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Numerical analysis of a sheet pile mooring wharf having several tie rods

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ABSTRACT: When an anchor pile-type sheet pile mooring wharf is constructed on soft ground, it sometimes undergoes tremendous lateral deformation due to the lateral flow of the ground that accompanies embankment construction behind the sheet pile. In the present study, various measures were considered to counteract this lateral flow of the ground. The results of the analysis led to the following conclusions: 1) By replacing the clay in front of the sheet pile with rubble mound, the horizontal displacement of the sheet pile could be reduced. 2) By increasing the horizontal distance between the sheet pile and anchor piles, the horizontal displacement could be greatly diminished. 3) When the horizontal distance between the sheet pile and anchor piles was unchanged, there was almost no reduction in horizontal displacement at the top of the sheet pile even if the number of steps of tie rods was increased.

1 INTRODUCTION

When an anchor pile-type sheet pile mooring wharf is constructed on soft ground, sometimes greater than expected horizontal displacement occurs on the top of the sheet pile, hindering the use of the wharf. This is probably the result of lateral deformation of too closely spaced sheet and anchor piles that occurs when the ground moves laterally during and after the construction of an embankment behind the sheet pile. At least three different reinforcement measures have been considered to prevent or suppress the lateral displacement of piles and make them resist the lateral flow of soft ground: 1) Replacing the soft soil in front of the sheet pile with sand, gravel, etc., 2) increasing the horizontal distance between the sheet and anchor piles, and 3) increasing the number of steps of tie rods. To investigate the results of these measures, we subjected the ground-structure system composed of soft ground, and sheet pile, anchor piles and rubble mounds, to two-dimensional consolidation deformation analysis.

2 GROUND MODEL AND MATERIAL CONSTANTS USED IN THE ANALYSES

The analysis considered the ground to be a two-phase material composed of an elasto-viscoplastic structural skeleton of Sekiguchi and Ohta (1977) and incompressible pore water, and the sheet pile, anchor piles and tie rods to be linear elastic beam elements. In addition, joint elements (Goodman, 1976) were inserted between the sheet or anchor piles, and the foundation. The finite element analysis (Kobayashi, 1984) was conducted under plane strain conditions.

Figure 1 is the ground profile used in the analysis. The upper part of the figure shows the entire profile used in the analysis, while the lower part depicts the area where the anchor piles and rubble mound were constructed.

Table 1 lists the material constants that were used to calculate the ground for the model. The upper and lower clay layers and the rubble mound were modeled as elasto-viscoplasticity following Sekiguchi and Ohta (1977) and the foundation layer was considered to be a linear elastic body.

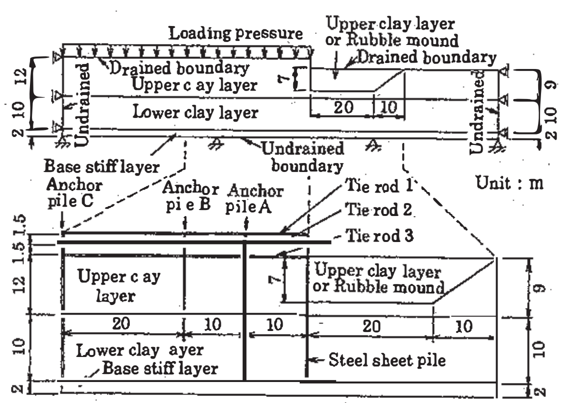

Figure 1. Ground profile used in the calculations.

Table 1. Soil parameters used in analysis.

Parameters		Upper clay layer	Lower clay layer	Rubble mound	Base stiff layer
Young's modulus	E(MPa)	-	-	-	9.80
Poisson's ratio	ν	0.0	0.0	0.30	0.33
Density	ρ (t/m^3)	1.600	1.600	1.600	1.800
Stress ratio at failure	M	1.484	1.484	1.735	-
Compression index	λ	0.173	0.173	8.315×10^{-3}	-
Swelling index	κ	0.027	0.027	2.810×10^{-3}	-
Initial void ratio	e_0	1.200	1.200	0.480	-
Anisotropic parameter	η_0	0.315	0.315	0.407	-
Initial volumetric strain rate	$\dot{v}_0$ (1/day)	10^{-5}	10^{-5}	10^{-5}	-
Secondary compression index	α	10^{-3}	10^{-3}	10^{-3}	-
Coefficient of permeability	k (m/day)	4.32×10^{-4}	8.64×10^{-5}	8.64×10^{4}	-

Table 2. Material constants of beam elements.

Properties	Sheet pile	Anchor pile	Tie rod
Bending rigidity EI(MN•m^2)	46.46	22.05	6.21
Axial rigidity EA(GN)	3.83	1.88	0.126

Table 2 shows the material constants for the sheet pile, anchor piles and tie rods used in the analysis. The material constants of the joint elements were joint rigidity in the vertical direction E_n of 10^7 kN/m^3, and in the tangential direction E_s of 10 kN/m^3.

The boundary conditions of displacement were as follows: Both the vertical and horizontal displacement of the upper boundary (ground surface) of the analytical profile in Figure 1 were unrestricted, the boundaries of both left and right sides were unrestricted in the vertical direction and restrained in the horizontal, and the lower boundary (bottom) was restrained both vertically and horizontally. As the hydrological boundary conditions in the analysis, drainage was allowed only in the upper boundary (ground surface) of the analytical profile in Figure 1; there was no drainage at any other boundary.

Assuming that the load acted uniformly on the ground surface behind the sheet pile and increased at a constant rate, the analysis considered various combinations of the following conditions:

1) Presence or absence of rubble mound in front of the sheet pile: If there was no rubble mound, that area became the upper clay layer.

2) Horizontal distance between anchor piles and sheet pile: As we can see in the lower part of Figure 1, the calculated horizontal distances from the sheet pile were 10m for anchor pile A, 20 m for anchor pile B and 40m for anchor pile C.

3) Number of tie rods: The positions of tie rods used in the calculations are shown in the lower part of Figure 1. Here, tie rod 1 signifies just one tie rod; two are denoted by tie rod 1 and tie rod 2; and three rods are shown as tie rods 1, 2 and 3.

4) The velocity of a uniformly distributed load acting on the ground surface behind the sheet pile: Calculated for 1.0 kPa/day.

Calculations were stopped when the finite element mesh in the ground was destroyed. This load is called the "critical load" for convenience. In addition, the conditions for the following calculations, particularly in sections where there were no calculation conditions, were 1) no rubble mound, and 2) anchor pile B.

3 ANALYTICAL RESULTS

3.1 *Effect of rubble*

Figure 2 shows the relation between the horizontal displacement of the top of the sheet pile and the load for the case of no anchor piles and load velocity of

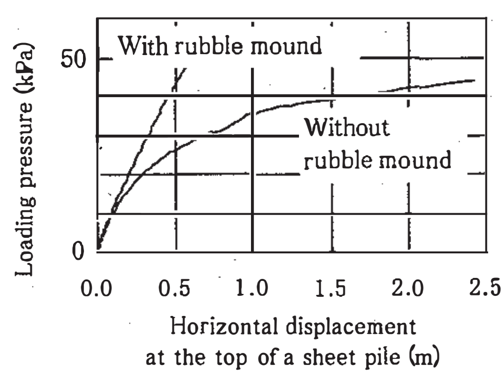

Figure 2. Effect of rubble mound on the relation between load and horizontal displacement of the top of the sheet pile.

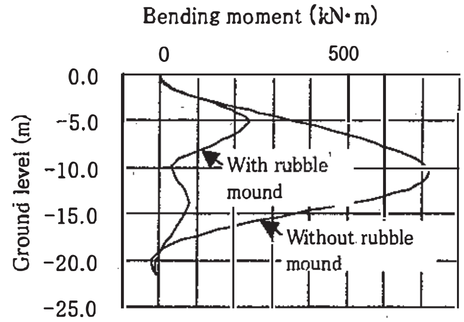

Figure 3. Effect of rubble mound on the depth distribution of the bending moment of the sheet pile.

1.0 kPa/day, and for both with and without a rubble mound. According to the figure, when there was no rubble mound, there was great horizontal displacement of the sheet pile, and its form was nonlinear.

Figure 3 shows, for the same calculations, the depth distribution of the bending moment of the sheet pile at that point in time when the load was 40 kPa. When the load was large, the rubble mound greatly reduced the maximum bending moment.

3.2 *Effect of anchor piles*

Figures 4(a) and 4(b), which show the cases of no anchor piles, and anchor piles A, B and C, illustrate the relation between load for one and three tie rods, respectively, and the horizontal displacement of the top of the sheet pile. Here we can see that as the distance between the anchor piles and sheet pile increased, the lateral displacement of the sheet pile decreased, and the "critical load" increased. A likely explanation is that as the lateral distance between the anchor piles and the sheet pile increased, the length of the anchor piles that were within the lateral flow region of the ground behind the sheet pile decreased.

Figures 5(a) and 5(b) show the results of calculations for depth distribution of bending moment of the sheet pile, made under the same conditions as in Figure 4. It is clear that the maximum bending moment was largest when there were no anchor piles, but when there were anchor piles, it decreased as the distance between the sheet and anchor piles increased. In addition, Figure 5(a) shows that for one tie rod, the bending moment near the ground surface was close to zero or negative at shallow depths, while at deeper depths it tended to be positive.

3.3 *Effect of tie rods*

Figures 6(a) and 6(b) show, for the cases of no rubble mound and rubble mound respectively, the relation between the load for one, two and three tie rods and the horizontal displacement of the top of the sheet pile. As we can see, this relation was only slightly affected by the number of tie rods. This means that even when the number of tie rods was in-

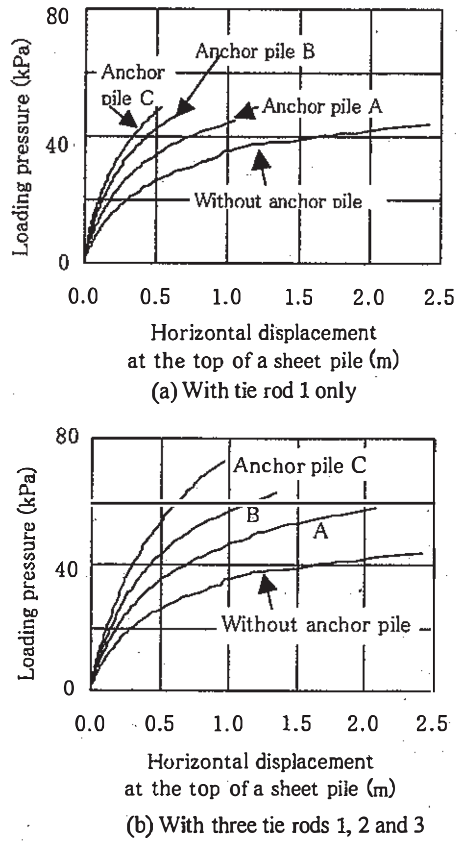

Figure 4. Effect of anchor piles on the relation between load and horizontal displacement of the top of the sheet pile.

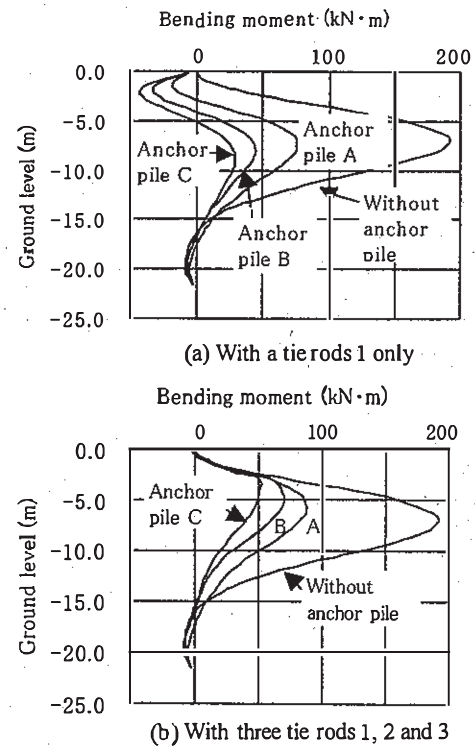

Figure 5. Effect of anchor piles on the depth distribution of the bending moment.

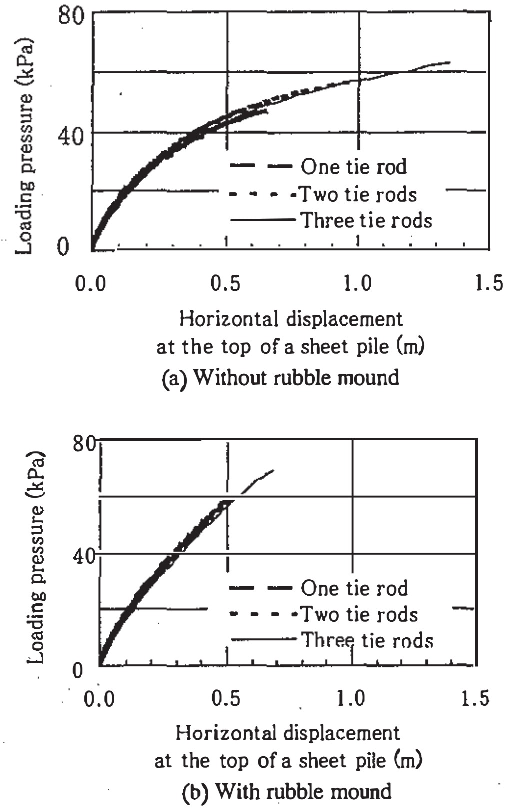

Figure 6. Effect of number of tie rods on the relation between load and horizontal displacement of the top.

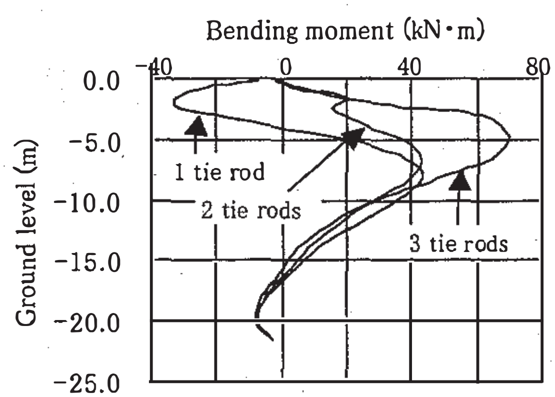

Figure 7. Effect of number of tie rods on the depth distribution of the bending moment of the sheet pile.

creased, the horizontal displacement of the sheet pile could not be suppressed. However, increasing the number of tie rods did tend to increase the "critical load" of the ground, that is, it helped to increase the lateral support effect of the sheet pile.

Figure 7, which is based on calculations made under the same conditions as Figure 6, depicts the depth distribution of the bending moment of the sheet pile at a load of 20 kPa. According to Figure 7, a negative bending moment occurred near the ground surface when there was one tie rod, and the greatest positive bending moment occurred when there were three tie rods.

4 CONCLUSIONS

A sheet pile mooring wharf built on soft ground was the object of this study. Numerical simulations were used to investigate the effects of rubble mounds on its bending moment and horizontal displacement, as well as the effects of the positioning of anchor piles, and the number of tie rods. The results led to the following conclusions:

1. The rubble mound helped to increase lateralsupport effect of the sheet pile, reducing the horizontal displacement and maximum bending moment.
2. Increasing the horizontal distance between the anchor piles and sheet pile helped to decrease both the maximum bending moment and horizontal displacement of the sheet pile, for the same load. This was apparently due to the fact that there was little effect of lateral flow in the ground on the anchor piles.
3. The relation between load and horizontal displacement of the top of a sheet pile was nearly constant, regardless of the number of steps of tie rods. However, increasing the number of steps of tie rods helped to increase the lateral support effect of the sheet pile. In addition, different numbers of steps of tie rods had different effects on the depth distribution of the bending moment of the sheet pile.

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