Evaluation of Effectiveness of PFS Method Using 3D Finite Element Method

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ABSTRACT

In order to improve the effectiveness of steel sheet-pile method for the countermeasure on soft ground settlement under embankment load, a PFS method was developed under the research group whose chair was Prof. Ochiai of Professor Emeritus at Kyushu University, Japan in 2005. At that moment, a series of in-situ full scale tests for this countermeasure method including PFS method which is the combination of end bearing sheet-pile with those of floating type were conducted in the City of Kumamoto, Japan under the Ministry of Construction (current name of this ministry is Ministry of Land, Infrastructure, Transportation and Tourism).

In this paper, the main objective is to discuss the quantitative evaluation of PFS method using coupling finite element analysis. Because of the geometry of PFS structures, this analysis was conducted in three dimensions. A numerical analysis was done for the cases of the full scale tests at the site in Kumamoto City, in which the field tests with the case of PFS method was conducted. A "t_{ij} model" developed by Nakai et al which can be considered the effect of intermediate principal stress was used as a constitutive model for clayey soil. Here, not only displacements in the ground but also the change of excess pore water pressure were compared.

Finally, based on those numerical studies, an effectiveness of PFS method as a countermeasure method was discussed.

Key words: *Steel sheet-pile, Soft soils, Countermeasures, Numerical Method, Elastoplastic*

1. Introduction

Steel sheet-pile has been widely used, especially for earth retaining or excavation. In those cases, the reduction of lateral displacement with its total stability has been expected and the installation of the sheet-pile is relatively easy, so that most of those works have been realized as a temporally ones. However, recently this sheet-pile method is being used as a permanent method for the prevention technique on slope failures, and that for the case of embankment construction, the sheet-pile has been constructed at the toe of embankment due to the purpose of stress shut down to the surrounding ground, so that the reduction of subsidence is expected at the area where the private housings are located. When the embankment is constructed on soft ground, the ground subsidence for not only the ground under the embankment but also the ones around embankment are serious problems and some countermeasures have to be considered. A steel sheet-pile method is one of the countermeasures for this problem as shown in **Fig. 1**. However, this type of structure has a cost problem when the area and depth of soft ground are wider and deeper,

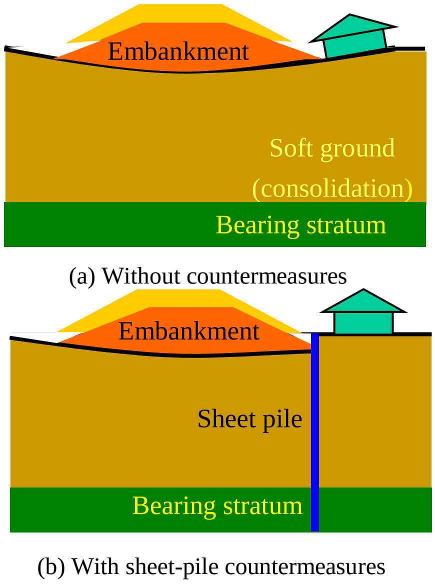


Fig. 1 Sheet-pile countermeasures

so that a development of new sheet-pile method was expected.

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 research 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,

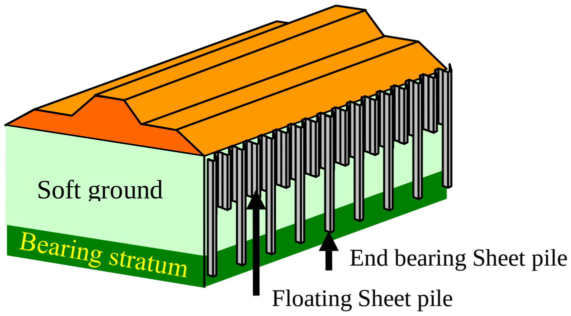


Fig. 3 PFS method

a new sheet-pile method called PFS method (**P**artial **F**loating **S**heet-pile) 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 **Fig. 2**. **Fig. 3** shows the details of this structure (PFS Method, Technical Manual, 2005).

In this paper, first of all, in-situ measurements at the site is introduced as a performance of PFS method and then, a numerical modeling using 3D FEM is conducted for one of the PFS construction sites. Finally, based on the results shown in this paper, the effectiveness of PFS method is convinced and the next step on this PFS method is briefly discussed.

2. Case history

A large number of in-situ full scale tests for PFS

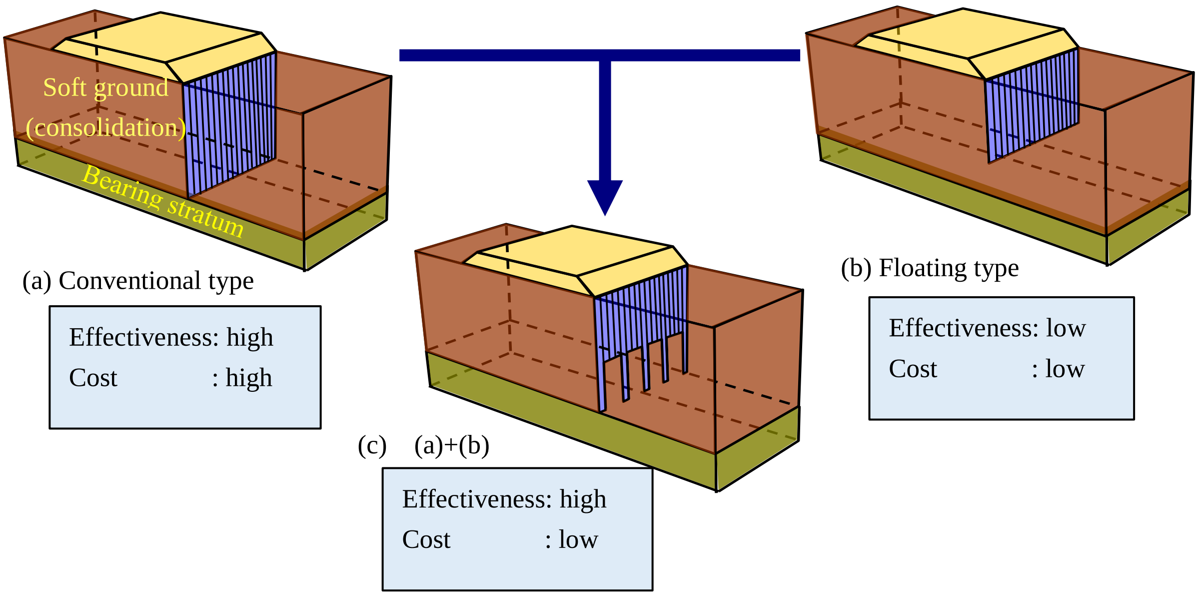


Fig. 2 Idea of PFS method

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. **Fig. 4** shows the soil profile at the site of in-situ test for PFS

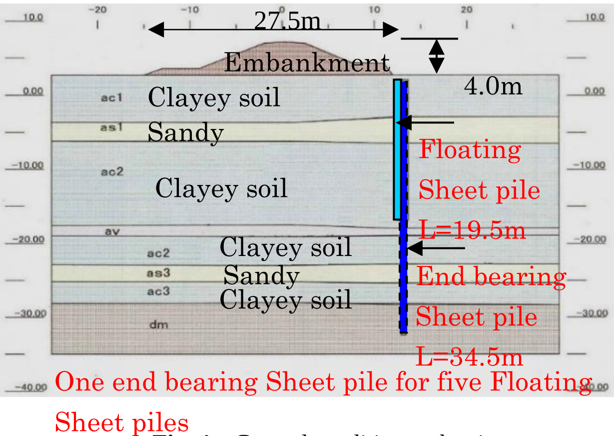


Fig. 4 Ground condition at the site

method. In this case, one end bearing sheet-pile for five floating sheet piles were constructed. **Fig. 5** shows the results of measurement for the settlements at the site and **Fig. 6** shows the results of lateral displacement at the toe of embankment. As easily realized, the effectiveness of

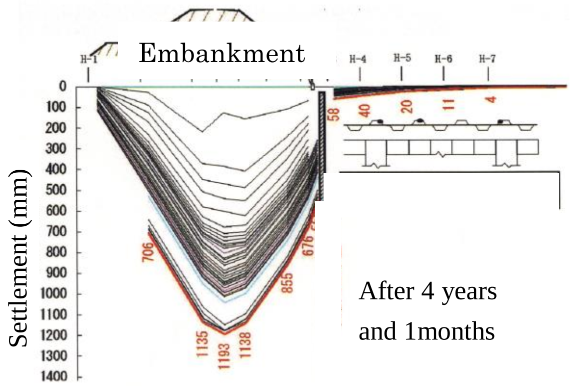


Fig. 5 Measurement results of subsidence at the ground surface

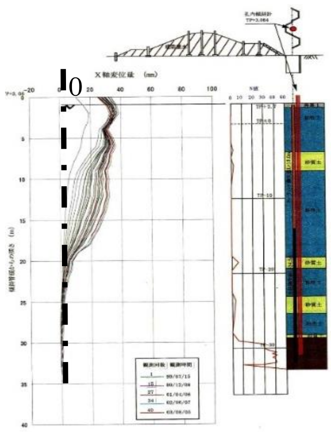


Fig. 6 Measurement results of lateral displacement at the toe of embankment

the PFS method is clearly shown. Since a large volume of sheet-pile materials were reduced, the cost of the PFS method is obvious and the construction time is also highly reduced because of the less volume of the sheet-piles.

3. Numerical analysis

3.1. Site condition

A series of numerical modeling were conducted for one of the site of PFS method. First of all, the information at the site in Kumamoto City, Japan is shown in **Fig. 7**, in which the height of embankment was 4m with 48 m width and the total length of the sheet-pile for end bearing was 30m while the floating part was 20m. The embankment was constructed by step by step loadings with total of 40 days as shown in **Fig. 8**. **Fig. 9** shows the soil condition, which is the multi-layer of sand and Ariake clay. In fact, the layers of Ac1, Ac2-U and Ac2-L were relatively soft clayey soils and the water level was relative shallow as 0.8m depth. It is obvious that total depth of the ground (H=25m) is mostly soft soil with SPT N-value of nearly zero.

3.2. FEM modeling

Based on the results of soil tests at the site and laboratory for the soils at the site, all the soil parameters were determined as shown in **Table 1**, in which the sandy ground was assumed as an elastic material while t_{ij} model (Nakai, 2013) was used for clayey ground. An elasto-plastic consolidation analysis was conducted with Finite Element Method (FEM) and here, because of the shape of PFS method, three dimensional analysis was conducted. **Fig. 10** shows the 3D mesh with those scaling for this analysis in which the total number of elements is 4550 for the ground. Sheet-pile was modeled by beam

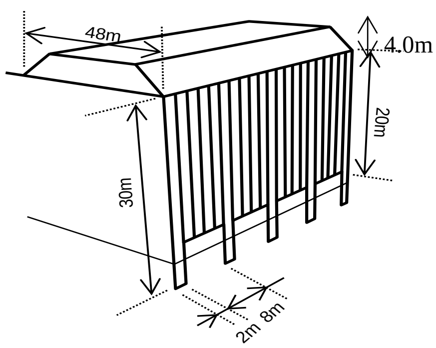


Fig. 7 PFS method at the site

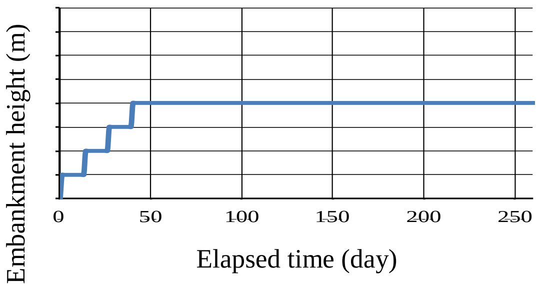


Fig. 8 Loading step at the site for FEM

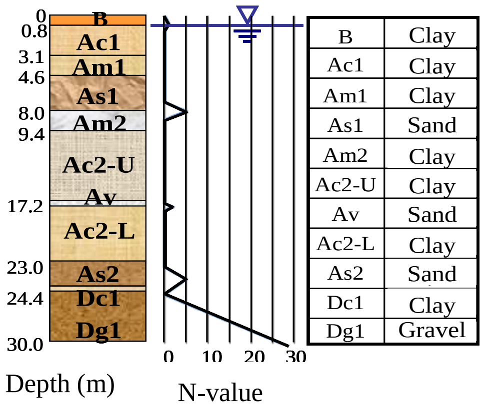


Fig. 9 Soil profile at the site for FEM

elements in which joint element was not used for the interaction behavior. And in the analysis, the step of embankment during construction was modeled by adding solid elements with its weight based on the loading process as shown in **Fig. 8**. In the analysis, the results such as total settlement at the center of the embankment with that of each soil layer and the change of excess pore water pressure were calculated.

3.3. Results and discussion

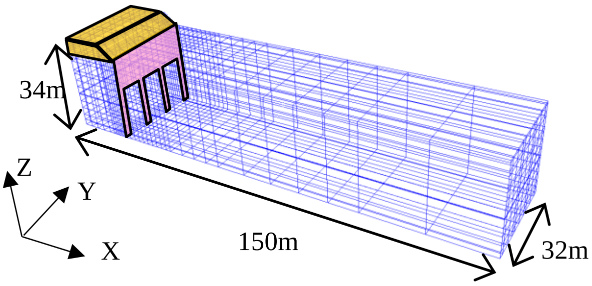
Fig. 11 shows the comparison between numerical results with those of observations at the site for settlements. Here, total settlement and those of 3 different clayey layers were compared. As easily realized from those figures, the numerical results can simulate real behaviors relatively well. **Fig. 12** also shows the same type of comparison for excess pore water pressure for different soil layers (Ac1, Ac2-U, Ac2-L, and As2). Although there are some difference between analysis results and those of measurements, especially just after the end of embankment, it can be said that over all behavior seems close enough for both results. **Fig. 13** shows the comparison between numerical results with those observations for the distribution of lateral displacement at the toe of the embankment after 250 days. As shown those comparisons, the numerical results can simulate real behavior to some extent and as a result, 3D FEM with elasto-plastic constitutive model by t_{ij} model can model the real behavior, fairly well.

4. Concluding remarks

In this paper, the numerical analysis on the PFS method was compared with the measurement results at the site and fairy good agreements were obtained. However, the location of the site of full scale test is limited, so that the performance of PFS method with different soil conditions have to be checked. In fact, one of the important requirement for the use of steel pile is

Table 1. Soil parameters for FEM

	λ	κ	β	Rcs	OCR	e_1	ν	γ_t(kN/m^3)	k (m/day)	E (kN/m^2)
B							0.33	17.0	8.60E-04	42
Ac1	0.45	0.042	1.12	1.63	1.0	3.14	0.26	14.6	4.00E-04	
Am1	0.16	0.02	1.07	1.37	1.0	1.55	0.31	16.7	5.40E-03	
As1							0.33	18.0	4.10E+00	184
Am2	0.2	0.023	1.10	1.52	1.0	1.38	0.28	17.0	6.60E-03	
Ac2-U	0.2	0.016	1.12	1.67	1.0	1.76	0.26	15.9	5.50E-04	
Av							0.33	17.0	9.10E-03	260
Ac2-L	0.31	0.023	1.09	1.45	1.0	2.52	0.29	14.7	1.00E-04	
As2							0.33	17.0	9.50E-02	538
Dc1	0.45	0.033	1.10	1.53	1.0	1.44	0.28	16.0	1.10E-03	
Dg1							0.33	19.0	3.90E+01	4880



Boundary conditions:
Y-Z plane: X-direction fix,
Drain condition
Z-X plane: Y-direction fix
Undrain condition
Bottom plane: X, Y, Z-directions fix
Undrain condition

Fig. 10 3D FEM modeling

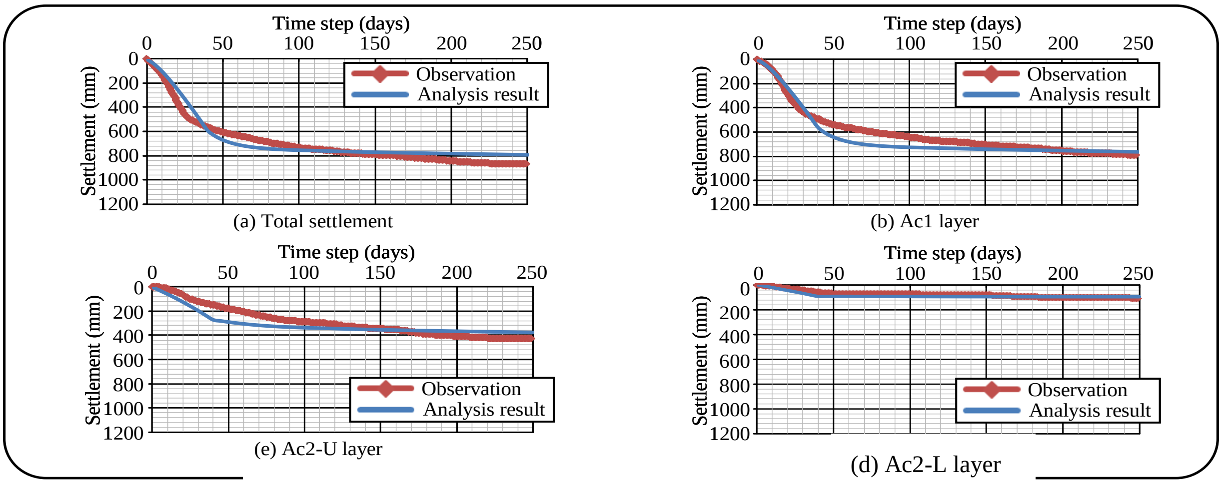


Fig. 11 Comparison of ground settlements

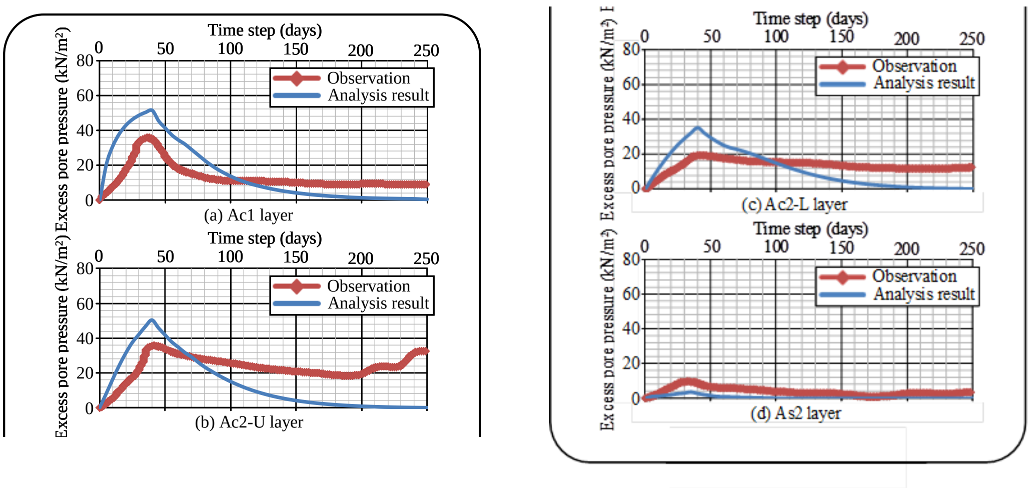


Fig. 12 Comparison of excess pore water pressures

how much the lateral displacement at the toe of embankment and this allowable value has to be determined to generalize this PFS method. And one more, as many of engineers concerned, the behavior during earthquake is important, especially in Japan. Therefore, the confirmation of performance under earthquake should be examined. Those should be the next target for the PFS method.

5. Acknowledgements

As mentioned in this paper, the development of PFS method was done under the research group of PFS method whose chair was Professor Emeritus of Kyushu University, Hidetoshi Ochiai. The authors would like to give their sincere gratitude to all the members of this committee for their enormous efforts to develop this method.

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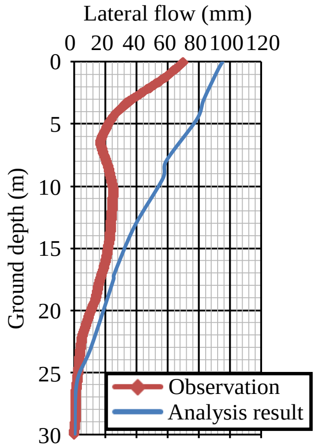

Fig. 13 Lateral displacement at the toe of embankment