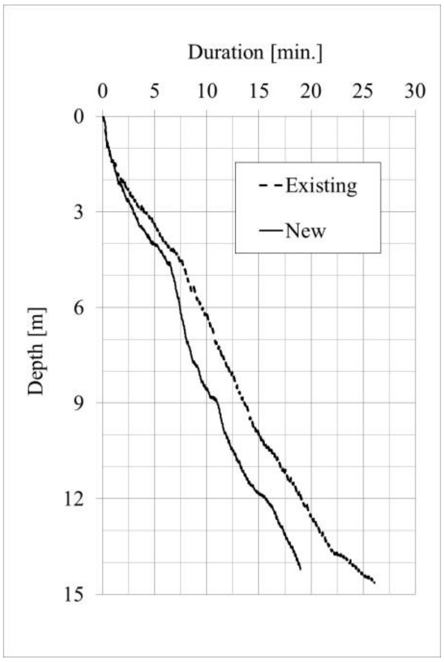


Fig. 6 Duration of a single pre-augering process.

The trial uses of the new automatic operation have been carried out at around 15 sites in Japan so far. It has been confirmed that the duration of a single pre-augering process or a single simultaneous-augering process operated by the new automatic operation system is reduced by from 15 to 40% from that operated by the existing automatic operation system or operated manually by an operator of a standard level, if the site is multi-layered or contains gravels or cobbles.

3. Estimation of subsurface information from press-in piling data

3.1. Outline of the estimation of subsurface information

As explained in Section 1.2., the technique of estimating subsurface information from the press-in piling data is expected to improve the reliability of the termination control of the press-in piling work and to provide an objective material for judging the necessity of adopting another press-in technique or modifying the embedment depth of piles. In Japan, for example, the issue of an adequate embedment of a pile into a bearing stratum has recently drawn much attention of citizens, due to an incident of a tilting building in Yokohama City in 2015 (Myall, 2015). In response to this incident, a notice was announced by MLIT (MLIT, 2016), which says that, 1) an adequate construction system should be assured, 2) the embedment of the pile base into the bearing stratum should be confirmed through witnessing or the use of the piling data, and 3) the construction record should be kept. This example provides a good reason for expecting the piling data to be utilized in the previously-mentioned manner.

Regarding the piling methods for bored piles or using vibratory hammers, there exist some methods to confirm the bearing stratum based on the electric current required for operating an auger or a vibratory hammer (Hashizume *et al*., 2002; JRA, 2015; JFCC & COPITA, 2017). For driven piles, methods to estimate a static vertical capacity of a pile based on the piling data obtained by using an instrumented pile (Likins, 1984; Rausche *et al*., 1985) are widely known. On the other hand, in the Press-in Method, efforts have been made to develop the estimation techniques in parallel with the data collection at press-in construction sites in Japan since 2007, in the same way as the development of the automatic operation. So far, the estimation techniques have been developed with regard to standard press-in, press-in with augering and rotary cutting press-in. The estimation techniques do not require any instrumentation with piles.

3.2. Outline of the estimation methods

In standard press-in, a pile is installed by a static jacking force without the use of any auxiliary methods. It follows that the process of the penetration of a pile is similar to that of a cone in CPT. This similarity is taken into account in the estimation method in standard press-in. The estimation process in standard press-in can be divided into four, as shown in **Fig. 7** (Ishihara *et al*., 2015a; IPA, 2017b). Firstly, the vertical jacking force applied to a pile by a press-in machine is decomposed into a base resistance (Q_b) and a shaft resistance (Q_s). Q_b is obtained as the difference between the jacking forces measured when the pile base passes a certain depth for the first time and for the second time in each cycle of the repeated penetration and extraction (Ogawa *et al*., 2012; Ishihara *et al*., 2015a). Secondly, a unit base resistance (q_b) and a unit shaft resistance (q_s) are obtained from Q_b and Q_s, by considering the area on which Q_b and Q_s are acting. For the area of the pile base, the plugging

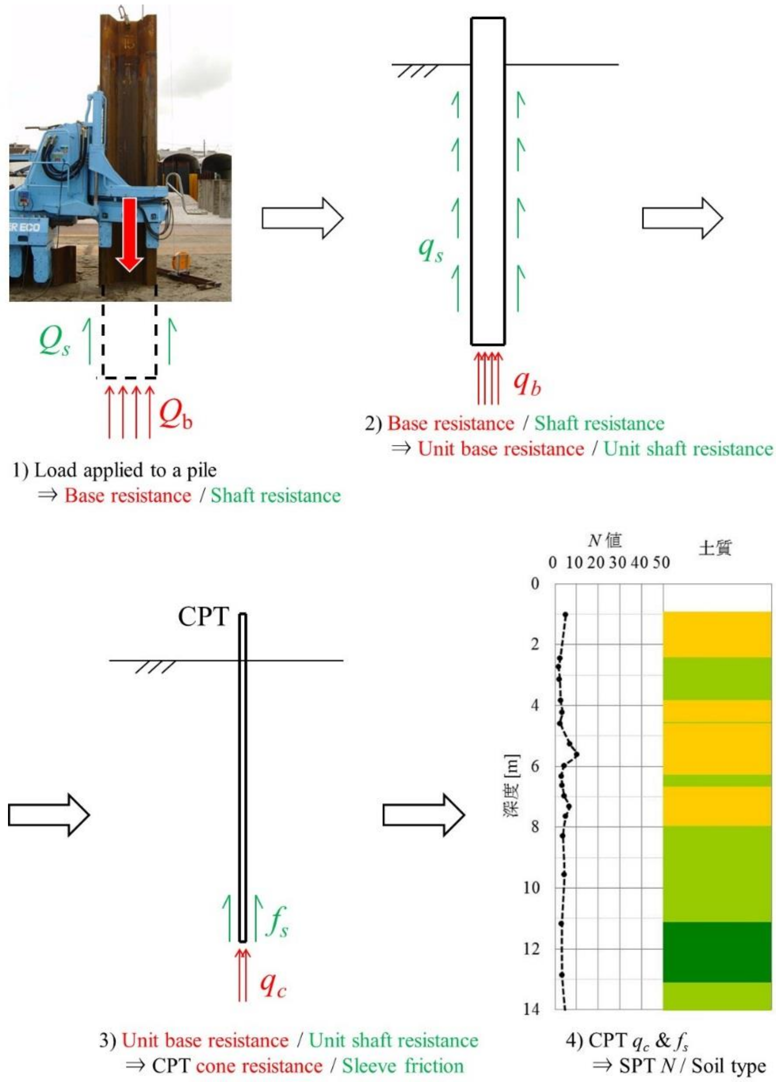


Fig. 7 Estimation process in standard press-in.

conditions are taken into account by introducing *IFR*, Incremental Filling Ratio, to define the effective base area (Ishihara *et al.*, 2018). Thirdly, the obtained q_b and q_s are converted into CPT q_c and f_s, by considering the scale effect on the plunging values of q_b (White & Bolton, 2005) and the rate effect based on the Finnie factor (Finnie *et al.*, 1994; White *et al.*, 2010; Bolton *et al.*, 2013). Finally, the soil type and SPT *N* are estimated from q_c and f_s, based on the methods developed by Robertson (1990) and Jefferies & Davies (1993) respectively.

Regarding press-in with augering, two estimation methods are proposed, based on the knowledge acquired in the field of rock drilling (Ishihara *et al.*, 2015a; IPA, 2017b). The first one is to estimate SPT *N* from a torque on the auger head (T_b), a penetration rate (v_d) and a rotation number (n) as shown in **Eq. (2)**, with A and γ being constants. This is based on the knowledge that the parameter $T_b/(d_c)^\gamma$, where d_c is the depth of cut (= v_d/n), is proportional to the unconfined compressive strength of a rock (Nishimatsu, 1972; Fukui, 1996; Fujimoto, 2005) and the assumption that the unconfined compressive strength and SPT *N* are in proportional relationship. The second one is the method known as MWD (Measurement While Drilling) (JGS, 2004), in which SPT *N* is estimated from T_b, v_d, n and a base resistance on the auger head (Q_b) as shown in **Eq. (3)**, with C_n the constant.

$$N = A\frac{T_b}{(v_d/n)^\gamma} \quad (2)$$

$$N = C_n\left(Q_b + 2\pi\frac{T_b}{v_d/n}\right) \quad (3)$$

The estimation process in rotary cutting press-in is divided into three, as shown in **Fig. 8**. Firstly, a vertical and a rotational jacking forces applied to a pile by a press-in machine (Q, T) are decomposed into a base and a shaft components (Q_b, Q_s, T_b and T_s), by introducing four equations (**Eqs. (4) - (7)**) where δ_{sp}, D_o and v_r are the frictional angle at the soil-pile interface, the outside diameter of the pile and the rotational rate of the pile shaft, respectively (Ishihara *et al.*, 2015b).

$$Q = Q_b + Q_s \quad (4)$$

$$T = T_b + T_s \quad (5)$$

$$\frac{T_b}{Q_b} = \frac{\tan\delta_{sp}}{3}D_o \quad (6)$$

$$\frac{T_s}{Q_s} = \frac{v_r/v_d}{2}D_o \quad (7)$$

Of these, **Eq. (6)** is based on the assumption that both Q_b and T_b are expressed by a unit base resistance (q_b), while **Eq (7)** is obtained by assuming that a frictional stress on the pile is shared by Q_s and T_s in the ratio of v_d to v_r. The validity of the latter assumption is discussed in Bond (2011). Secondly, a value of $\delta E/\delta V$, which is the energy (δE) required for deforming a soil below the pile base by a volume of δV, is calculated from Q_b and T_b. $\delta E/\delta V$ is an index called Specific Energy, which is widely used to represent the performance of machines for rock drilling (Teale, 1965; Hughes, 1972). According to Hughes (1972), Li & Itakura (2012) and others, there is a linear correlation between the Specific Energy in rock drilling and the unconfined compressive strength of the rock. By extending it, the Specific Energy required for penetrating something into a ground may be assumed as being in proportion to the unconfined compressive strength of the ground. Therefore, thirdly and finally, by considering the proportional relationship between the Specific Energy required for rotary cutting press-in and that for the penetration of an SPT sampler, SPT N value is obtained.

3.3. Case studies

Figs. 9 and **10** are the comparison between the subsurface information obtained by SPT and that estimated from the piling data in standard press-in (C11-05 and J0617-05), in which a closed-ended tubular pile with D_o = 318.5mm and a sheet pile with the width of 600mm were pressed-in at v_d = 20mm/s and 30mm/s respectively. The peak values of N and the soil type are well estimated, while the values of N other than the peak values are underestimated. The previous case studies including these two have revealed that the effect of the plugging condition on the estimated results is significant while the effect of the penetration rate is not (Ishihara *et al*., 2015a; IPA, 2017).

Fig. 11 is the comparison between the subsurface information obtained by SPT and that estimated from the piling data in the pre-augering process in press-in with augering, using an auger head with the number of wings of three and the outside diameter of 450mm. The trend of the variation of N with depth is well estimated, while big differences are found at some depths. Through the case studies including this, these differences are

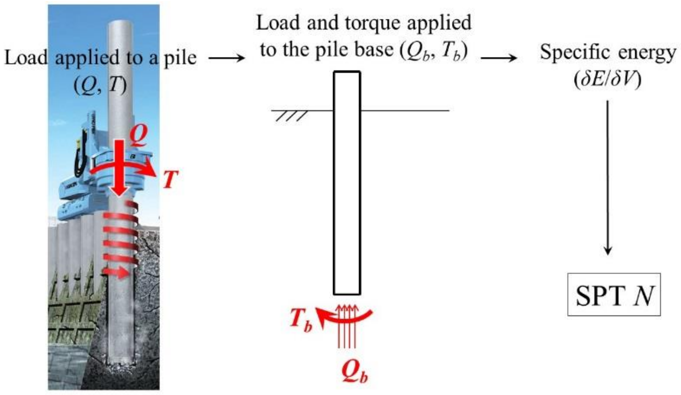


Fig. 8 Estimation process in rotary cutting press-in.

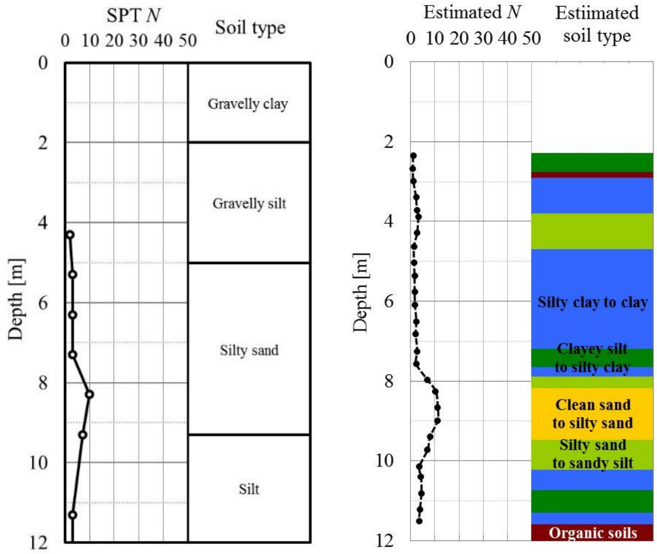


Fig. 9 Results of SPT and estimation (C11-05).

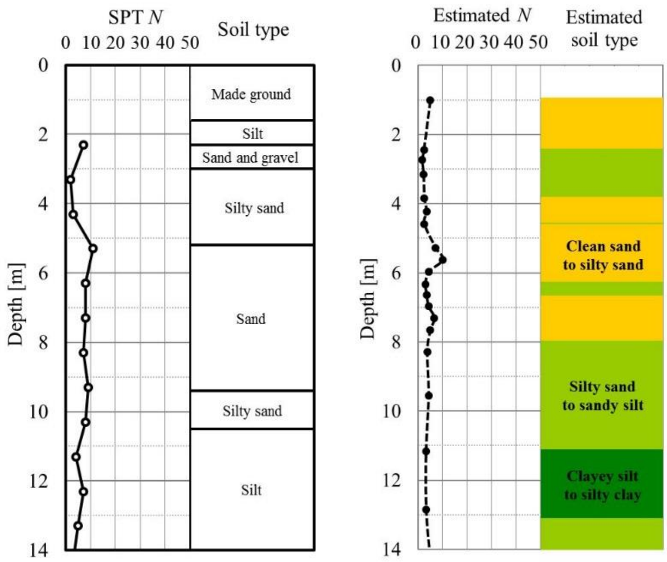


Fig. 10 Results of SPT and estimation (J0617-05).

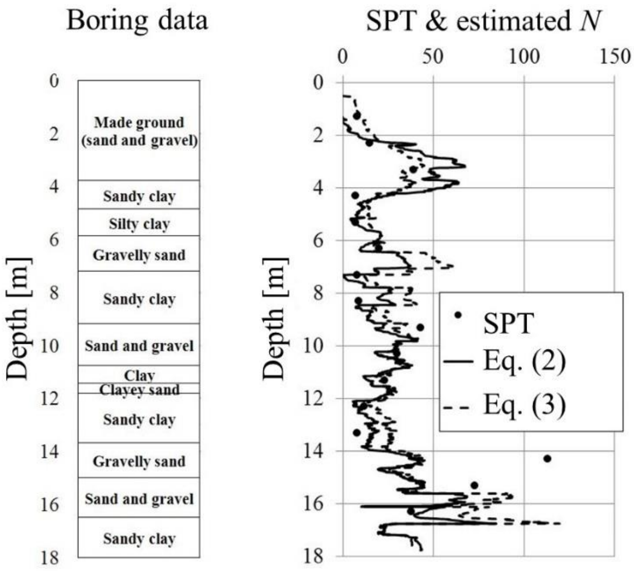
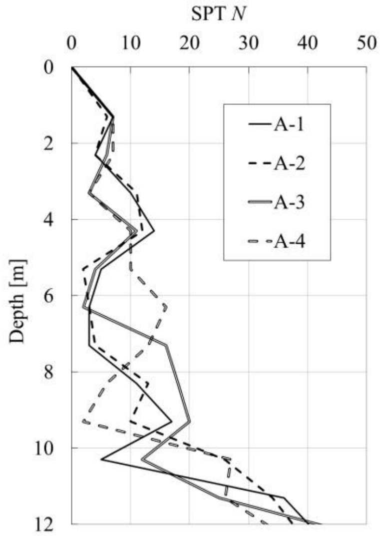


Fig. 11 Results of SPT and estimation (pre-augering process in press-in with augering).

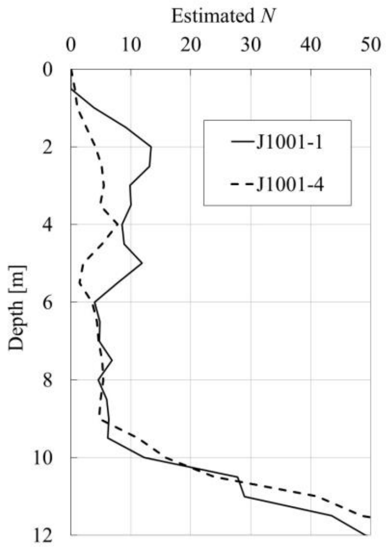
believed to be associated with the existence of large gravels or stones, judging from the records in SPT (Ishihara *et al*., 2015a; IPA, 2017).

Fig. 12 is the comparison between the subsurface information obtained by SPT and that estimated from the piling data in rotary cutting press-in. The trend of the variation of *N* with depth is well estimated in this case, where the plugging condition were confirmed as almost constant with depth. Another other case study, on the other hand, has clarified that the effect of the plugging condition on the estimated results is significant (Ishihara *et al*., 2015b; IPA, 2017). If the plugging condition varies with depth, it is recommended to measure the length of the soil column inside the pile with a sufficient frequency of data sampling and obtain the values of *IFR* continuously with depth.

It should be borne in mind that the validity of SPT results is not always assured, especially if the ground contains gravels and stones. For example, an SPT sampler sometimes penetrate through the layer containing gravels and stones without hitting them (Ogawa *et al*., 2013), as its outside diameter is as small as around 50mm. Mitsuhashi (1995) points out that the diameter of gravels and stones should be assumed to be at least three times as large as what is indicated in the SPT results. Therefore, in some cases, if the subsurface information estimated from the piling data significantly differs from the SPT results, it will be better to conduct additional site investigation not only by means of SPT but also of other methods such as a trial digging and a large-diameter core tube sampling (Watanabe *et al*., 2006). A ground-penetrating radar may be another option if its difficulty in distinguishing cobbles from cavities (Kimura *et al*., 2000) is overcome. A surface-wave method may also be adopted if its resolution is improved.



(a) Results of SPT.



(b) Results of estimation.

Fig. 12 Results of SPT and estimation (rotary cutting press-in).

4. Summary

Two techniques of utilizing the press-in piling data, which are expected to serve as construction techniques supported by ICT (Information and Communication Technology) to enhance the rationality of the design and construction of the structures with piles, were introduced in this paper. One is the automatic operation of the press-in machine and the other is the estimation of the subsurface information.

The technique of the automatic operation, developed for press-in with augering, has been confirmed to be effective in reducing the duration of the pre-augering process by from 15 to 40% in general, especially if the site is multi-layered or contains gravels or cobbles.

The validity of the estimation methods developed for standard press-in, press-in with augering and rotary cutting press-in were confirmed through the case studies. In some cases, differences were found between the estimated and the investigated results, and the main reasons for these differences were interpreted as the effect of the plugging condition or the existence of gravels or cobbles.

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