Cambridge-Giken Collaborative Working on Pile-soil Interaction Mechanisms

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ABSTRACT

The Cambridge - Giken collaborative research was started in 1994, based on the strong awareness of Mr. Akio Kitamura, President of Giken, Ltd., on the issues related to construction. Every summer two students stay in Kochi, Japan, to carry out field and model tests using press-in machines and other experimental facilities in Giken, so that they can learn this technology by experience. This paper introduces an outline of the summer projects conducted in Kochi each year, and summarizes some research findings on the performance of a pressed-in pile, the estimation of subsurface information from piling data and the performance of a sheet pile wall.

Key words: *Pressed-in pile, Press-in piling data, Sheet pile wall*

1. Outline of Cambridge-Giken collaboration

The Cambridge - Giken collaboration research was started in 1994, based on the strong awareness of Mr. Akio Kitamura, President of Giken, Ltd., of the issues related to construction (Kitamura, 2017). Every summer two students stay in Kochi, Japan, to carry out field and model tests using press-in machines and other facilities in Giken, so that they can learn this technology by experience. In some cases, they conduct model tests or numerical analyses in their own laboratory as well. Dr. Malcolm Bolton supervised the research activities of the students until 2013, while Mr. Teruo Nagayama led the field testing team in Giken until 2009. These roles have been succeeded by the authors.

This paper introduces an outline of the summer projects in Kochi (Section **2.**), and summarizes some research findings on the performance of a pressed-in pile (Section **3.**), the estimation of subsurface information from piling data (Section **4.**) and the performance of a sheet pile wall (Section **5.**).

2. Overview of the summer projects in Kochi

2.1. 1995-1996: Effect of water jetting

Field tests were conducted using a press-in machine to investigate into the effect of water jetting on reducing press-in time in dense sand. U-shaped sheet piles with a width of 400mm (SP-III) was used. The size of the water-jetting nozzle was varied between 6.5 to 8.5mm, with a flowrate of about 320ℓ/min. Two different nozzle shapes (directions of jetting) were examined as well. The effect of these parameters on press-in time was analyzed, and the mechanisms were discussed qualitatively.

Matthew Carter and Fiona Gooch were involved in this project.

2.2. 1997-1998: Investigation into the pressure bulb

The resistance on the base of the sheet pile during press-in was obtained by measuring the strain due to the hoop stress around the holes in the base of the sheet pile, as shown in **Fig. 1**. The unit base resistance in dense sand in **Fig. 2** was approximately constant at 35MPa when the penetration depth was from 3m to 6m, which is of the same order of magnitude as the crushing strength of coarse sand.

David White, Peter Kirkham and Naomi Lyons were involved in this project. The details of the project are reported by White (1998).

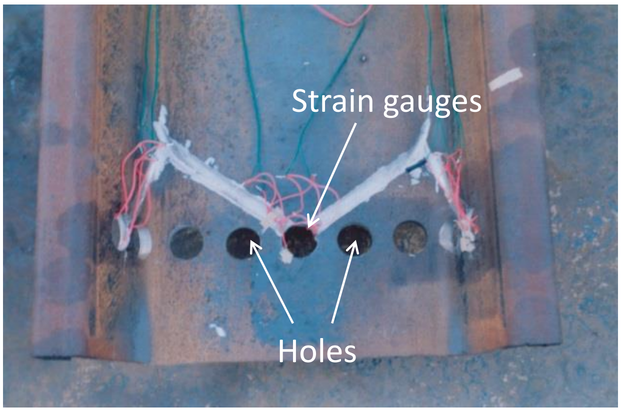


Fig. 1 Sheet pile to measure the base resistance

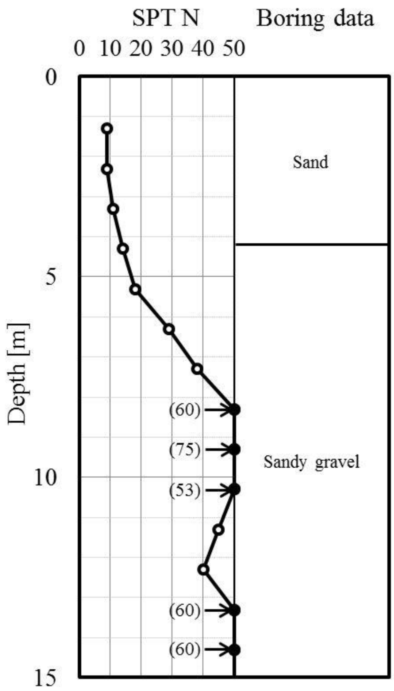


Fig. 2 Site profile (N2-1)

2.3. 1998-1999: Press-in force and pile type / Press-in speed

The press-in force during press-in was compared using U-shaped sheet piles, H-shaped sheet piles and open-ended tubular piles. Two press-in rates were adopted. An attempt to estimate the press-in force based on CPT data was discussed, and the necessity of considering the effect of the soil plug in the pan of the sheet pile was pointed out.

Peter Kirkham and Haramrita Sidhu were involved in this project.

2.4. 1999-2000: Measurement of soil plug strength

The phenomenon of plugging was investigated using a separate-type tubular pile. The pile was pressed-in, extracted and separated into two, as shown in **Fig. 3**, so that the inner soil column could be directly observed. The creation, dissolution and re-creation of soil plug during press-in was confirmed, and the mechanism of the creation of the soil plug was discussed.

Haramrita Sidhu and Timothy Finlay were involved in this project. Details are reported by White *et al*. (2000).

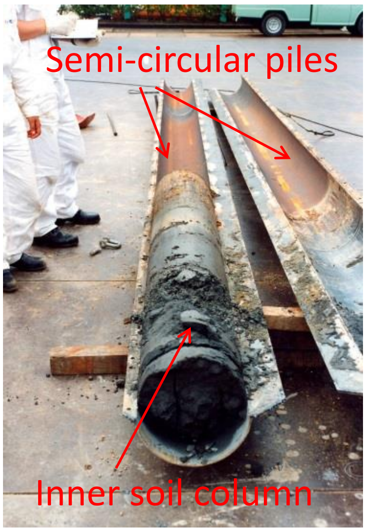


Fig. 3 Tubular pile to observe plugging

2.5. 2000-2001: Friction cutter / Strain measurement

A double-tubed tubular pile, shown in **Fig. 4**, was pressed-in to investigate the horizontal earth pressure on the internal surface of the pile. Piles with and without friction cutters on their base were also pressed-in, to investigate their effect on reducing press-in force. The friction cutter reduced the shaft resistance during press-in but had little effect on the base resistance.

Timothy Finlay and Yueyang Zhao were involved in this project. Details are reported by Finlay *et al*. (2001a) and Finlay *et al*. (2001b).

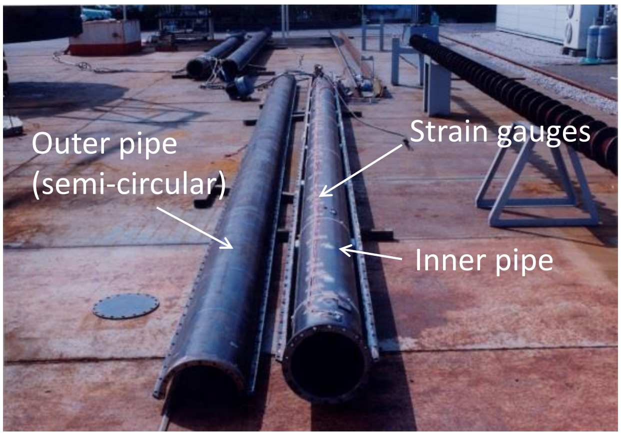


Fig. 4 Tubular pile to measure the plug strength

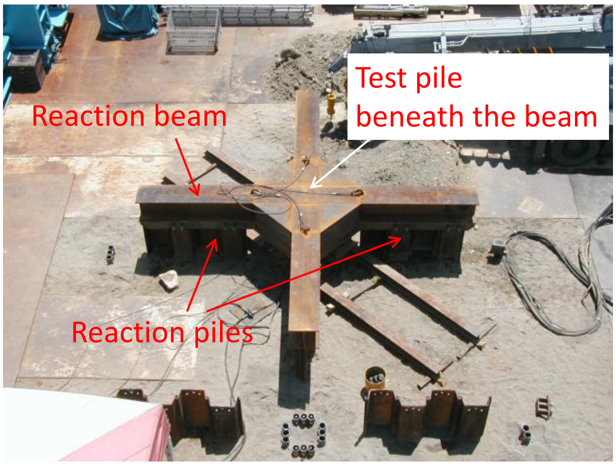


Fig. 5 Vertical load test on a pile group

2.6. 2001-2002: Press-in force and bearing capacity

A double-tubed tubular pile was pressed-in. A static vertical load test was conducted and the bearing capacity was measured.

Yueyang Zhao and Gulin Yetginer were involved in this project. Details are reported by Zhao (2002) and Zhao & White (2006).

2.7. 2002-2003: Features of pressed-in group piles / Vibration measurement

Open-ended tubular piles with an outer diameter of 101.6mm were pressed-in as a cell foundation in a square or a circular manner. A static vertical load test was conducted as shown in **Fig. 5**, and the group effect on the press-in force and the bearing capacity of these pressed-in piles was investigated. The press-in force increased with the progress of the construction of the cell foundation, as shown in **Fig. 6**. The group efficiency in terms of the bearing capacity, if the capacity of the single pile was taken as the press-in force of the first pile in the group, was slightly greater than unity.

David Rockhill, Gulin Yetginer and Andrew Deeks were involved in this project. Details of tests on the features of pressed-in group piles are reported by White *et al*. (2002), Yetginer (2003), Yetginer *et al*. (2003) and Yetginer *et al*. (2006). On the other hand, details of the field measurements of the vibration associated with the press-in piling are reported by Rockhill (2003) and Rockhill *et al*. (2003).

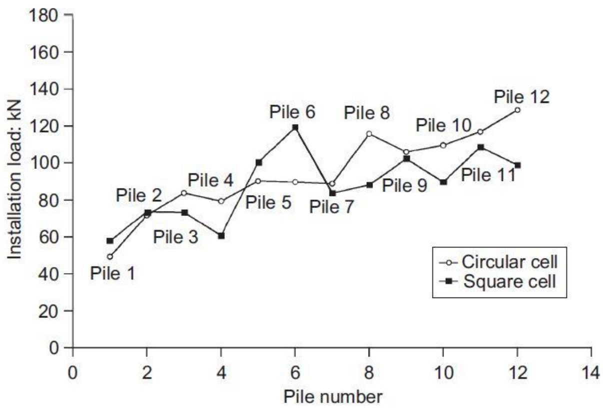


Fig. 6 Effect of the number of piles on installation load (Yetginer *et al*., 2006)

2.8. 2003-2004: Load test on groups of pressed-in piles

Open-ended tubular piles with an outer diameter of 101.6mm were pressed-in in a circular manner. Two circular groups of piles were constructed, one with a constant embedment depth (**Fig. 7a**) and the other with two different embedment depths for each pile (**Fig. 7b**). The bearing capacity of these groups were comparable, even though the embedment depth of some piles in the group in **Fig. 7b** was smaller than the other piles. The group efficiency in terms of the bearing capacity, if the capacity of the single pile was taken as the press-in force of the first pile in the group and the capacity of the pile group was taken as the plunging load, was approximately equal to unity. On the other hand, the stiffness of the group decreased with an increasing number of piles in the group.

Andrew Deeks and Melvin Hibberd were involved in this project. Details are reported by Deeks (2004) and Deeks *et al*. (2006).

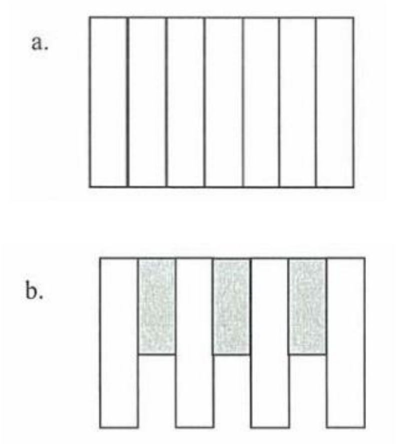


Fig. 7 Pile wall with different embedment depth

2.9. 2004-2006: Penetration resistance / Soil plug and bearing capacity

Cone Penetration Tests (CPTs) and load tests on pressed-in closed-ended tubular piles were conducted at two different sites in Kochi. The closed ended-pile had an outside diameter of 318.5mm and was equipped with a load cell on its base to measure the base resistance. It was found that the load-displacement curves for base resistance and shaft resistance during the load test was well modelled by a parabola considering G_0/q_c, where G_0 is the small strain shear modulus and q_c is the cone resistance in CPT. The load test results, together with this parabolic model, as shown in **Fig. 8**, suggested a higher stiffness of pressed-in piles compared with piles installed by conventional piling methods.

Melvin Hibberd, Helen Dingle and Andrew Jackson were involved in this project. Details are reported by Dingle (2006), Deeks & White (2007) and White & Deeks (2007).

2.10. 2006-2007: Mechanism of increase in pull-out resistance

Three types of piles were used in this project: a U-shaped sheet pile with a width of 400mm (SP-III), a hat-shaped sheet pile with a width of 900mm (25H) and a closed-ended tubular pile with an outside diameter of 318.5mm. The closed-ended pile was equipped with a load cell on its base and several pore pressure transducers on its shaft. Extraction resistance was investigated with different lengths of curing period, in a soft alluvial soil shown in **Fig. 9**. Although set-up was confirmed, the extent of set-up was not clearly linked with the dissipation of excess pore water pressure. In some tests, the peak value of extraction resistance appeared not at the commencement of extraction but when the pile was extracted by a substantial distance (more than 1m), as shown in **Fig. 10**. It was suggested that the penetration resistance could be well expressed by replacing $q_{c,ave}$ with q_b in the UWA-05 pile capacity prediction method,

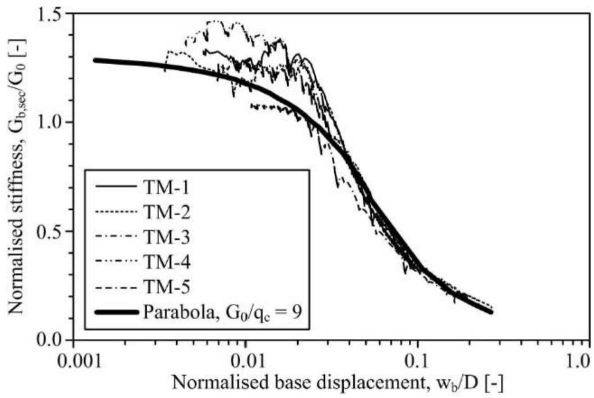


Fig. 8 Stiffness of pressed-in piles and a parabolic model (White & Deeks, 2007)

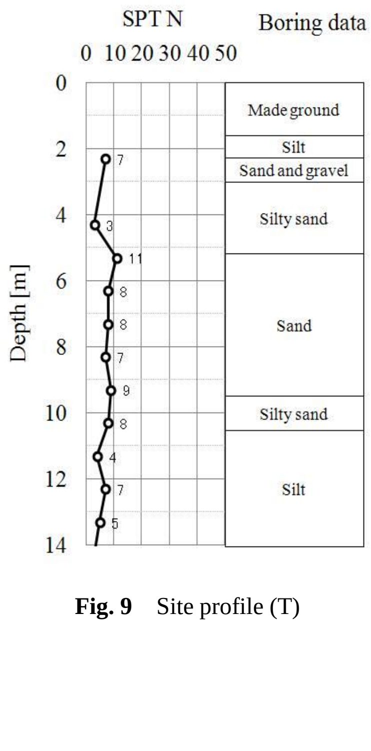
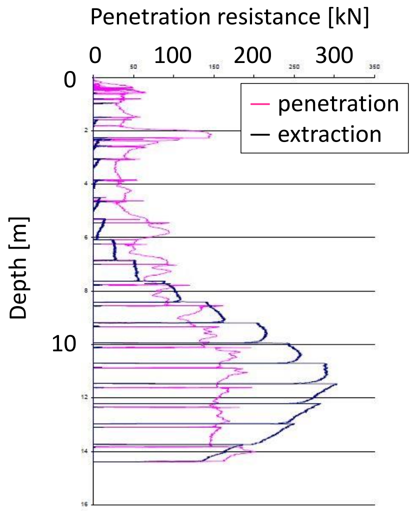
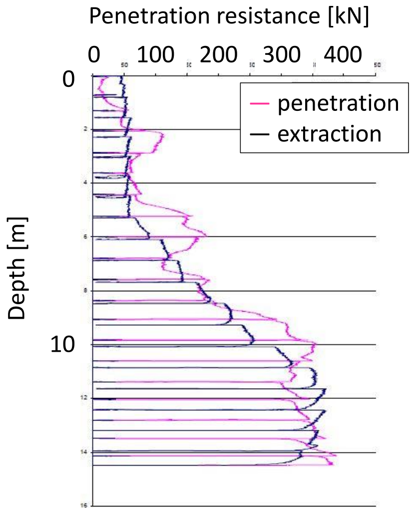


Fig. 9 Site profile (T)



(a) U-shaped sheet pile, with zero curing period



(b) Closed ended tubular pile, with zero curing period

Fig. 10 Site profile (T)

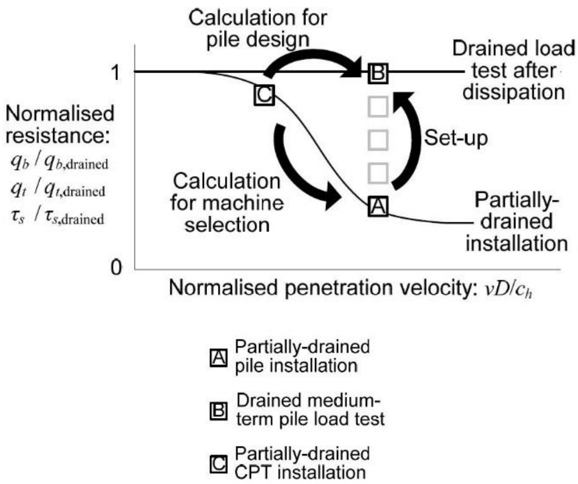


Fig. 11 Difference in drainage condition during load test and press-in (Jackson *et al*., 2008)

where $q_{c,ave}$ is a CPT cone resistance averaged by Dutch method and q_b is a base resistance during press-in, to compensate for the difference in drainage condition during load test and press-in as shown in **Fig. 11** (Jackson *et al*., 2008).

Andrew Jackson and Marcus Gillard were involved in this project. Details are reported by Jackson (2007) and Jackson *et al*. (2008).

2.11. 2007-2008: Penetration resistance and set-up

A closed-ended tubular pile with an outside diameter of 318.5mm, instrumented with a load cell on its base and several pore pressure transducers on its shaft, was pressed-in at 3 different penetration rates (2, 12 and 30 mm/s). After 3 different curing periods (0, 15 and 60 min.), the pile was extracted to confirm the extent of set-up in extraction resistance. The base resistance was reduced at higher penetration rates (**Fig. 12a**), while the shaft resistance showed the opposite trend (**Fig. 12b**). Set-up in extraction resistance was confirmed. In some tests, peak values of extraction resistance were found not at the commencement of extraction but when the pile was extracted by more than 1 m. This tendency was more apparent for tests with shorter curing periods.

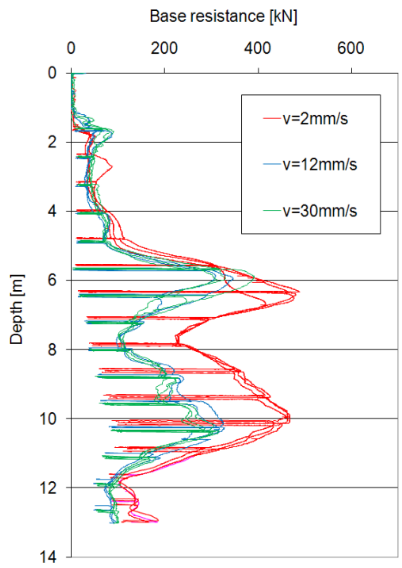
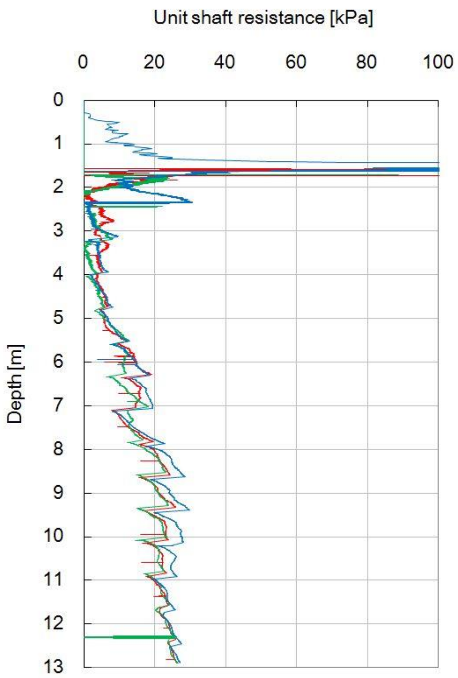
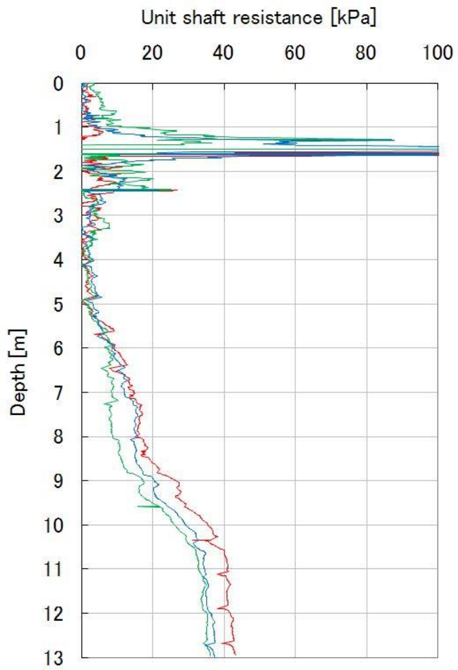


Fig. 12a Rate effect on base resistance (Ishihara *et al*., 2011)

Marcus Gillard and Paul Shepley were involved in this project. Some of the test results are reported by Ishihara *et al*. (2009).



(b-1) Penetration rate = 2mm/s



(b-2) Penetration rate = 30mm/s

Fig. 12b Rate effect on shaft resistance (Ishihara *et al*., 2011)

2.12. 2008-2009: Plugging during press-in

A double walled open-ended tubular pile with outside and inside diameters of 318.5 mm and 199.9 mm, as shown in **Fig. 13**, was used in this project. The pile was equipped with 3 earth pressure transducers on its base to measure the base resistance. Four earth pressure transducers and pore pressure transducers were placed inside the pile. The pile was pressed-in at two different penetration rates (2 and 10 mm/s) down to 11m, followed by load tests with different curing periods (85 minutes, 1 day and 10 days), in a soft alluvial soil as shown in **Fig. 14**. It was confirmed that the strength of the soil plug was greater if the penetration rate was low, as shown in **Fig. 15**. On the other hand, a set-up ratio, the ratio of the resistance measured in the load test to the resistance measured at the end of installation, was identified. At a curing period of 10 days, the set-up ratios were confirmed to be around 1.5 and 3.5 for base and shaft resistance respectively, as shown in **Fig. 16**.

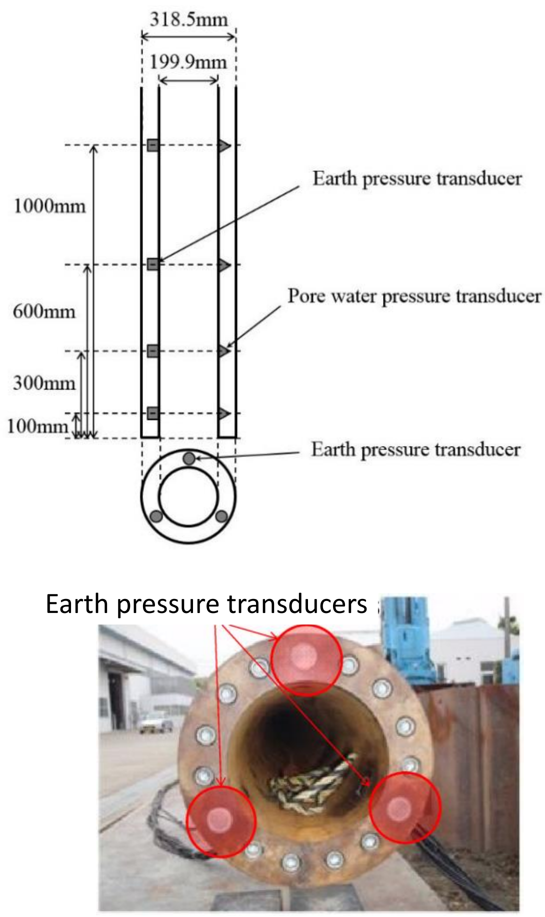


Fig. 13 Tubular pile to investigate the behavior of inner soil column

Paul Shepley and Olusomi Delano were involved in this project. Details are reported by Shepley (2009) and Ogawa *et al*. (2009).

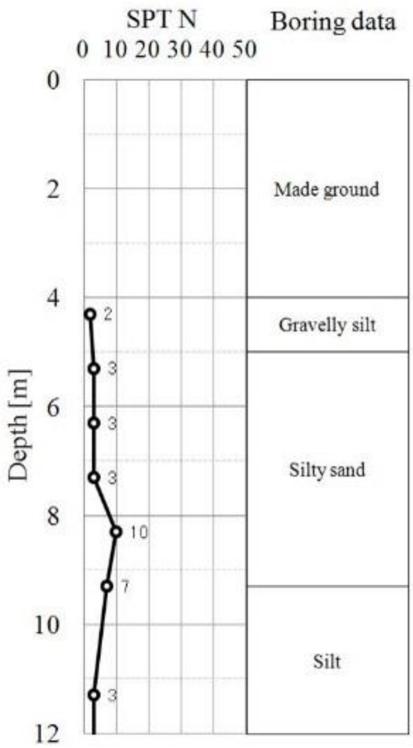


Fig. 14 Site profile (N)

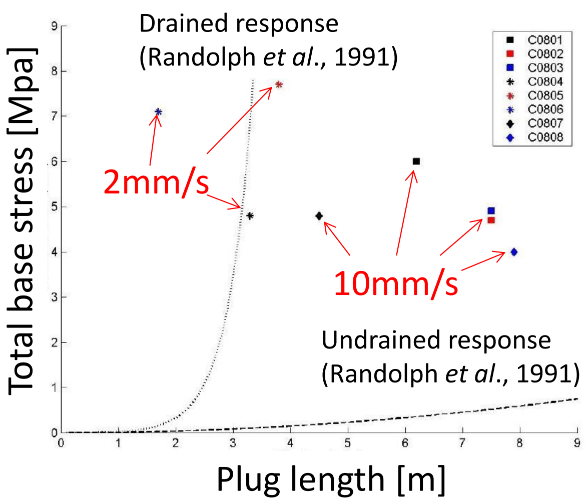


Fig. 15 Rate effect on plug strength (Shepley, 2008)

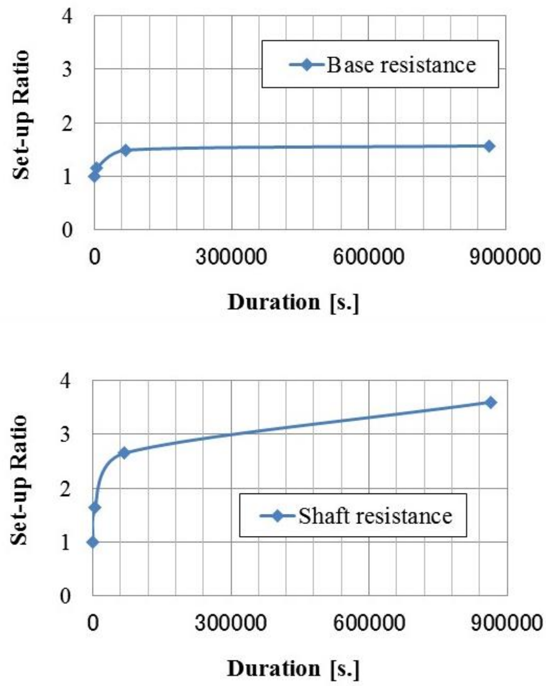


Fig. 16 Set-up ratio of a pile installed by standard press-in

2.13. 2009-2010: Effect of repeated penetration and extraction

Two types of piles were used in this project: a U-shaped sheet pile with a width of 400mm (SP-III) and a closed-ended tubular pile with an outside diameter of 318.5mm. The closed-ended pile was equipped with a load cell on its base and several pore pressure transducers on its shaft. The pile was pressed-in monotonically or with repeated penetration and extraction (also called as surging, cyclic jacking and so on), at different sets of combination of rates and displacements of penetration and extraction. The results showed that shaft resistance was reduced by repeated penetration and extraction, regardless of the ground condition (penetration depth). On the other hand, base resistance was reduced in layers where cohesive soils were dominant. No clear trend was found between the pore water pressure and the penetration resistance in repeated penetration and extraction.

Olusomi Delano and Thomas Bond were involved in this project. Details are reported by Delano (2010) and Ogawa *et al*. (2011).

2.14. 2010-2011: Reduction of penetration resistance during rotary press-in

Two types of piles were used in this project: a closed-ended tubular pile with an outside diameter of 318.5 mm and an open-ended tubular pile with an outside diameter of 500mm. The closed-ended pile was installed by standard press-in and rotary press-in at different penetration rates and rotation rates. It was found that the base resistance was reduced by increasing the penetration rate, showing a trend explained based on Finnie factor (White *et al*., 2010), in which the rate effect is attributed to the drainage condition. The rotation was confirmed to reduce the shaft resistance significantly but have little influence on the base resistance. The reduction of the shaft resistance was greater at larger velocity ratio (the ratio of the rotation rate to the penetration rate). This was attributed to a more horizontal direction of friction mobilized at the pile-soil interface, as indicated in **Fig. 17**. On the other hand, the extent of plugging was not mitigated by rotation; the length of the soil column inside a pile installed by rotary press-in was not shorter than that installed by standard press-in, as shown in **Fig. 18**. This is contradictory to the assumption that the internal shaft resistance is reduced by rotation in the same way as the external shaft resistance (White *et al*., 2010), and was concluded to be due to the difference in the ground condition down to 4m below the ground surface.

Thomas Bond and Travis Winstanley were involved in this project. Details are reported by Bond (2011) and Nishigawa *et al*. (2011).

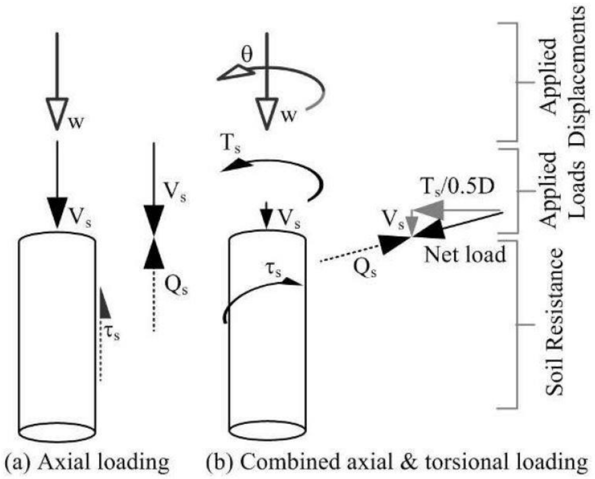


Fig. 17 Effect of rotation on shaft resistance (White *et al*., 2010)

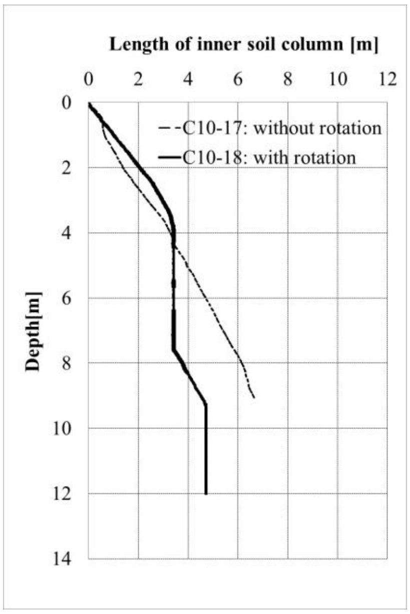


Fig. 18 Variation of inner soil column length with depth

2.15. 2011-2012: Spatial distribution of pore water pressure during press-in

Three closed-ended piles with an outside diameter of 318.5mm were used in this project. Each pile was equipped with a load cell on its base, 5 pore pressure transducers and 5 earth pressure transducers on its shaft. Two of the piles were used as measurement piles while the other one was pressed-in as a test pile, as shown in **Fig. 19**. The distance between the test pile and the measurement piles were maintained as either 1, 2, 3 or 5 times the outside diameter of the piles. During press-in, the pore water pressure measured by the measurement piles increased to its peak value until the pile base passed the depth of the transducers, and then started to decrease to a residual value. As shown in **Fig. 20**, It was confirmed that the spherical cavity expansion analysis provided a lower bound of the peak values of pore water pressure generated when the pile was pressed-in in a soft alluvial soil shown in **Fig. 14**.

Travis Winstanley and Ewa Hazla were involved in this project. Details are reported by Winstanley (2012).

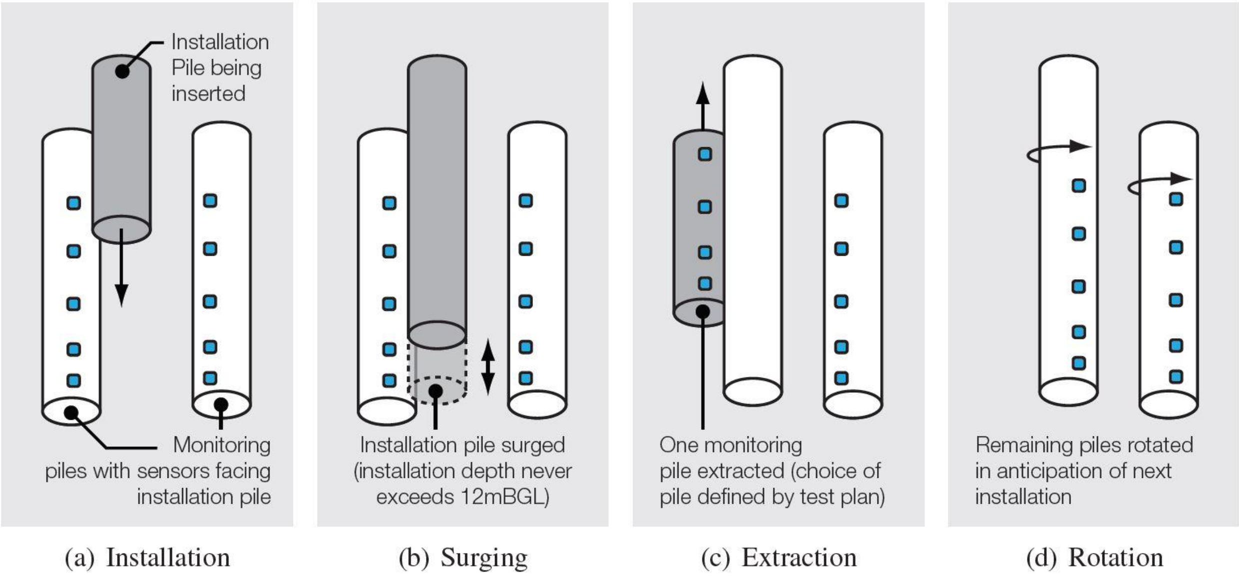


Fig. 19 Test procedure to measure the spatial distribution of pore water pressure (Winstanley, 2012)

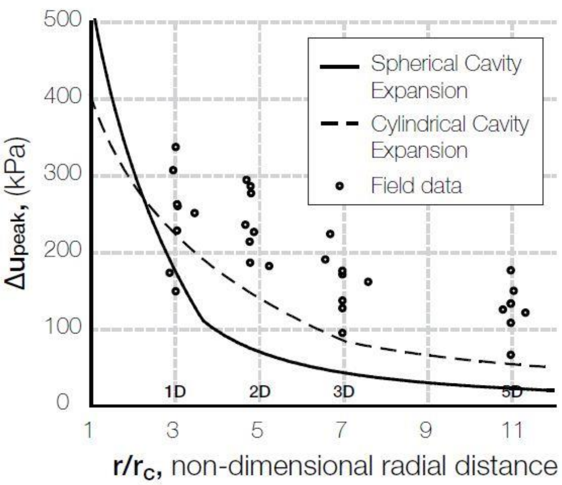


Fig. 20 Excess pore water pressure measured in the test and estimated by cavity expansion theory (Winstanley, 2012)

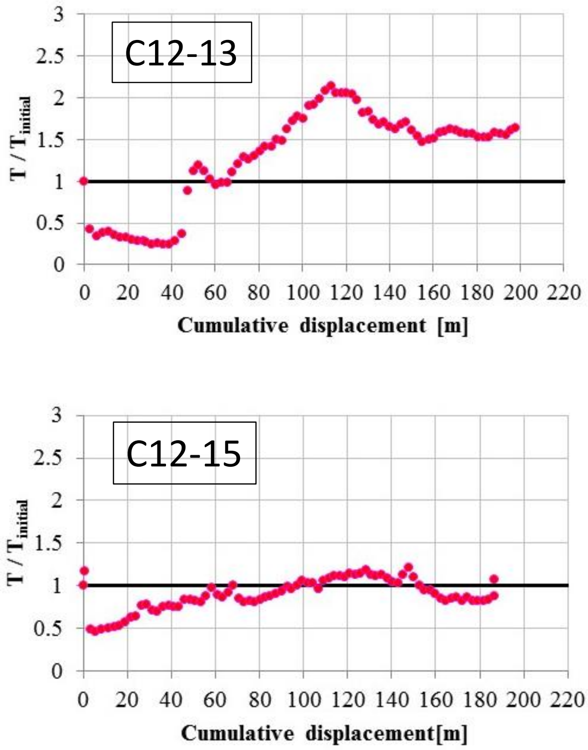


Fig. 21 Variation of torque with rotational displacement (Rotation rate = 100mm/s, depth of pile base = 11.5m)

2.16. 2012-2013: Reduction of friction during rotary cutting press-in of an open-ended tubular pile in sand

Open-ended tubular piles with an outside diameter of 800mm were used in this project. The piles were installed into a dense sandy ground shown in **Fig. 2** by rotary cutting press-in with water injection. When the pile was processed to have surface projections, which had been expected to be effective in reducing the shaft resistance, the penetration resistance was greater than when the pile did not have the surface projections, which was contrary to the expectation. When the non-processed pile was continuously rotated at a constant depth, the rotational torque did not keep decreasing with an increasing rotational displacement, as shown in **Fig. 21**.

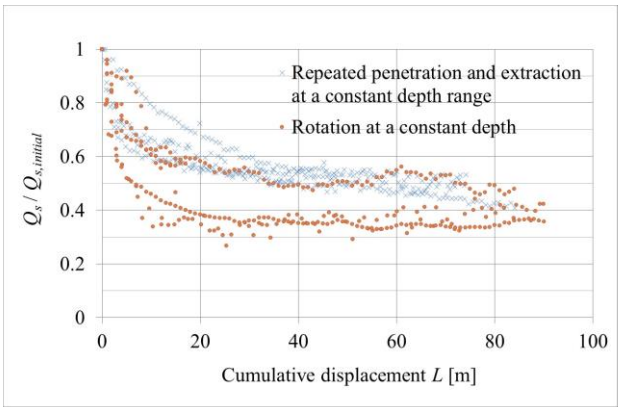


Fig. 22 Tubular pile to measure the plug strength

This result was different from those confirmed in the previous years as shown in **Fig. 22**, in which the rotational torque decreased by more than 50% with an increasing rotational displacement when a pile with an outside diameter of 318.5mm embedded in a soft alluvial ground shown in **Fig. 14** was rotated at a constant depth. These differences are presumably due to different effects of dilatancy.

Ewa Hazla and Gongyan Gao were involved in this project. Details are reported by Hazla (2013).

2.17. 2013-2014: Performance of steel sheet pile walls

Three types of cantilevered sheet pile walls were dealt with in this project. One was a 'Normal wall' in which sheet piles were embedded vertically. Another was a 'Slanting wall' where sheet piles were embedded with an inclination angle of 5 degrees. The other was the 'IP (Implant preload) Wall' in which sheet piles were embedded with an inclination angle at their base of 5 degrees and were elastically deflected toward the excavation side, as shown in **Fig. 23**. When a surcharge was applied on the ground surface behind the wall, the horizontal displacement of the walls was largest for the Normal wall and smallest for the IP wall. Two underlying mechanisms were inferred, which will be introduced in detail in Section **5.2.**

Gongyan Gao and Glyn Stevens were involved in this project. Details are reported by Gao (2014), Ishihara *et al*. (2015) and Ogawa *et al*. (2017).

2.18. 2014-2015: Mechanism of water-binding during rotary press-in in dense sand

Water-binding is a phenomenon that is sometimes encountered when installing a pile in sand assisted by water injection. Muddy water coming up to the ground surface along the pile shaft, which will be observed when a pile is being installed smoothly, is lost and the penetration resistance suddenly increases. To investigate the mechanism of water-binding, circular and semi-circular model piles with an outside diameter of 48.6mm and a soil tank of 1000mm square with a depth of 1200mm were used in this project. The soil tank had

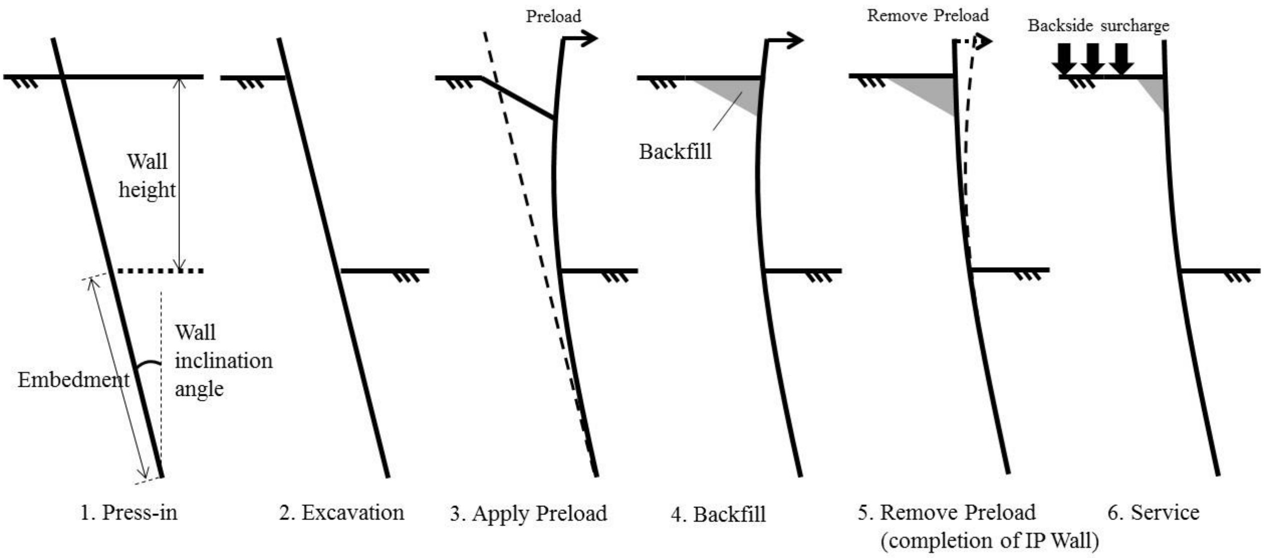


Fig. 23 Construction procedure of IP Wall (Ishihara *et al.*, 2015)

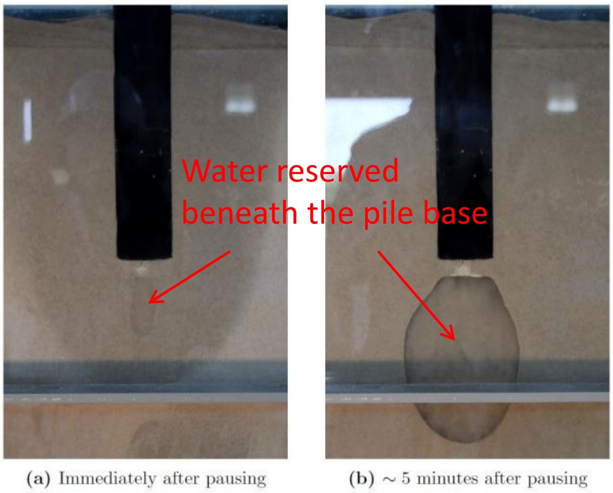


Fig. 24 Visualization of penetration process with water injection (Stevens, 2015)

an acrylic plate on one of its four sides, and a saturated model ground was prepared inside the soil tank by mixing a saturated silica sand #7 using a stirring bar. The semi-circular pile was pressed-in assisted by water injection against the acrylic plate, so that the penetration process could be visualized as shown in **Fig. 24**. The circular pile was installed by rotary press-in assisted by water injection at the center of the model ground, with different penetration rates, rotational rates and flowrates to confirm the conditions on which the water-binding is triggered. From the tests using the semi-circular piles, the process of the creation of 'interface liquefaction' and the disappearance of it (i.e. water-binding) was observed, and three parameters were identified as critical for sustaining the interface liquefaction: the water pressure at the edge of the pile base, the water pressure required to sustain the interface liquefaction and the flowrate available for interface liquefaction. An analytical model was proposed by assuming that the cause of water-binding is the sufficient pressure in the liquefied region to transmit all water though the pores, and was confirmed to be able to predict the depth of water-binding observed in the tests in which the circular pile was installed in the saturated sand.

Glyn Stevens and Andrei Dobrisan were involved in this project. Details are reported by Stevens (2015).

2.19. 2015-2016: Verification of the resilience of Implant levees against tsunami

Two sets of experiments were carried out in this project. One was to investigate the horizontal load imposed by tsunami on a wall in an overflowing condition, by means of model tests using an experimental facility called the Tsunami Simulator, as shown in **Fig. 25**. The other was a static horizontal load tests on two piles with the same outside diameter of 1000mm and different thicknesses of 12mm and 24mm, to observe the deformation characteristics of piles embedded in dense sand beyond its elastic limit. The results of the model tests showed that the tsunami load in an overflowing condition can be safely estimated by an existing estimation method, excluding instantaneous loads measured when the model tsunami hit the wall. Based on the results of the load tests, it was confirmed that the stiffness and bending moment profile of the pile were well estimated by DNV (1992). On the other hand, the horizontal capacity of the pile was confirmed to be underestimated by a factor of 2 by the p-y method, which has been pointed out by many researchers including Kirkwood (2015). The findings will be taken into account when designing tsunami mitigation structures with piles, whose effects were investigated by Suzuki *et al*. (2016a) and Suzuki *et al*. (2016b).

Andrei Dobrisan and Yan Zhuang were involved in this project. Details are reported by Dobrisan (2016) and Dobrisan *et al*. (2018).

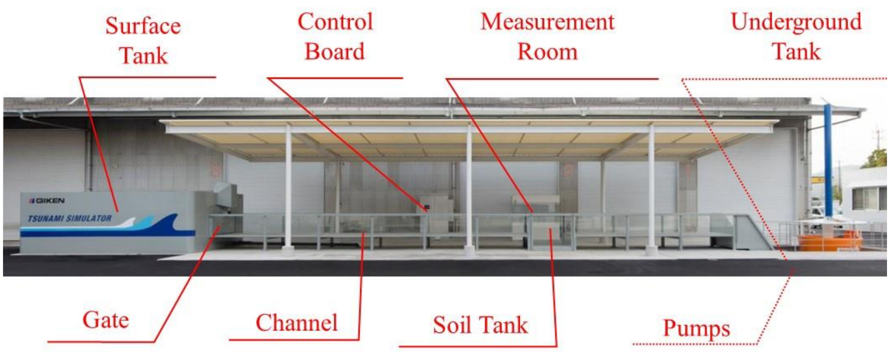


Fig. 25 Tsunami simulator (Ishihara *et al*., 2018a)

2.20. 2016-2017: Design and construction of sheet pile retaining wall with and without the stabilization of excavation base

Two types of sheet pile pits were designed and constructed under the ground condition of **Fig. 14**. One was a square pit No.1 with a horizontal length of 8.4m, an embedment depth of 10m and an excavated depth of 5m. The other was a rectangular pit No.2 with a horizontal length of 8.4m and 6m, an embedment depth of 16.5m and an excavated depth of 9.5m. The excavation base in the pit No.2 was stabilized by a number of concrete columns before the excavation, as shown in **Fig. 26**. The deformation of the wall due to the stabilization and the excavation was measured manually by an inclinometer. As shown in **Fig. 27**, the wall was pushed outwards due to the stabilization and then pushed inwards due to the excavation. Together with the results of FEM analysis in which the stabilization process was modelled by thermal expansion, the effectiveness of the stabilization was discussed qualitatively.

Yan Zhuang and Marla Gillow were involved in this project. Details are reported by Zhuang (2017).

2.21. 2017-2018: Mechanism of water jetting

Two sets of sheet piles equipped with pore pressure transducers were used in this project. One pile was installed prior to the installation of another, so that the pore water pressure not only on the shaft of the pile being installed but also in the ground at a certain distance from the pile being installed can be measured. Data obtained during press-in with water jetting in unsaturated dense sand indicated in **Fig. 2** showed that the build-up of high excess water pressure was limited to the region that is near from the jet nozzle equipped in the pile base. Results of detailed analysis of the data shown in **Fig. 28** suggested that a high stress region near the base of the sheet pile caused a build-up of base resistance, preventing further penetration of the pile, until enough water pressure was built up at the pile base to reduce the stress of the high stress region. The high water pressure was able to be built-up around the pile base even in relatively permeable soils, presumably because the repeated penetration and extraction at a constant depth range caused crushing of sand particles, forming an impermeable film in the pile base as shown in **Fig. 29**.

Marla Gillow and Jennifer Chambers were involved in this project. Details are reported by Gillow (2018) and Gillow *et al*. (2018).

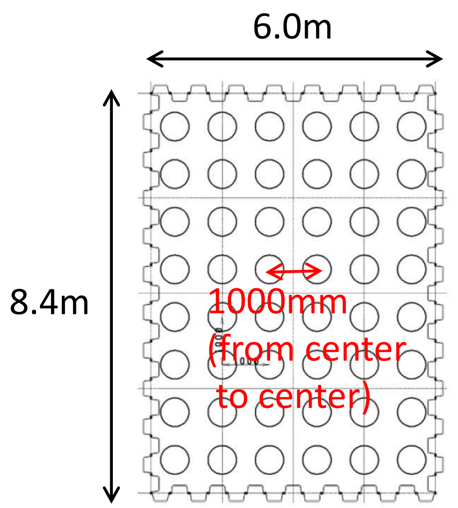


Fig. 26 Stabilization of excavation base (Zhuang, 2017)

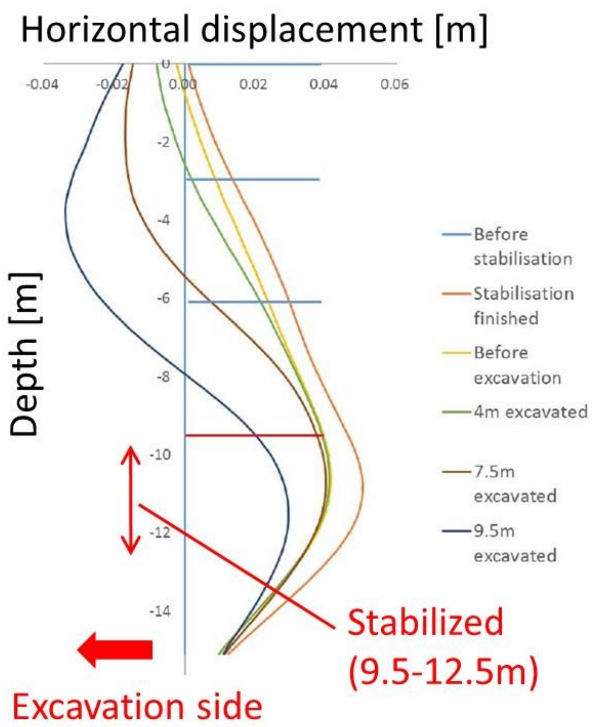


Fig. 27 Horizontal displacement of a sheet pile pit due to stabilization and excavation (Zhuang, 2017)

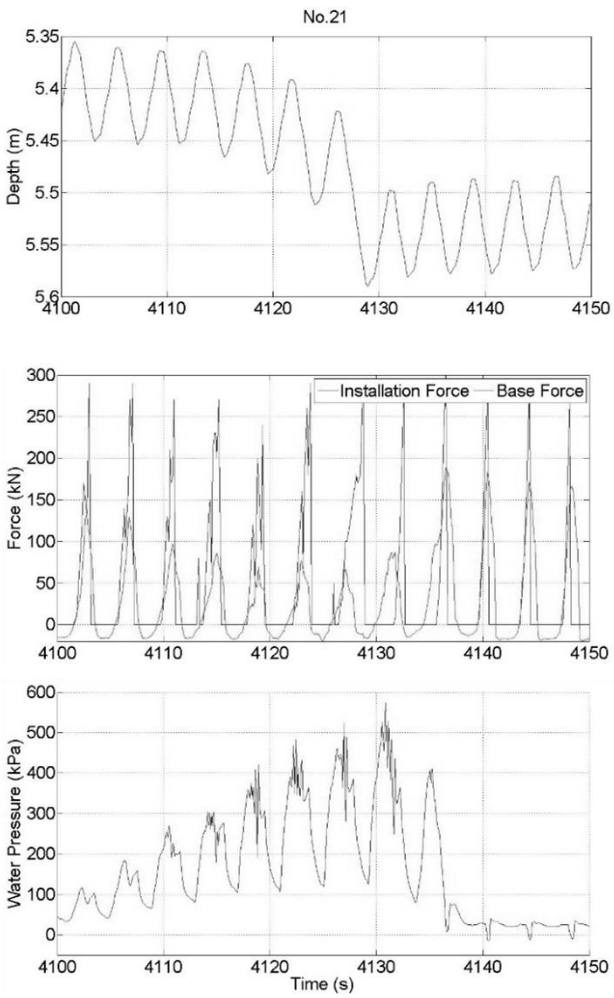


Fig. 28 Variation of depth, force and water pressure during press-in with water jetting (Gillow *et al*., 2018)

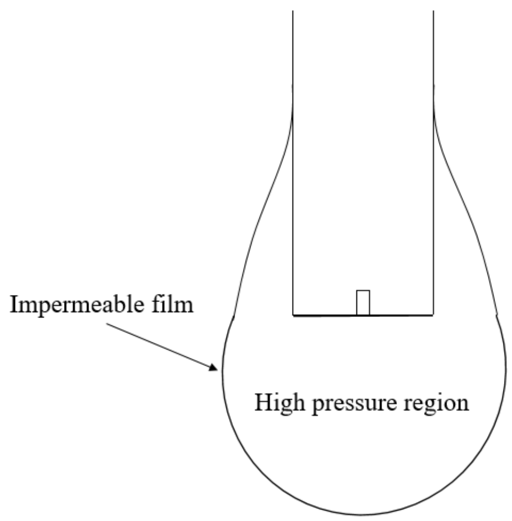


Fig. 29 Conjectured key mechanism of water jetting (Gillow *et al*., 2018)

3. Performance of pressed-in piles

3.1. Vertical capacity of a pile installed by standard press-in

As the penetration mechanisms of a CPT cone and a pressed-in pile are similar, it seems to be reasonable to estimate the vertical capacity of a pile installed by standard press-in from CPT data. White & Deeks (2007) and White *et al*. (2010) argued that the vertical capacity of a pile installed by standard press-in can be estimated by modifying the values of coefficients in UWA-05 framework, which is a CPT-based design method originally prepared for offshore driven piles (Lehane *et al*., 2005). In this framework, a base capacity (q_{bf}) and a shaft capacity (q_{sf}) of driven piles are expressed as:

$$q_{\mathrm{bf}}=(0.15+0.45A_{\mathrm{r}})q_{\mathrm{c,ave}} \tag{1}$$

$$q_{\mathrm{sf}}=aq_{\mathrm{c,ave}}A_{\mathrm{r}}^{\ b}\left\{\max\left(\frac{h}{D_{\mathrm{o}}},2\right)\right\}^{c}\tan\delta_{\mathrm{cv}} \tag{2}$$

where $q_{\mathrm{c,ave}}$ is the CPT cone resistance averaged by Dutch method, A_{r} is the area ratio of the pile adjusted for the plugging condition, h is the distance from the pile base, D_{o} is the outer diameter of the pile and δ_{cv} is the constant volume pile-soil friction angle. Parameters a, b and c represent the stress drop around the pile base, the effect of the plugging condition and the effect of the friction fatigue respectively.

Table 1 shows the comparison of the values of the parameters for driven and jacked piles (White *et al*.,

Table 1. Comparison of driven and jacked piles in UWA-05 framework (White *et al*., 2010)

	Driven piles (UWA-05)	Jacked piles (tentative)
Base resistance, $\alpha = q_{b,0.1}/q_c$	α = 0.15 → 0.6, varying linearly with A_r	α = 0.15 → 0.9, varying linearly with A_r
Maximal shaft resistance, $a = q_c/\tau_{sf,max}$	a = 33 (comp.) a = 44 (tens.)	
End condition, $\tau_{sf,max}$ open/closed = $A_r^{\,b}$	b = 0.3	
Friction fatigue, $\times(h/D)^c$	c = -0.5	-0.4 < c < -0.2

2010). The ratio of q_{bf} to q_c of jacked piles is higher than that of driven piles. This will be because the jacked piles tend to plug more easily due to the reduced effect of inertia (Liyanapathirana *et al*., 2001) and the greater amount of soil is displaced during piling. The value of parameter *c* of jacked piles is smaller, meaning that the effect of friction fatigue is smaller for jacked piles than for driven piles. This will be because the number of cyclic motion of the pile during piling is smaller in jacked piles.

3.2. Vertical stiffness of a pile installed by standard press-in

According to Dingle (2006) and Deeks & White (2007), the vertical stiffness of a jacked pile (a pile installed by standard press-in) is well expressed by a parabolic model, which is expressed as:

$$\frac{q_b}{q_{bf}} = -\left(\frac{w}{w_{bf}}\right)^2 + 2\frac{w}{w_{bf}} \qquad (3)$$

$$w_{bf} = \frac{\pi(1\text{-}\nu)}{4}\frac{q_{bf}}{G_{b,init}}D_o \qquad (4)$$

where q_b is the base resistance when the settlement of the pile base is w, w_b is the settlement when q_{bf} is mobilized, ν is the Poisson's ratio and $G_{b,init}$ is the initial soil stiffness. They argued, by comparing the parabola representing the results of the centrifuge load tests of themselves as well as of the field load tests of Dingle (2006) and the trend curves for bored piles (Ghionna *et al*., 1993; Berardi & Bovolenta, 2005) and for driven piles (API, 2000), that the axial stiffness of a jacked pile at a typical working settlement (from $0.02D_o$ to $0.1D_o$) is greater than that of a bored pile by a factor of 10 and that of a driven pile by a factor of 5, as shown in **Fig. 30**. One reason will be the effect of the loading history. The soil beneath the base of the jacked pile experiences a static loading and unloading at the end of installation. This means that the load test is a reloading process, in which a greater stiffness can be obtained compared with the case where the soil beneath the pile base is loaded for the first time, as shown in **Fig. 31** (JGS, 2002).

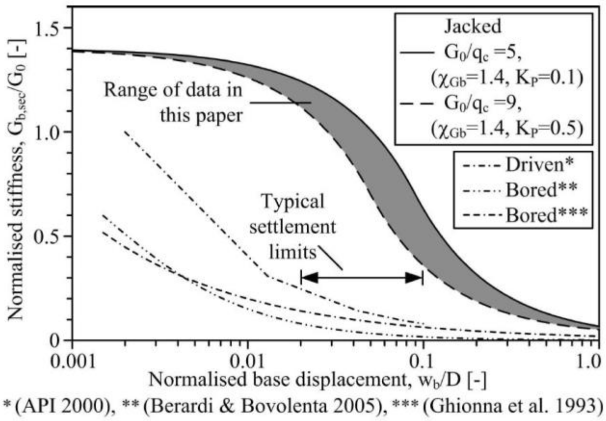


Fig. 30 Stiffness of jacked, driven and bored piles (Deeks & White, 2007)

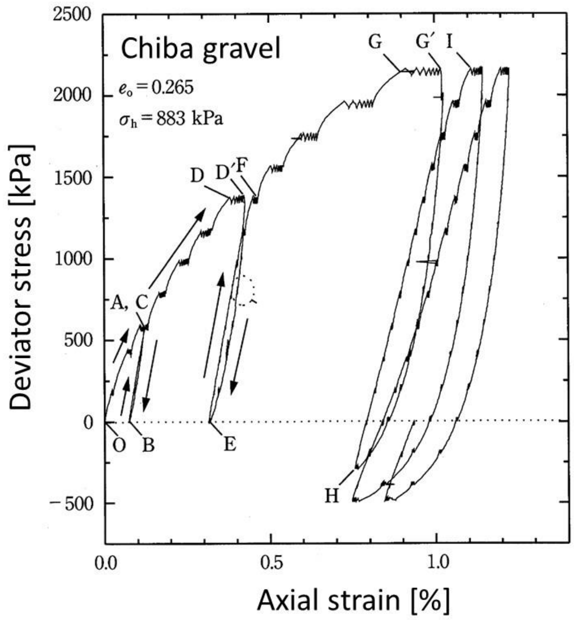


Fig. 31 Typical example of a load-unload-reload curve of soil (JGS, 2002)

4. Use of press-in piling data to estimate subsurface information

4.1. Estimating CPT q_t, soil type and SPT *N* from data in standard press-in

The similarity in the penetration mechanism of a pressed-in pile and a CPT cone was taken into account to develop an estimation method in standard press-in (Ishihara *et al*., 2015b; IPA, 2017). The estimation process can be divided into four.

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), based on a simple assumption as shown in **Fig. 32** (Ogawa *et al*., 2012) which is expressed by the following equations:

$$Q_b = Q_1 - Q_2 \tag{5}$$

$$Q_s = Q_2 \tag{6}$$

where Q_1 and Q_2 are 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. 'A certain depth' is recommended to be $0.15D_o$ below the depth where the second penetration is started, to avoid the influence of the soil collapsed into the cavity beneath the pile base (Ishihara *et al*., 2015b). The validity of **Eqs. (5)** and **(6)** can be confirmed in **Fig. 33**, which was obtained during the press-in of a closed-ended tubular pile with D_o = 318.5mm.

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 conditions are taken into account based on a linear correlation between the plug strength and *IFR* (Incremental Filling Ratio), which was found in a monotonic penetration of a model pile at 1g in a dry sand with a relative density D_r of 30% as shown in **Fig. 34** (Lehane & Gavin, 2001) as well as in a monotonic and cyclic penetration of a model pile at 1g in a dry sand with D_r = 60% as shown in **Fig. 35** (Ishihara *et al*., 2018b).

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 as shown in **Fig. 36** (White & Bolton, 2005) and the rate effect based on the Finnie

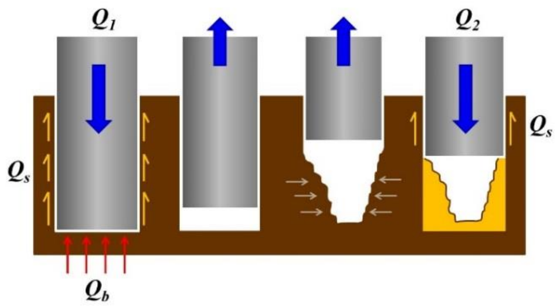


Fig. 32 Decomposition of jacking force into base and shaft resistance (Ogawa *et al*., 2012)

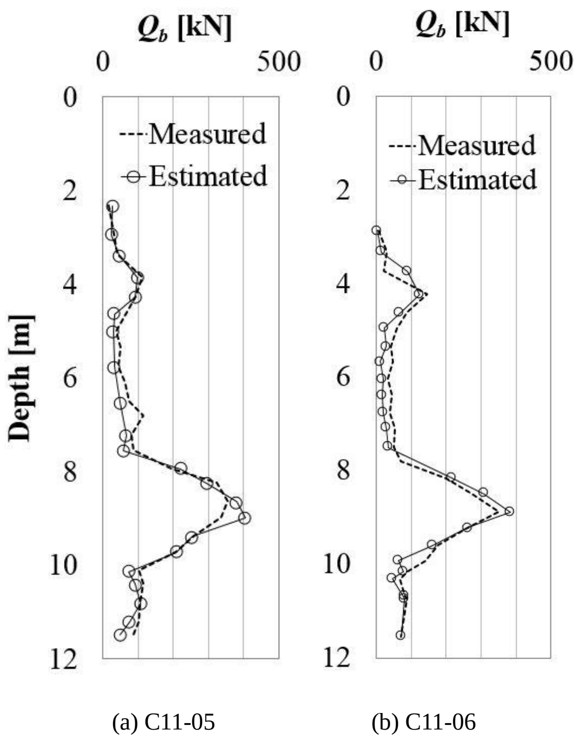


Fig. 33 Comparison of measured and estimated base resistance in standard press-in (Ishihara *et al*., 2015b)

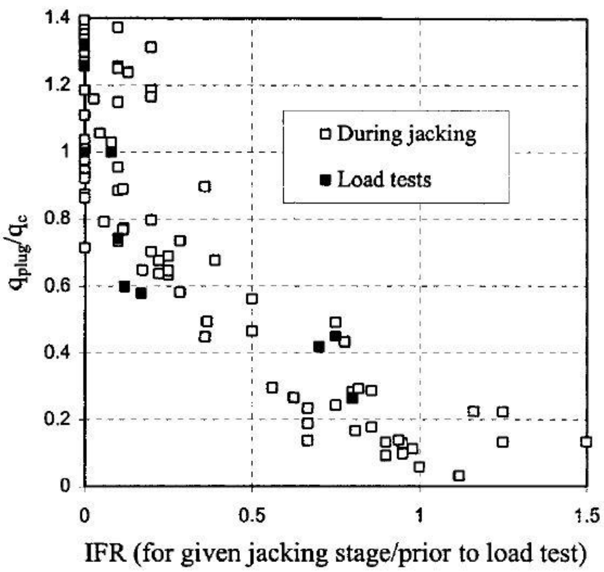


Fig. 34 Relationship between plug strength and *IFR* in monotonic penetration (Lehane & Gavin, 2001)

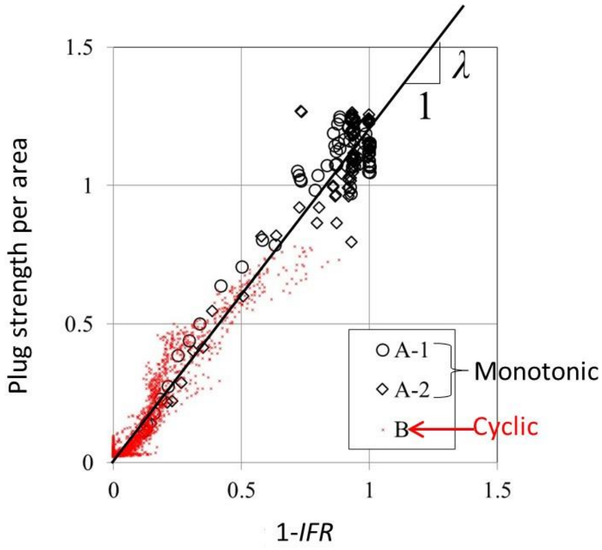


Fig. 35 Relationship between plug strength and *IFR* in monotonic or cyclic penetration (Ishihara *et al*., 2018)

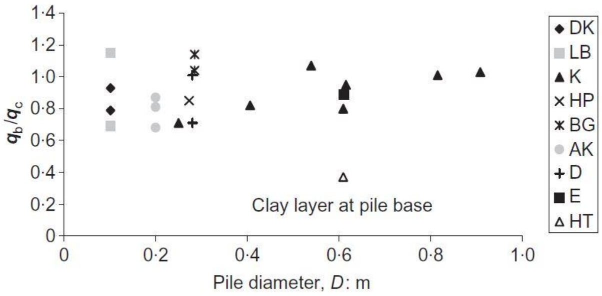


Fig. 36 Scale effect on base capacity (White & Bolton, 2005)

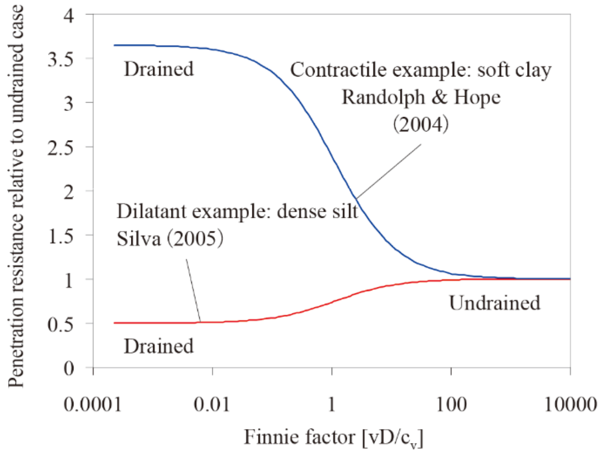


Fig. 37 Rate effect on base resistance (White *et al*., 2010)

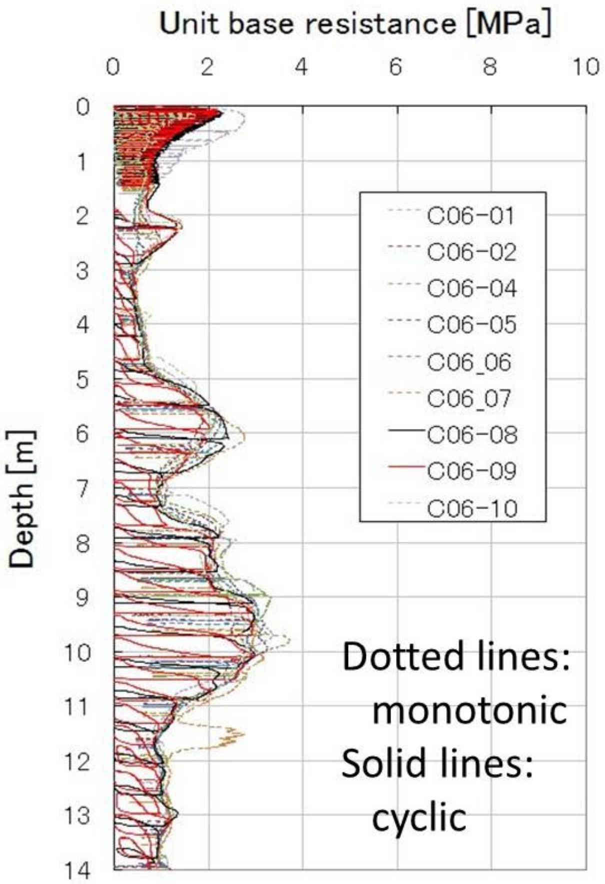


Fig. 38 Effect of repeated penetration and extraction on base resistance (Ishihara *et al*., 2011)

factor (Finnie & Randolph, 1994) as shown in **Fig. 37** (White *et al*., 2010).

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. The validity of the estimated results is discussed by Ishihara *et al*. (2015b).

As explained above, this method requires the penetration process to be associated with the repeated penetration and extraction. It was confirmed in a field test using a closed-ended tubular pile with D_o = 318.5mm in a soft alluvial soil shown in **Fig. 9** that the repeated penetration and extraction has little effect on the envelope of Q_b as shown in **Fig. 38**, while it significantly reduces Q_s as shown in **Fig. 39** (Ishihara *et al*., 2011). It follows that this method underestimates CPT q_t or SPT *N* because of the reduced value of Q_s. However, as the effect of Q_s on the estimated results was confirmed to be

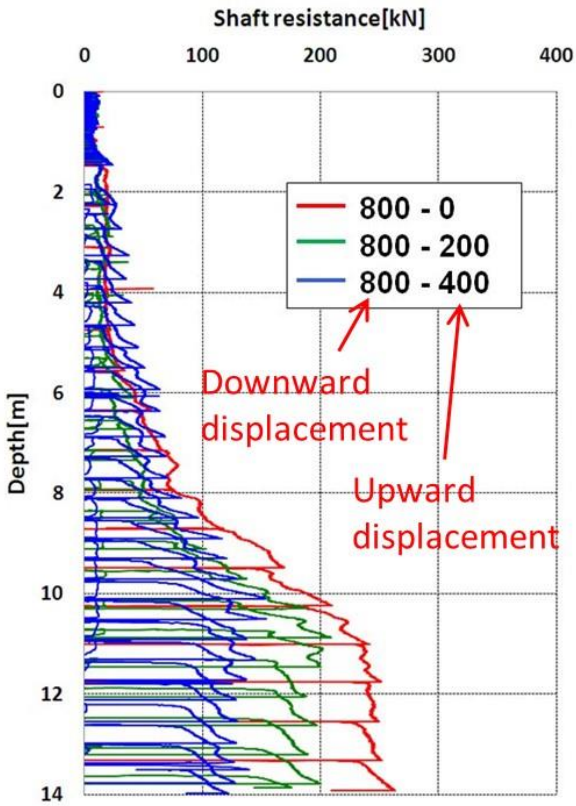


Fig. 39 Effect of repeated penetration and extraction on shaft resistance (Ishihara *et al*., 2011)

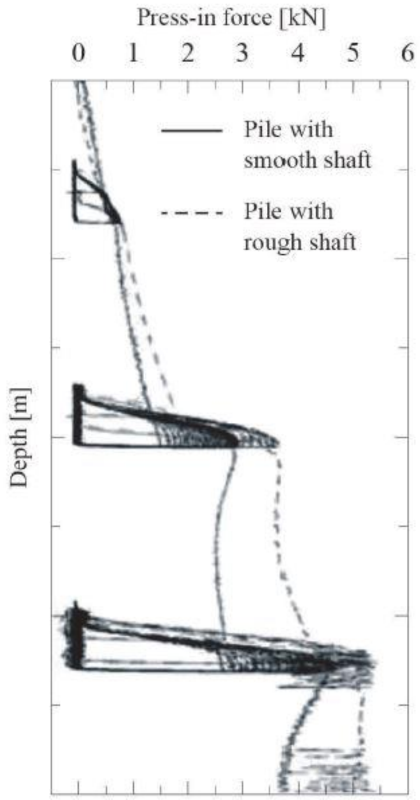


Fig. 40 Effect of repeated penetration and extraction At a constant depth range on base resistance (Burali d'Arezzo et al., 2013))

insignificant (Ishihara *et al*., 2009), this point is not essential. On the other hand, the repeated penetration and extraction at a constant depth range leads to a significant increase in Q_b as shown in **Fig. 40** (Burali d'Arezzo *et al*., 2013). As Q_b directly influences the estimated results, it leads to a significant overestimation. Attention has to be paid when a large number of cyclic motions are applied to a pile at a constant depth, which is probable when penetrating though a hard layer under a manually-set limitation of Q for example.

4.2. Estimating SPT *N* from data in rotary cutting press-in

The estimation process in rotary cutting press-in is divided into three: 1) estimating a vertical and rotational resistance at the pile base from a vertical and rotational jacking force, 2) estimating Specific Energy (Teale, 1965) consumed at the pile base and 3) estimating SPT *N* based on the assumption that the Specific Energy consumed at the base of the pile is comparable to that consumed at the tip of the SPT sampler. The validity of the estimated results is discussed by Ishihara *et al*. (2015c).

In the first process, the vertical and 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. (7) - (10)**) 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*., 2015c).

$$Q = Q_b + Q_s \tag{7}$$

$$T = T_b + T_s \tag{8}$$

$$\frac{T_b}{Q_b} = \frac{\tan\delta_{sp}}{3} D_o \tag{9}$$

$$\frac{T_s}{Q_s} = \frac{v_r / v_d}{2} D_o \tag{10}$$

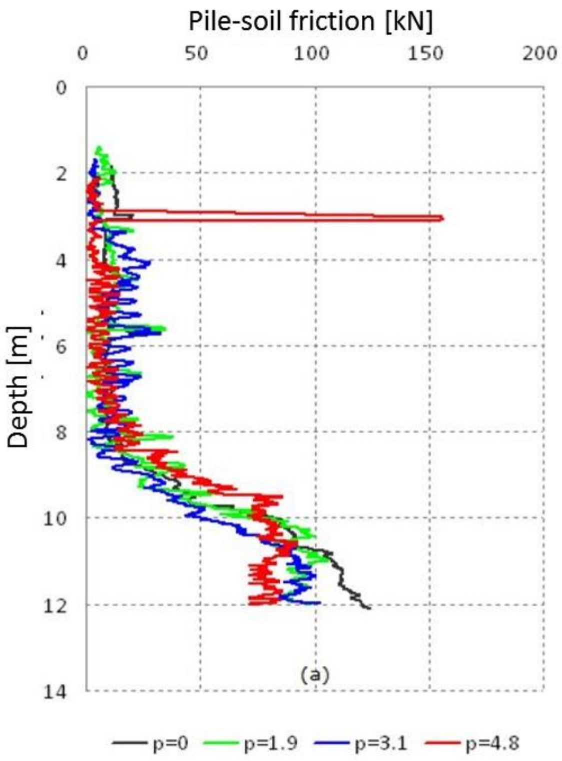


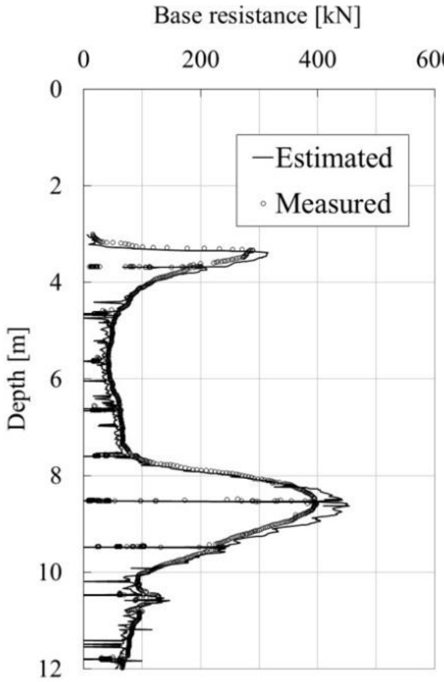
Fig. 41 Pile-soil friction calculated from Q_s and T_s (Bond, 2011)

Of these, **Eq. (9)** is based on the assumption that both Q_b and T_b are expressed by a unit base resistance (q_b), while **Eq (10)** is obtained by assuming that a pile-soil friction is shared by Q_s and T_s with the velocity ratio of v_d to v_r. The latter assumption was discussed by White *et al*. (2010) as shown in **Fig. 17**, which was confirmed as valid when the velocity ratio was smaller than 5 as shown in **Fig. 41** but as invalid for greater velocity ratio due to the effect of excess pore water pressure (Bond, 2011). Comparison of estimated and measured values of Q_b in **Fig. 42** (Ishihara *et al*., 2015c) demonstrates the validity of **Eqs. (7) - (10)**.

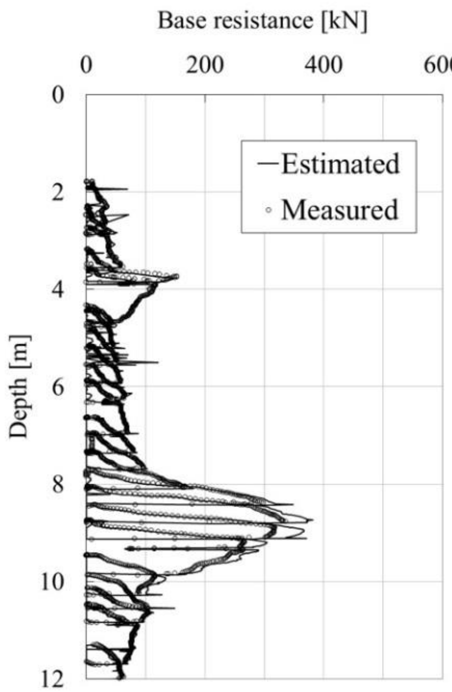
5. Performance of a sheet pile wall

5.1. Deformation of different types of sheet pile walls

As discussed in **2.17.**, three types of sheet pile walls were constructed, and their deformation due to a surcharge was compared (Gao, 2014). As summarized in **Fig. 43**, the horizontal displacement of the IP Wall due to a surcharge of 20kPa was reduced by 99% at the wall head and 74% for the entire wall, compared with that of



(a) C11-10, without repeated penetration and extraction



(b) C11-13, with repeated penetration and extraction

Fig. 42 Comparison of measured and estimated base resistance in rotary press-in (Ishihara *et al*., 2015c) the slanting wall (Ishihara *et al*., 2015a). Different deformation patterns were confirmed: the maximum displacement was found at the wall head in the slanting wall while it was found near the excavation base in the IP Wall.

5.2. Mechanism of the high stiffness of IP Wall

Two mechanisms shown in **Fig. 44** were conjectured for the higher stiffness of IP Wall. The first mechanism is the loading history of the soil in the excavation base. In IP Wall, the excavation base is preloaded horizontally, due to the Preload in the upper part of the wall. When the wall is applied with the surcharge, the excavation base experiences the second loading, in which it shows higher stiffness. This is similar to what can be seen in the load-unload-reload curve of a soil shown in **Fig. 31**.

The second conjectured mechanism is that, due to the elastic reaction from the wall, the horizontal stress of the soil behind the wall is increased, and subsequently, the Mohr's circle becomes smaller as shown in **Fig. 45** and the plastic region of the soil behind the wall decreases. This will reduce the displacement of the soil behind the wall.

Numerical analyses were carried out by ignoring the backfill materials (Ishihara *et al*., 2015a), and the two mechanisms were confirmed to exist. The first mechanism was more influential, presumably due to the ignorance of the backfill material in the analysis model.

5.3. Determination of the amount of the preload

A key issue in designing the IP Wall is the determination of the appropriate amount of the Preload. A simple method was proposed by focusing only on the first mechanism, as conceptually summarized in **Fig. 46**, in which the appropriate amount of the Preload should correspond to the amount of the surcharge in terms of the effect on the soil in the excavation side (Ishihara *et al*., 2015). In this concept, the deformation of the soil in the excavation side is represented by the summation of the horizontal displacement of the wall below the excavation base, while the effect of the Preload and the surcharge is commonly expressed by the combination of the horizontal load and moment at and around the cross point of the wall and the excavation base.

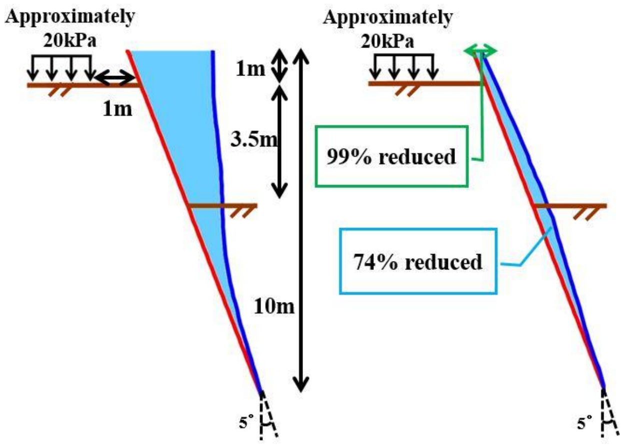


Fig. 43 Deformation of slanting wall and IP Wall due to surcharge (Ishihara *et al*., 2015a)

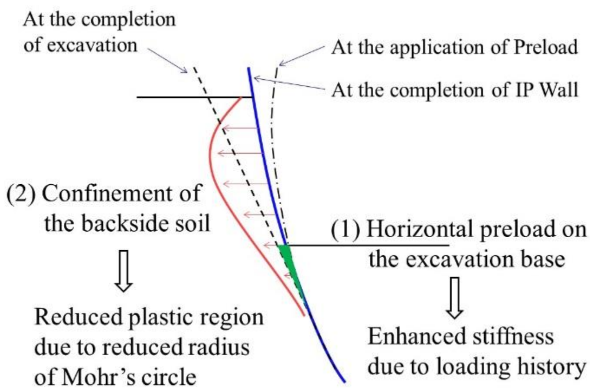


Fig. 44 Mechanism of performance of IP Wall

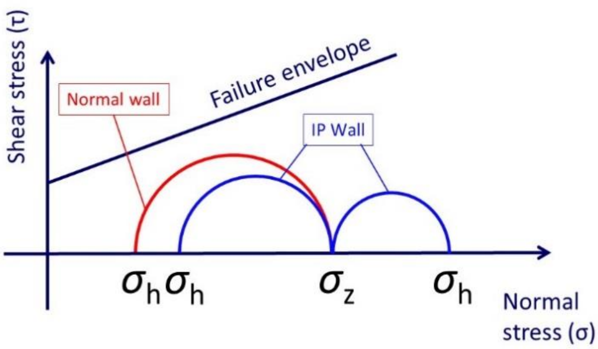
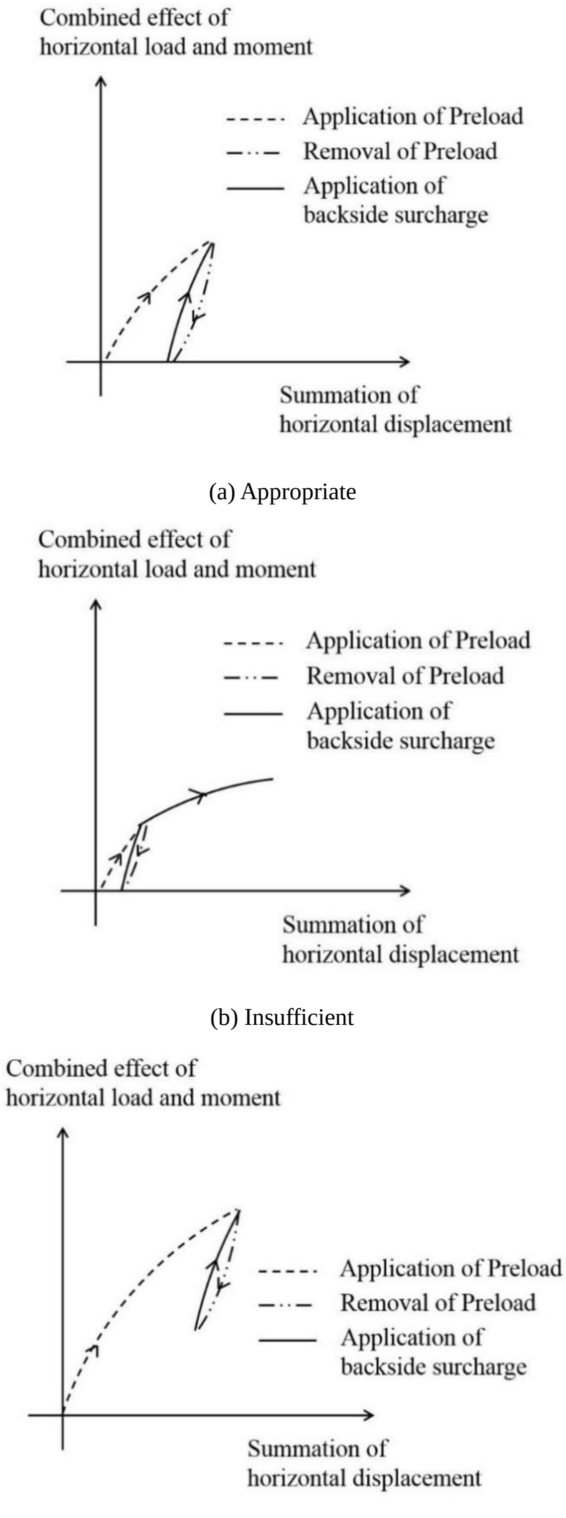


Fig. 45 Reduced radius of Mohr's circle due to Preload



(a) Appropriate

(b) Insufficient

(c) Excessive

Fig. 46 Conceptual diagram to determine the amount of Preload (Ishihara *et al*., 2015a)

6. Summary

The Cambridge - Giken collaboration research has focused on wide range of topics on press-in engineering since 1994, in terms of the mechanism of pile-soil interaction as well as the performance of piles and pile walls. The research findings suggest that 1) the pressed-in pile shows higher vertical and horizontal performance than piles installed by other methods, 2) the piling data can be utilized for estimating subsurface information and 3) sheet piles can be used not only for temporary structures but also as members of structures.

7. Acknowledgements

Technical and financial supports over the whole years of this joint research by Mr. Akio Kitamura, the continuous supervision and the provision of academic essences by Dr. Malcolm Bolton, technical advices from Dr. Kozo Tagaya, Dr. Masaaki Terashi Dr. Osamu Kusakabe and the members of IPA-TC2, are highly appreciated. Special contributions were made by Mr. Teruo Nagayama, Mr. Yukinori Horikawa, Mr. Yasutaka Yokotobi, Mr. Kensuke Inomata, Mr. Tatsuo Nose, Ms. Nanase Ogawa, Ms. Mai Nishigawa and Mr. Koichi Okada to complete the summer projects in Kochi.

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