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State of the art report on steel sheet pile method in geotechnical engineering -development of PFS method

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ABSTRACT: Steel sheet piles have been used mainly for the purpose of temporary works such as excavation and pre-construction structures. However, recently those application fields have been expanded to the permanent structures such as foundation structures. This paper is the state of the art report on steel sheet pile method as earth works. Recently, so called PFS method has been developed and the application fields, such as the countermeasure methods for any kinds of natural disasters including heavy rain and earthquake, are expanding. Based on these current situations, the recent development of the sheet pile method is summarized including the activities of Technical Committee No.3 under International Press-in Association. Finally, one of the recent developments on the construction technique, which is press-in method, is briefly summarized.

1 INTRODUCTION

When excavations or retaining works are done safely, some countermeasure techniques against ground failures are needed and sheet piles have been used not only in Japan but also around the world. Most of the sheet piles are made of steel and its shape is not plain plate but has some special shape. Figure 1 (Steel Sheet pile manual, 2014) shows some of the sheet piles in Japan and it has been standardized depending on the regions and countries. Sheet pile is one of the construction methods and had been often used as a temporary work such as for the case of excavation to stabilize cutting slope and often used as a wall with flexible stiffness in the soils to resist earth or water pressures. The applications in coastal engineering as a quay walls at the port and harbor are also quite familiar for the sheet piles. The functions of the sheet piles are categorized by following three topics (Steel sheet pile manual, 2014)

1) retaining structures including free-standing method, retractable one, and cut and saw,
2) impermeable structures, and
3) stress shut down.

The expected effectiveness can also be categorized as any countermeasures such as,

1) subsidence of soft ground,
2) stability with seismic actions,
3) reinforcement of main structures, and
4) reduction of environmental impacts.

Recently, the applications as permanent structures have been increased and those are as foundations or countermeasures for any natural disasters. In fact, the author has done a series of studies on the development of so called PFS (**P**artially **F**loating **S**heet pile) method for the countermeasure of ground subsidence due to river embankment construction and based on those studies, the PFS method has been implemented with its design concept (PFS method, Technical Manual, 2005)

In this paper, firstly, the steel sheet pile method in geotechnical engineering is summarized and details on the development of PFS method is introduced. Then, activities of the technical committee (TC3) on the topic of the steel sheet pile method, which was established under International Press-in Association (IPA) from 2017 to 2019, are briefly presented with the studies made on effectiveness of the method as countermeasures against natural disasters such as earthquakes. Summary of this TC activities presented in this paper includes not only the effectiveness of the method itself but also some practical construction techniques and design methodologies well associated with the press-in technique.

2 DEVELOPMENT OF THE PFS METHOD

2.1 *Overview*

The sheet pile method has been used as a permanent structure for the prevention technique on slope failures. For the case of embankments constructed along rivers, sheet piles have been sometimes employed at the toe of the embankment for the purpose of stress cut off from the surrounding ground to reduce subsidence of the area where the private houses are closely

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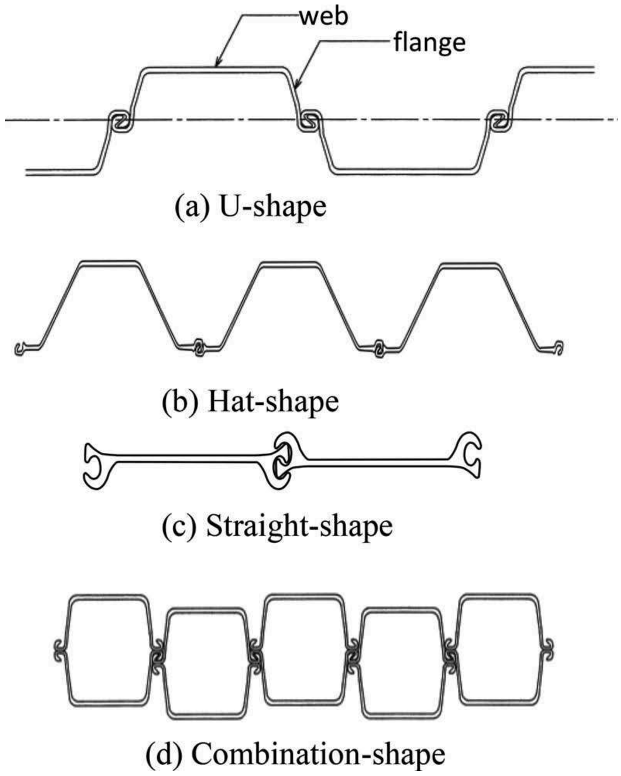


Figure 1. Different types of sheet piles (Steel sheet pile manual, JASPP, 2014).

located along rivers. Such a situation is frequently encountered when the embankment is constructed on soft ground. In such a case, the ground not only under the embankment but also adjacent ground may suffer a serious subsidence problem. Then, some countermeasures have to be considered. A steel sheet pile method is one of the candidates for this type of problem as shown in Figure 2. However, it has a cost problem especially when the area and depth of soft ground are wider and deeper. Now, a development of new sheet pile method is strongly awaited. In 1975, a collaborative study was started between Kyushu University and the Ministry of Construction (Ministry of Land, Infrastructure, Transportation and Tourism at present) in Japan. Under this collaboration, a series of in-situ full scale tests were conducted in Kyushu area. Based on those activities, a technical committee for developing a new sheet pile method was established in 2003 in which the chair was Prof. Hidetoshi Ochiai, Professor Emeritus of Kyushu University, Japan. In 2005, a new sheet pile method called PFS method was proposed under the activities of this committee. In this method, the end bearing sheet pile and that of floating type were combined to deal with its effectiveness and cost as shown in Figure 3. Figure 4 shows the details of this structure (PFS Method, Technical Manual, 2005).

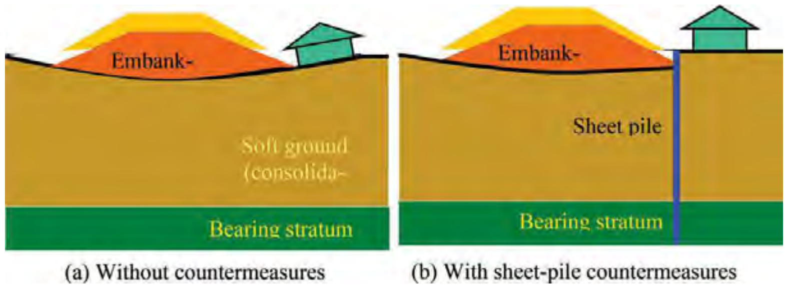


Figure 2. Sheet-pile countermeasures.

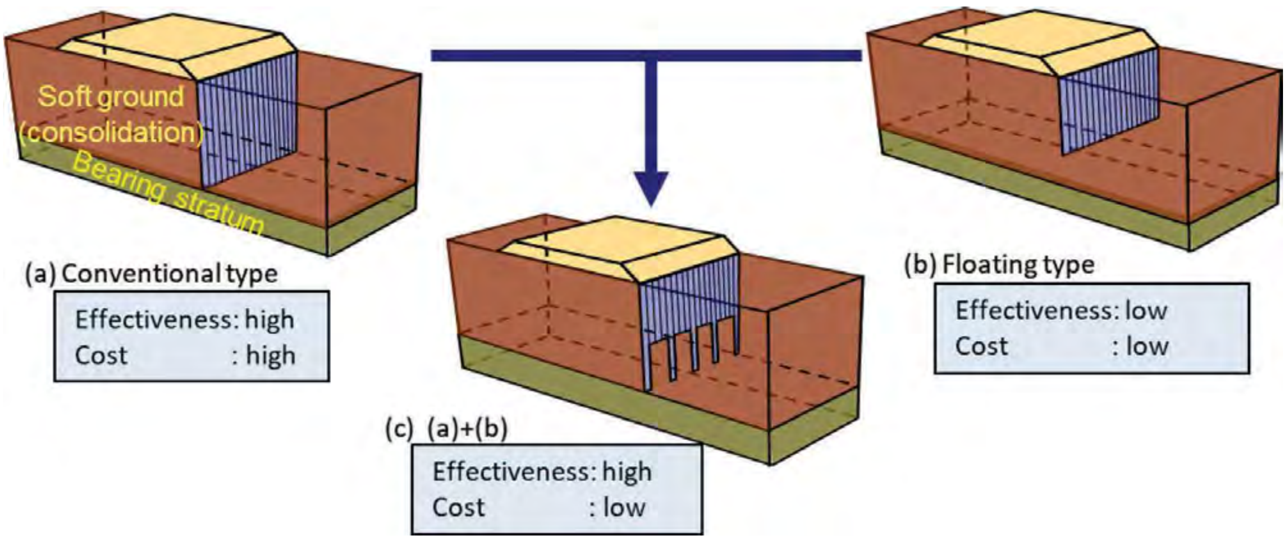


Figure 3. Idea of PFS method.

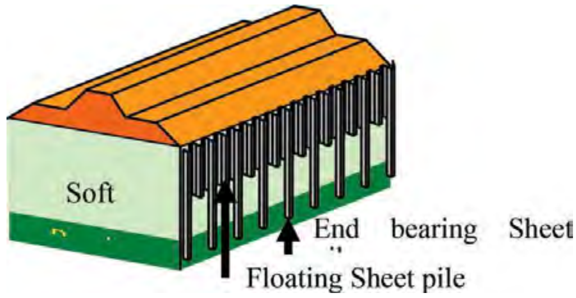


Figure 4. PFS method.

Photo 1. Photo. after the PFS construction.

2.2 *In situ experiments*

A large number of in-situ full scale tests for PFS method were conducted in Kumamoto City, Japan. This area is well known as a region of Ariake clay which is highly sensitive clay and its depth is up to 40m. Figure 5 shows the soil profile at the site of in-situ test for PFS method. In this case, one end bearing sheet pile with five floating sheet piles were constructed as one unit of the sheet piles. Figure 6 shows the results of measurement for the subsidence at the site and Photo 1 shows the view of the site after PFS construction. Since a large volume of sheet pile materials were reduced, the cost of the PFS method is obvious and the construction time was also highly reduced because of the less volume of the sheet piles.

2.3 *Concept of design*

Under the activities of research committee of the PFS method, a simple design method was proposed in 2003 and this idea is shown in Figure 7 which is the combination of spring with beam elements. It is noted that the basic idea, in the beginning, is the consideration of only vertical displacement.

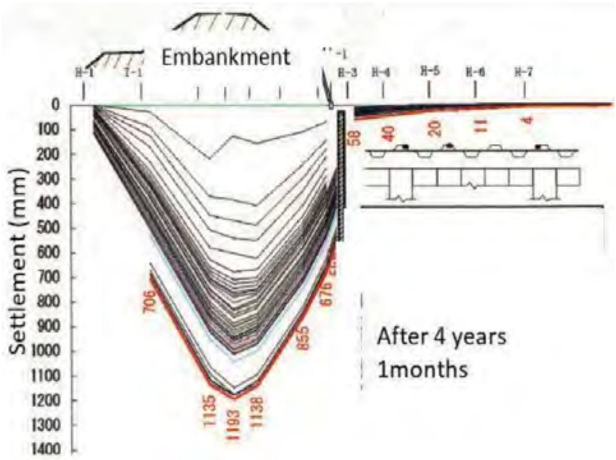


Figure 6. Results of measurements.

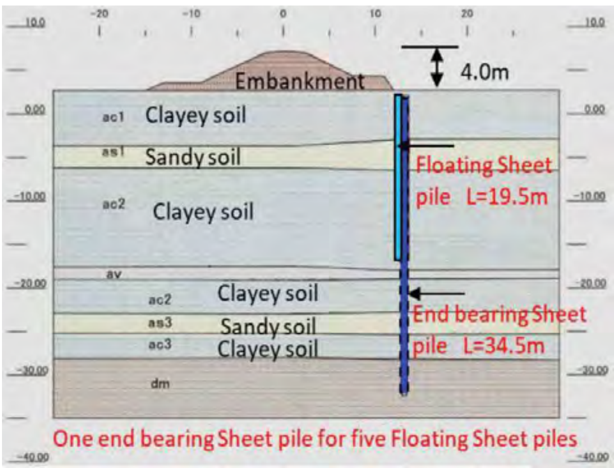


Figure 5. Ground condition at the site.

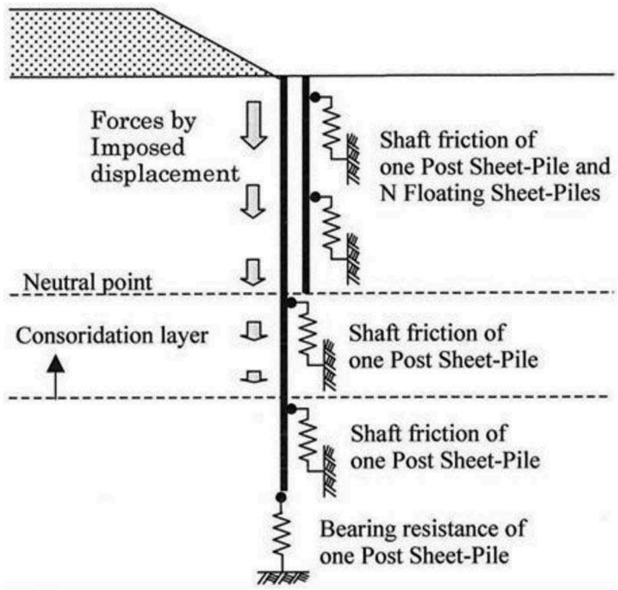


Figure 7. Simplified design model.

3 CURRENT ACTIVITIES ON THE DEVELOPMENT OF THE STEEL SHEET PILE

3.1 *Introduction of technical committee No.3 under IPA*

Steel sheet pile method has long been used as a temporary construction work but in recent years, it has been used as a permanent structure including the applications on the port and harbor structure. The PFS method is one of the methods to construct near the toe of the embankment as a measure to settle the embankment construction on soft ground, and this method is a partially floating sheet piles with the combination of the end bearing sheet piles and its cost effectiveness and construction feasibility can be easily recognized. Regarding the steel sheet pile method, the effectiveness under the earthquake motion has been also reported in the recent 2011 off the Pacific Coast of Tohoku Earthquake and the 2016 Kumamoto Earthquake in Japan but there are still the needs for the quantitative discussion to clarify the effectiveness of the method.

The objective of this committee is to propose the quantitative scope of application such as the quantitative discussion on the lateral displacement of the ground due to embankment construction and also to discuss its effectiveness and performance under the earthquake. In fact, the idea of starting this technical committee was based on the “PFS method technical manual” published in March, 2005 by the PFS research committee. Although it summarizes the policy on design and construction, those were based on the limited field data, so that it needs to include the general condition such as earthquake performance. Specifically, as an activity for three years from 2017 to 2019, the following terms of reference were shown:

1) To reconsider the quantification of the lateral displacement of the ground as a condition for the use of countermeasures against subsidence;
2) To discuss the precise performance of PFS method under the earthquake;
3) To propose guidelines for the application of the PFS method, and
4) To disseminate this method in Asia.

First, for 1), the concept of lateral displacement conditions as application conditions of this method from both experimental and numerical analysis is summarized with aiming at the propose of the design manual. With regard to 2), using the results of centrifugal model tests and dynamic finite element analyses, the behavior under dynamic loading of this method is confirmed and the earthquake resistance should be validated. For 3), the design manual draft is prepared. Lastly, for 4), a series of seminar with the contents of this committee’s activities are organized every year in Asia. In addition, securing young talent in the construction industry today is widely concerned. Therefore, the committee will promote younger engineers and researchers to support their activities. The other point is to disseminate the information internationally on our technology.

In this committee, members from industry, government, academia, stakeholders and experts were selected. We established five WGs (Working Groups) with the aim of making the missions of the committee clear. Those are

1) WG1 (Field investigation): Data collection and analysis of the steel sheet pile construction method in Kumamoto after the 2016 Kumamoto earthquake;
2) WG2 (Laboratory experiments): Preliminary experiments and basic behaviors by centrifugal model tests;
3) WG3 (Numerical analysis): Determination of analytical condition (analysis case) and numerical modeling;
4) WG4 (Design): Confirmation of the basic matters concerning the design of the PFS method; and
5) WG5 (Overseas): Seminar on steel sheet piling method in Asia

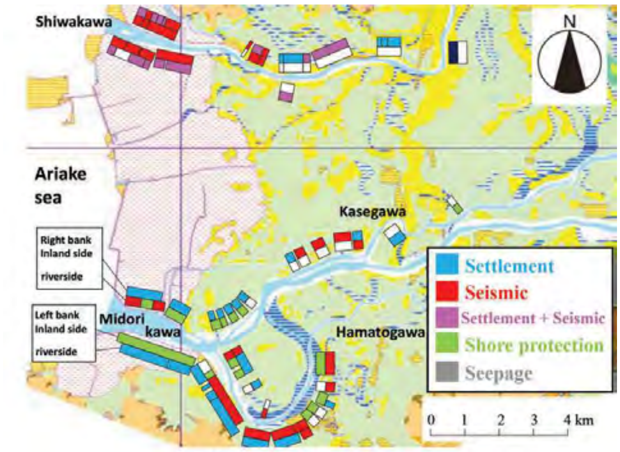
Those WG activities are summarized in this paper.

3.2 *WG1: Field investigation*

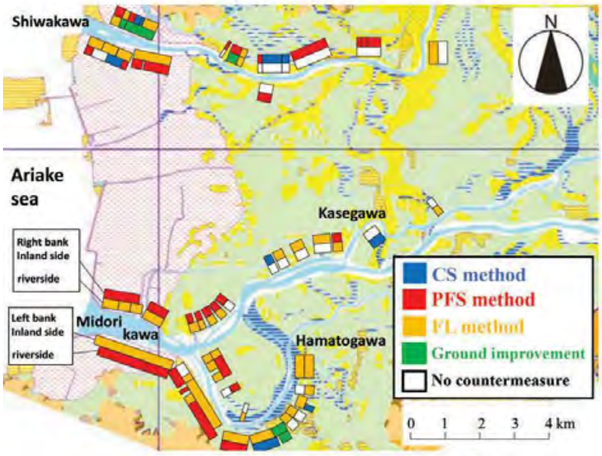
In this section, research outcomes of WG1 (field investigation) will be outlined. Details of some of these researches can be found in Yamamoto *et al.* (2018a), Yamamoto *et al.* (2018b), Yamamoto (2019), Kasama *et al.* (2019) and Kasama *et al.* (2020).

3.2.1 *Application of the steel sheet pile method in Kumamoto Prefecture*

Figure 8 shows the location and purpose of the steel sheet pile construction method in the Shirakawa, Midorikawa, Hamato and Kase Rivers in the Kumamoto Plain. The left and right sides of the river are indicated in two colors, respectively, and the color of the side near the bank indicates the front side of the river (outside of the bank) and the side farther from the bank indicates the back side of the river (inside of the bank). In some sections, solidification is used for ground improvement, but most of the sections are reinforced with steel sheet piles. In Shirakawa River located in the northern part of the Kumamoto Plain, the inner side of the embankment near the house was reinforced for the purpose of only subsidence or both subsidence and earthquake resistance, while the outer side of the embankment was reinforced for earthquake resistance. In terms of construction methods, various combinations of bottoming out, the methods of PFS, FL (Floating) and ground improvement were used to reinforce the embankment near the mouth of the river. This is because field tests were conducted between 1995 and 2000 to investigate the effects of combinations of these methods. The FL method was also used at a point 9 km from the mouth of the Shirakawa River.



(a) Purpose of countermeasures



(b) Type of steel sheet pile method

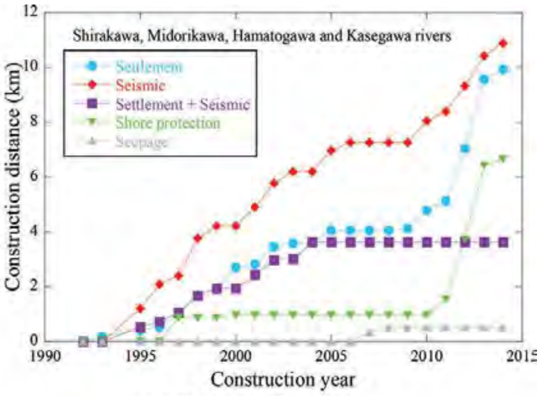
Figure 8. Location of steel sheet pile method.

A reinforcement of the embankment was carried out on the inner side of the Midorikawa and Hamato Rivers to prevent subsidence, and on the outer side of the embankment, reinforcement of the embankment was carried out for the purpose of constructing a revetment using earthquake resistance measures or sheet pile method. Most of the river embankments were reinforced by the PFS and FL methods on the inner and outer sides of the embankment, respectively. In the case of Kase River, which is in the middle of Midori River, no countermeasures were taken on the outer side of the bank, and the inner side of the bank was partially reinforced by the embankment by PFS and FL methods. Table 1 shows the statistics of the sheet pile lengths used for each method in the rivers. The column of PFS method shows the sheet pile lengths of both end bearing and floating sheet piles used and their sheet pile length ratios. The average sheet pile lengths for end bearing (CS method) and floating method (FL method) are 34.2 m and 14.6 m, respectively, indicating that the end bearing sheet pile is about twice as long as the FL method. In the meantime, the average end bearing and floating sheet pile lengths of the PFS method are 38.7 m and 25.5 m, respectively. Figure 9 (a) shows the trend of construction period

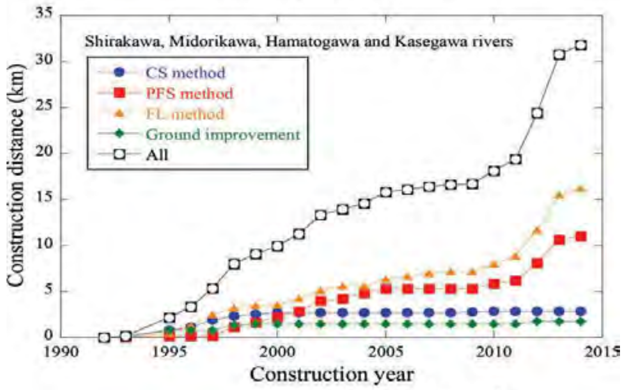
Table 1. The statistics of sheet pile length.

	No.	Mean (m)	Mode (m)	COV^*	Min (m)	Max (m)
CS method	35	34.2	37	0.24	14	42
FL method	121	14.6	15	0.41	8	30
PFS method						
End supporting	99	38.7	40.5	0.13	28	53
Floating	99	25.5	25.5	0.22	11.5	36.5
Ratio**	99	0.66	0.86	0.20	0.27	0.90

* The coefficient of variation
** The ratio of floating sheet pile and end supporting sheet pile



(a) Purpose of counter-



(b) Type of steel sheet pile

Figure 9. Construction history.

of steel sheet pile method and ground improvement classified by purpose and construction method. The construction period of the sheet pile method and sheet pile revetment has been increasing at a constant rate and the construction period of the sheet pile revetment has been increasing rapidly since 2010. On the other hand, the volume of steel sheet pile construction method, which is the objective of both subsidence control and earthquake resistance, has remained unchanged since 2004. Figure 9 (b) shows the relationship between the year of construction and the length of construction of each sheet pile method in the four rivers of the Kumamoto Plain. Here, it is easily realized that the number of construction of the PFS and FL methods has increased rapidly after 2010. It is noted that Figure 10 shows the flow chart of the design method for the steel sheet pile due to earthquake motion. This idea is based on the liquefaction problem on river embankment construction.

3.2.2 *Adaptation of the steel sheet pile method in Kumamoto Prefecture*

The subsidence of the river embankment after the Kumamoto earthquake was calculated based on the cross-sectional survey at the top of the embankment conducted by the Kyushu Regional Bureau of the Ministry of Land, Infrastructure, Transport and Tourism at a pitch of 200 m and this survey was conducted immediately after the earthquake. In the case of damage to the embankment caused by the Kumamoto earthquake, the subsidence of the embankment was not so large as to cause the loss of the embankment function, because the water level of the embankment was lower than the outside water level of the Tohoku earthquake. Figure 11 shows the probability density distributions of the subsidence of each type of embankment. The legend in the figure. shows the type of sheet piling method for the inner side of the embankment. The subsidence of the no countermeasure section is measured at 551 points and is distributed over a wide range of -1.28 m to 1.56 m, whereas the subsidence of the section reinforced by the various steel sheet piling methods is concentrated in the range of -0.08 to 0.39 m. In order to investigate the effect of various

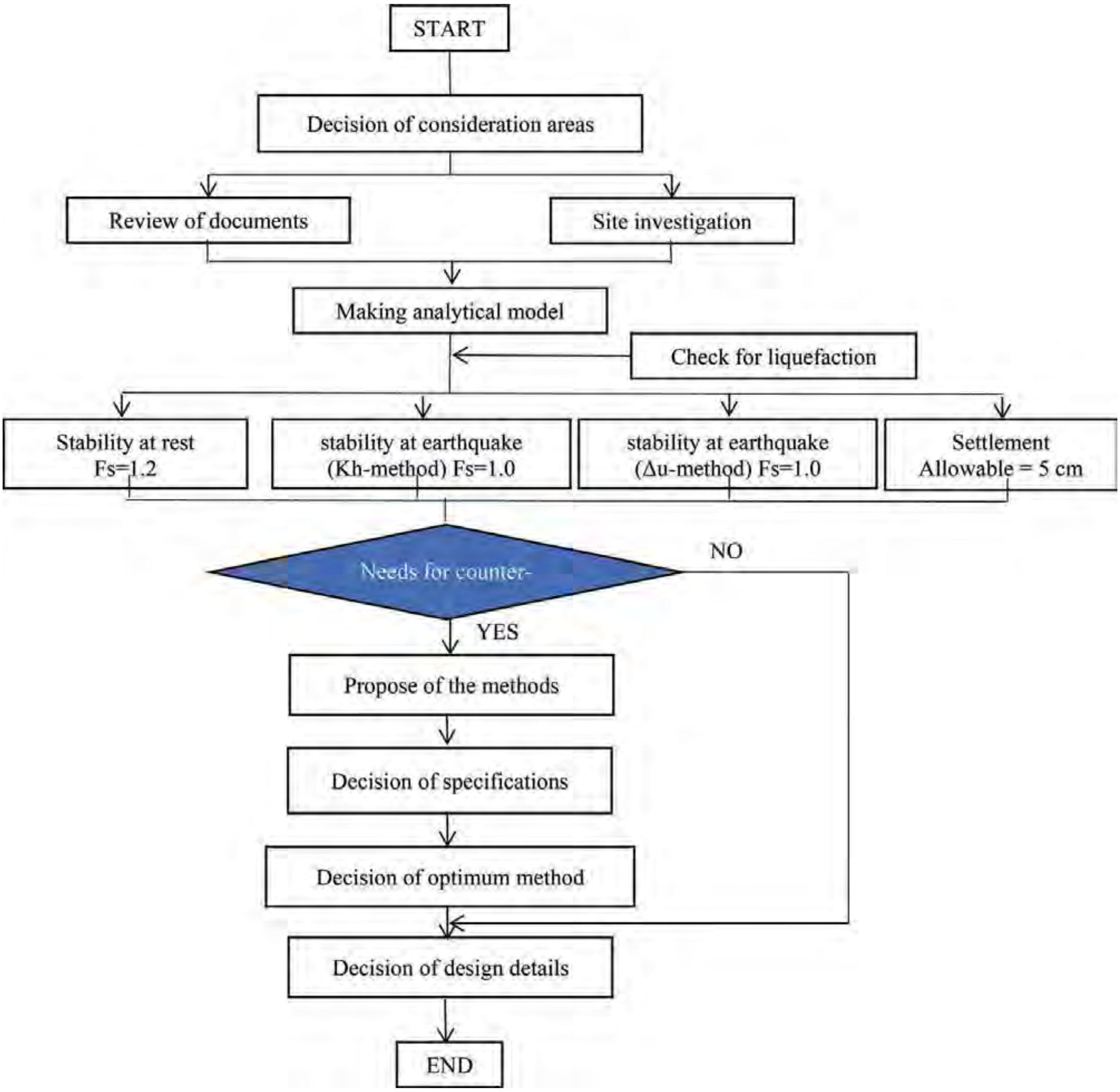


Figure 10. Design chart for earthquake.

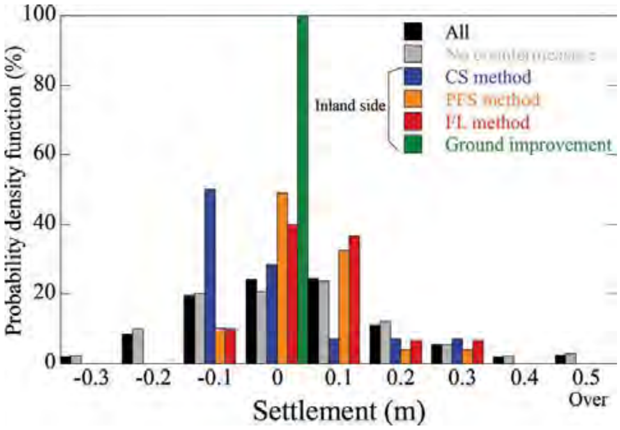


Figure 11. Probability density function of Settlements.

methods and combinations of methods on subsidence control, Table 2 summarizes the statistics of subsidence caused by earthquakes. There are 14, 49 and 15 points in the embankment where the CS, PFS and FL method were applied, respectively, and combination of FL method, ground improvement and no countermeasure was applied on the outer side of the embankment. In addition, there were 15 points where FL method was applied on the outer side of the embankment and no countermeasure was applied on the inner side of the embankment, and there was one point where both the inner and outer sides of the embankment were improved. When the inner side of the embankment was reinforced by the embankment, the average subsidence of the embankment was the largest and the range between the maximum and the minimum values varied widely from -0.08 m to 0.39 m for the embankment method and the FL method. The mean subsidence of

Table 2. Statistics of seismic settlement.

Island side	River side	No.	Mean	*COV**	Max (m)	Min (m)
All		645	0.10	2.24	1.56	-1.28
No Countermeasure		551	0.10	2.36	1.56	-1.28
Countermeasure		64	0.09	1.06	0.39	-0.08
CS method	FL method	4	0.15	1.44	0.39	-0.08
	GI**	2	0.03	1.41	0.07	0.00
	No	8	0.01	5.06	0.13	-0.07
PFS method	FL method	29	0.11	0.84	0.38	0.00
	GI**	3	0.08	1.09	0.15	-0.02
	No	17	0.04	0.90	0.14	-0.01
FL method	FL method	4	0.08	1.11	0.15	-0.04
	GI**	3	0.09	0.73	0.16	0.05
	No	8	0.16	0.39	0.26	0.08
No GI**	FL method	15	0.13	1.00	0.39	-0.06
	GI**	1	0.05	-	0.05	0.05

* : The coefficient of variation
** : Ground improvement

the embankment with the CS method (inside the embankment) and the ground improvement method (outside the embankment), and the no countermeasure (outside the embankment) was 0.03 m and 0.01 m, respectively, which is almost zero. When the inner side of the embankment was reinforced by the PFS method, the average subsidence of the embankment reinforced by the FL method (outside of the embankment), ground improvement (outside of the embankment), and no countermeasure (outside of the embankment) was 0.11 m, 0.08 m, and 0.04 m, respectively, which is a small value. When the embankment was reinforced by the FL method, the mean subsidence was slightly higher than 0.16 m and 0.13 m for either the inner or outer side of the embankment, respectively. In addition, the subsidence of the embankment reinforced on the outside of the embankment tended to be larger than that of the other methods, for example, 0.39 m was observed at the point where the embankment was reinforced by the FL method. The average subsidence of the combination of FL reinforcement and ground improvement was 0.08 m and 0.09 m, respectively.

3.3 *WG2: Laboratory experiments*

In this section, research outcomes of WG2 (laboratory experiments) will be outlined. Details of some of these researches can be found in Hizen *et al.* (2018), Kijima (2018), Inoue (2019), Iwasaki (2019), Kashiwagi (2019), Akimoto (2020), Kijima (2020) and Oka (2020).

3.3.1 *Earthquake resistance of PFS in liquefied ground: Centrifuge Model Test*

The behavior of the PFS in liquefied ground was investigated by centrifuge model tests. The equipment used was a beam-type centrifuge with an effective radius of 1.5 m owned by Kansai University. The scale of the model was set to 1/50 (centrifugal acceleration 50*g*, *g* is the acc. due to gravity), and the ground was a two-layered ground (10.0 m thick, 22.5 m wide, and 10.0 m deep in prototype scale) consisting of loosely packed saturated sand (Toyoura standard sand) and clay (kaolin + gypsum) (Figure 12). The thickness of the PFS model (model scale: 1.2 mm) was determined so that the bending stiffness was the equivalent to that

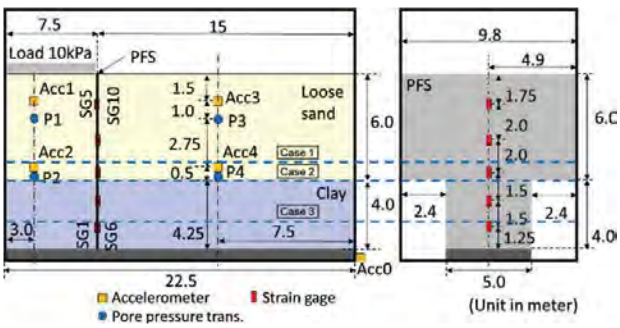


Figure 12. Cross sectional view of model test (for Case 2).

of the U-shaped sheet pile type 3. The PFS model consisted of two parts; one is the end-bearing sheet pile with 10 m in length and 9.8 m depth, and the other is floating sheet piles with 6 m in length and 5 m depth. The bottom edge of the end bearing sheet pile model was fixed for both rotation and displacement. A stainless steel plate as the embankment load with a distributed load of 10 kPa was applied to the ground surface. A half-section model was used for all experiments, with the symmetry axis at the center of the embankment cross-section. The test was conducted in three cases as shown in Table 3, and the embedment depth of the floating sheet pile was varied by changing the thickness of the upper sand layer. As shown in Figures 13(a)-(c), the input acceleration is a tapered sinusoidal wave lasting for 20 seconds. 5 accelerometers (Acc 0~Acc 4), 4 pore water pressure transducers (P1~P4), 10 strain gages on the sheet pile (SG1~SG10) were installed in the model. Also settlements of ground surface, and lateral displacements of the steel sheet pile were measured by hand.

3.3.2 *Results of centrifuge tests*

The acceleration responses under the embankment (Figures 13(d)-(f)) show a large decay in amplitude in all cases, reflecting the liquefaction of the ground. In Case 2, there is a tendency of one-sided oscillation, which may be due to the dilatancy spike caused by the displacement of the sheet pile.

Table 3. Test cases.

	Layer thickness (m)			
	Sand	Clay	Dr (%) of sand	Input PGA (m/s^2)
Case 1	5.0	5.0	60.3	1.7
Case 2	6.0	4.0	51.9	1.0
Case 3	8.0	2.0	45.4	1.0

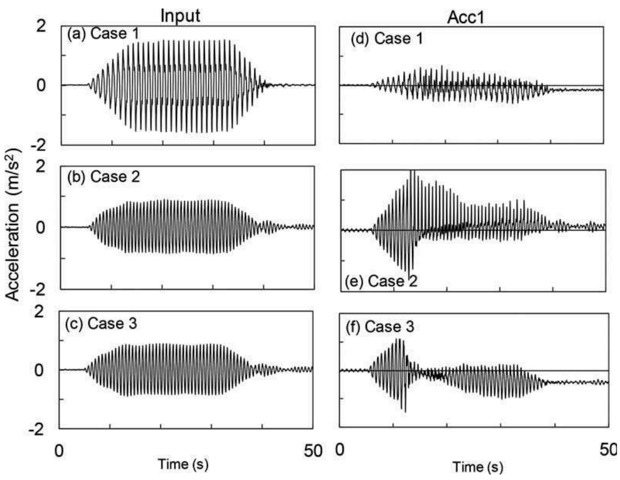


Figure 13. Time history of earthquake record (input and accl).

As for the settlement of the ground surface due to excitation, Figure 14 shows that the average settlement of the entire ground surface is 0.33m to 0.35m, while the settlement of Case 3 is 0.49m larger than that of Case 2. In addition, the settlement of the free ground is the smallest in Case 3, suggesting that the free ground was uplifted due to the large displacement of the sheet pile in Case 3.

The profile of bending moment calculated from the sheet pile strain (Figure 15) shows that the maximum value of the bending moment in Case 1 and Case 2 is found near the corner between the end-bearing sheet pile and floating sheet pile, while it occurs at the bottom in Case 3. This means that if the bottom of the floating sheet pile is not rooted in the non-liquefied layer (Case 3), the sheet pile may be deformed significantly by the lateral flow of sand due to liquefaction. The amount of deformation depends on the bending stiffness of the bottom of the sheet pile. However, it is necessary to root the bottom of the floating sheet pile into the non-liquefied layer when liquefaction is expected.

3.4 *WG3: Numerical analysis*

In this section, research outcomes of WG3 (numerical analysis) will be outlined. Details of some of these researches can be found in Nakai *et al*. (2018), Fujiwara *et al*. (2019) and Fujiyama (2020).

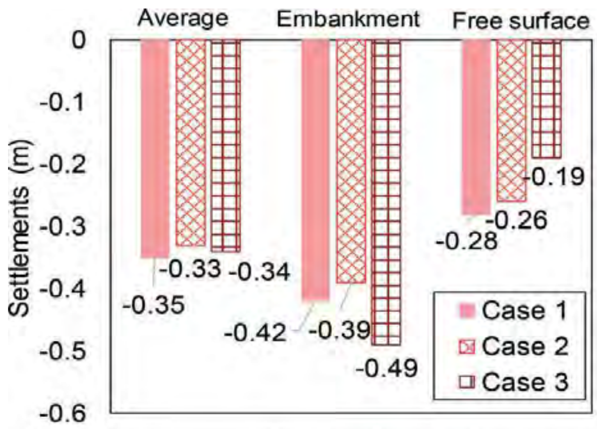


Figure 14. Ground subsidence due to earthquake.

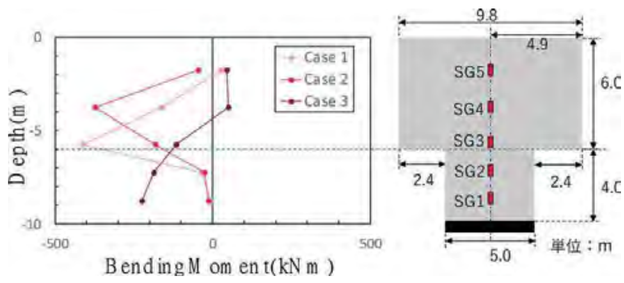


Figure 15. Distribution of bending moment at the maximum stage.

3.4.1 *Verification of lateral displacement suppression effect during embankment construction*

When constructing embankments on soft ground, the PFS method is effective in suppressing subsidence of the embankment due to the edge cutting effect, without the need for continuous placement of steel sheet piles up to the support layer as in the past. On the other hand, the effect of suppressing lateral displacement to the embankment land has not been fully verified. Therefore, in this section, we verified the lateral displacement suppression effect of the PFS method during embankment construction, paying particular attention to the stratum composition. Figure 16 shows the finite element mesh used in the analysis. The analysis code is the 3D finite element method program FEMtij-3D, and a linear elastic body is used for the sand layer and an elasto-plastic body (Sekiguchi-Ohta model) is used for the clay layer as the constitutive model of the ground material. The embankment height was 3.4 m and the crown width was 6.0 m, referring to the actual river embankment in the Kikuchi River, Kumamoto Prefecture. The material parameters were determined based on the results of the ground survey conducted at the same location. Figure 17 shows a model diagram of the PFS sheet pile. In this study, the spacing between the end bearing sheet piles was fixed at 5, and the embedment length of the PFS sheet piles was changed in 3 ways. Table 4 shows the stratum composition. The total stratum thickness was fixed at 30 m, and the clay layer thickness and sand layer thickness were systematically changed.

(1) Lateral displacement in unmeasured ground

Figure 18 shows the distribution of lateral displacement during embankment construction on unmeasured ground, and Figure 19 shows the relationship between the maximum lateral displacement and the sand thickness ratio. Looking at Figure 18, it can be seen that the thinner the sand layer on the surface is the larger the lateral displacement becomes. When there is no sand layer on the surface and only the clay layer, the lateral displacement is particularly large and reaches up to 80 cm. It was also found that the maximum value of lateral displacement occurs near the boundary between the sand layer and the clay layer.

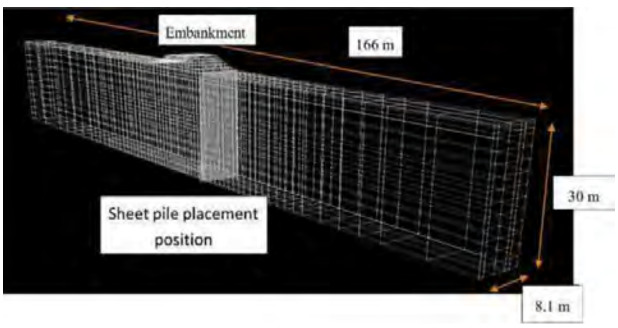


Figure 16. Finite element mesh.

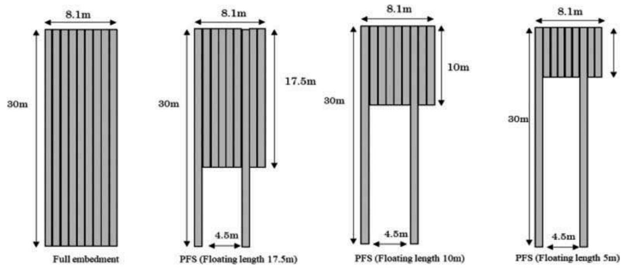


Figure 17. Examination model of PFS method.

Table 4. Stratum composition used for the study.

Clay	30m	29.5m	27.5m	25m	20m	15m
Sand	0m	0.5m	2.5m	5m	10m	15m
Total	30m					

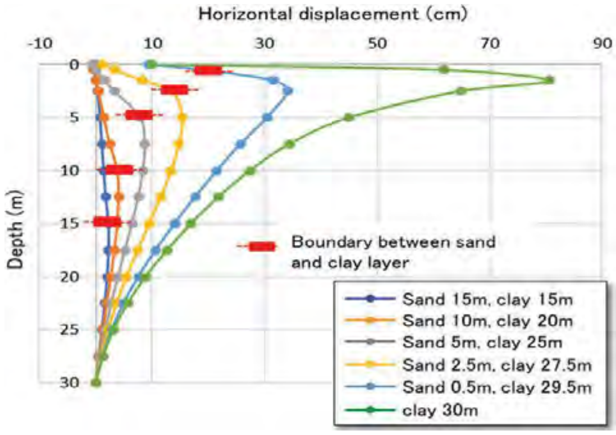


Figure 18. Lateral displacement distribution with respect to the depth direction in case of non-countermeasure.

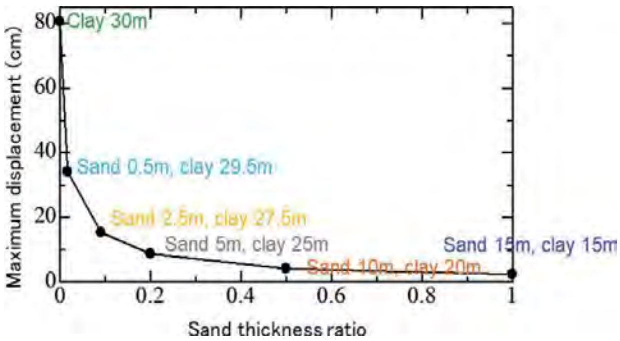


Figure 19. Relationship between maximum lateral displacement and stratum composition in case of non-countermeasure.

(2) Lateral displacement in sheet pile reinforcement ground

Figure 20 shows the relationship between the maximum lateral displacement and the sand thickness ratio with respect to the all-landing sheet pile

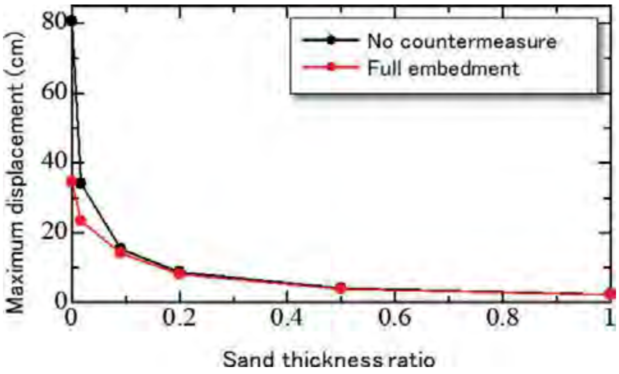


Figure 20. Relationship between maximum lateral displacement and stratum composition in case of full-embedment countermeasure.

reinforcement ground (the figure is omitted, but the maximum value of the lateral displacement occurs near the boundary between the sand layer and the clay layer, which is common to the unmeasured ground.). Although the lateral displacement is reduced compared to the unmeasured ground, large lateral displacement occurs when the sand layer on the surface is thin.

(3) Lateral displacement in PFS sheet pile reinforcement ground

Figures 21 and 22 show the relationship between the maximum lateral displacement and the sand thickness ratio with respect to the PFS sheet pile reinforcement ground. Figure 21 shows the PFS sheet pile with a long embedment length of 10 m, and Figure 22 shows a short embedment length of 5 m. In addition, ● indicates the maximum lateral displacement in the end bearing sheet pile, and ▲ indicates the maximum lateral displacement in the floating sheet pile. When the floating sheet pile length is long (Figure 21), the countermeasure effect is almost the same as that of all-landing sheet pile reinforcement ground, and the lateral displacement suppression effect of the PFS method when there is a sand layer on the surface layer can be confirmed. On the other hand, when the floating sheet pile length is short (Figure 22), the lateral displacement is large in the region where the sand thickness ratio is small. This is due to the soil slipping through and squeezing out from the floating sheet pile, suggesting that the PFS sheet pile reinforced ground does not have a sufficient lateral displacement suppression effect when the floating sheet pile length is short. In this section, using 3D FEM analysis, the lateral displacement suppression effect of the PFS method in sand-clay alternating layer ground was verified by focusing on the sand thickness ratio. As a result, the following conclusions were obtained. If there is not enough sand layer on the surface (sand thickness ratio is 0.2 or less), even if the steel sheet pile method (total landing/PFS method) is used, the amount of lateral displacement during embankment construction cannot be sufficiently suppressed. However, if there is a sand layer on the surface and the sand thickness ratio is 0.2 or more, the lateral displacement can be suppressed by the steel sheet pile method. When using the PFS method, if the floating sheet pile length is short, the ground will slip through and squeeze out in the floating part, and a sufficient lateral displacement suppression effect cannot be obtained. Therefore, the floating sheet pile length should be set appropriately (sufficiently long).

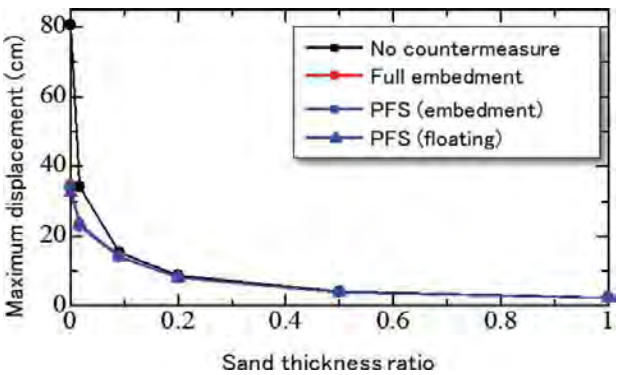


Figure 21. Relationship between maximum lateral displacement and stratum composition in case of PFS method (embedment depth of floating piles are as deep as 10m).

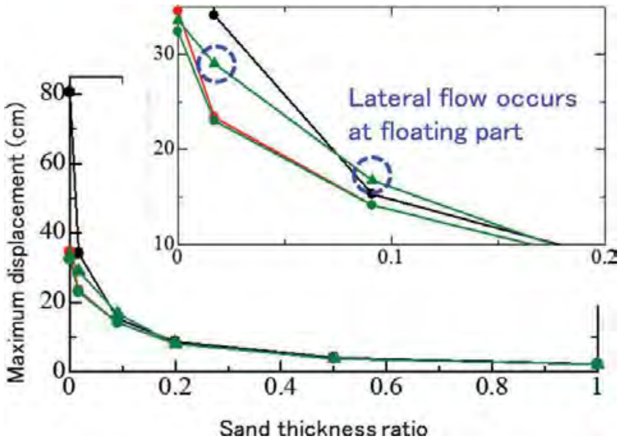


Figure 22. Relationship between maximum lateral displacement and stratum composition in case of PFS method (embedment depth of floating piles are as shallow as 5m).

3.4.2 *Seismic performance verification in the event of an earthquake*

In the Kumamoto earthquake (2016), there are many reports that the seismic effect was exhibited in the PFS sheet pile reinforced ground constructed as a countermeasure against the subsidence of the embankment. Therefore, in this section, the seismic performance verification of the PFS method was performed numerically. Although the PFS sheet pile reinforcement ground is a three-dimensional problem, it is difficult to carry out a three-dimensional analysis of the actual ground on a regular basis. Therefore, first, we propose a simple two-dimensional modeling method for the PFS method. After that, seismic performance verification of PFS sheet pile reinforced ground in sand-clay alternating layer ground was carried out.

3.4.3 *Numerical analysis of ground slip-through behavior between end bearing sheet piles and floating sheet piles*

A seismic response analysis using a simple model was performed to understand the ground slip-through behavior between the end bearing sheet pile and the floating sheet pile. The analysis code used is the liquefaction analysis program LIQCA (Oka *et al*., 1994; Oka *et al*.,1999). Figure 23 shows the finite element mesh used in the analysis. A 1/4 cross-section model assuming symmetry was used. 8 m from the surface layer is assumed as a liquefied layer with a relative density of about 40% and 4 m below is assumed as a non-liquefied layer with a relative density of 90%. A sine wave with an amplitude of 9.0 m/s^2 and an input frequency of 3.0 Hz was applied to all nodes at the lower end for 10 seconds. Figures 24 and 25 show the distribution of lateral flow (horizontal displacement) due to liquefaction at the piles and floating sheet piles when the floating sheet pile length is 7m and 1m, respectively (the pile spacing is 1.0, 2.5, 5.0 and 10.0). The amount of lateral flow of the PFS sheet pile method is less than that of the unmeasured ground. On the other hand, in the floating sheet pile section, lateral flow at the lower part of the floating sheet pile is larger when the distance between the piles is wider or the embedment length of the floating sheet pile is shorter. This trend is similar to that of the lateral displacement during embankment construction shown in Section 1.1. Figure 26 is a cross-sectional view of the horizontal displacement at a depth of 7 m when the floating sheet pile length is 1 m. An arcuate lateralflow is generated starting from the end

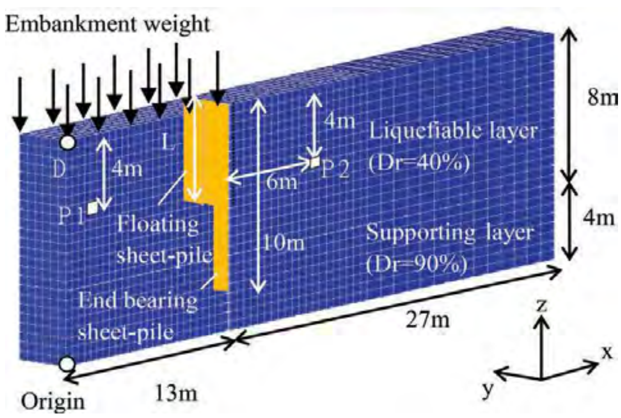


Figure 23. Finite element mesh.

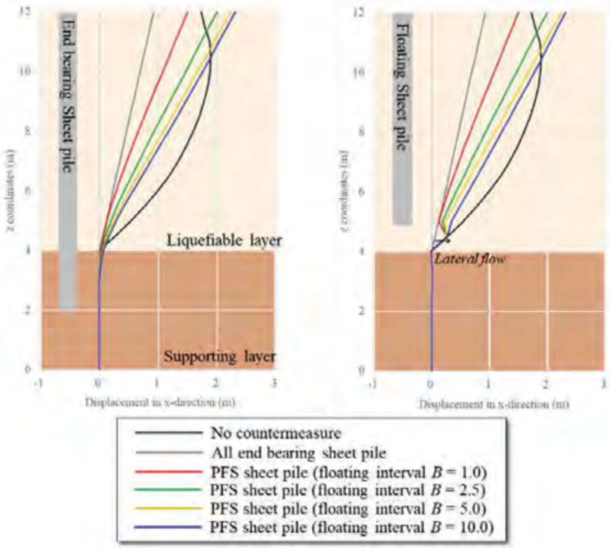


Figure 24. Distribution of lateral flow due to liquefaction in PFS method with its floating pile embedment 7m.

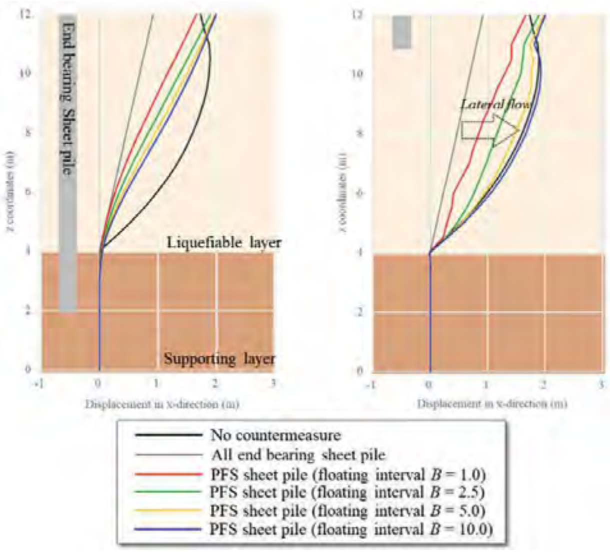


Figure 25. Distribution of lateral flow due to liquefaction in PFS method with its floating pile embedment 1m.

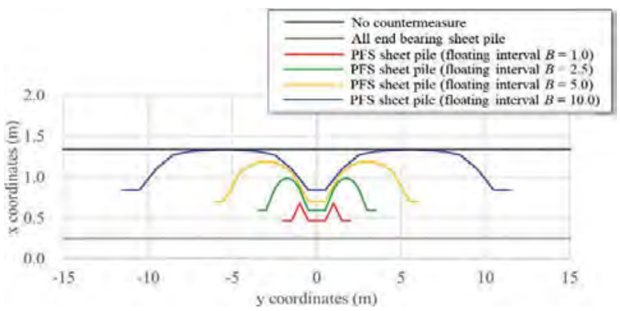


Figure 26. Cross section of horizontal Displacement.

bearing sheet pile, and when the end bearing sheet pile spacing is wide, it matches the maximum lateral flow amount in the unmeasured ground.

3.4.4 *Simple two-dimensional modeling of PFS method*

Figure 27 shows a schematic diagram of a simple two-dimensional model of the sheet pile reinforcement ground. Although the sheet pile shows a complicated shape, it is considered as a mixture with the surrounding ground, and modeled so that the rigidity and weight per unit depth are equal. Next, Figure 28 shows a schematic diagram of the simple two-dimensional modeling of the PFS method. The space between the end bearing sheet piles was regarded as one unit, and the mixture of the replacement sheet pile and the surrounding ground existing in one unit was modeled so that the rigidity and weight per the same depth would be equal. Figure 29 shows a comparison between the 3D analysis when the floating sheet pile length is 4 m and the 2D plane strain analysis results using the simple 2D modeling method of the PFS method proposed in this section. It can be seen that the lateral displacement of the two-dimensional analysis result is smaller than that of the three-dimensional analysis result, regardless of the end bearing sheet pile spacing. Figure 30 shows the horizontal displacement distribution map by the three-dimensional analysis with the two-dimensional analysis results superimposed. It was found that the

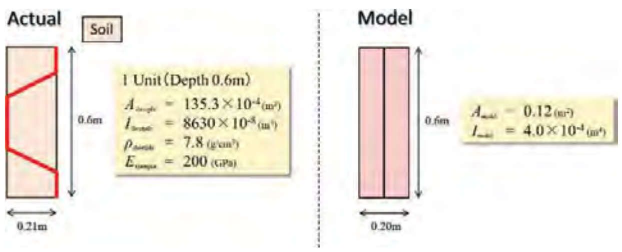


Figure 27. Schematic figure of simple 2D Modelling of sheet pile.

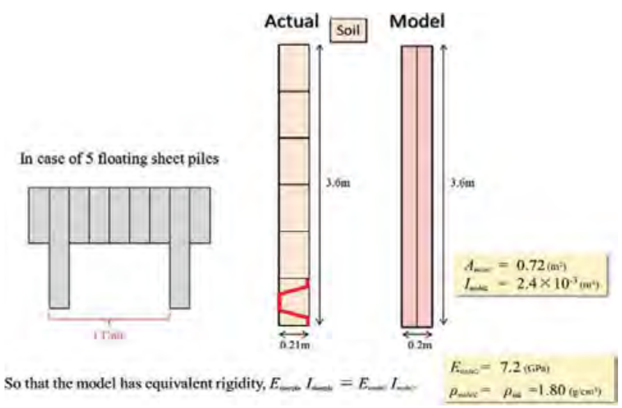


Figure 28. Schematic figure of simple 2D modelling of PFS method.

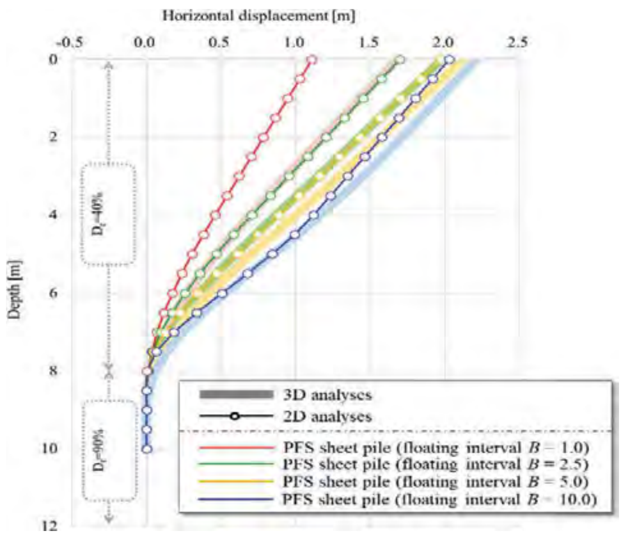


Figure 29. Comparison of lateral flow between 2D and 3D analysis.

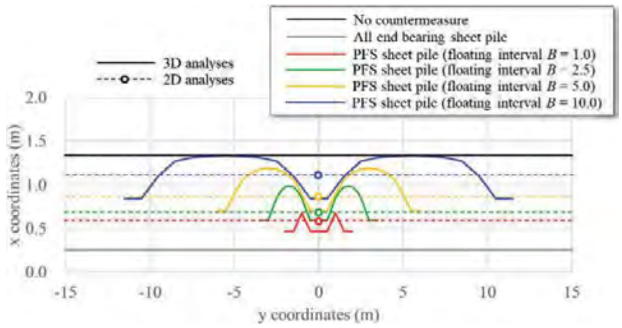


Figure 30. Comparison of lateral flow between 2D and 3D analysis (cross section).

simple two-dimensional model of the PFS method proposed in this section is just the average value of the lateral flow amount generated in an arc shape between the end bearing sheet piles. In reality, it shows a three-dimensional expansion of the lateral flow amount, but it was confirmed that a simple two-dimensional modeling can be used based on the fact that it shows its average behavior.

3.4.5 *Seismic performance verification of PFS method in sand-clay alternating layer ground*

Subsequently, a seismic response analysis of sand-clay alternating layers ground was carried out for the purpose of verifying seismic performance of the PFS method. The analysis code used is GEOASIA (Asaoka *et al.*, 2002; Noda *et al.* 2008). Figure 31 shows the finite element mesh used in the analysis. The analysis section was determined with reference to the river embankment in the Kikuchi River basin, Kumamoto Prefecture. The elasto-plastic parameters used in the analysis are determined based on the results of various mechanical tests of undisturbed samples collected in the

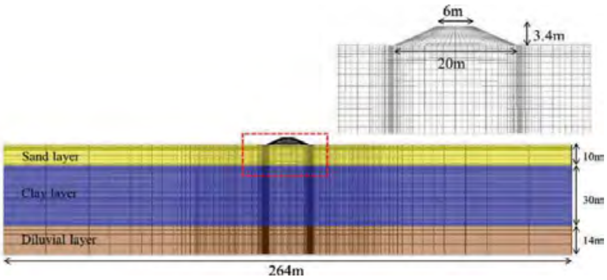


Figure 31. Finite element mesh.

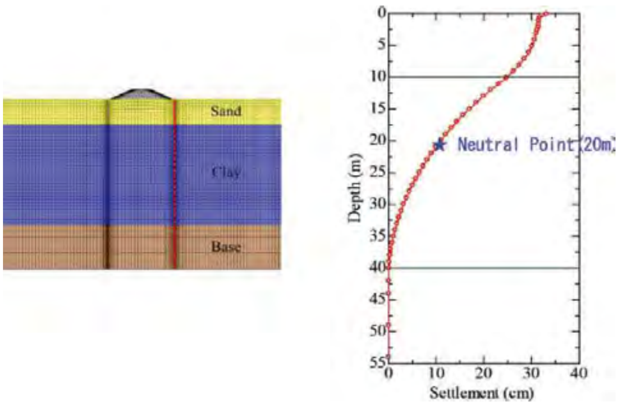


Figure 32. Determination of neutral point (floating pile length).

field. Figure 32 shows the distribution of horizontal displacement at the embankment toe at the time of embankment. Similar to the actual observational data, it shows an inverted S-shaped curve in the depth direction. According to the PFS method design and construction manual, the floating sheet pile length was set as its neutral point of 20 m. Figure 33 shows the ground conditions examined in this section. On the left side of the drawing, it was assumed that there were all landing sheet piles up to the base, and the right side was carried out in four ways: (a) no measures, (b) all landing, (c) floating, and (d) PFS. The method of 3.4.4 was used to model the sheet pile. Figure 34 shows the input seismic motion used in the

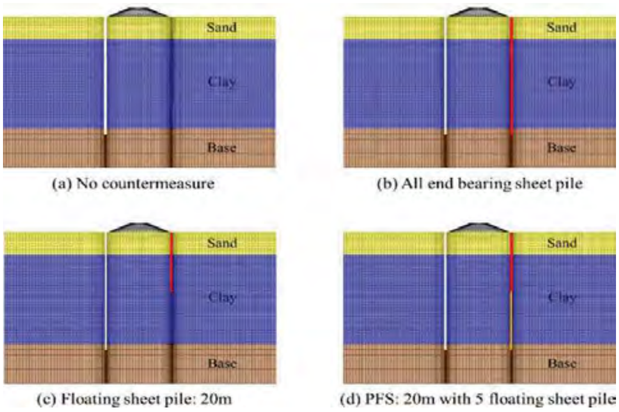


Figure 33. Analysis condition.

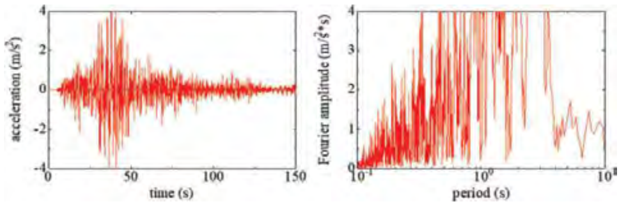


Figure 34. Input seismic motion.

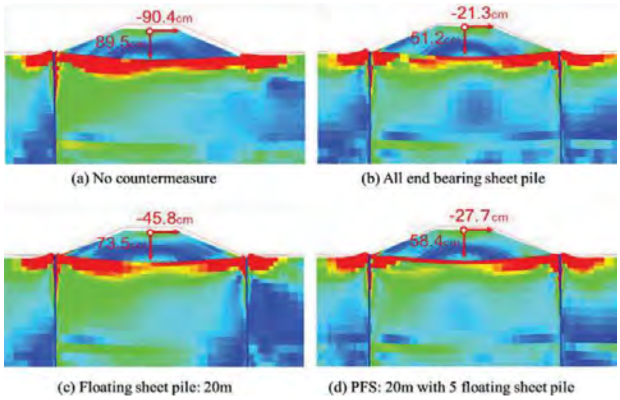


Figure 35. Comparison of embankment Deformation.

analysis. This is an assumed Nankai Trough earthquake with a long duration and long-period components. Figure 35 shows the shear strain distribution 10 years after the occurrence of the earthquake (enlarged display around the embankment) along with the amount of subsidence and horizontal displacement at the top of the embankment. In the case of unmeasured ground, the deformation of the embankment is very large, but in the case of all landing reinforcement ground, the effect of suppressing deformation during an earthquake can be confirmed, especially in horizontal displacement. Although not as much as the all landing, floating sheet pile and PFS method can also confirm the suppression effect. In addition to the smaller amount of subsidence and horizontal displacement compared to the floating method, the PFS method has a deformation suppression effect close to that of the end bearing method, confirming the seismic performance of the PFS method. Figure 36 shows the depth distribution of the lateral displacement in

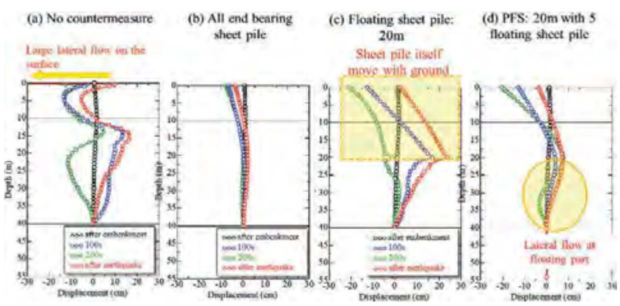


Figure 36. Lateral flow distributions of each Countermeasure.

the sheet pile. In the case of unmeasured ground, it can be seen that it sways greatly from side to side during the earthquake from shallow to deep, but in the case of all landing reinforcement ground, there is almost no lateral flow in the deep part, and the ground surface. In the case of floating sheet pile reinforced ground, since the floating sheet pile flows together with the ground, the amount of lateral flow near the ground surface becomes large, and there is a concern that the ground will be deformed in the embankment. On the other hand, in the case of the PFS method reinforced ground, it can be seen that the amount of lateral flow near the ground surface is suppressed, although slipping and swelling occur in the deep part. As a result of checking the seismic performance of the PFS method in the sand-clay alternating layer ground, the following conclusions were obtained.

- As for the embankment deformation caused by the earthquake, no countermeasures ≫ floating> PFS> all landing, so that the seismic effect of the PFS method was confirmed.
- When the seismic motion is large, the PFS method is considered to be more effective in suppressing lateral flow, especially near the ground surface, than the floating sheet pile (the floating sheet pile may flow along with the ground).

3.5 *WG4: Design*

In this section, research outcomes of WG4 (design) will be outlined.

3.5.1 *Introduction*

The PFS method itself was developed as "a construction method to prevent the settlement of the surrounding ground due to new embankment construction or bulky embankment construction" in "the ground which has a sand layer at the surface and where consolidation settlement is more dominant than horizontal displacement in response to load increase". However, there is a concern that the sand layer at the surface may liquefy during an earthquake, so liquefaction countermeasures are inevitably required in the ground conditions where the PFS method may be applied. As for the seismic reinforcement of embankment structures on liquefied ground, the technical standards are being developed by the management departments of each structure. For example, in the case of river embankments in Japan, the Public Works Research Institute (PWRI) has published a manual on design methods (PWRI,2016). For example, for a river embankment, a manual from the PWRI describes the design method of the embankment, in which steel sheet piles are rooted into the non-liquefiable layer, and the horizontal resistance of the sheet piles determines the lateral flow of the ground under the embankment. On the other hand, these technical standards for seismic reinforcement do not include the design concept of the PFS method as a countermeasure for close construction.

Against this background, the WG4 (design) has been working to organize and separate the PFS method, which is a "proximity construction countermeasure," from the "seismic reinforcement countermeasure" in each field, and to revise the design manual so that it can be practically used to easily design the PFS method, which is both a seismic reinforcement countermeasure and a proximity construction countermeasure. As a summary of the results, the main revisions of the design manual are shown below.

3.5.2 *Determination of applicable conditions*

The PFS method can be applied to the following ground conditions:

When the load increase caused by the embankment makes it necessary to take countermeasures against ground subsidence due to consolidation of the clay layer, but when direct countermeasures are not necessary because the displacement in the horizontal direction is suppressed by the surface sand layer. It was necessary to have a simple method to determine this from limited practical information. In this manual, the following three methods are presented.

1) Empirical method
   In this method, the applicability is judged based on the regional ground characteristics and construction results. For example, the Kumamoto area falls under this category.
2) Statistical method
   In this method, the required thickness of sand layer is determined based on the statistical analysis of past construction results, as shown in Figure 37 and Figure 38. In this method, the required thickness of the sand layer is determined based on the statistical analysis of past construction results, as

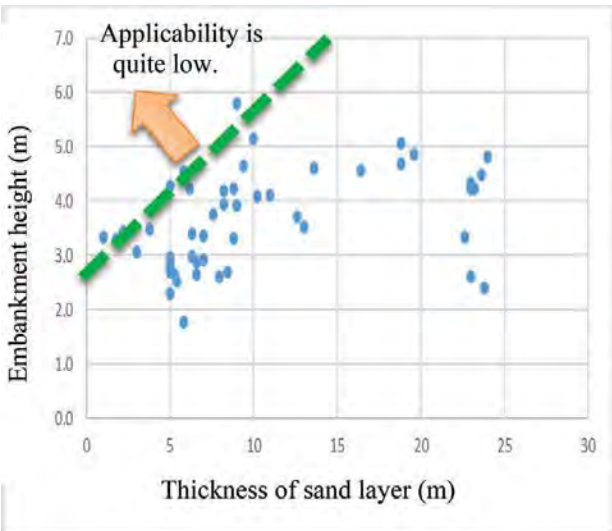


Figure 37. Applicability assessment chart based on construction results (Evaluation by absolute values of sand layer thickness and embankment height).

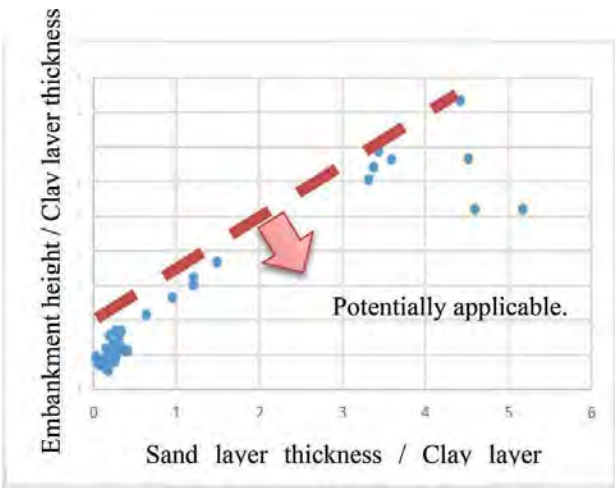


Figure 38. Applicability assessment chart based on construction results (Evaluation by ratio of sand layer thickness and embankment height to clay layer thickness).

shown in those figures, reflecting the results of WG1 (Field investigation).

3) Analytical methodIn this method, the nonlinear finite element method studied by WG (Numerical analysis) is used for evaluation.

3.5.3 *Design concept of seismic reinforcement measures*

The design concept of the seismic reinforcement of the PFS method is usually the same as that of the steel sheet pile method (design concept of the seismic reinforcement), which ignores the end bearing sheet pile in various fields. It is clear from the results of WG2 (Laboratory experiments) and WG3 (Numerical analysis) that this approach is at least on the safe side. It is also mentioned in the manual that it is possible to design with the resistance of end bearing sheet piles by using detailed analysis such as the 3D nonlinear finite element method, which can take into account the effect of ground slip between the piles.

3.5.4 *Determinants of the main design parameters*

Based on the analysis of the design concept of each field and the results of trial design, the determinants of the main design specifications of the PFS method are analyzed as follows.

1) Floating sheet pile lengthDetermined by the neutral axis depth determined from the allowable displacement.
2) Type of steel sheet pile (thickness and sectional stiffness)Regardless of the purpose of seismic countermeasure, it is necessary to have a type of sheet pile that can be driven to the bearing stratum (the deeper the bearing stratum and the stronger the stratum above the bearing stratum, the larger the type of steel sheet pile (i.e., the larger the thickness and the sectional rigidity)).
3) Sheet pile length and space (pitch) of end bearing sheet pileThe length of the sheet pile should be at least longer than the depth of the bearing layer determined by the soil conditions. The length of the sheet pile should be at least longer than the depth of the bearing layer determined by the ground conditions. The space (pitch) between the end bearing sheet piles should be determined so that the vertical bearing capacity is sufficient to withstand the negative friction.

Table 5. Table of contents for design manual.

1. General remarks
   1.1 Objectives
   1.2 Positioning of the construction method
   1.3 Scope of application
   1.4 About this manual
   1.5 Related standards
   1.6 Basic concepts of PFS method
   1.7 Investigation, design, and construction procedures
2. Site investigation
   2.1 Objectives
   2.2 Contents and items
   2.3 Planning
3. Design
   3.1 Basic concept
   3.2 Determination of applicability
   3.3 Setting basic specifications
   3.4 Consideration of earthquake
   3.5 Consideration of countermeasures for surrounding ground
   3.6 sheet pile head treatment
4. Construction
   4.1 Installation of sheet pile
   4.2 Construction procedure
   4.3 Points to note for the use of water jet

3.5.5 *Table of contents of the design manual*

The table of contents of the revised design manual is shown in Table 5. The main feature of the manual is that the flow is designed to minimize the number of design trials.

In the design of civil engineering structures in Japan, seismic design is very important and has a great influence on the specifications of the structures, but the design methods are becoming more sophisticated. The design of civil engineering structures in Japan is very important and has a great impact on the specification of structures. However, the design methods are becoming more and more sophisticated. Therefore, the seismic design work in practice requires a large amount of human resources, and the development of a simple seismic design method is very important for the diffusion of the technology and the efficient development of social infrastructure. The design manual will contribute to improving the efficiency of the practical work when the PFS method is used together with the seismic reinforcement method.

4 PRESS-IN TECHNIQUE

The Press-in Method, originated in Kochi, is a piling method that installs piles with a static jacking force while gaining a reaction force from previously installed piles. Since it is a static method, it generates less noise and vibration (White *et al*., 2002; White & Deeks, 2007). In addition to the function of a press-in machine to gain a reaction force from previously installed piles, the press-in machine and its related devices (power unit, crane and so on) can walk on top of the previously installed piles. Owing to these functions, this piling method can save temporary works or large construction areas for reaction weights or conventional types of cranes by the spatially-efficient piling system (called "GRB System") as shown in Figure 39.

The resistance applied to the pile from the ground during installation has to be controlled smaller than the sum of the reaction forces obtained mainly from the previously installed piles. In Standard Press-in (press-in without installation assistance), the resistance will be controlled by a repetition of penetration and extraction (called "surging") or by the penetration rate. There are several researches that confirmed the effect of surging to reduce the shaft resistance (Burali d'Arrezzo *et al*., 2013). Increasing the penetration rate is effective in reducing the penetration resistance if the soil is contractile (White *et al*., 2010). If the ground condition is too hard for Standard Press-in, the use of installation assistance is

Figure 39. Press-in piling system that requires no temporary works (GRB System).

effective. In Press-in with Water Jetting, the penetration resistance is reduced by the erosion of the soil and the build-up of the pore water pressure around the pile base (Gillow *et al*., 2018). In Press-in with Augering, the reduction of the penetration resistance is attained by excavation and temporary lift-up of the soil beneath the pile base. In Rotary Cutting Press-in where a tubular pile with cutting teeth on its base is pushed and rotated at the same time to be installed into the ground, the vertical penetration resistance is reduced by the cut of the soil (or a rock or a concrete) beneath the pile base as well as by the decomposition of the frictional stress acting on the pile surface into vertical and horizontal directions. The above-mentioned penetration techniques in the Press-in Method are summarized in Figure 40.

Standard Press-in	Press-in with Water Jetting	Press-in with Augering	Rotary Cutting Press-in
			
Press-in a pile without installation assistance	Press-in a pile wile applying water-jetting in the pile base	Press-in a pile while excavating the soil around the pile base	Rotate and press-in a pile equipped with base cutting teeth

Figure 40. Penetration techniques in the Press-in Method.

One of the case histories that typically summarize the features of the Press-in Method is shown in Figure 41 (White *et al*., 2010). This was the project of renovating the river levee in Tokyo. Under a strict spatial restriction due to the highway bridge above the levee and the buildings along the river, steel tubular piles were installed directly into the ground by penetrating though the concrete structures of the old levee, while doing away with the necessity of the removal work of the old levees and the temporary works for a crane that affects the river flow.

Another feature of the Press-in Method is the acquisition of the piling data by the automatic system equipped in the press-in machine. The data includes the time, penetration depth, jacking force, rotational torque and so on. Recent researches have developed methods of utilizing the press-in piling data for estimating subsurface information, which are summarized in IPA (2017) that provides recommendations on their applicability to real projects based on the validity of the estimation results at the moment.

On the other hand, the pile installed by the Press-in Method has a feature to effectively utilize the resistance of the ground. White & Deeks (2007) showed that the capacity of the pressed-in pile is higher than that of driven or bored piles, mainly due to the higher extent of soil plugging which leads to greater volume of soil displacement and to the smaller extent of friction reduction due to the cyclic motion of the pile (friction fatigue). Deeks & White (2007) demonstrated that the stiffness of the base response of the pressed-in pile is also higher than that of driven or bored piles, mainly due to the loading history of the pile (static loading and unloading at the end of installation of the pressed-in pile). Li (2010) confirmed in his centrifuge model tests that the pressed-in pile exhibited higher horizontal stiffness under horizontal loads than the bored pile which were embedded in dense sands.

Figure 41. Renovation of river levee in Tokyo by Rotary Cutting Press-in Method.

(a) Single pile wall (b) Double sheet pile wall

Figure 42. Application of pile walls to coastal levees in Kochi Coast as liquefaction countermeasure.

It has been expected that the above-mentioned advantages in the performance of the pressed-in piles be reflected in the performance of structures with piles. Such structures are exemplified by retaining walls, coastal levees, circular or rectangular walls and so on. Figure 42 shows a project in Kochi Coast, which was conducted in direct control of Ministry of Land, Infrastructure, Transport and Tourism (MLIT), to improve the seismic performance of the coastal levees (Ishihara *et al*., 2020). Pile walls were installed by the Press-in Method in the levee body, so that the height of the levee is maintained even when the ground is liquefied by the significant seismic motion expected in the coming Nankai Trough earthquake. In addition to the performance for liquefaction, the structure is expected to show tenacity for tsunami loads (Furuichi *et al*., 2015). Varieties of other case histories related with the Press-in Method can be found in IPA (2016) and IPA (2019).

5 CONCLUSIONS

Steel sheet pile method was discussed as a state of the arts report. This method had long been used as temporary works in geotechnical engineering but recently more applications to a permanent structure have been extended. In this paper, the development of PFS method which was originally proposed as a countermeasure for soft soil subsidence due to river embankment constructions. And recently, this method has been tried to discuss on the applications to earthquake. This was done by Technical Committee under IPA. There are a large number of natural disasters such as heavy rains and earthquakes and the sheet piles can be an effective countermeasure such as the stability of the river embankments. A construction technique called press-in method has accelerated the application of the sheet pile method. Finally, more wide varieties of the usage of the sheet pile can be expected not only as the construction technique but also as the countermeasure method for any kinds of natural disasters related to geotechnical engineering problems.

ACKNOWLEDGEMENT

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