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3D fem analysis of partial floating steel sheet piling method on two-layered ground

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ABSTRACT: This paper presents the result of a finite element method to evaluate the effectiveness of the partial floating steel sheet piling method (PFS method) for the stability of embankment on two-layered soft ground. In order to clarify a suitable ground layer structure for the PFS method, ground is assumed to consist of a sand layer as a surface layer and a clay layer as a bottom layer, and the settlement and the lateral displacement of soft ground due to the construction of an embankment are investigated changing the thickness ratios of sand and clay layers. In addition, the effect of the length of a floating sheet pile of the PFS method is investigated on the ground deformation under different ground layer structures. Finally, suitable ground layer structures for the PFS method and the minimum length of floating sheet piles are discussed to reduce the lateral displacement of soft ground.

1 INTRODUCTION

There is one of ground reinforcement technologies, called a steel sheet piling method to reduce the ground settlement and the lateral displacement of soft ground due to the construction of a river embankment. In the steel sheet piling method, there are a conventional method (called "the CS method") penetrating steel sheet piles to the supporting layer, a floating steel sheet piling method (called "the FS method") not penetrating to the supporting layer, and the partial floating steel sheet piling method (called "the PFS method") that is a combination of the FS method and the CS method. A steel sheet piling method including the PFS method has been widely used as a reinforcement technology for river embankments in Kumamoto Prefecture, Japan.

Ochiai et al (1991) verified the effectiveness of CS and FS methods for the settlement reduction countermeasure based on the field test and the finite element analysis. They concluded that the stress cutoff effect of steel sheet piles was effective for reducing settlement and lateral displacement of soft ground due to embankment construction. Kimizu and Otani (2010) compared the reinforcement effect of the CS and PFS methods on the soft ground deformation due to embankment construction using the 3D finite element analysis. Furuichi et al (2015) and Fujiwara et al (2017) evaluated the seismic behavior of embankment with steel sheet pile based on the result of a model test and a numerical analysis.

The objective of this study is to evaluate the effectiveness of the PFS method for the reduction of deformation of two-layered soft ground due to embankment construction using the 3D finite element method. In order to clarify a suitable ground layer structure for the PFS method, soft ground is assumed to consist of a sand layer as a surface layer and a clay layer as a bottom layer, and the settlement and the lateral displacement of soft ground due to the embankment construction are investigated by changing the thickness ratios of sand and clay layers. In addition, the effect of the length of a floating sheet pile of the PFS method is investigated on the soft ground deformation under different ground layer structures comparing with/without the reinforcement of the CS method. Finally, suitable ground layer structures for the PFS method and the minimum length of a floating sheet pile are discussed to reduce the lateral displacement of soft ground.

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2 NUMERICAL PROCEDURE

A 3D soil-water coupled finite element method developed by Nakai (2007) was used in this study. Figure 1 shows the schematic diagram of soft ground consisting of a sand layer as a surface layer and a clay layer as a bottom layer which is a typical ground structure of the Kumamoto Plain in Japan. It is assumed that the depth of the supporting layer is 30 m and the ground water level is at the top of the ground. Clay layer was modeled as Sekiguchi-Ohta model while sand layer was modeled as elastic material. Figure 2 shows finite element mesh used in this study. The bottom boundary in Figure 2 is fixed for x, y and z directions while side boundary is fixed for x and z directions (free for y direction). In addition, bottom and side boundaries are drained condition. The embankment (wet unit soil density = 17.4 kN/m^3) is assumed to be 3.4 m in height, 6.0 m on the top side and 19.6 m on the bottom side. The embankment construction was completed in 76 days.

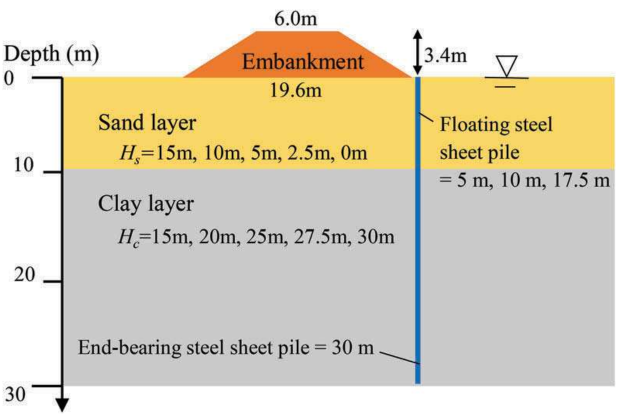

Figure 1. Schematic diagram of model ground.

Firstly, in order to investigate the influence of the sand layer on the clay layer on the deformation of soft ground, the settlement and the lateral displacement of soft ground due to the embankment construction are analyzed by changing the thick-ness ratios of sand and clay layers from 0 (no sand layer) to 1.0 (15 m sand layer and 15 m clay layer). Table 1 summarizes the input parameters for sand and clay layers, which are determined by element tests conducted to soil samples taken from the Kumamoto Plain.

Next, in order to reduce the settlement and the lateral displacement of soft ground, the geometry of the PFS method consisting of floating sheet piles with an end-bearing sheet pile was carefully modelled in the 3D FEM analysis. Namely, the unit of five floating sheet piles with one end-bearing sheet pile for the typical PFS method was modelled as a solid element. The sheet pile was installed at the toe of the embankment. It is assumed that the length and the width of an end-bearing sheet pile is 30 m and 0.9 m respectively. The length of a floating sheet pile of the PFS method is changed from 5 m, 10 m and 17.5 m to propose an effective length of a floating sheet pile to reduce the soft ground deformation. For the comparison, the CS method consisting of only one end-bearing sheet pile was also analyzed. From the practical application of PFS method in Kumamoto Prefecture in Japan (Kasama et al., 2020), the mean length ratio of floating sheet pile and end-bearing sheet pile is 0.66 ranging from 0.27 to 0.9.

Table 2 indicates the material properties of the sheet pile. The modelling of steel sheet pile as a solid element in the FE analysis was referred to Nakai et al (2017).

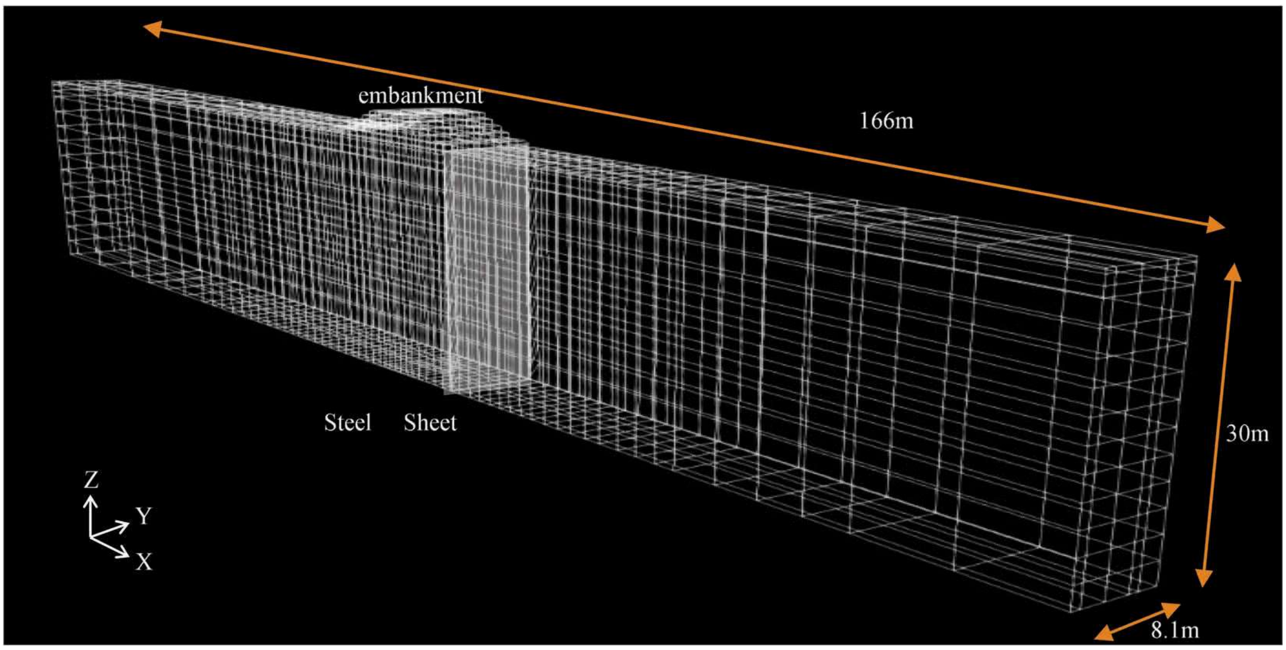

Figure 2. 3D finite element mesh.

Table 1. Input parameters for sand and clay layers.

	Sand layer	Clay layer
Elastic modules E (kPa)	9806	5295
Poisson's ratio ν	0.30	0.41
slope of the critical state line in e-ln$p$ space λ	-	0.54
slope of the overconsolidated line in e-ln$p$ space κ	-	0.04
slope of the critical state line in p-q space M	-	1.63 (ϕ = 39.8 °)
Initial void ratio e_0	0.89	2.59
Wet unit weight γ_t (kN/m^3)	18.24	14.32
Permeability (m/day)	1.15*10^{-2}	5.30*10^{-3}

Table 2. Input parameters for steel sheet pile.

Elastic modules E (kPa)	3.2*10^7
Moment of inertia of area (m^4)	6.7*10^{-4}
Cross sectional Area (m^2)	2.0*10^{-1}

3 EFFECT OF SAND LAYER

Figure 3 shows the evolution of settlement vs time at the axis of the embankment due to the embankment construction for a given thickness ratio of sand clay layers. It is seen that instantaneous settlement was remarkable irrespective of thickness ratios, which was finished within 76 days (the day of completion for embankment construction). After causing instantaneous settlement, consolidation settlement for all thickness ratios gradually occurred and completed within 912 days. It was anticipated that the total settlement for only one clay layer is 230 cm. It can be characterized that the total settlement greatly reduces due to the existence of the sand layer. Namely, even if there is a sand layer of 0.5 m thick on the clay layer, the total settlement sharply reduces to 70 % of that for only one clay layer. In addition, the total settlement for the soft ground with a sand layer of 15 m thick on a clay layer of 15 m thick is 11.7 cm, which corresponds to only 5 % of that for only one clay layer.

This is because the embankment load was widely distributed and reduced due to the existence of sand layer, and the heaving deformation of clay layer due to embankment load was restrained due to the self-weight of sand layer.

Figure 4 shows the total ground settlement after consolidation depending on the thickness ratios of sand and clay layers. It is noted that the location of the toe of the embankment is 10 m from the axis of the embankment. It is seen that there is a large settlement at the toe of the embankment while there is also ground heaving behind the toe. The magnitudes of the total settlement and the ground heaving decrease as the thickness of sand layer increases. In other words, the existence of sand layer on the clay layer is effective for reducing the ground deformation of soft ground due to the embankment construction. However, even if there is a thin sand layer on a clay layer, the embankment construction affects the ground deformation away from the embankment. It is suggested that reinforcement or ground improvement for the embankment is needed to control the propagation of settlement due to the embankment construction.

In order to investigate the effect of sand layer on the lateral displacement of ground due to the embankment construction, Figure 5 shows the final horizontal displacement of the ground just below the toe of the embankment against the ground depth. When there is no sand layer on the clay layer, the maximum horizontal displacement of 80 cm is obtained at the depth of 1.0 m. When there is a sand layer of 0.5 m thick on the clay layer, the maximum horizontal displacement reduces 50 % of that for no sand layer. It can

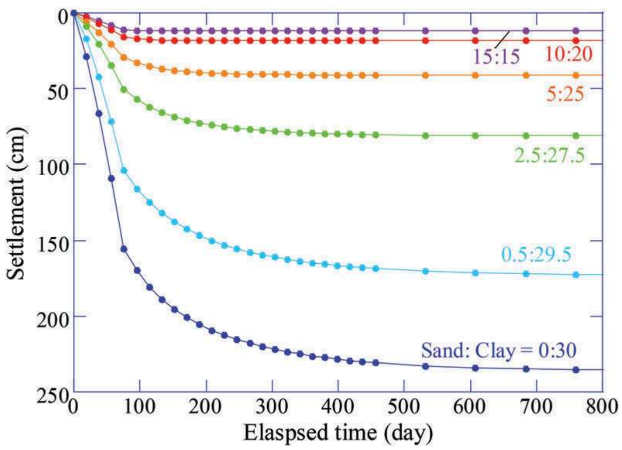

Figure 3. Evolution of settlement vs time at axis of embankment.

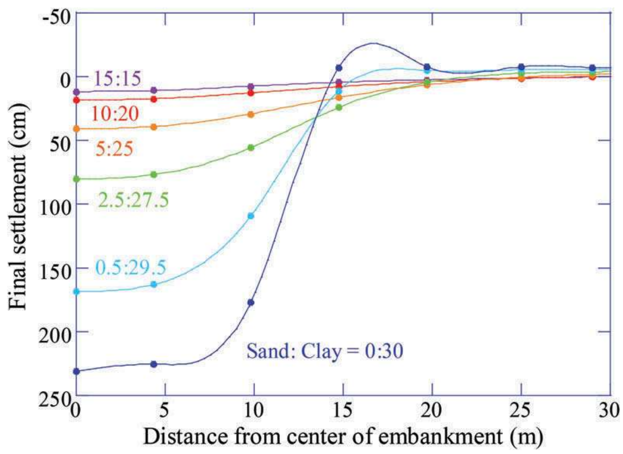

Figure 4. Ground surface settlement and sand layer thickness.

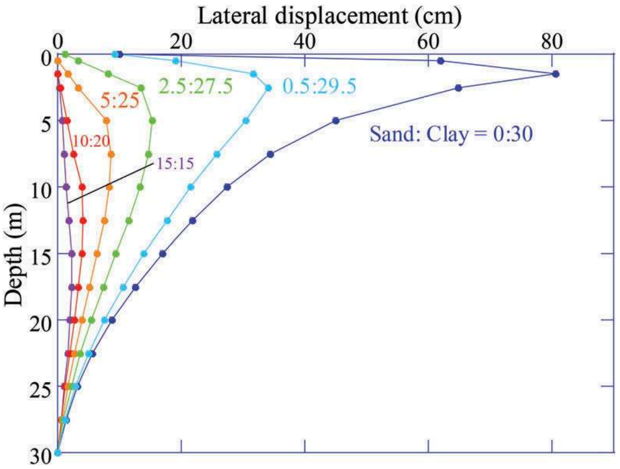

Figure 5. Lateral displacement and sand layer thickness.

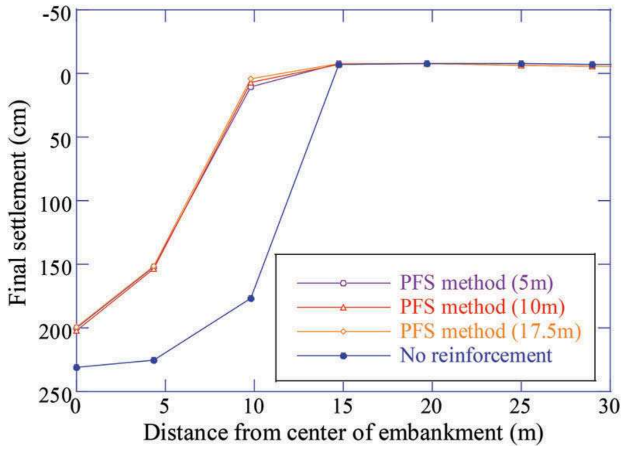

Figure 7. Ground surface settlement with/without PFS method.

be characterized that the maximum horizontal displacement greatly reduces due to the existence of the sand layer similar to the ground settlement. For cases with the sand layer, the maximum horizontal displacement is obtained slightly below the boundary between the sand layer and the clay layer.

4 EFFECT OF PFS METHOD

In order to investigate the effectiveness of the PFS method for the settlement countermeasure, Figure 6 shows the evolution of ground settlement vs time at the axis of the embankment for the soft ground without a sand layer. It is seen that consolidation settlement is reduced by the PFS method while instantaneous settlement due to the embankment construction is similar to that for no reinforcement. The total settlement of ground reinforced by the PFS method is 86 % of that for no reinforcement irrespective of the length of floating piles for the PFS method.

Figure 7 shows the total ground settlement after consolidation for the ground with/without the PFS method for the ground without a sand layer. Due to the reinforcement of the PFM method, ground settlement and heaving beyond the toe of the embankment is well reduced and the propagation of ground deformation due to the embankment construction is well controlled irrespective of the length of a floating pile for the PFS method. Therefore, it can be suggested that the PFS method is effective for restricting the ground settlement and heaving due to the embankment construction.

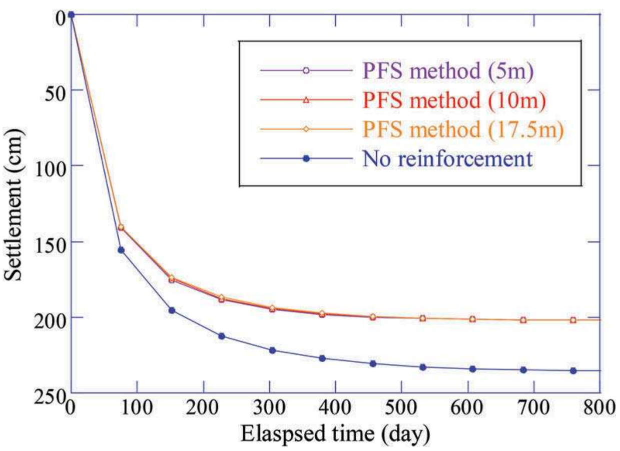

Figure 6. Evolution of settlement vs time with/without PFS method.

In order to evaluate the effective length of a floating pile of the PFS method for the ground without a sand layer, Figure 8 shows a lateral displacement of ground just below the toe of the embankment for the floating pile length of 5 m, 10 m and 17.5 m together with the result for no reinforcement. It is seen that the lateral displacement for the end-bearing pile reduces to 50 % of that for no reinforcement irrespective of the length of the floating pile. Namely, the influence of the length of floating pile for the PFS method is very small on the lateral displacement on the end-bearing pile. On the other hand, the lateral displacement for the floating pile is slightly larger than that of the end-bearing pile. In addition, the tip of the 5 m floating pile shows a large lateral displacement compared to those for other floating piles. Therefore, it is considered that a 5 m floating pile is not enough to restrain the lateral displacement of ground due to the embankment construction.

In order to discuss the effective two-layered ground condition for the PFS method, Figure 9 shows the lateral displacement of ground just below the toe of the embankment for a given thickness ratio of sand and clay layers. In this figure, the lateral displacement at the end-bearing pile is shown as dots and that at the floating pile is shown as lines. The difference between the end-bearing pile and the floating pile becomes large when the length of the floating pile is 5 m and the thickness of the sand layer less than 2.5 m. In addition, the tip of the

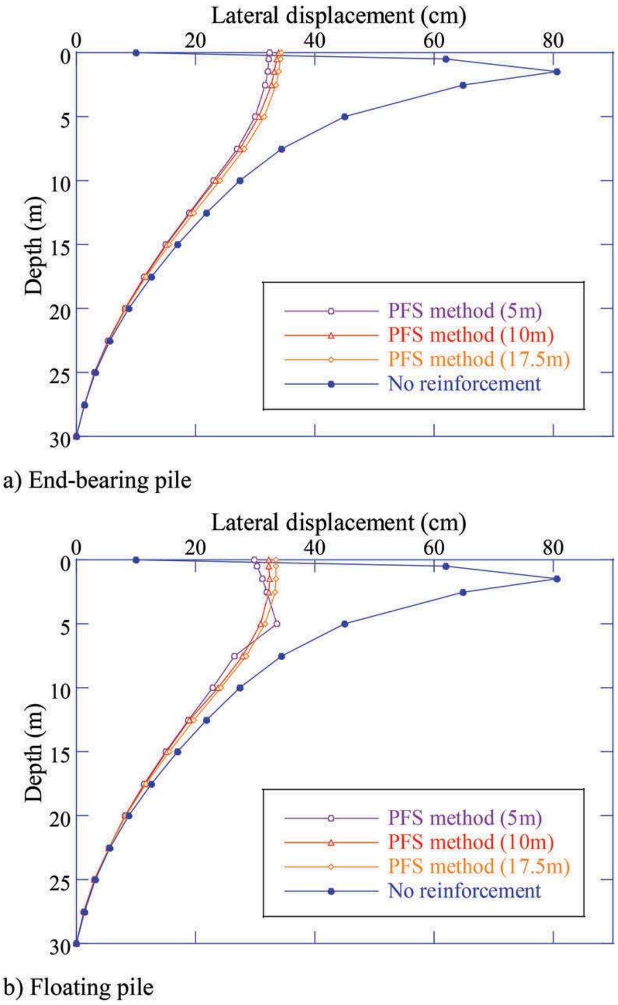

Figure 8. Ground surface settlement with/without PFS method.

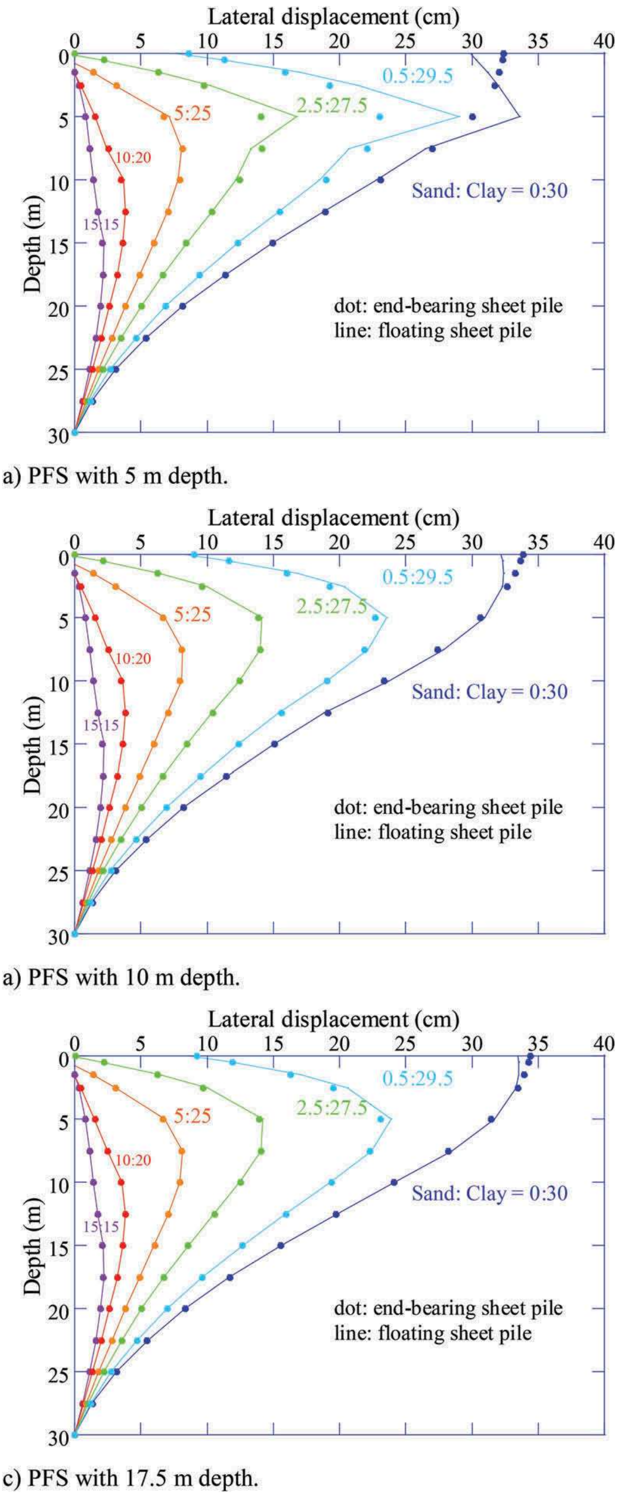

Figure 9. Lateral displacement of ground reinforced with PFS.

floating pile for 5 m length is not well fixed indicating the maximum horizontal displacement for small thickness ratio. However, the lateral displacement is well restrained with 10 m and 17.5 m floating piles for a given thickness ratio.

In order to evaluate the effectiveness of the PFS method for the settlement countermeasure of two-layered soft ground due to the embankment construction, the reduction ratio R, which is the final lateral displacement divided by that for the ground without a sand layer and reinforcement, was calculated. Figure 10 shows the reduction ratio R against the thickness ratio of sand and clay layers. The reduction ratio R sharply increases as the thickness ratio increases, which suggests that the effect of a sand layer on a clay layer is very large on the restrain of soft ground deformation due to the embankment construction. When the thickness ratio is more than 0.2 (which corresponds to the sand layer of 5 m on the clay layer of 25 m), the lateral displacement reduces 85 % of that for no sand layer and no reinforcement.

Figure 11 shows the reduction ratio R only due to the effect of the PFS method. The reduction ratio R is 0.6 for the no sand layer condition and becomes zero for the thickness ratio more than 0.2. In other words, the PFS method is considered to be suitable for soft ground without a sand layer or with a sand layer less than 5 m thick.

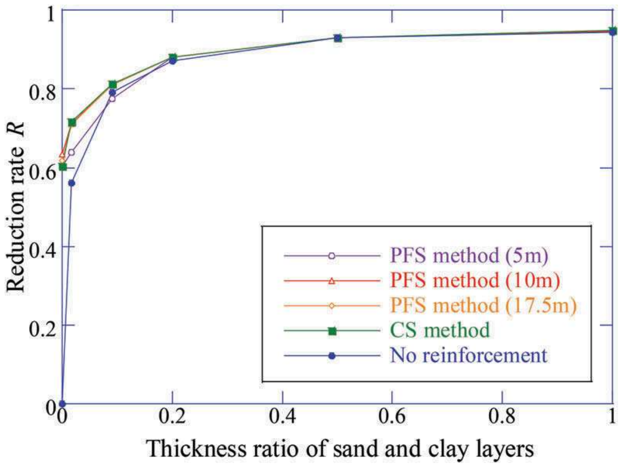

Figure 10. Reduction rate of lateral displacement.

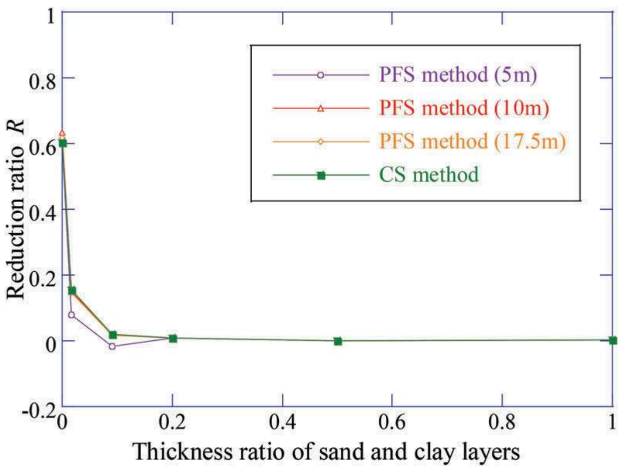

Figure 11. Effect of PFS on lateral displacement reduction.

5 SUMMARY

In order to investigate the effectiveness of the partial floating steel sheet piling method (PFS method) for the settlement countermeasure of two-layered soft ground due to embankment construction, a series of 3D soil-water coupled FE analyses was conducted. The main conclusions are as follows:

1. The total settlement and lateral displacement of soft ground greatly reduces due to the existence of the sand layer. This is because the embankment load was widely distributed and reduced due to the existence of the sand layer and the heaving deformation of the clay layer due to embankment load was restrained due to the self-weight of the sand layer.
2. Due to the reinforcement by the PFM method for embankment, the ground settlement and heaving beyond the toe of the embankment is well reduced and the propagation of ground deformation due to the embankment construction to surroundings is well controlled irrespective of the length of a floating pile for the PFS method.
3. The floating pile of 10 m for the PFS method is enough to restrain the lateral displacement of ground due to the embankment construction irrespective of thickness ratio of sand and clay layers because the tip of the floating pile for 5 m length is not well fixed indicating the maximum horizontal displacement for the thickness ratio less than 0.2.

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