Application of Press-in Method to Coastal Levees in Kochi Coast as Countermeasures Against Liquefaction

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ABSTRACT: There had been a concern that coastal levees in Kochi would lose their functions due to the settlement caused by liquefaction of the underlying ground as well as the wide-area ground subsidence of 2 meters in the coming huge Nankai Trough earthquake. Protected inlands were supposed to suffer from the long-term flood due to the succeeding tsunami. To cope with these problems, 13-kilometer-long levees in Kochi Coast have been appointed to be in direct control of Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and have been under construction for seismic reinforcement. Requirements for this construction project were as follows: (1) levees have to be tenacious and their deformations have to be restricted below the allowable values, (2) construction should have minimal impacts on the surrounding environment and human activities, and (3) construction should be carried out at high speed and at low cost, even though cobbles and obstacles are contained in the ground. Under these requirements, reinforcement using sheet piles or tubular piles, along with the Press-in Method as their installation method, was chosen as a solution. This paper explains in detail the background and the decision making process of selecting the construction method for reinforcing the coastal levees in Kochi Coast, as well as the results of piling work in Nino and Nii sections.

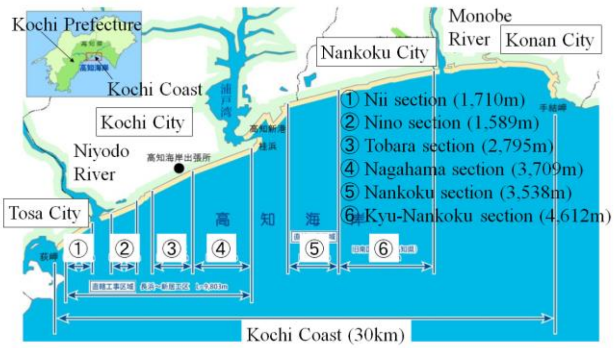
KEYWORDS: Coastal Levee, Liquefaction, Tsunami, Pile Wall, Press-in

1. INTRODUCTION

1.1 Outline of Kochi Coast

Kochi Prefecture is located in a southern part of Shikoku Island in Japan and is faced on the Pacific Ocean, as shown in Figure 1(a). According to Ministry of Agriculture, Forestry and Fisheries (2012), the area of its land and forest are 710,506ha and 596,783ha respectively; 84% of its land is covered with the forest, which is the highest number in Japan. Most of the plains suitable for urban human activities are in or near the 30-kilometer-long coastal area called Kochi Coast, which lies in the middle part of the coast in Kochi Prefecture, as shown in Figure 1(b). Therefore, population in Kochi Prefecture is concentrated in cities along the Kochi Coast: Tosa, Kochi, Nankoku, and Konan from the west to the east.

(a) Kochi (Wikipedia)



(b) Kochi Coast
(Kochi Office of River and National Highway, MLIT, 2013)

Figure 1 Location of Kochi and Kochi Coast

Kochi Coast has suffered from natural disasters repeatedly, as shown in Table 1 (Shikoku Regional Development Bureau, MLIT, 2008). It has experienced strong earthquakes and succeeding

Table 1 Natural disasters and damages experienced in Kochi Coast (MLIT, 2008)

Date	Event	Damage
October 4, 1707	Earthquake (M8.4) & tsunami	1,844 deaths
November 5, 1854	Earthquake (M8.4) & tsunami	372 deaths
December 21, 1946	Earthquake (M8.1) & tsunami	679 deaths
August 21, 1970	Typhoon	Damages in coastal levees and revetments
August 18 - September 1, 1974	Typhoon	Collapse of 295m coastal levees, loss of farm land and 4ha flood
September 30, 1979	Typhoon	Collapse of 219m coastal levees, damage of 974.5m coastal levees
August 21, 1990	Typhoon	Damage of 1,029m coastal levees
July 29, 1991	Typhoon	Collapse of 176m coastal levees and erosion of 1,615 foreshores
August 8, 1993	Typhoon	Damage of 110m coastal levees
August 21, 2001	Typhoon	3-4m settlement of 450m wave dissipating works and collapse of 100m coastal levees
October 13, 2002	Typhoon	Damage of coastal levees
September 6, 2005	Typhoon	Damage of offshore breakwaters, coastal levees, jetties and wave dissipating blocks
July 14, 2007	Typhoon	Damage of 55m artificial reefs, 65m gently sloped levees and 300m offshore breakwaters

tsunami generated in Nankai Trough every 100 or 150 years. It has also been hit by high tides and high waves due to typhoon every year, as it is in one of the typical courses of typhoons. Coastal levees were built by Kochi Prefecture from 1940's to 1960's (Shikoku Regional Development Bureau, MLIT, 2008). However, excessive consumption of sand and gravels in this area has brought about a problem of erosion of sandy shores, and several types of structures including offshore breakwaters, headland defences (Figure 2), artificial reefs and artificial nourishments have been introduced as countermeasures since 1970's (Shikoku Regional Development Bureau, MLIT, 2008; Kochi Office of River and National Highway, MLIT, 2016). Projects on these countermeasures have been further promoted since the middle of 1990's, to cope with the progress of erosion due to decreased amount of sediments from Niyodo River and the deterioration of coastal levees (Shikoku Regional Development Bureau, MLIT, 2008). More recently, projects on seismic reinforcement of coastal levees in Kochi Coast have been strongly carried out since 2011, in response to the 2011 Great East Japan Earthquake in 2011 (Uchiyama, 2015).

1.2 Outline of Press-in Method

The Press-in Method is one of the piling techniques that use a static jacking force to install piles. It mitigates environmental problems of noise and vibration that have been associated with other conventional piling techniques such as percussive or vibratory hammers (White *et al.*, 2002; White & Deeks, 2007).

It is also featured by its spatial efficiency; since a 'press-in' piling machine gains a reaction force from the previously installed piles, there is no need of bulky weights that will occupy a large space. This feature is emphasized in a piling system in Figure 3, where a press-in machine and its related devices (power unit, pile pitching crane and pile transporter) are all positioned and walk on top of the wall of piles previously pressed-in.

This principle of the Press-in Method to gain a reaction force from the previously installed piles requires the resistance on piles being pressed-in to be sufficiently smaller than the possible maximum reaction force. In standard press-in (using no auxiliary methods), this can be attained by adopting a technique of repeated penetration and extraction, which is effective in reducing mainly the shaft resistance (Ishihara *et al*., 2009; Delano, 2010; Burali d'Arrezzo, *et al*., 2013). Adoption of auxiliary methods is also effective. The development of press-in with augering, in which the piling process is assisted by augering (Figure 4), and rotary cutting press-in, in which a tubular pile with 'teeth' on its base is installed by using an axial jacking force (jacking force) and a rotational jacking force (torque) at the same time, has significantly expanded the applicability of the Press-in Method to hard grounds. Figure 5 is a typical example of rotary cutting press-in for renovating a revetment along a river under the existing highway bridge in Tokyo, where the existing concrete revetment are penetrated through by the steel tubular piles without being removed (White *et al.*, 2010).

Another feature of the Press-in Method is that it is possible to obtain continuous data of penetration depth, jacking force, etc. in parallel with the piling work itself, by using an automatic measurement system equipped in press-in machines. Figure 6 shows a concept summarizing the use of press-in piling data, which is expected to make the process of construction planning or design of pile foundations more reasonable and effective in terms of accountability, cost and duration (Ishihara *et al.*, 2015).

Typical examples of structures with piles or pile walls, where appropriate embedment depths are assured to make use of the strength and stiffness of the soil in resisting to the external loads on themselves, are self-retaining walls, coastal levees, bridges and functional cell foundations. The performance of some of these structures have been investigated into by full-scale tests as well as model tests and numerical analyses (Ishihara *et al.*, 2015; Ishihara *et al.*, 2016; Ogawa *et al.*, 2017).

Figure 2 Headland defenses in Kochi Coast (picture from Kochi Office of River and National Highway, MLIT, 2016)

Figure 3 Piling system that requires no temporary works

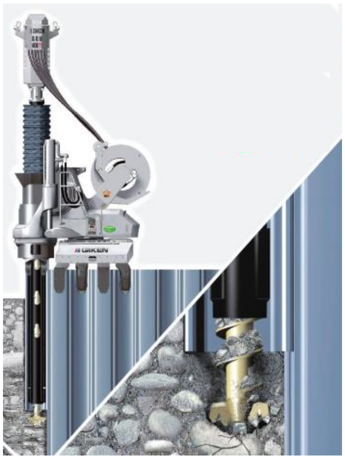


Figure 4 Press-in with augering

Figure 5 Renovation of revetments under highway bridges

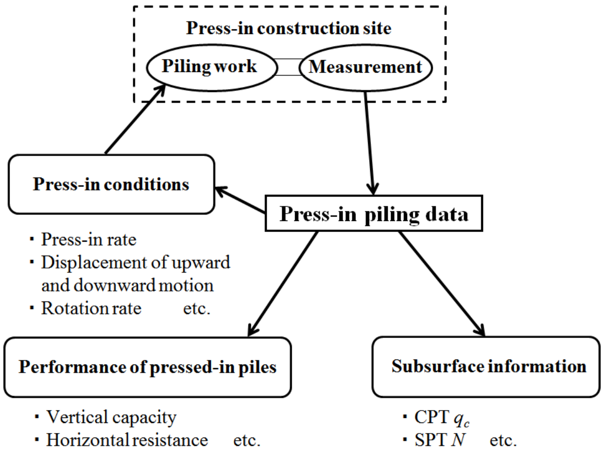


Figure 6 Use of press-in piling data

1.3 Objectives of this paper

This paper provides an overview of the project of seismic reinforcement of coastal levees in Kochi Coast. Section 1 have introduced the characteristics of Kochi Coast and the Press-in Method. The background and the decision making process of adopting the Press-in Method in this project are explained in Section 2. The information of press-in piling in several sections in this project is reported in Sections 3 and 4.

2. REINFORCEMENT OF COASTAL LEVEES IN KOCHI COAST

2.1 Background

The hugest natural disaster expected in Kochi Coast in the near future is the earthquake whose epicentre is in Nankai Trough with the magnitude of 9.0 in the worst case (Cabinet Office, Government of Japan, 2012). The probability of occurrence of this earthquake in the coming 30 years is 70% (The Headquaters for Earthquake Research Promotion, 2013). As shown in Figure 7 (Cabinet Office, Government of Japan, 2012), tsunami of as high as 34m, which is the highest value in Japan, are expected in two districts in Kochi Prefecture, and the expected height in Kochi Coast is 15 - 25m. Together with the tsunami with a large height, a ground settlement due to the elastic reaction of the continental plate (Fitch & Scholtz, 1971; Kanamori, 1972; Ando, 1982) or the densification of the ground due to the seismic motion (Okano, 1988; Okano & Kimura, 1996) is expected in this area. For examples, settlements of around 1.5m and 2.4m are expected in Kochi City and in Sukumo City respectively (Kochi Prefecture, 2014). In addition, liquefaction of the ground is expected in some parts of Kochi Coast due to the strong earthquake motion, as the ground is composed of sand with small amount of fines content. For the purpose of maintaining the functions of the coastal levees when it experiences the expected earthquake and tsunami, a construction project of reinforcing the coastal levees in Kochi Coast was started in 2011.

2.2 Selection of construction method

The earthquake to be considered in this project was determined by Kochi Prefectural Committee of Earthquake and Tsunami Disaster Prevention Technologies as the one presented by Central Disaster Management Council (Central Disaster Management Council, 2003): Tonankai-Nankai Earthquake with the magnitude of 8.6 (Kochi Office of River and National Highway, MLIT, 2016; Okabayashi, 2013). The tsunami to be considered in this project was categorized into two: a tsunami with a certain frequency of occurrence of from once in several decades to once in one hundred and several decades (tsunami of Level 1), and a tsunami that has a very low frequency of occurrence but will bring about significant damages (tsunami of Level 2). The coastal levees were designed to be reinforced by considering the tsunami of Level 1: the one generated by the above-mentioned earthquake with the magnitude of 8.6 (Kochi Office of River and National Highway, MLIT, 2016; Okabayashi, 2013). The planned height was determined as the highest of the expected heights in each coastal region: 8m in Kochi Central Coast and in Nankoku Konan Coast for examples (Kochi Office of River and National Highway, MLIT, 2016). On the other hand, the basic policy for the tsunami of Level 2 was determined to be the integration of structural and non-structural countermeasures, with the main option being the evacuation (Kochi Office of River and National Highway, MLIT, 2016).

Typical patterns of the land use around the existing coastal levees in Kochi Coast are summarized in Figure 8 (Okabayashi, 2013). The levees are faced on either a prefectural road, houses or agricultural fields. On the opposite side of the levees are sandy shores where creatures including sea turtles are living. Therefore, the following six items were considered in selecting a construction method; (1) structure should be tenacious against the tsunami of Level 2, (2) deformation of the levee due to liquefaction should be smaller than allowable values, (3) less noise and vibration should be generated during construction, (4) restriction of traffic should be avoided as much as possible, (5) construction spaces in sandy shores should be minimal, and (6) the period and cost of construction should be shorter and smaller (Yasuoka, 2016).

Several construction methods including the ground improvement, double sheet pile walls and counterweight fills were compared, and finally the double sheet pile walls and a single tubular pile wall were adopted. The single tubular pile wall was more advantageous in most sections, as the construction space was severely limited because of the existence of other structures adjacent to the levee or of the requirement for reducing the frequency of traffic regulation. Figures 9 - 12 show the typical types of structures adopted in four sections in Kochi Coast (Kochi Office of River and National Highway, MLIT, 2016). In Nii section, the single tubular pile wall

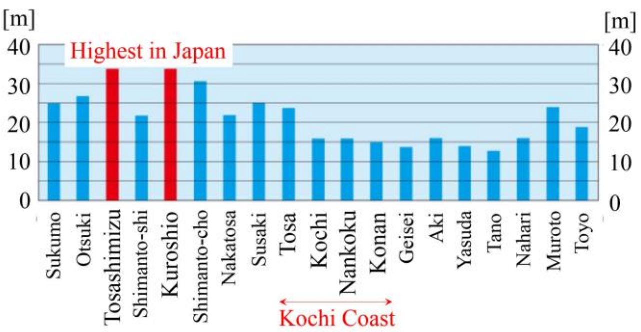
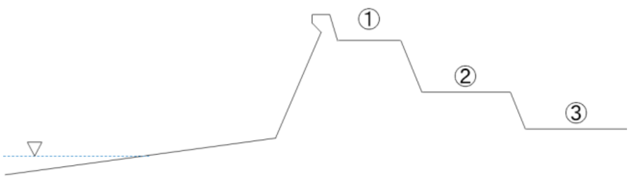


Figure 7 Expected height of tsunami in Kochi Prefecture (Kochi Prefecture, 2014)



①	②	③
Road for inspection	Prefectural road	Fields or houses
Road for inspection	Fields or houses	Prefectural road
Pavement	Prefectural road	Fields or houses

Figure 8 Typical patterns of land use around the existing coastal levees in Kochi Coast (Okabayashi, 2013)

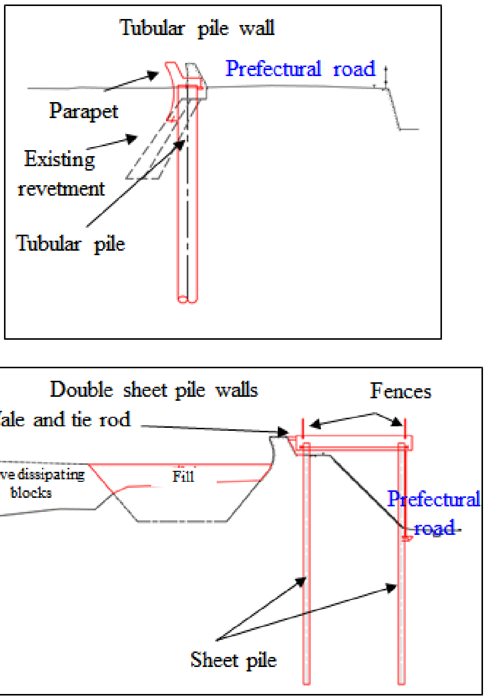


Figure 9 Typical types of structures adopted in Nii section (Kochi Office of River and National Highway, MLIT, 2016)

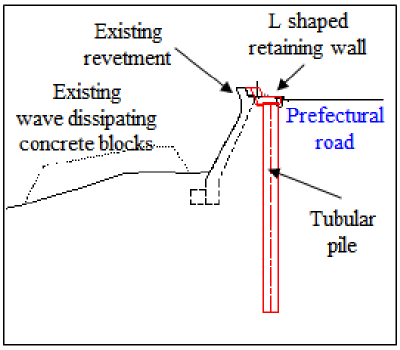


Figure 10 Typical types of structures in Nagahama section (Kochi Office of River and National Highway, MLIT, 2016)

or double sheet pile walls were adopted, taking into account the shape of the existing levee and ground conditions. In Nagahama, Tobara and Nankoku sections, the single tubular pile wall was adopted, as the construction space was limited due to the adjacent houses, greenhouses or a prefectural road. These structures with piles are expected to be effective, even when they experience the tsunami of Level 2, in securing longer time for evacuation, shortening the period for eliminating road obstacles after tsunami, or mitigating the long-term flood after tsunami, as suggested by Okabayashi (2013), since they are more resilient against tsunami (Ishihara *et al.*, 2018).

As it was expected that some obstacles such as large cobbles exist in the fill materials of the coastal levees, sheet piles were installed by the press-in method with augering (New Technology Information System (NETIS) No. CB-980118-V) which is shown in Figure 4. In this method, sheet piles are installed together with the augering device (auger screw covered by a casing). If the ground condition is too hard to be coped with by this procedure, the sheet pile installation will be preceded by pre-augering using the ageing device. For tubular piles, rotary cutting press-in method (NETIS No. KT-060020-A) was adopted in which a tubular pile with cutting

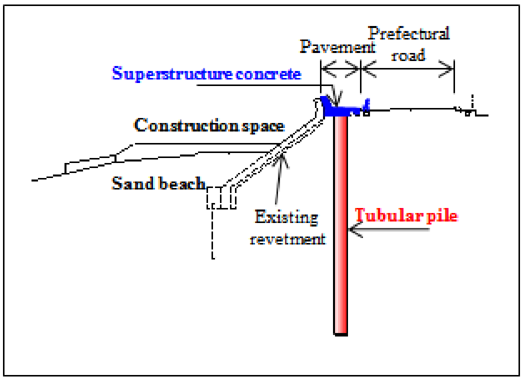


Figure 11 Typical types of structures in Tobara section (Kochi Office of River and National Highway, MLIT, 2016)

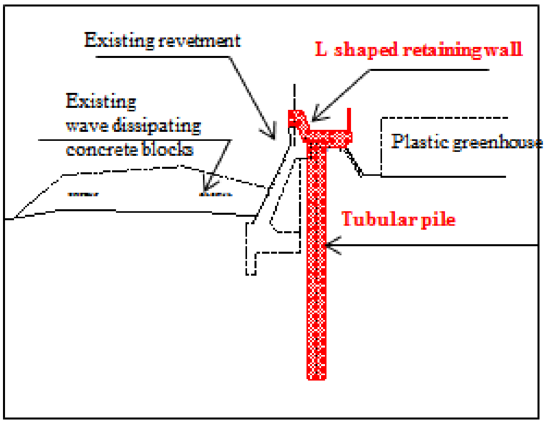


Figure 12 Typical types of structures in Nankoku section (Kochi Office of River and National Highway, MLIT, 2016)

Figure 13 Rotary Cutting Press-in Method

teeth in its base is pushed and rotated simultaneously, as shown in Figures 5 and 13.

2.3 Effects of adopting Press-in Method

In some conventional piling methods, temporary works for construction spaces and stock yards are required all along the levees. On the other hand, temporary works required in the Press-in Method are limited to those for securing the spaces for laying the piles or for assembling and disassembling the press-in machines. Figure 14 is the comparison of the area of temporary works required in a conventional piling method using a direct support type pile driver and the Press-in Method in Nagahama section (Kochi Office of River and National Highway, MLIT, 2017). The area of temporary works in the Press-in Method was around one third of that in the conventional piling method. More significantly, as shown in Figure 15, the amount of materials necessary for temporary works such as wave-dissipating blocks, concrete and sands were reduced by about 85% in this section (Kochi Office of River and National Highway, MLIT, 2017).

On the other hand, Figure 16 is the comparison of the number of sea turtles' coming to the shore or bearing their eggs measured in the coasts in Kochi Prefecture (Kochi Prefecture, 2017). Considering that the construction in Nino section in Haruno district was completed within the fiscal year of 2012, it can be said that the construction was not influential to sea turtles' lives, which demonstrates the environmental friendliness of the Press-in Method.

In addition to the resilience against liquefaction, the coastal levees with piles or sheet piles can also be expected to resilient against tsunami. Results of numerical analyses carried out by Furuichi *et al.*, 2015, for example, shows that a coastal levee with double sheet pile walls effectively maintain its function when experiencing an earthquake and the succeeding tsunami, even if the excess pore water pressure in the ground inside and outside of the two walls due to the seismic motion does not completely dissipate.

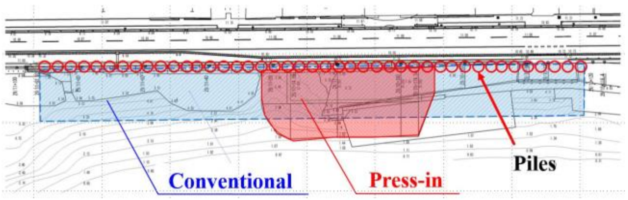
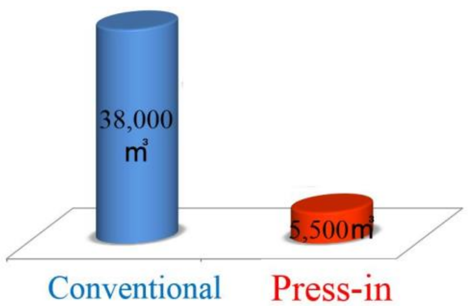
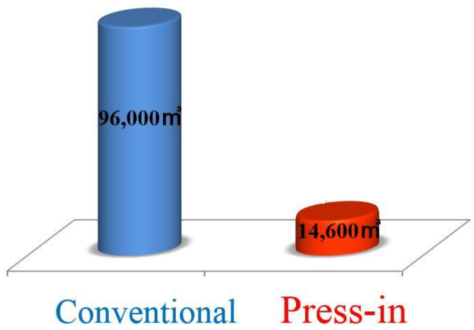


Figure 14 Area required for temporary works (Kochi Office of River and National Highway, MLIT, 2017)



(a) Wave dissipating blocks and concrete



(b) Sands

Figure 15 Amount of materials for temporary works (Kochi Office of River and National Highway, MLIT, 2017)

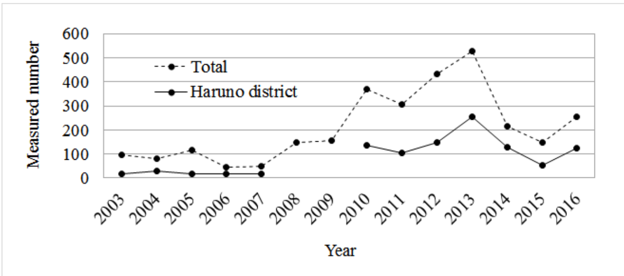
3. PRESS-IN PILING AT NINO SECTION (DOUBLE SHEET PILE WALL)

3.1 Type of structure and specification of piles

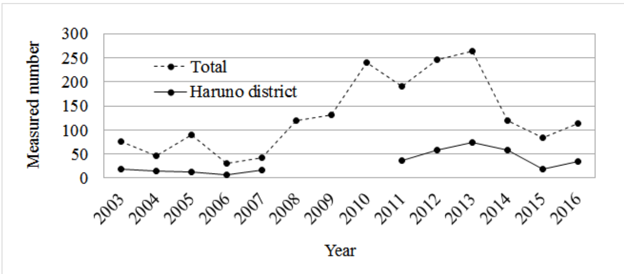
The situation of construction in Nino section is shown in Figure 17. Double sheet pile walls were adopted. The distance between the two walls was in between 5m and 6m. The top of the two walls were connected by tie rods, as shown in Figure 18. U shaped sheet piles with the width of 600mm (SP-IVw) and the length of in between 15.0m and 16.5m were used. The base of the sheet piles were embedded in the non-liquefiable layer so that the height of the levee can be maintained when it experiences the expected earthquake. The number of sheet piles installed were 2399, and the length of the levee reinforced was approximately 700m. The press-in piling work was completed within 4 months, from August to November in 2012.

3.2 Ground condition and specification of press-in machine

A typical ground condition in this section is shown in Figure 19. It mainly consists of layers of sands and gravels with the maximum values of SPT N of around 25, which is the criterion of adopting some auxiliary methods such as water jetting or augering (International Press-in Association, 2016). In addition, as shown in



(a) Number of sea turtles' coming to the shore



(b) Number of sea turtles' bearing eggs

Figure 16 Variation of activities of sea turtles in Kochi Coast

Figure 17 Situation of construction in Nino section

Figure 18 Connection of two walls by tie rods

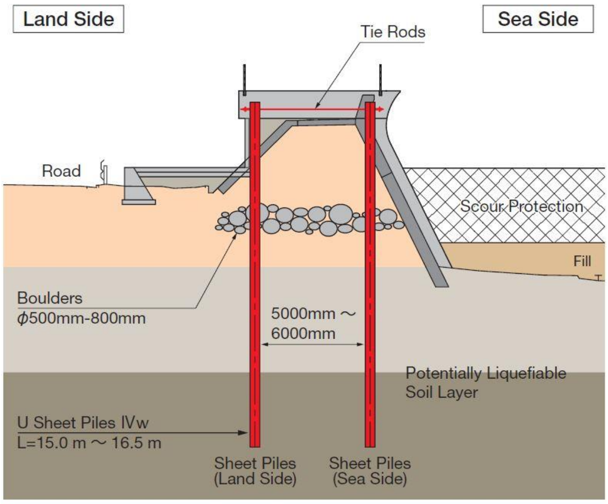


Figure 20 Expected cobbles or boulders in the existing levee

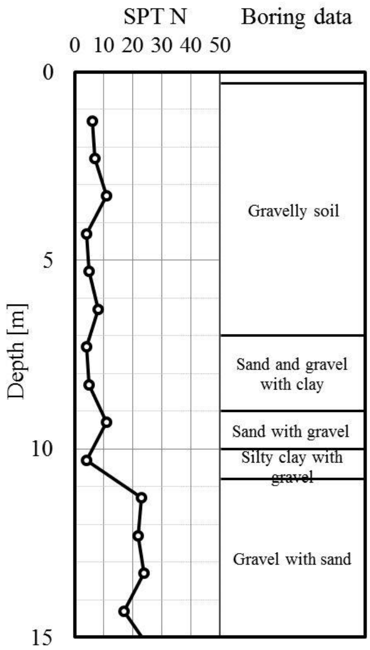
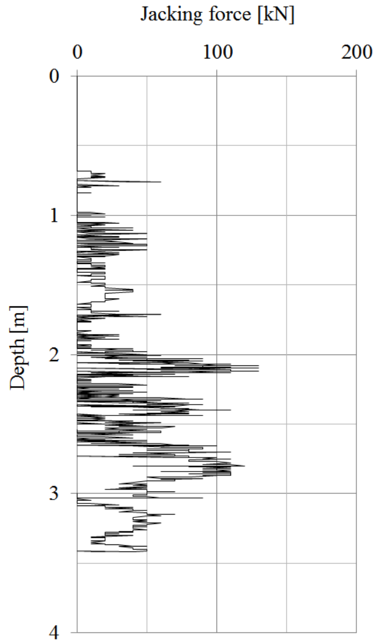


Figure 19 SPT result in Nino section



(a) Jacking force

Figure 21 Press-in piling data in Nino section

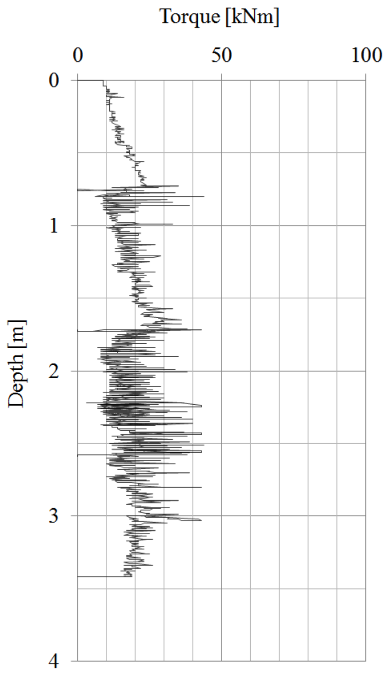
Figure 20, large cobbles or boulders were expected to be contained in the body of the existing coastal levee. Therefore, a press-in machine for press-in with augering was selected in this section.

3.3 Example of press-in piling data

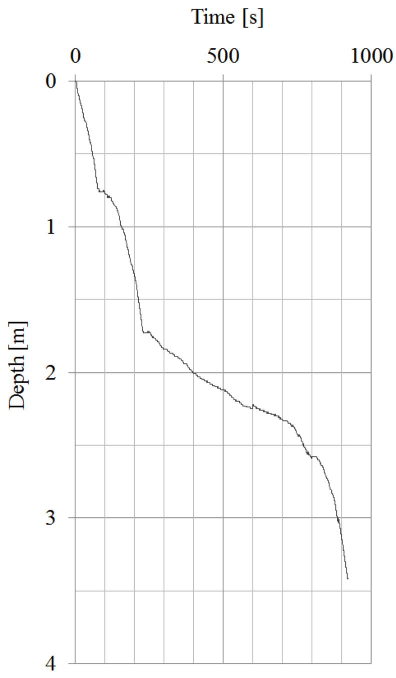
In press-in with augering, mainly two kinds of piling procedures are adopted (International Press-in Association, 2016). The first one is to attach an augering device, which consists of an auger screw with an auger head and a casing to cover the auger screw, to a sheet pile and install both the augering device and the sheet pile at the same time while augering the soil beneath the sheet pile by rotating the auger screw. The second one is to pre-auger the soil by installing and extracting the augering device and then install a sheet pile together with the augering device. The second procedure is adopted when converted SPT *N* values (*N'*), calculated by Eq. (1) (JGS, 2013), are greater than 75. Here, $z_{spt,50}$ is the penetration depth of the SPT sampler corresponding to the blow count of 50.

$$N' = 50 \times \frac{0.3\,[m]}{z_{spt,50}\,[m]} \tag{1}$$

Figure 21 is an example of the piling data obtained during the pre-augering process. Since the vertical jacking force was applied discontinuously to piles in order to cope with the large cobbles contained in the existing coastal levee, fluctuation and peak values in jacking force and torque were not so significant, while the variation of time was not constant. The existence of large cobbles can be more clearly detected when the piling data are processed to provide the estimated SPT *N* as shown in Figure 22, based on the method proposed by Ishihara *et al.*, 2015. In this case, large values of estimated SPT *N* can be found in the depth range of from 1.8m to 2.8m, in which the penetration process was presumably influenced by the existence of the large cobbles.



(b) Torque



(c) Time

Figure 21 Press-in piling data in Nino section

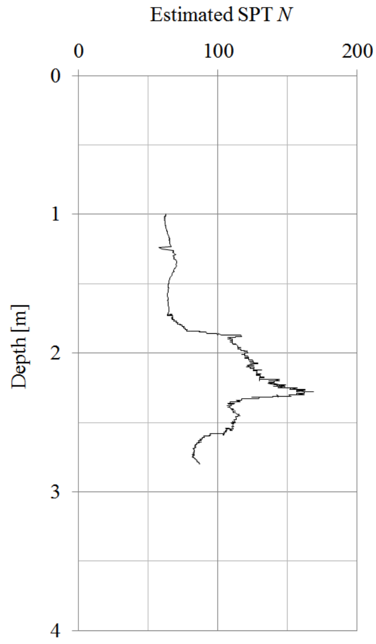


Figure 22 SPT N estimated from piling data in Nino section

Figure 23 Situation of construction of single pile wall in Nii section

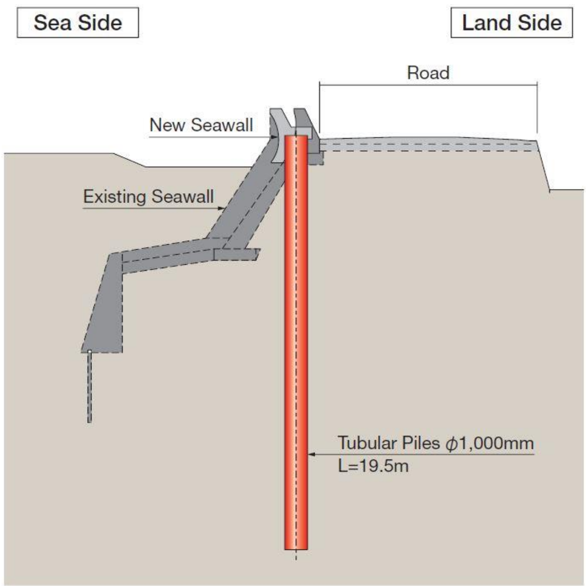


Figure 24 Cross section of single pile wall in Nii section

4. PRESS-IN PILING AT NII SECTION (TUBULAR PILE WALL)

4.1 Type of structure and specification of piles

In Nii section, double sheet pile walls and a single tubular pile wall were adopted, depending on the shape of the existing levee and ground conditions. The situation of construction of the single pile wall is shown in Figure 23. Tubular piles with the outer diameter of 1000mm and the length of 19.5m were used, as shown in Figure 24. These piles were equipped with teeth on their base, so that they can penetrate though hard ground or obstacles in the body of the levee including the remained concrete of the existing seawall. The number of piles installed were 906, and the length of the levee reinforced was 1074.4m. The press-in piling work was completed within 9 months, from January to September in 2014.

4.2 Ground condition and specification of press-in machine

One of the SPT results obtained in Nii section are shown in Figure 25. Sands and gravels are dominant, with the maximum value of converted SPT *N* (*N'*) greater than 100. To cope with this hard ground condition, and to satisfy the requirement to reduce the amount of muddy disposals as a result of the use of water during the piling work, rotary cutting press-in method was preferred to press-in with water jetting. Several types of machines for rotary cutting press-in were introduced into this section.

4.3 Example of press-in piling data

In rotary cutting press-in, a vertical and a rotational jacking forces are applied to a pile equipped with cutting teeth on its base. The direction of the vertical jacking force is generally in two ways while that of the rotational force is in one way. The limitations for the vertical (and sometimes rotational) jacking force are manually set, so that the piling work can be proceeded within the capacity of the reaction force obtained mainly from the pull-out resistance (and horizontal resistance) of the previously installed piles. The installation process is usually assisted by an injection of water at the pile base, the amount of which is significantly smaller than that adopted in press-in with water jetting.

One example of a set of press-in conditions such as the rate of downward, upward and rotational motion (v_d, v_u, v_r), manually set limitations for jacking force (Q_{max}), the upward displacement applied to a pile when jacking force reaches Q_{max} (l_u), and the flow rate of the water injected at the pile base (f_w) are shown in Table 2. The actual values of v_d, v_u and v_r may sometimes be smaller than the values in the table, especially when the piling machine needs to generate large jacking forces.

The piling data obtained based on these press-in conditions is shown in Figure 26. In general, when installing a pile into a dense

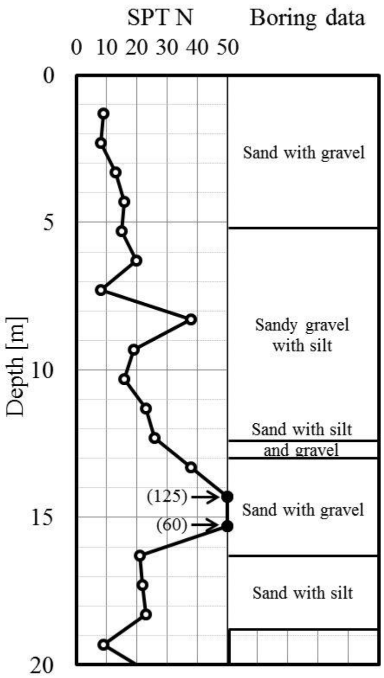


Figure 25 SPT result in Nii section

Table 2 Example of press-in conditions adopted in Rotary Cutting Press-in Method in Nii section

v_d [mm/s]	v_u [mm/s]	v_p [mm/s]	Q_{max} [kN]	l_u [mm]	f_w [ℓ/min.]
10	70	340	400 - 600	40	<120

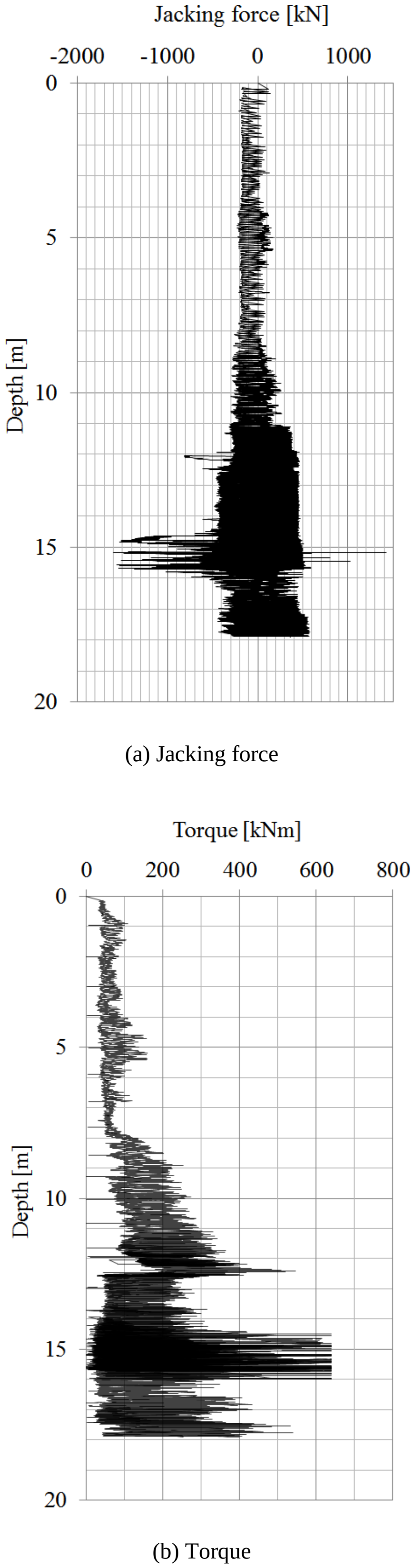


Figure 26 Press-in piling data in Nii section

sand by rotary cutting press-in method, it is desirable to maintain muddy water continuously coming from the pile base to the ground surface along the pile shaft, as it promotes smooth penetration by reducing the friction between the pile and the soil. At the depths of around 12m and 15m, this muddy water was observed to disappear, leading to the sudden increase in the friction between the pile and the soil. This is the phenomenon called 'water-binding' (Stevens, 2015), which is well-known to the piling contractors, and large values of jacking force and torque were required to overcome the increased friction. As seen in the figure, the torque frequently reached the maximum value attained by the press-in machine at around 15m. The pile was then extracted three times by from 0.5 to 2m to dissolve the water binding. On the other hand, the installation process becomes more difficult as the penetration depth increases, because of the growing resistance of the soil onto the pile due to the increase of overburden pressure as well as the generation of soil plug inside the pile. A large number of cycles of repeated penetration and extraction were adopted especially below 13m to maintain the resistance as small as possible, which can be confirmed by highly overlapping lines in Figure 26.

5. CONCLUDING REMARKS

The characteristics of Kochi Coast and the Press-in Method were introduced, succeeded by the explanation of the background and the decision making process of adopting the Press-in Method for the project of seismic reinforcement of coastal levees in Kochi Coast. Results of press-in piling, including the examples of press-in piling data obtained in Nino and Nii sections, were summarized. This construction method was successful in providing solutions for severe requirements in the aspects of design and construction; the performance of the structure was assessed to be satisfactory, while the cost, duration and the environmental impact of the construction process was maintained to be reasonably small. It is expected that the remaining sections in the eastern part of Kochi Coast will be successfully completed as well in the near future and that the reinforced coastal levees contribute to reducing the damages and economic or cultural losses in this district due to the coming huge Nankai Trough earthquake and tsunami.

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