Effect of Seismic Reinforcement of Sheet Pile Quay Wall Using Ground Anchor

M. Yoshida & M. Mitou
Penta-Ocean Construction Co., Ltd., Japan

O. Kiyomiya
Waseda University, Japan

S. Tashiro
TOA Corporation, Japan

K. Gouda
Toyo Construction, Japan

SUMMARY:
This paper describes the results of shaking table tests and effective stress analyses that have been conducted to investigate the effect of seismic reinforcement of a sheet pile quay wall using ground anchors. The displacement of the quay wall has been fairly constrained by the arrangement of ground anchors, and their effectiveness has been confirmed by both the testing and analysis. The analytical results show that the behavior of a quay wall with ground anchors has been fairly well simulated by the analysis. Further, it has also been confirmed that the deformation of a quay wall with ground anchors is greatly reduced when non-liquefiable backfill sand is used.

Keywords: Ground anchor, Seismic reinforcement, Sheet pile quay wall

1. INTRODUCTION

Many quay walls have suffered significant damage during recent large earthquakes because of the inertial force of the quay wall, liquefaction, seismic earth pressure, dynamic water pressure, etc. Sheet pile quay walls were heavily damaged during the 1993 Kushiro-Oki Earthquake and the 2000 Tottori-ken-Seibu Earthquake, and large seaward displacement of quay walls was caused by the inertial force and the liquefaction of backfill sand. Since it is feared that large earthquakes will occur in the near future in Japan, the seismic reinforcement of quay walls is an urgent need in order to secure access routes from the sea for the transport of critical materials, and to protect existing facilities against such earthquakes.

A ground anchor for reinforcement is one of a number of seismic reinforcement methods that are used to constrain the displacement of a quay wall. This method has recently been applied to many existing quay walls because it involves a lower cost and a smaller work space than other methods, and employs recently established design and corrosion protection methods. With respect to the seismic behavior of a ground anchor, Yamamoto and Toriihara (2003) conducted shaking table tests and finite element method (FEM) analyses of a slope with a ground anchor. As the results of their tests and analyses, they confirmed that the tensile force of the ground anchor greatly changed and increased. Kandatsu and Kiyomiya (2007) confirmed the seismic characteristics of a sheet pile quay wall with a ground anchor for reinforcement by conducting FEM analyses. However, the seismic behavior of a sheet pile quay wall with a ground anchor for reinforcement has not been sufficiently clarified, because few case studies of seismic behavior have been conducted on the basis of experiments or analyses.

In this study, shaking table tests with a 1:17 scale model in a 1G field have been conducted to investigate the effect of seismic reinforcement of a sheet pile quay wall with ground anchors. Further, effective stress analyses of the test results have been conducted in order to simulate the seismic behavior of a sheet pile quay wall with ground anchors. By the arrangement of the ground anchors, the displacement of the quay wall has been fairly constrained and the effectiveness of the anchor has been confirmed by both the testing and analysis. The results also indicate that the ground anchor affects the deformation and the bending moment of the sheet pile in response to the shaking motions. Moreover, the analytical results show that the tensile force of the ground anchors, the movement of the quay wall and the backfill sand in these tests have been fairly simulated by the analysis.

2. TEST AND ANALYSIS

2.1. Test procedure

Shaking table tests with a 1:17 scale model in a 1G field have been performed to investigate the effect of seismic reinforcement of a sheet pile quay wall with a ground anchor. The scaling factors of various parameters in a 1G gravitational field for the soil-structure-fluid system is calculated using the relationship given in Iai (1988) for a model-to-prototype ratio of 1:17 (Table 1). Large three-dimensional underwater shaking table assemblies are used in the testing program. The shaking table is mounted on a water pool that is 15 m long, 15 m wide, and 2 m deep.

Table 1. List of scaling law factors

Parameter	Scaling factors	prototype/model
length	λ	17
density	1	1
time	$\lambda^{0.75}$	8.37
stress	λ	17
water pressure	λ	17
displacement	$\lambda^{1.5}$	70.09
strain	$\lambda^{0.5}$	4.12
acceleration	λ	1
permeability	$\lambda^{0.75}$	8.37
flexural rigidity	$\lambda^{4.5}$	344,366
longitudinal rigidity	$\lambda^{2.5}$	1,192

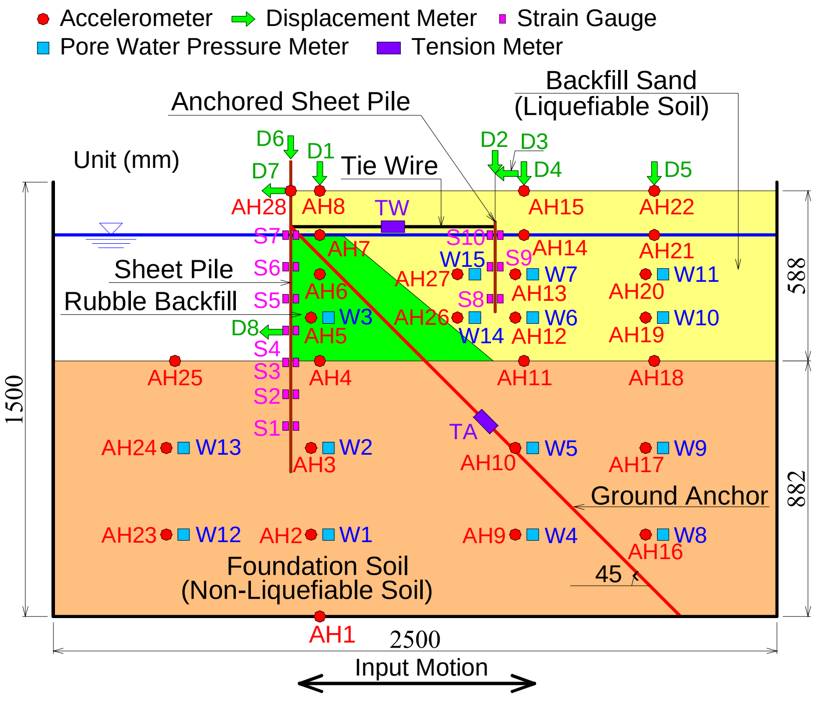

Figure 1. Cross section of test model

Figure 1 shows a cross-section of the test model. The sheet pile quay wall without a ground anchor is designed by trial, based on old technical standards (Japan Port and Harbour Association, 1989). The soil container is made of steel, and has a width of 2.5 m, a length of 1.3 m, and a height of 1.5 m. The model's sheet piles and its anchored sheet piles consist of 6-mm-thick and 3-mm-thick steel plates, respectively, with consideration of the scaling law. To eliminate the influence of the friction between the container and the soil, the sheet piles consist of three parts: a central part and two dummy parts. All the monitoring devices are positioned on the central sheet pile.

The foundation soil and backfill sand are adjusted to a relative density of 80% and 60%, respectively, using Soma-sand No. 5 (D_{50} = 0.3mm). The rubble backfill is prepared using Grade 6 crushed stone with a particle size of 13~20 mm. The model ground anchors and model tie wires consist of steel rods (D = 6mm). The former are installed between the sheet piles and the container base at an angle of 45° with the horizontal. The latter are installed between the sheet piles and the anchored sheet piles.

Two test cases have been examined that has been compared the behavior of the quay walls with and without ground anchors. The input motion is the N-S component of the strong motion recorded at Port Island, Kobe, Japan during the 1995 Hyogo-ken Nanbu Earthquake. The record is shown in Figure 2. The duration of the shaking in the model testing is based on the time axis of an accelerogram of the event, which is reduced by a factor of 8.37 in consideration of the scaling law.

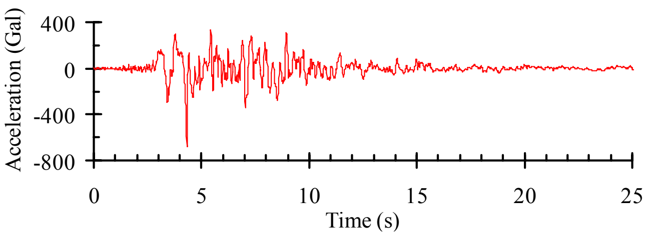

Figure 2. Input strong motion record (prototype)

2.2. Analysis procedure

Effective stress analyses have been carried out by using the same model dimensions as are used in the 1G model test. Figure 4 shows the finite element mesh used in the analyses. In consideration of the condition of the rigid container that is used, the degrees of freedom of the displacements at the base are fixed both horizontally and vertically, and the horizontal displacements are fixed at the side boundaries.

The effective stress model of the sands used in this study is a strain space multiple mechanism model (Iai *et al.*, 1992). The parameters of the sands are determined by backfitting to the results of a past shaking table test performed on a one-dimensional soil layer (Tashiro *et al.*, 2009). The parameters are listed in Table 2. The parameters for defining the characteristics of shear deformation are G_{ma}, K_{ma}, σ_{ma}', ν, and ϕ_f. Further, the parameters of the dilatancy are ϕ_p, w_1, p_1, p_2, c_1, and S_1.

The model sheet pile and anchored sheet pile are idealized by the linear beam elements; the flexural rigidity *EI* of these two piles are 3.7 and 0.46 kN/m^2/m, respectively. The model tie rod and ground anchor are idealized by the linear spring elements; the longitudinal rigidity *EA* of them are 2.9×10^4 kN/m.

Table 3 shows the cases used in the analysis. Two series of analyses have been carried out. In one, tests of different conditions for the ground anchors have been simulated by analyses that address the use of liquefiable backfill sand versus non-liquefiable backfill sand (Series A). In the other series, the analyses investigate the influence of the arrangement of ground anchors on the displacement of the quay walls, the bending moment of sheet piles, and the tensile force of the ground anchors (Series B).

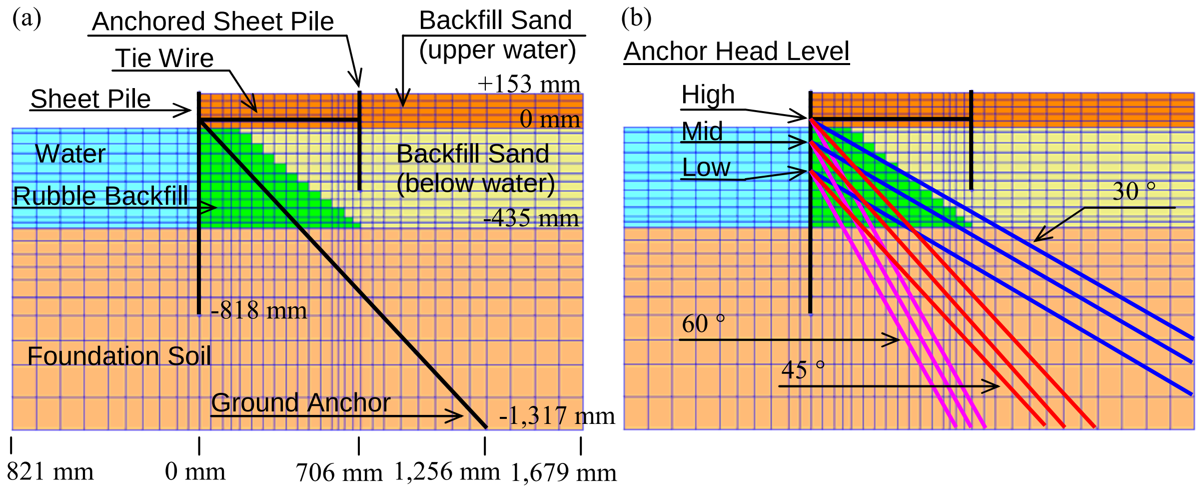

Figure 3. Finite element mesh for analysis: (a) Analysis of liquefiable condition of backfill sand (Series A); (b) Analysis of arrangement of ground anchors (Series B)

Table 2. List of soil parameters in analysis

	Parameter		Backfill Sand (upper water)	Backfill Sand (below water)	Foundation Soil	Rubble Backfill
	Wet unit weight	γ_t (kN/m^3)	18.3	18.3	18.7	19.6
	Porosity	n	0.45	0.45	0.45	0.45
Parameters for deformation characteristics	Initial shear modulus	G_{ma} (kPa)	10,068	5,568	9,805	180,000
	Initial bulk modulus	K_{ma} (kPa)	26,256	14,520	25,569	469,400
	Standard confining pressure	σ_{ma}' (kPa)	-	3.0	5.2	98.0
	Poisson's ratio	ν	0.33	0.33	0.33	0.33
	Internal friction angle	ϕ_f (degree)	40.0	40.0	40.0	40.0
	Hysteretic damping factor	h_{max}	0.24	0.24	0.24	0.24
Parameters for dilatancy characteristics	Phase transformation angle	ϕ_p (degree)	-	28.0	28.0	-
		w_1	-	1.7	3.8	-
		p_1	-	0.9	0.9	-
		p_2	-	0.8	0.8	-
		c_1	-	1.5	3.0	-
		S_1	-	0.005	0.005	-

Table 3. List of analysis cases in Series A

Case	Ground Anchor condition	Backfill sand condition
Case-A1	Without anchor	Liquefiable
Case-A2	With anchor	Liquefiable
Case-A3	Without anchor	Non-liquefiable
Case-A4	With anchor	Non-liquefiable

Table 4. List of analysis cases in Series B

Case	Anchor head level	Angle of ground anchor
Case-B1	High	30 °
Case-B2	High	45 °
Case-B3	High	60 °
Case-B4	Mid	30 °
Case-B5	Mid	45 °
Case-B6	Mid	60 °
Case-B7	Low	30 °
Case-B8	Low	45 °
Case-B9	Low	60 °

As input motions of the analyses, the acceleration records measured by accelerometer No. AH1 in the tests are adopted. Before the dynamic response analysis, static analysis is performed with gravity in order to simulate the initial stress condition in the model tests prior to shaking.

3. RESULTS AND DISCUSSION

3.1. Effect of seismic reinforcement of sheet pile quay wall using a ground anchor

Figure 4 shows the measured and computed time histories of the horizontal response acceleration at the ground surface (AH8), the excess pore water pressure in the backfill sand (W11), the horizontal displacement at the upper part of the sheet pile (D7), and the tensile force of the tie wire (TW) and the ground anchor (TA). Note that in the test results, the sheet pile displacement and the excess pore water pressure ratio of the backfill sand appear to increase linearly with increasing acceleration. The peak acceleration values of the ground surface without and with ground anchors are 799 Gal and 571 Gal, respectively. This indicates that the active earth pressure during earthquakes is reduced by reinforcement with ground anchors. The backfill sand liquefied because the excess pore water pressure ratio reached 1.0. This result shows that the earth pressure at rest to sheet piles during earthquakes increased, and the bearing capacity of the anchored sheet piles during earthquakes decreased. The horizontal permanent displacement of the sheet pile without ground anchors was 19 mm, and that with ground anchors was 15 mm. Thus, the sheet pile displacement was reduced by more than approximately 20% owing to the reinforcement of ground anchors. The peak tensile force value of the ground anchor (4.0 kN/m) was approximately 4 times greater than that of the tie wire (1.1 kN/m). The displacement wave configuration of the sheet pile was similar to the tensile force wave configuration of the ground anchor. These results indicate that the large seaward displacement of quay walls is caused by an inertial force, the liquefaction of backfill sand, and reduction in the bearing capacity of the anchored sheet piles during shaking, and that the displacement of the sheet piles is constrained by reinforcement with ground anchors.

Figure 4 shows that the time histories of the acceleration, pore water pressure ratio, and tensile force of the ground anchors obtained in the analyses are in good agreement with the measurements, though the computed values of the excess pore water pressure ratio are larger than the measurements in the period prior to the sheet pile displacement. In both the measurements and computations, the sheet pile displacement is reduced by the reinforcement of ground anchors. The computed displacement of the sheet piles under the condition that the backfill sand is liquefiable, is smaller than it is under the condition that it is non-liquefiable, because the bearing capacity of the anchored sheet piles during earthquakes is not reduced under a non-liquefiable condition.

Figure 5 shows the measured and computed distribution of the maximum bending moment of sheet piles obtained from the tests and analyses. The test results show that the maximum values of the bending moment of the sheet pile without a ground anchor are approximately 30% larger than those obtained using ground anchors. This reduction in the maximum values of the bending moment of the sheet pile owing to the use of ground anchors is in close agreement with the results of the analyses. Moreover, the analysis results shown in Fig. 5 indicate that the configuration of the distribution of the bending moment of the sheet piles obtained by the analyses is similar to that obtained in the tests.

Figure 6 shows the computed deformation and distribution of maximum shear strain after shaking. As seen in Fig. 6(a), the sheet pile displacement for the no-anchor condition is largest at the top. In contrast, the computed deformation and distribution shown in Fig. 6(b) for the condition of reinforcement with a ground anchor are the largest at the middle of the sheet pile, because the displacement of the top of the sheet pile is constrained by the tensile force of the ground anchors. As a result, the maximum shear strain of the soils decreases. Moreover, under the condition that non-liquefiable backfill sand is used, the displacement of the sheet pile and the maximum shear strain` of the soils shown in Figs. 6(c) and (d) is reduced owing to the ground anchors.

3.2. Influence of arrangement of ground anchors

Figures 7 and 8 show the computed distribution of the horizontal permanent displacement, and the maximum bending moment of the sheet piles in terms of the arrangement of the ground anchors, respectively. The results in Fig. 7 indicate that the displacement at the middle of a sheet pile is the

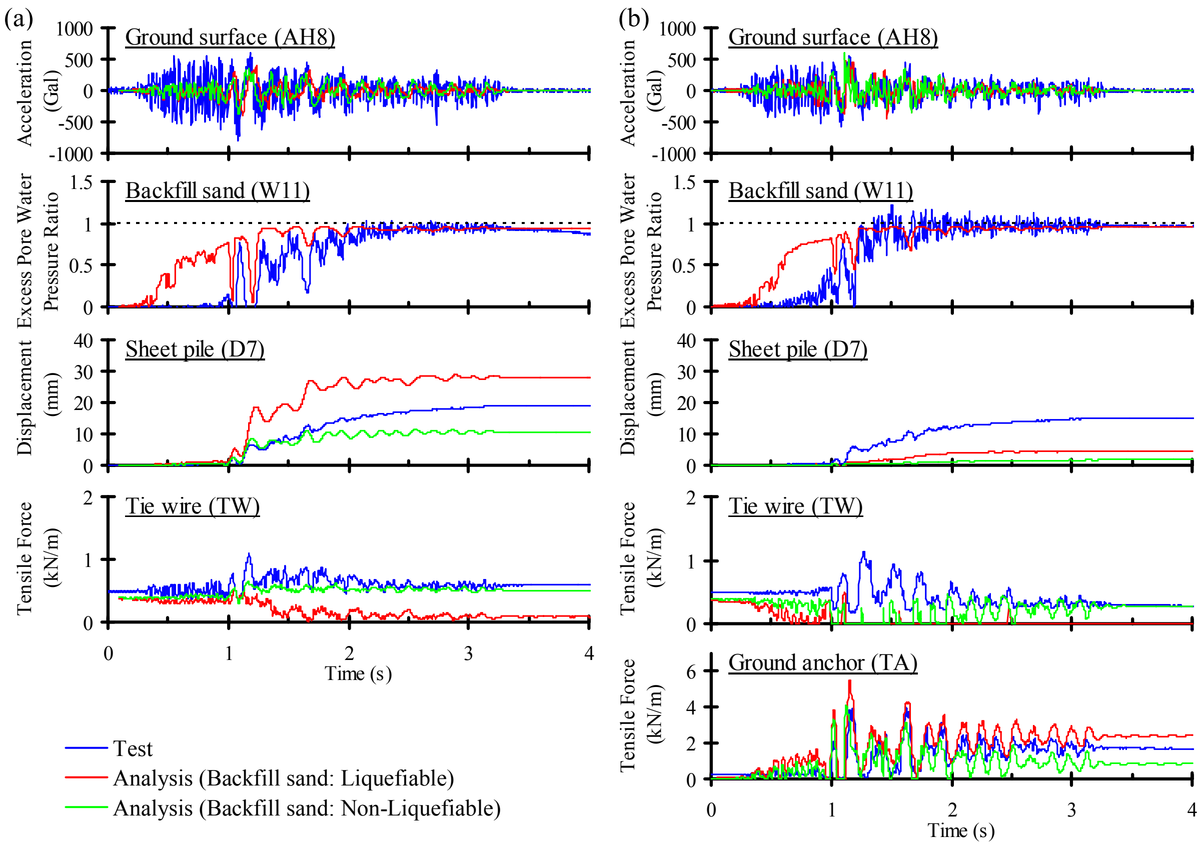

Figure 4. Comparison of time histories obtained by the test and the analysis: (a) Without ground anchor, (b) With a ground anchor

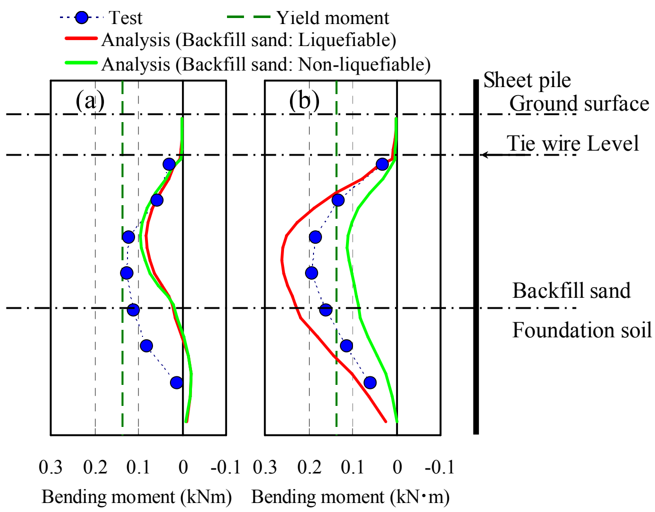

Figure 5. Comparison of distribution of maximum bending moment of sheet pile obtained by the test and the analysis: (a) Without ground anchor, (b) Wtih a ground anchor

largest under the condition that the level of the ground anchor head is high, while the displacement at the top is the largest under the condition that the level of the ground anchor head is low. Figure 8 shows that the lower the position of the ground anchor head, the smaller the bending moment. As can be seen in Figs. 7 and 8, the angle of the position of the ground anchors is smaller, in which case the displacement of a sheet pile is smaller but its bending moment is larger.

The installation of the ground anchor positioned at the lower part of a sheet pile requires work to be done underwater. As a result, the smaller the angle of the position of a ground anchor, the higher the

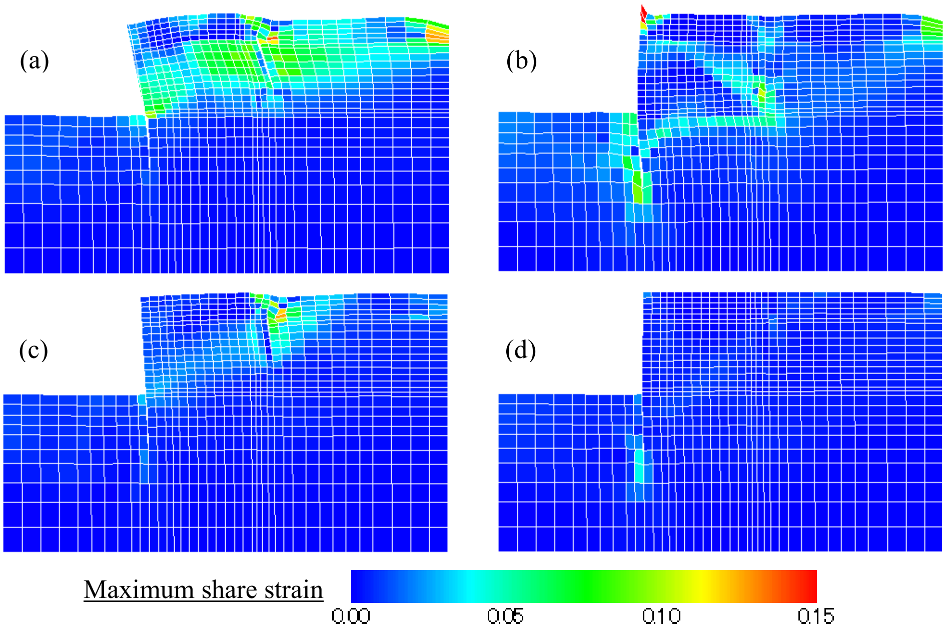

Figure 6. Computed permanent deformation (Displacement magnification: 5 times) and distribution of maximum shear strain: (a) Case-A1, (b) Case-A2, (c) Case-A3, (d) Case-A4

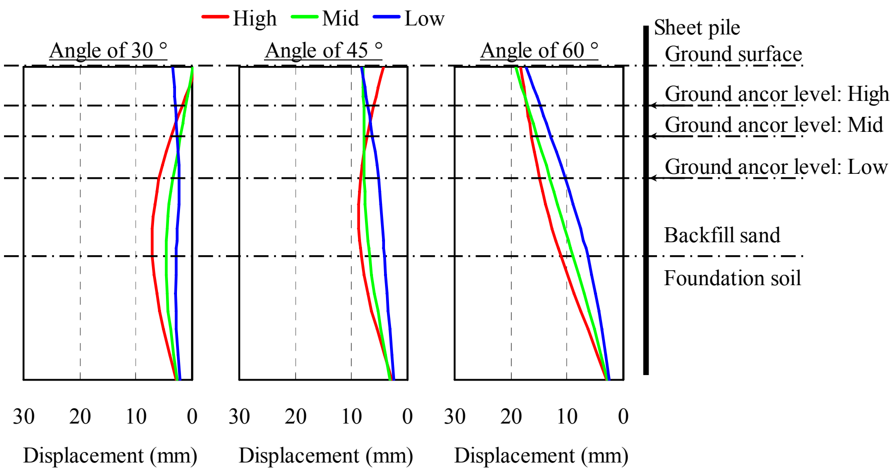

Figure 7. Computed distribution of permanent displacement of sheet pile by arrangement of ground anchor

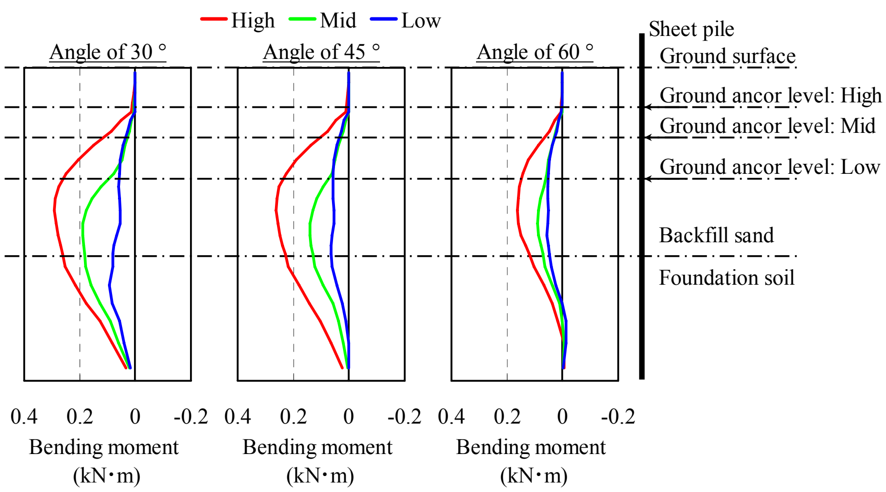

Figure 8. Computed distribution of maximum bending moment of sheet pile by arrangement of ground anchor

cost because the anchor length is longer. For these reasons, the arrangement of a ground anchor should be decided with consideration of both the workability and the cost.

4. CONCLUSION

In this study, shaking table tests with a 1:17 scale model in a 1G field have been conducted to examine the effect of the seismic reinforcement of sheet pile quay walls using ground anchors. Further, effective stress analyses have been carried out to simulate the seismic behavior of the reinforced sheet pile quay walls in these tests, and to verify the effectiveness of the arrangement of ground anchors. The following are the main findings of this study:
1) The test results indicate that large seaward displacement of quay walls is caused by the inertial force, the liquefaction of the backfill sand and the reduction in the bearing capacity of the anchored sheet piles during shaking, and the displacement of the sheet pile quay walls is constrained by reinforcement with ground anchors. These test results are in close agreement with the analysis results.
2) These results regarding the reduction in the maximum values of the bending moment of the sheet pile obtained with the use of ground anchors in the tests is close agreement with those in the analyses. Moreover, the configuration of the distribution configuration of the bending moment of sheet piles obtained by the analyses is similar to that by the tests.
3) The analysis results indicate that the displacement of the sheet piles under the condition that the backfill sand is liquefiable, is smaller than under the condition that it is non-liquefiable; because the bearing capacity of the anchored sheet piles is not reduced under the non-liquefiable condition.
4) The analysis results for different arrangement of ground anchors showed that an angle of the poison of the ground anchors and the level of ground anchor head have an influence on distribution configuration of displacement and bending moment of sheet pile quay walls.
5) The arrangement of a ground anchor should be decided with consideration of both the workability and the cost, because the installation of a ground anchor that is positioned at the lower part of a sheet pile involves underwater work, and the cost of a ground anchor at a small angle with horizontal is high because of the long anchor length that is required.

Our analyses apparently have failed to quantitatively simulate the tensile force of the tie wires. This warrants future work on method accurately evaluating the parameters. Nonetheless, it is notable that the effect of the seismic reinforcement of sheet pile quay walls using ground anchors, and the applicability of an effective stress analysis is confirmed by the tests and analyses.

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