Centrifuge Model Tests and Image Analyses of a Levee with Partial Floating Sheet-pile Method

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ABSTRACT

A steel sheet pile is used as a settlement countermeasure method for levees on soft ground. It is expected that settlement of landside ground can be suppressed by penetrating steel sheet piles nearby toe of slope of the levee. In order to improve the performance of existing two methods, full bottom landing and floating method, the Partial Floating Sheet-pile method (PFS method) was proposed. However, the PFS method has a limited number of experimental studies and construction examples. Thus, the effect of the PFS method is not well-understood. In this study, a 1/50 scale ground models with levees and two types of sheet pile walls were built and self-weight consolidation experiments were conducted with and without the countermeasure using centrifuge apparatus. The objective was to confirm the effect of the PFS method on the settlement of landside ground and failure mode of the levees. The experimental results showed that the countermeasure cases suppressed the settlement of landside ground more than the non-countermeasure case. It was observed from image analyses that in the countermeasure cases, relative displacement of clay layer occurred near sheet piles. Continuous shear strain induced by relative displacement is considered to cause cracks on the slopes of the levees.

Key words: *PFS method, centrifuge model test, image analysis*

1. Introduction

A steel sheet pile method is used as a countermeasure for settlement of levees on soft ground. It is expected that a settlement of landside ground of levees can be suppressed by penetrating steel sheet piles nearby toe of slope. There are some types in the steel sheet pile method. The full bottom landing method that penetrates sheet pile to a support layer has high suppression effect, but its construction cost is high. The floating method that does not penetrate sheet pile to a support layer has low suppression effect, but its construction cost is low. As an alternative of the two, the Partial Floating Sheet-pile method (PFS method) in which some sheet piles penetrate to a support layer and the others stop in soft ground was proposed (Okuda *et al.*, 2005, Miyamoto *et al.*, 2005, Tanabe *et al.*, 2005). Obase (2008) reported pilot construction and preliminary analysis of the PFS method and showed its effectiveness as the countermeasure. However, studies of the PFS method including experimental tests are still limited. Therefore, the level of suppression effect of the PFS method is not well-understood. Much more research efforts are needed for practical applications and design guideline.

In this study, the authors addressed the above research needs by performing a series of experimental studies of the PFS method. The experimental models consist of 1/50 scale ground models and two types of sheet piles and self-weight consolidation experiments are conducted using centrifuge apparatus. The objective was to confirm the effectiveness of the PFS method for the settlement of landside ground and failure modes. Also, this study used image analysis (Ueno *et al.*, 2014) to capture development of strain around sheet piles in a clay layer. This paper presents details of the experimental setups, results as well as the applied image analysis.

2. Centrifuge model test

2.1. Soil material

The test model consists of three layers, a support layer, a clay layer, and a levee. For the support layer material, Mikawa silica sand No.3 was used. For the levee, mixed sand with Mikawa silica sand No.7 and fine sand of whose ratio by weight is 8:2 was used. Material properties are tabulated in **Table 1**.

Clayey slurry made from a mixture of kaolin clay, gypsum and water were poured into soil container after the sheet pile model was installed at the prescribed position. Gypsum consumes free water in the slurry and solidifies it in four days due to hydration reaction. This procedure provides two advantages; the strength can be adjusted by changing compounding ratio, and the consolidation speed for preparation become fast.

The mixing ratio and curing period were determined based on the results of a series of unconfined compression test preliminary conducted prior to this study. Finally, the mixing ratio with water was set so that material A (gypsum: water = 10:4) and material B (kaolin clay: water = 10:8) were 17:83. Curing period was set to five days.

The properties of solidified clay are tabulated in **Table 2**. The results of unconfined compression test for solidified clay are shown in **Fig. 1**. When compressive strain exceeded 10%, slight strain softening was observed. The compressive strength only in Case 2 is large, but in other cases it is almost the same. Therefore, it was judged that the same degree of clay layer can be prepared each time.

Oedometer tests were also conducted, and the pressure characteristics of c_v and m_v are shown in **Fig. 2**. Because c_v is larger than the lower representative value 200 (cm^2/d) of alluvial clay, the consolidation time is considered to be shorter. This is another advantage of this material for model tests.

Table 1. Material properties of the support and levee layer

	support	levee
Soil particle density, ρ_s (g/cm^3)	2.64	2.65
Maximum void ratio, e_{max}	1.02	1.01
Minimum void ratio, e_{min}	0.74	0.42
Maximum dry density, ρ_{dmax} (g/cm^3)		1.75
Optimum moisture content		12.0

Table 2. Material properties of solidified clay

Soil particle density, ρ_s (g/cm^3)	2.70
Liquid limit, w_L (%)	70.1
Plastic limit, w_P (%)	40.4
Plasticity index, I_P	29.7
Engineering classification	MH
Compression index, C_c	0.55
Consolidation yield stress, p_c (kN/m^2)	60.0

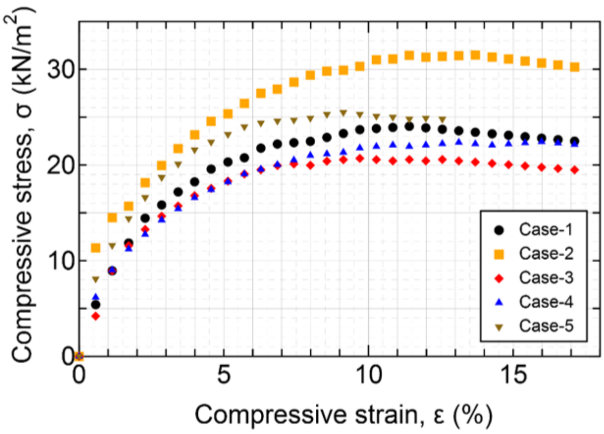


Fig. 1 Results of unconfined compression test

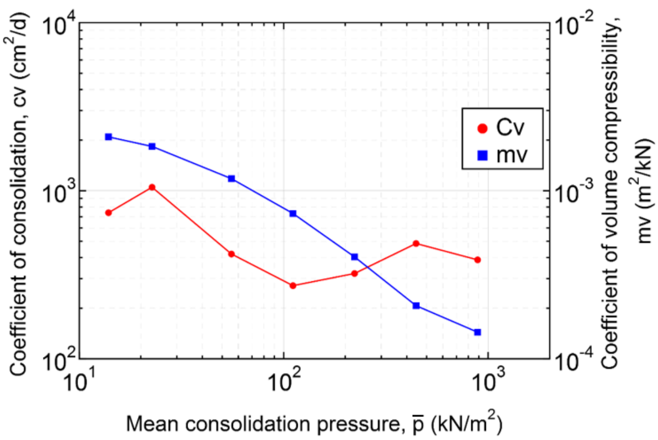


Fig. 2 Stress characteristics of c_v, and m_v

2.2. Model preparation

The model configuration and measurement points are shown in **Fig. 3**. The dimensions are shown in the model scale. The model was 1/50 scale. The test model was built in a rigid container with the internal dimensions of 450mm width, 350mm height and 200mm depth.

For the support layer, Mikawa silica sand No.3 wet with distilled water was damped well to make the ground 50mm high. In the case of installing a sheet pile model, it was penetrated into the support layer at this stage.

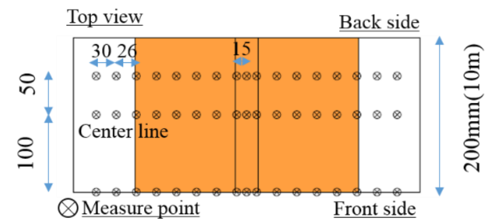
For the clay layer, Kaolin clay, gypsum and water were mixed thoroughly and run into slurry state and poured into the container to ensure sufficient ground height. The entrapped air in the clay layer was removed using a vibrator. After the above processes were completed, wet cloth and lap covered to the model ground so as not to dry. After 4 days passed, the container front glass was taken up once and colored sand for image analysis were spread. In addition, the ground surface was shaped so that the prescribed height and the initial height were measured at 51 points as shown in **Figs. 3(a)**. The wet density and moisture content of the clay layer were 1.61t/m^3 and 70.0% as representative value.

For the levee, mixed sand was compacted in five layers with a target of moisture content w=12% and the degree of compaction Dc=85% on the completed the clay layer. Levee dimensions were 30mm crest width, 65mm height, 290mm bottom width and 1:2 slope gradient. After completion of the levee, the initial height of slope and crest were measured at 39 points only a part of the levee as shown in **Figs. 3(a)**.

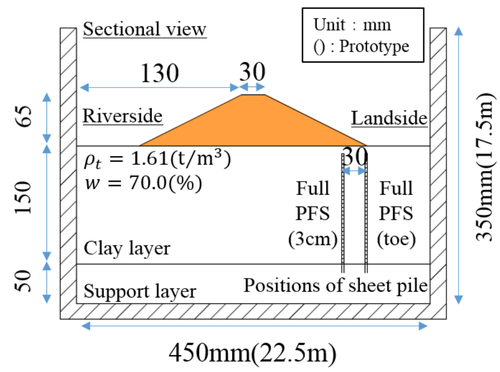
The sheet pile models used in the test are shown in **Figs. 4(a, b)**. A stainless steel plate with 3mm thickness is used. Full bottom landing sheet pile and the PFS model are shown in **Figs. 4(a)** and **Figs. 4(b)**, respectively. The dimensions are shown in the model scale.

2.3. Experimental conditions

The self-weight consolidation experimental cases are shown in **Table. 3**. Five cases were conducted; i.e. non-countermeasure (NC), installing a full sheet pile around toe of the slope of the levee (Full(toe) and Full(1.5m)) and installing the PFS around toe of the slope of the levee (PFS(toe) and PFS(1.5m)). Positions of sheet pile are shown in **Figs. 3(a)**. The applied centrifuge acceleration was 50g field in all experiments. The centrifuge time was about 20 minutes before reaching 50g and 60 minutes after reaching 50g. In addition, all experiments were conducted on 5 days from the start of curing.

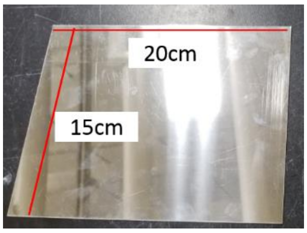


(a) Top view

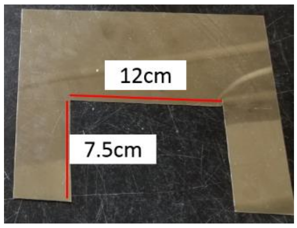


(b) Sectional view

Figs. 3(a, b) Model configuration



(a) Full sheet pile



(b) PFS

Figs. 4(a, b) Sheet pile models

Table 3. Self-weight consolidation experimental cases

Case code	Sheet pile	Position of sheet pile
NC		
Full(toe)	Full	Toe of slope
PFS(toe)	PFS	Toe of slope
Full(1.5m)	Full	1.5m from toe of slope
PFS(1.5m)	PFS	1.5m from toe of slope

3. Experimental results

3.1. Settlements

A side view after experiment in the case of PFS(toe) is shown in **Fig. 5**. As the clay used was entirely white material, colored sand is spread over the side surface of the clay using spoon for image analysis. However, the colored sand and the clay are not completely in close contact. Clear settlements of levee were observed and the surface of clay layer was concaved.

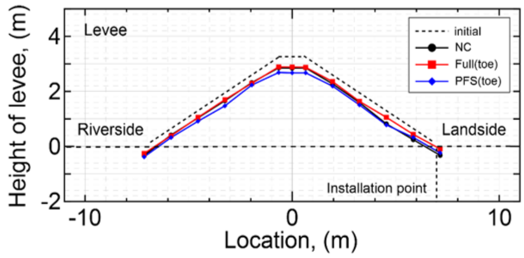
Comparisons of the settlements are shown in **Figs. 6(a)** and **7(a)**: **Figs. 6** for Full(toe) and PFS(toe), while **Figs. 7** for Full(1.5m) and PFS(1.5m). In these figures, the heights above the initial surface of clay layer were measured along the center line in **Fig. 3(a)** after 2,500 hour consolidation in prototype scale. The heights and locations are described in prototype scale, here after.

The settlements observed in Full(toe) tend to be smaller values comparing with other cases. Otherwise in **Figs. 7(a)**, those from Full(1.5m) show largest settlements along the riverside slope. However, on the landside ground, the settlements obtained in cases of Full(1.5m) and PFS(1.5m) are clearly smaller than those in NC case.

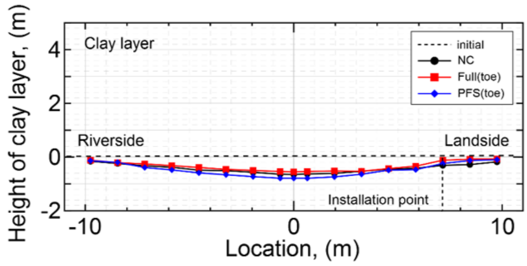
Comparisons of the settlements of clay layer are shown in **Figs. 6(b)** and **7(b)**. Although the values of settlements at the center of the levee were fluctuated, the settlements on the landside ground are clearly suppressed by sheet pile installation. Additionally, the surface on the landside ground is almost parallel to the horizontal line except the case of NC.

The results discussed above imply that most components of settlement on landside ground were produced not due to the levee, but due to self-weight consolidation of clay layer itself during centrifuge loading. Therefore, it can be concluded that sheet pile installation is effective to suppress settlement on landside ground and isolate it from the influence of consolidation due to levee.

Fig. 5 Side view after experiment (PFS(toe))

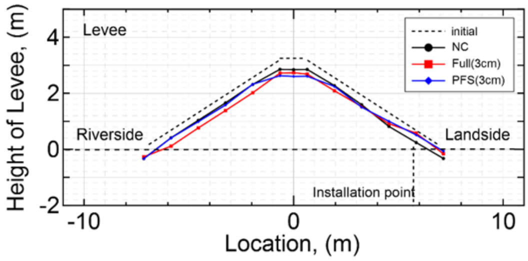


(a) Surface of levee

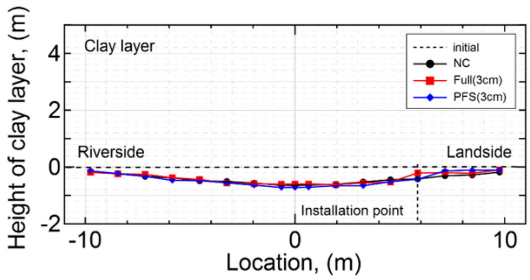


(b) Surface of clay layer

Figs. 6(a, b) Settlements (Full(toe) and PFS(toe))



(a) Surface of levee

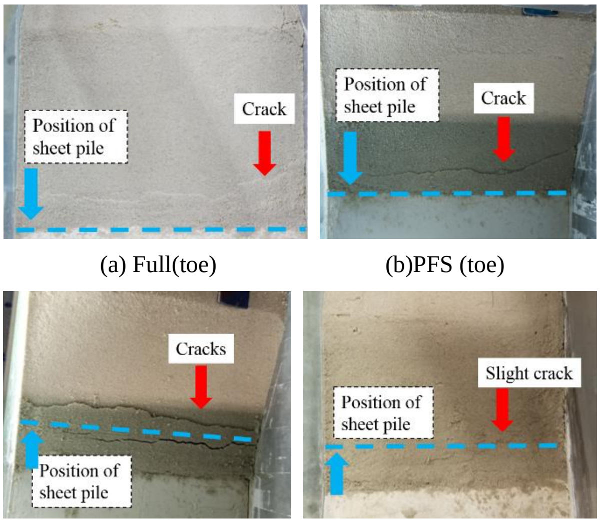


(b) Surface of clay layer

Figs. 7(a, b) Settlements (Full(1.5m) and PFS(1.5m))

3.2. Cracks on landside slope

Clear cracks parallel to the edge of the slope were observed on landside slope except in the case of NC, as shown in **Figs. 8(a-d)**. It can be considered that shear deformation, which affects levee was developed along the sheet pile because of suppression of settlement by sheet pile installation.



(a) Full(toe) (b)PFS (toe)

(c) Full(1.5m) (d) PFS(1.5m)

Figs. 8(a-d) Cracks appearing around landside slope

4. Image analysis

Deformations in a clay layer were measured and visualized by using an image analysis method introduced in Ueno et al. (2014). Simple shear strain γ_s and pure shear strain γ_p are defined as,

$$\gamma_s = \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \tag{1}$$

$$\gamma_p = \varepsilon_x - \varepsilon_y = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \tag{2}$$

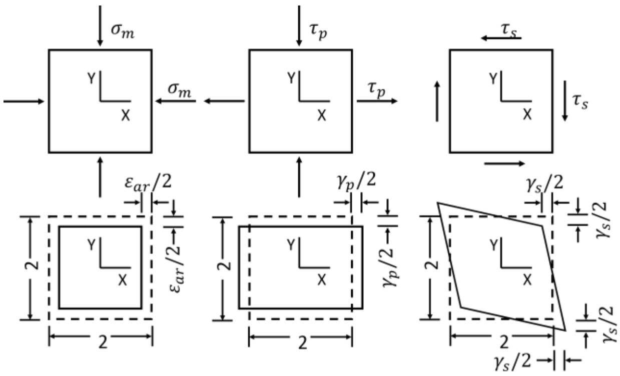
where u and v are displacements in x and y coordinates, respectively. The maximum shear strain can be derived from γ_s and γ_p by using **Eq. 3**. The definitions of stress and strain are showed in **Fig. 9**. The strain circle on Mohr's diagram is showed in **Fig. 10**.

$$\gamma_{max} = \sqrt{\gamma_p^2 + \gamma_s^2} \tag{3}$$

The case of PFS(1.5m) as an example of distributions of vertical displacement after about 2500 hours is shown in **Fig. 11**. Comparing image analysis and experimental result, the vertical displacement of the clay layer's surface after 2,500 hours consolidation was generally consistent. Also, similar tendencies were seen in other cases. Therefore, it is thought that the colored sand moved together with the clay layer.

Distributions of simple shear strain γ_s in the cases of NC and PFS(toe) after about 1,600 hours consolidation are shown in **Figs. 12(a-b)**. The γ_s observed in the case of NC distributed symmetrically as shown in **Figs. 12(a)**. On the other hand, as you can see clearly from **Figs. 12(b)**, simple shear deformation was vertically concentrated along position of sheet pile if the sheet pile walls exist.

To show typical shear deformation induced by the levee, distributions of maximum shear strain γ_{max} after 1,600 hour consolidation in the case of PFS(toe) are shown in **Fig. 13**. It is considered that the development continuous shear strain induced by relative displacement is due to the occurrence of cracks in the levees.



Figs. 9 Definitions of stress and strain

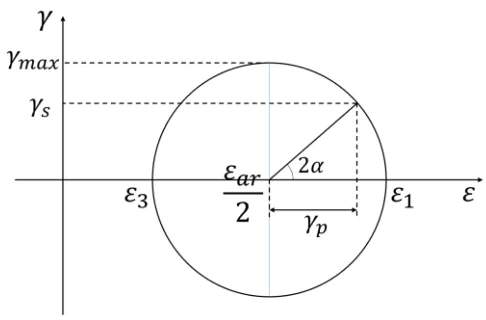


Fig. 10 Strain circle on Mohr's diagram

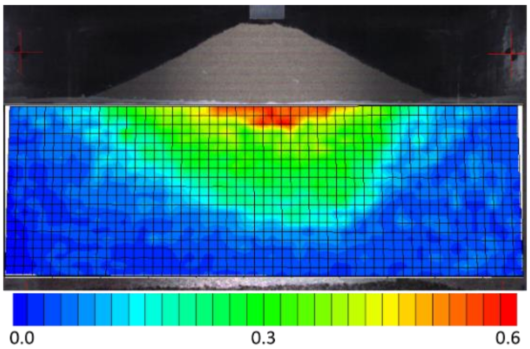
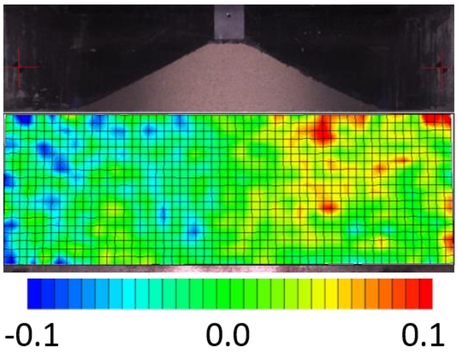
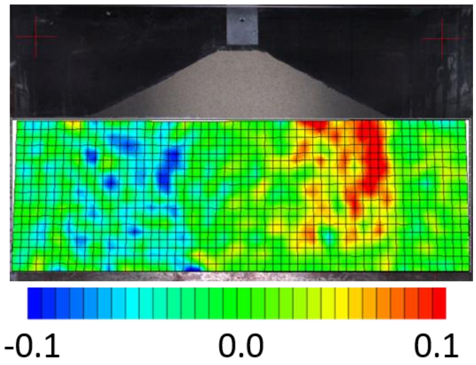


Fig. 11 Distribution of vertical displacement (PFS(1.5m))



(a) NC



(b) PFS(toe)

Figs. 12(a-b) Distribution of simple shear strain

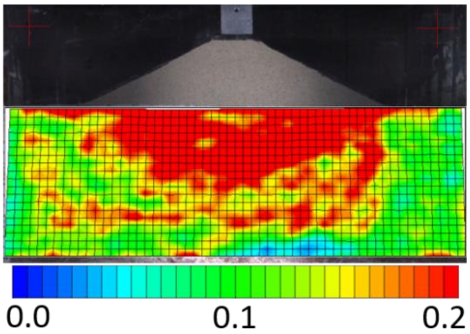


Fig. 13 Distribution of maximum shear strain (PFS(toe))

5. Conclusion

In this study, in order to evaluate the effect of the PFS method, a 1/50 scale ground models with levees and two types of sheet pile walls were built and self-weight consolidation experiments were conducted with and without the countermeasure using centrifuge apparatus.

As a result, the values of settlements at the center of the levee were fluctuated, the settlements on the landside ground are clearly suppressed by sheet pile installation. Additionally, the surface on the landside ground is almost parallel to horizontal line except the in case of non-countermeasure. And, it was observed from the image analyses that in the countermeasure cases, relative displacement occurred near the sheet piles in the clay layer. Continuous shear strain induced by relative displacement is considered to cause cracks on the slopes of the levees. Therefore, shear strain may occurs in the actual levee, but it is considered that because the clay layer deforms by long time consolidation, clear cracks have not occurred.

In the future, it is necessary to require the shape of highly effectiveness for the PFS method without causing cracks in the levee. In order to examine crack development factors in detail, verification experiments will be conducted by changing the condition of the levee as well as the clay layer.

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