Deformation suppression effect of double steel sheet pile method for river levee on soft ground against mega earthquake

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ABSTRACT

As there are concerns about the occurrence of a mega earthquake, appropriate earthquake resistance evaluation and seismic countermeasures for river levees are urgent issues. The authors previously investigated the reinforcing effect of steel pipe sheet piles placed at the foot of the embankment on a river levee built on an alternating layer of sand and clay that simulates the typical alluvial plains of Japan. Through the result of seismic response analysis, it was shown that if the sheet pile penetration is shallow to clayey layer, deep slippage that passes through the tip of the sheet pile will occur, so it is necessary to deepen the penetration to the supporting layer. In this paper, we investigated the effectiveness of the double steel pipe sheet pile method in which steel pipe sheet piles connected with tie rods are installed on both shoulders of the slope instead of at the foot of the slope, expecting to reinforce the levee body itself. As a result, it was found that slippage occurring within the clay layer, stretching and subsidence of the embankment were greatly suppressed, and a high restraint effect could be expected against large deformations caused by the soft clay layer.

Key words: *River levee, Double steel sheet pile method, Sand/clay alternating layer, Seismic response analysis*

1. Background

As there are concerns about the occurrence of mega earthquakes such as the Tokyo Metropolitan Earthquake and the Nankai Trough Earthquake, appropriate earthquake resistance evaluation and seismic countermeasures for river levees are urgent issues. The authors have so far studied the behavior of a river levee built on alternating layers of thickly deposited soft clay and sand with an *N*-value of almost zero that simulates the typical alluvial plains of Japan, and the reinforcing effects of steel pipe sheet piles placed at the foot of the embankment (Nakai et al., 2017). In this study, we conducted seismic response analysis using soil-water coupled finite deformation analysis called GEOASIA (Noda at al. 2008), incorporating elasto–plastic constitutive equations (Super/subloading Yield Surface (SYS) Cam-clay model (Asaoka et al., 2002)) to describe sand, intermediate soil, and clay within the same theoretical framework. Through the results of seismic response analysis, it was demonstrated that if the sheet pile penetration is shallow to clayey layer, a deep slippage that passes through the tip of the sheet piles will occur, so it is necessary to deepen the penetration to the supporting layer. In addition, it was demonstrated that if sheet piles are installed on only one side of an embankment, the deformation on the other side will be greater, and even greater damage might occur. Moreover, the deformation suppression effect of the levee body itself is small, thus if the levee body is in a loose condition, it is not possible to suppress the settlement and lateral deformation of the levee body.

Therefore, in this study, we investigated the effectiveness of the double steel pipe sheet pile method in which steel pipe sheet piles connected with tie rods are installed on both shoulders of the slope instead of the foot of the slope, expecting to reinforce the levee body itself in addition to preventing liquefaction of the foundation ground.

2. Analysis condition

2.1. Finite element mesh and ground condition

We conducted the following three cases (**Table 1**) with reference to previous study.

Table 1. Analyses condition

Case 1	No reinforcement (without sheet piles)
Case 2	Reinforced sheet pile with length L = 20 m (shallow penetration)
Case 3	Reinforced sheet pile with length L = 23 m (deep penetration)

The steel pipe sheet pile was assumed to have an outer diameter of φ = 700 mm and a width of t = 10 mm. In Cases 2 and 3, steel pipe sheet piles were inserted from the slope shoulder after the embankment construction, and the pile heads were tied with tie rods. **Fig. 1** shows the finite element mesh used in the analysis. The analysis area is 1.0 km horizontally wide, and this figure is an enlarged view of the areas near the left and right embankments. The steel pipe sheet pile was modeled as a one-phase elastic body, and the elastic modulus and density were set to give equivalent stiffness and weight as actual ones. The tie rod was expressed using the distance invariant condition of two finite element nodes at the connection with the sheet pile (Asaoka et al., 1998).

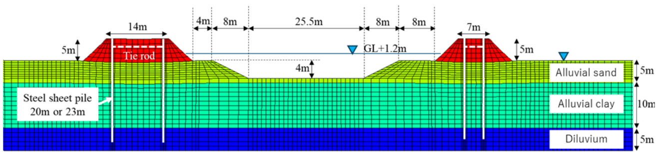


Fig. 1 Finite element mesh

The geological structure was a simplified from the actual ground, consisting of alternating layers diluvium, alluvial soft clay, and alluvial loose sand from deeper part. The clay obtained from the boring survey has an *N*-value of almost zero, and the shear wave velocity V_s is estimated to be 20 to 40 m/s. After constructing a river levee with a height of 5.0 m and a slope of 1:1, the river channel was excavated, and the water level of the river was raised to GL + 1.2 m. The width of the embankment crest is 7.0 m on the right bank and 14.0 m on the left bank. The hydraulic boundary is set to zero water pressure so that the ground surface matches the groundwater level. The bottom and both sides of the mesh are modeled as undrained conditions. The hydraulic boundary of the elements on the outside of the embankment gives water pressure to the elements according to the height of the water level. The material constants were determined by reproducing various mechanical tests of the undisturbed samples using the SYS cam clay model. For the initial conditions, the degree of soil skeleton structure (structure, overconsolidation, and anisotropy) and initial stress ratio were assumed to be uniform in each layer, and the specific volume was distributed according to the overburden pressure.

2.2. Input ground motion

Fig. 2 shows the input seismic motion, which comprises the Tokai, Tonankai, and Nankai triple-linked seismic waves near Nagoya Port. A simple shear deformation boundary with lateral boundary elements was set at both ends of the boundary (Noda et al., 2009; Asaoka et al., 1998), and a viscous boundary equivalent to V_s = 300 m/s (Noda et al., 2009; Lysmer and Kuhlemeyer, 1969) was used at the bottom of the FEM mesh. The seismic waveform was input horizontally simultaneously at all nodes of the bottom boundary.

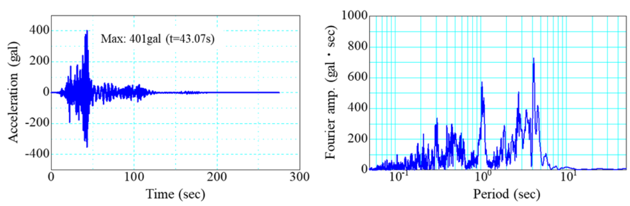


Fig. 2 Input seismic motion

3. Analysis results

3.1. Reinforcing effect of double steel pipe sheet pile method

Figs. 3 to 5 show the distributions of shear strain, excess pore water pressure ratio, and degree of structure, respectively for each case. The same finite element mesh was used in all cases. Because of the small mesh width at the assumed sheet pile locations, Case 1 also appears to have sheet piles, but the assumed sheet pile locations are the same soil material as the surrounding area. The degree

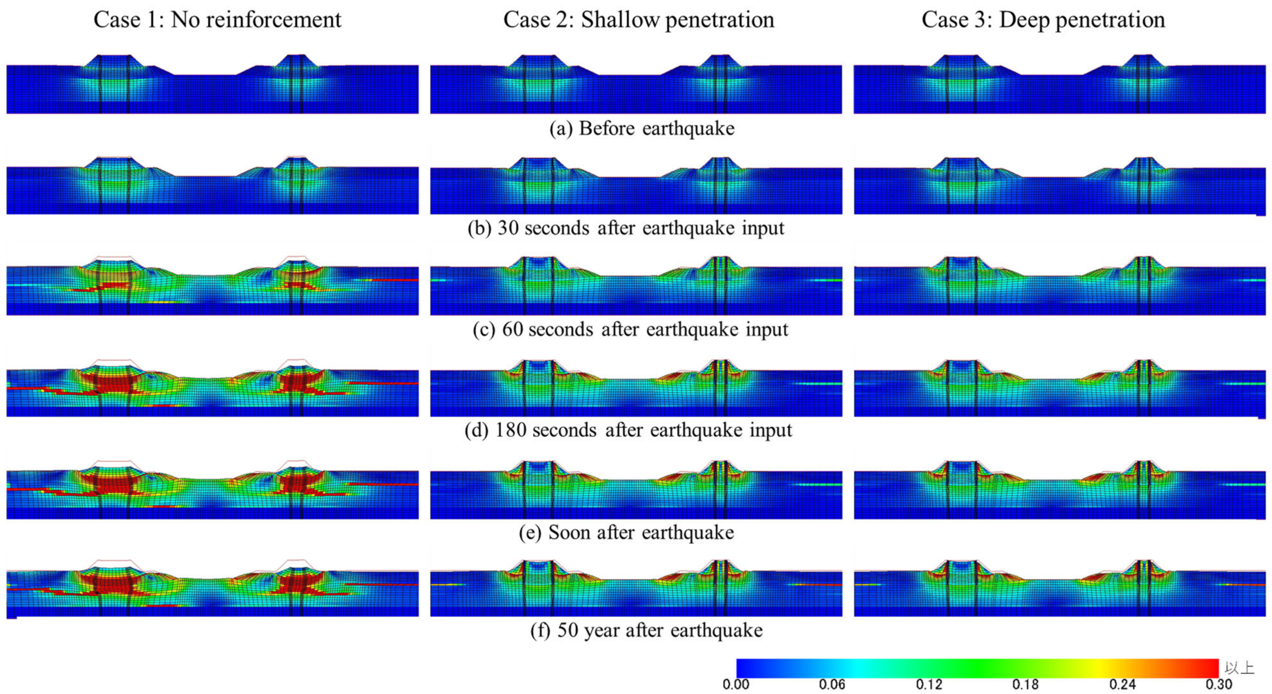


Fig.3 Distributions of shear strain

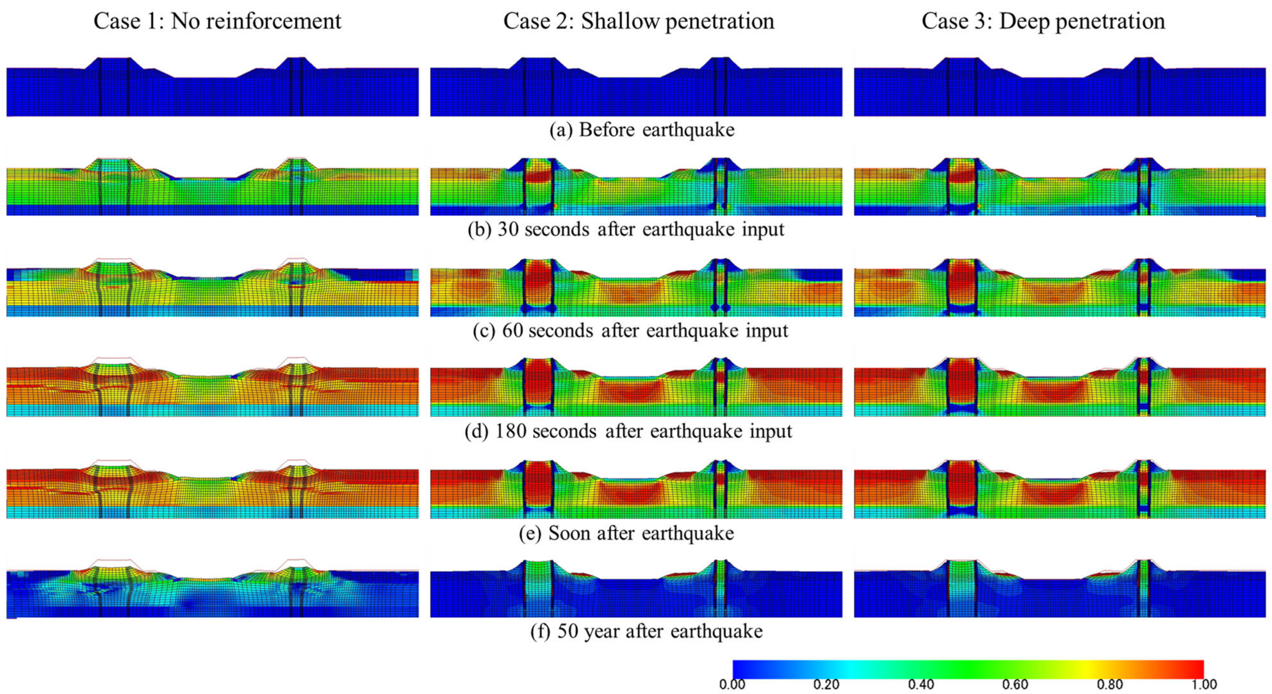


Fig. 4 Distributions of excess pore water pressure ratio

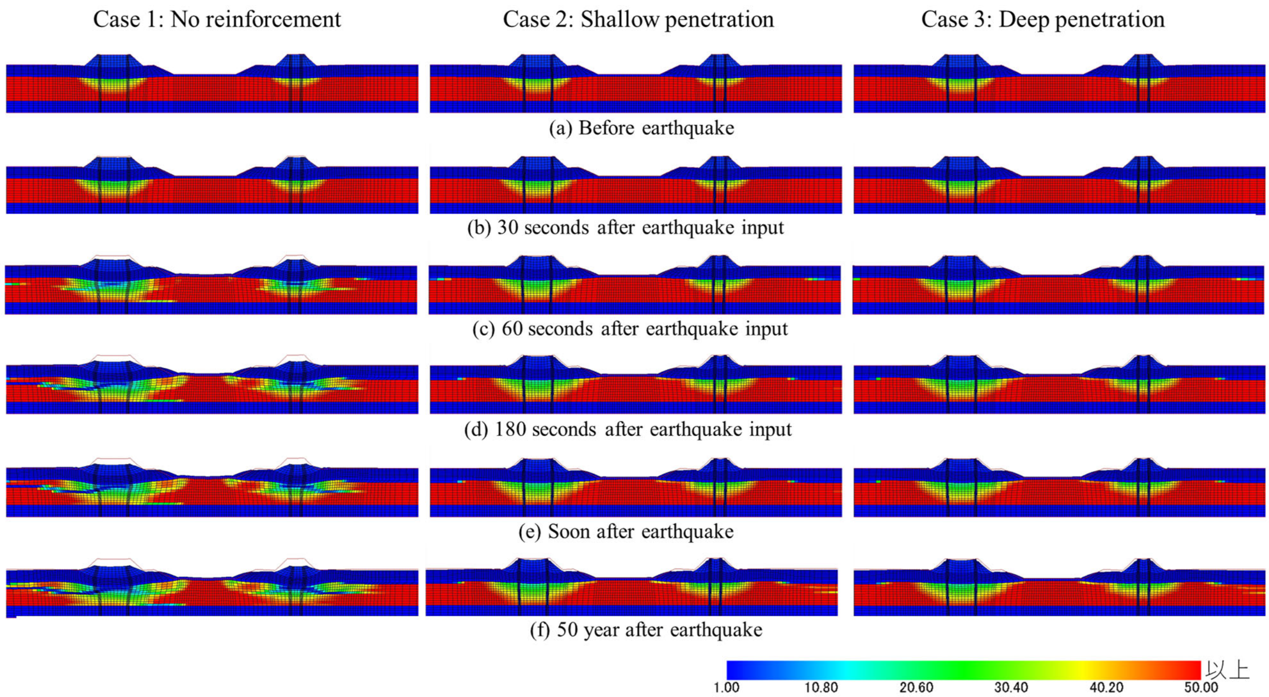


Fig.5 Distributions of degree of structure

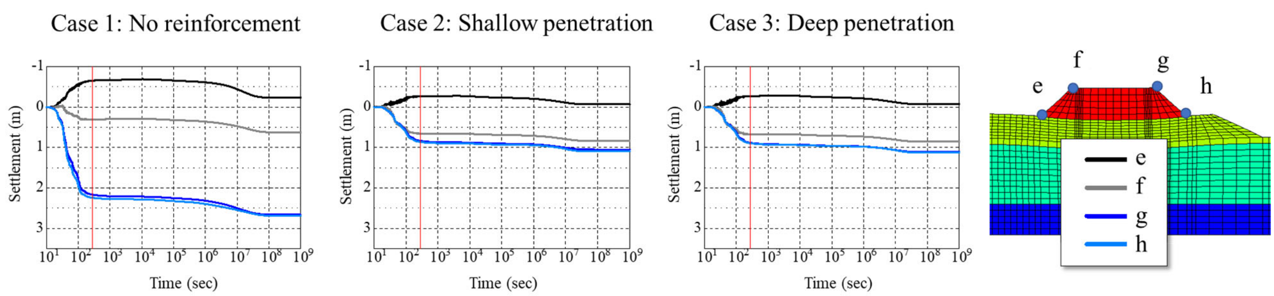


Fig.6 Amount of settlement at the foot and shoulder of the left bank

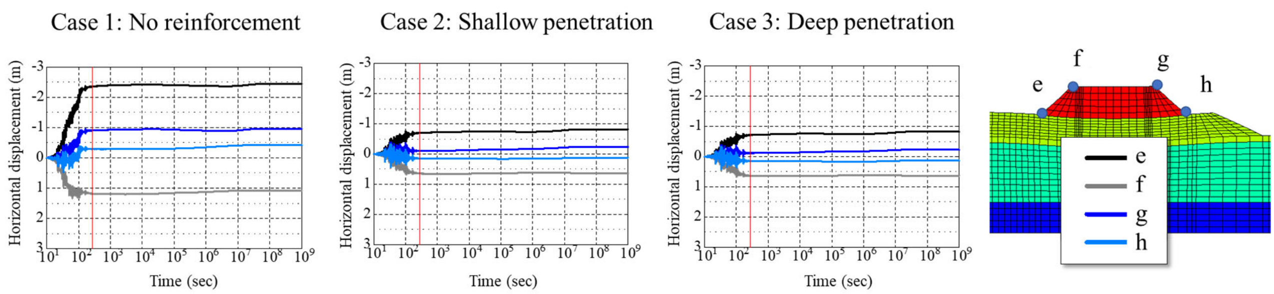


Fig. 7 Amount of horizontal displacement at the foot and shoulder of the left bank

of structure is an index that quantitatively expresses the bulkiness of the soil skeletal structure. The greater the degree of structure, the greater the void ratio under the same effective stress. Collapse of structure means disturbance of the soil, leading to plastic compression.

Figs. 6 and 7 show the amount of settlement and horizontal displacement at the foot and shoulder of the left bank, respectively. Since there is no significant difference in the settlement and horizontal displacement of the embankment between the right and left banks, only the results of left bank embankment is shown.

In the case of no reinforcement (Case 1), arcuate slippage occurs within the soft clay layer directly beneath both levee bodies, and it can be seen that the levee bodies are sinking deeply. Since the excess pore water pressure increases (mean effective stress decreases) at the location where slippage occurs, it is clear that the seismic damage of the clay layer during an earthquake is caused by the decrease in rigidity (the disturbance of soft clay) due to repeated shearing. Therefore, the degree of structure at this location is also significantly lowered. The top of the embankment sank approximately 2.0 m during the earthquake and continued to settle approximately 0.6 m after the earthquake as the positive excess pore water pressure that accumulated during the earthquake dissipates. Due to the settlement of the embankment, the riverbed rises, and the river area decreases. In addition, the slippage of the embankment causes the levee body to stretch by approximately 3.5 m. Based on the above considerations, if the clay is in a soft condition at a high level of the structure, and especially near areas subject to uneven loads such as directly beneath river embankments, seismic damage can occur even in clay layers that were previously thought not to cause earthquake damage.

Next, we will discuss the reinforcing effect of the double steel pipe sheet pile method. In both Cases 2 and 3, there is almost no difference in the presence or absence of penetrating into the diluvium at the tip of the sheet pile, and the large deformation caused by liquefaction of the sand layer and slippage in the clay layer that occurred in Case 1 is strongly suppressed. The amount of settlement at the shoulder of the levee body is 1.0 m, which is suppressed to about 40% compared to the case without countermeasures. Moreover, stretching of the foot of the levee was also suppressed to 1.5m, which was about 43% of that without any measures. In Cases 2 and 3, the excess pore water pressure ratio (**Fig. 4**) increased during the earthquake in the sand layer and clay layer surrounded by

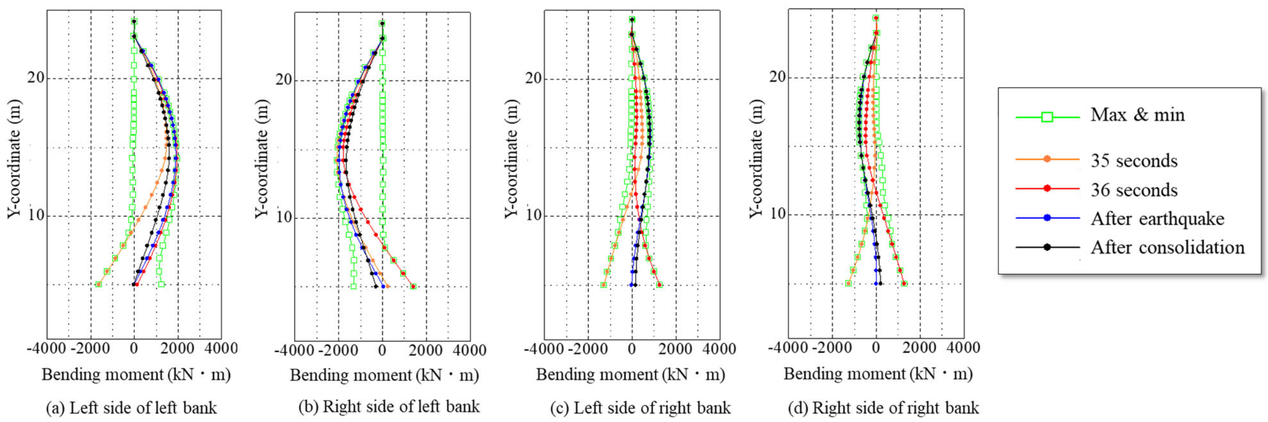


Fig. 8 Temporal changes in the bending moment in the depth direction acting on the sheet piles in Cases 2

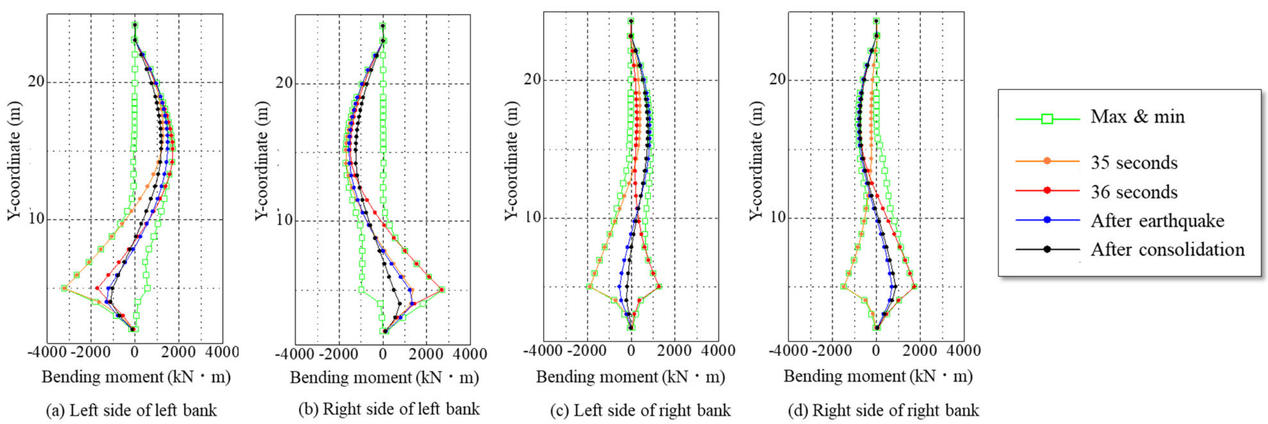
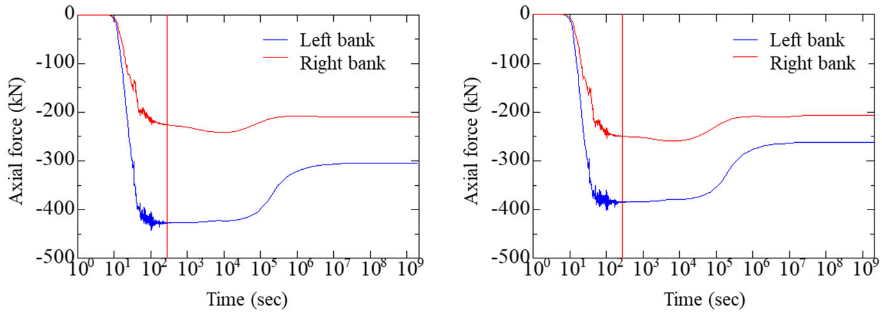


Fig. 9 Temporal changes in the bending moment in the depth direction acting on the sheet piles in Cases 3



(a) Case 2 (short penetration) (b) Case 3 (long penetration)

Fig. 10 Change over time in the tie rod axial force for Cases 2 and 3

sheet piles. This is because significant unloading occurs in this region, leading to increase the overconsolidation ratio, which suppresses the occurrence of plastic deformation and causes almost no structural disturbance (**Fig. 5**). One of the important notices is that there is no significant difference in the effectiveness of preventing deformation between the two cases, indicating that deformation can be suppressed without penetrating the tip of the sheet pile into the diluvium.

3.2. Bending moment of sheet pile and axial force of tie rod

Figs. 8 and 9 show the temporal changes in the bending moment in the depth direction acting on the sheet piles in Cases 2 and 3, respectively. In this analysis, steel pipe sheet piles are modeled using a linear elastic body, and the yielding is not taken into consideration. The yield moment of the sheet pile with the specifications set here (φ = 700 mm, t = 10 mm) is 860kN･m. Therefore, it can be seen that according to the original specifications, all the sheet piles would yield near the main shocks. However, if the sheet pile of short length (Case 2) is replaced with φ = 800 mm, t = 20 mm, and the sheet pile of long length (Case 3) is replaced with φ = 1300 mm, t = 22 mm, the yield moment can be kept below the yield value. In fact, steel pipe sheet piles with such specifications exist. **Fig. 10** shows the change over time in the tie rod axial force for Cases 2 and 3. From this figure, a large tensile force is generated in the tie rod to suppress the deformation of the embankment during an earthquake, but it decreases and converges over time. Although the details are omitted, there are tie rods with specifications that can withstand this axial force. Also, unlike the bending moment of sheet piles, the axial force of tie rods is greater when they are short. This is because the deformation at the bottom of the long sheet pile (Case 3), where the tip of the sheet pile is penetrated into the diluvium, is relatively small. In this way, there is an optimal specification depending on the conditions of the ground and sheet piles, and it is also influenced by design concepts such as whether or not to allow yielding of the steel pipe sheet piles.

4. Concluding remarks

Considering the upcoming review of the "Earth Embankment Principles" for river levees, this study uses soil-water coupled finite deformation analysis to propose a double steel sheet pile method, in which steel pipe sheet piles connected with tie rods are installed on both shoulders of the slope.

In river levees on soft ground consisting of alternating layers of loose sand and soft clay with a small *N*-value (locations where local loads are applied), in addition to liquefaction of the sand layer during an earthquake, the stiffness of the clay layer decreases due to disturbance. The shear slippage caused by the lowering causes sinking of the levee body and lateral flow, and there is a risk that the function of the levee will deteriorate significantly due to a decrease in river area. Although not mentioned in this study, the natural period of the soft layer becomes longer due to the liquefaction of the thickly deposited soft sand layer and the disturbance of the clay layer, resulting in long-term earthquake motion with a rather long period component of several seconds to 5 seconds. Resonance with long-period earthquakes will occur, and the damage will become more serious. This kind of ground is often found in sedimentary basins and alluvial plains, including areas below sea level where large cities are located. However, the specifications of existing steel pipe sheet piles indicate that this construction method can be expected to have high earthquake resistance (deformation restraint effect).

In the future, we will continue to model the sheet pile as an elastoplastic body and conduct systematic analyses with a view to develop design concepts considering factors such as the length of the sheet pile, the size of the embankment, the influence of the stratigraphy of the ground, and the impact of repeated earthquakes. Also, it is necessary to implement it in an actual specific manner.

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