BEHAVIOR OF SHEET PILE QUAY WALL DEEPENED AND IMPROVED GROUND BY THE CDM METHOD UNDER EARTHQUAKE LOADING

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ABSTRACT: Quay wall is very varied in structure types, such as gravity, sheet pile, and open berth types. In reality, many quay walls were constructed in the past, which had low front water depth and bearing capacity. Thus, it is necessary to renovate these quay walls to enhance their performance and increase their bearing capacity. This paper studied to increase the font water depth of the existing sheet pile quay wall by deepening the seabed in front of the wall. To ensure and increase the bearing capacity of the quay walls after renovation, the ground in front of the wall was strengthened by cement deep mixing (CDM) before deepening. By using the numerical simulation method, the study focused on evaluating the behavior of sheet pile quay walls under earthquake loading. Some typical responses of the sheet pile, such as deformation, displacement, and bending moment, were investigated and compared with and without CDM cases. In addition, the effect of the CDM strength and area on the behavior of the sheet pile wall was also considered. The results indicated that ground improvement before deepening decreased significant bending moment and displacement of the sheet pile wall. The displacement of the sheet pile decreased with increasing strength of the area of the CDM until they reached certain values.

KEYWORDS: Sheet pile quay wall, cement deep mixing, numerical simulation, quay wall deepening, ground improvement.

1. INTRODUCTION

Many existing quay walls built in the last decades have small capacity. Currently, these quay walls are degraded and cannot satisfy the current demand for freight. The studies involving quay wall renovation have attracted the attention of many authors. Khan et al. [1, 2] evaluated the static and dynamic behavior of a sheet pile quay wall strengthened by cement-treated soil at the seaside using the geo-centrifuge test. Various test cases were carried out, including the sheet pile wall before and after the upgrade. During the test, the deformation of the quay wall, input-output accelerations, and earth pressure behind the wall was recorded to evaluate the static and dynamic response. The results implied that the improvement sharply increased the sheet pile resistance under static and seismic loading. The bending moments of the sheet pile wall decreased. The horizontal displacement also decreased significantly with an increase in the CDM area until it reached a limitation. Nakamura et al. [3] introduced some new technologies to renovate the sheet pile structure in the port using lightweight treated soil replacement for backfill, added tie rods, and added new sheet pile infront of the sheet pile wall. A study case was conducted based on the suggested idea, which allowed designers to select a suitable design method and structure type as possible. Based on the results, the paper proposed a design process to renovate the sheet pile wall. Senarathne [4] consider the influence of deepening seaside ground on the existing anchored and cantilever sheet pile structures in the cohesionless ground. An additional sheet pile wall was embedded from the seaside of the existing quay wall to support the main structure. The numerical simulation was applied to evaluate the influence of the improvement on the deformation and stability of the quay wall, and the results of this model were verified by a physical model conducted in a laboratory. The results showed that the stability of the quay wall significantly increased after improvement. Nguyen et al. [5, 6] considered the static response of the caisson-type quay wall strengthened by rubble foundation grouting and excavation. A series of cases of grouted rubble was proposed and analyzed using the FEM to select the most reasonable dimension and shape. The results demonstrated that this method increased 2 m of front water depth and increased the stability of the renovated quay wall. In the next step of this study, Kim et al. [7] and Nguyen [8] compared the dynamic response using the geo-centrifuge test and numerical simulation. Various input motions with increasing amplitude were applied to the models. By comparing experimental and numerical studies, the study implied that the grouting rubble mound under the front toe of the caisson could ensure and increase the seismic resistance of the quay wall after deepening.

As can be seen, the technologies used to renovate the quay wall were varied; it depended on the structure type and real condition of the existing quay wall. This study evaluated the ability to upgrade the sheet pile quay wall by strengthening the ground in front of the wall using the cement deep mixing, then dredging the seabed to increase front water depth. The cement deep mixing (CDM) method is a technique to chemically solidify and strengthen soft ground by in-situ mixing of the soil with cement slurry. Until today, the CDM has become one of the most common soil improvement methods with many advantages such as good quality, reasonable cost, wide application range, and less environmental impact [9].

In this framework, a study case of upgrading the quay wall conducted in Vietnamese conditions was introduced and numerically analyzed using the PLAXIS 2D program [10]. Based on the analysis, the displacement, bending moment were compared between the quay walls with and without improvement. Especially using the finite element (FE) simulation, this research could conduct the parametric studies by changing some factors that were difficult to perform by the experimental model. Particularly, the paper focused on considering the effect of the improvement area, and CDM strength on the sheet pile behavior.

2. CASE STUDY

The cross-sections of the quay walls before and after renovation are shown in Figure 1 (a) and (b), respectively. The characteristic of steel sheet pile, steel pile, and tie rod are listed in Table 1. This quay wall located in Hai Phong city, Vietnam. The height of the existing quay wall was 13.5 m, the front water depth was 10 m, and it could receive 10000 DWT of ships. After dredging, the water depth increased by 1m, and the quay wall could be used for 20000 DWT of vessels.

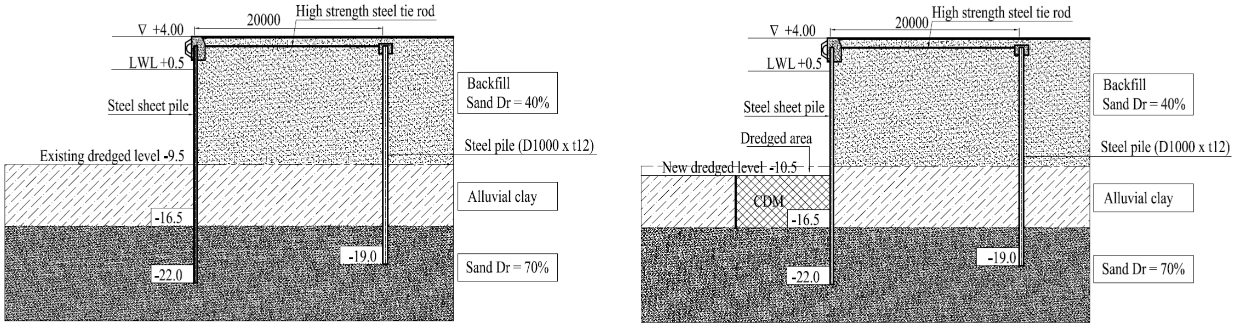
Table 1. Properties of structures [11]

Parameters	Symbol	Value	Unit
Steel sheet pile Profile width	w	500	mm
Profile height	h	225	mm
Section area	A	306	cm^2/m
Inertia moment	I	86000	cm^4/m
Young modulus	E	2.1E+8	kN/m^2
Yield strength	f_y	300	MPa
Elastic bending moment capacity	$M_{el,max}$	1146	kNm/m
Plastic bending moment capacity	$M_{pl,max}$	1357	kNm/m
Anchor pile Outside diameter Thickness	 D t	 1000 12	 mm mm
Tie rod Section area Yield strength Yield force	 A f_y $F_{el,max}$	 6E-4 355 421.5	 m^2 MPa kN

3. NUMERICAL SIMULATION

3.1. Finite element modeling

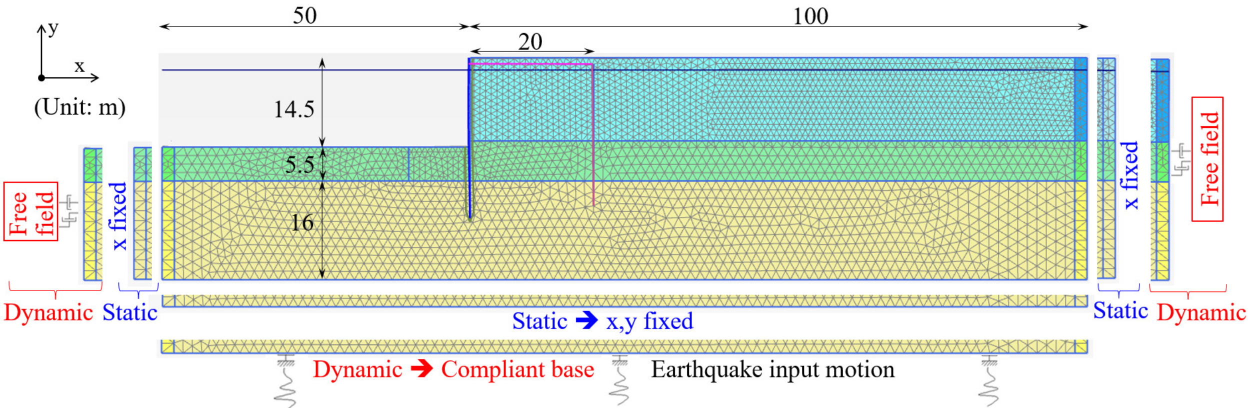
Figure 2 shows the FE models for the quay wall after dredging with and without the CDM improvement. In the models, the plate element simulated the sheet pile, while the embedded beam row element was used for the anchor pile. The node-to-node anchor element modeled the tie rod. The behavior of these structural components was simulated using the Linear elastic model, while the Mohr-Coulomb model was used for the CDM. The models were simulated using 15-node triangular plane strain elements. For the



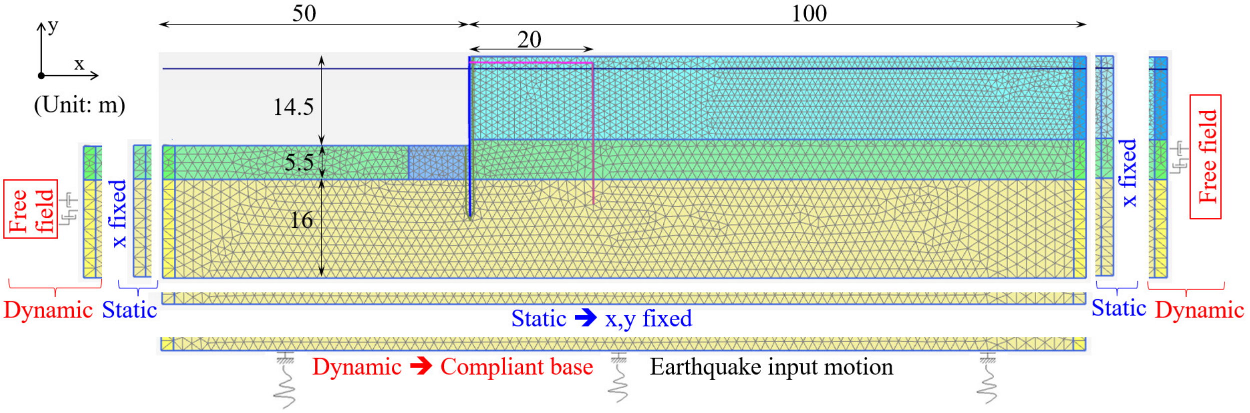
(a) Existing quay wall

(b) Renovated quay wall

Figure 1. Cross-sections of the quay wall considered in this study



(a) Dredging of the quay wall without improvement



(b) Dredging of the quay wall with the improvement using CDM

Figure 2. Finite element models of the quay walls

static condition, the side boundaries were fixed horizontally, and horizontal and vertical directions were fixed at the base [12]. In the dynamic analysis, the free field boundary condition was applied on both sides, and the compliant base boundary was assigned at the bottom [13]. The interface angle was taken as 0.7 times the internal friction angle of the material near the sheet pile [14, 15]. The backfill was simulated as drained in the static stages, while the undrained behavior was applied for the dynamic steps.

The parameters of the CDM zone used in this study are listed in Table 2.

Table 2. The properties of the CDM zone [2,16]

Unit weight (kN/m^3)	Undrained shear strength (kPa)	Young modulus (kPa)
20	500	100000

3.2. Models and parameters of soil layers

In this study, the HS-small model was used to simulate soil behavior in static and earthquake conditions, except for the dynamic response of backfill. The UBC3D-PLM model is an effective stress elastoplastic model suitable for simulating the liquefaction behavior of sands and silty sands under seismic loading [10]. It was applied to model the dynamic and liquefaction behavior of the backfill. The basic parameters of the model and their values used in this research are listed in Table 3 and Table 4.

3.3. Earthquake excitation

The PLAXIS 2D program provides the ability to analyze the system behavior under earthquake loading in the time domain. In this study, the acceleration time history records of earthquake motions namely Coalinga were used in the analysis. The excitations were collected from the website of the Pacific Earthquake Engineering Research Center [18] had properties close to the Vietnamese design spectrum proposed in the standard TCVN 9386:2012 [19] for Hai Phong city. Before applying to the analysis, these motions were modified more suitably with the Vietnamese design spectrum, as presented in Figure 3 and Figure 4. The modification was conducted using the Matlab program based on the method proposed by Lilhanadn and Tseng [20, 21] and developed by Hancock et al. [22].

Table 3. The HS-small model soil properties [11,17]

Parameters	Symbol	Layer 1	Layer 2	Layer 3	Unit
Soil type		**Loose sand**	**Alluvial clay**	**Medium dense sand**	
Relative density	D_r	40	-	70	%
Unsaturated unit weigh	γ_{unsat}	17	16	18	kN/m^3
Saturated unit weight	γ_{sat}	20	19	20	kN/m^3
Friction angle	j	34	-	37	Degree
Cohesion/Undrained shear strength	c	-	40	-	kPa
Dilatancy angle	y	4	0	7	Degree
Young Modulus	E	-	-	-	kPa
Reference secant modulus	E_{50}^{ref}	24000	15000	42000	kPa
Reference oedometer modulus	E_{oed}^{ref}	24000	15000	42000	kPa
Reference loading/Unloading modulus	E_{ur}^{ref}	48000	30000	84000	kPa
Power for stress-level dependency of stiffness	m	0.500	0.500	0.500	-
Failure ratio	R_f	0.950	0.920	0.913	-
Reference shear modulus at very small strains	G_0^{ref}	87000	70000	100000	kPa
Threshold shear strain at which Gs reduce 70%	g	0.00016	0.00018	0.00013	-
Reference pressure	P_{ref}	100	100	100	kPa
Permeability coefficient	k	1.16E-06	3.00E-10	1.90E-07	m/s

Table 4. The UBC3D-PLM model soil properties [11]

Parameters	Symbol	Layer 1	Unit
Relative density	D_r	40	%
Standard penetration resistance	$(N_1)_{60}$	10	-
Elastic bulk modulus factor	k_B^{*e}	624	-
Elastic shear modulus factor	k_G^{*e}	891	-
Plastic shear modulus factor	k_B^{*p}	1301	-
Constant volume friction angle	φ_{cv}	30	Degree
Peak friction angle	φ_p	34	Degree
Rate of stress-dependency of elastic bulk modulus	m_e	0.5	-
Rate of stress-dependency of elastic shear modulus	n_e	0.5	-
Rate of stress-dependency of plastic shear modulus	n_p	0.4	-
Densification factor	f_{dens}	0.45	-
Post-liquefaction factor	f_{Epost}	0.02	-
Failure ratio	R_f	0.73	-

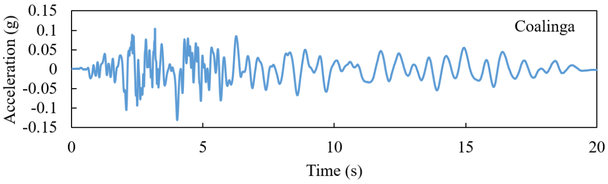


Figure 3. Outcrop rock acceleration time histories of the earthquake motions after matching with the Vietnamese standard design spectrum for the target PGA of 0.11g

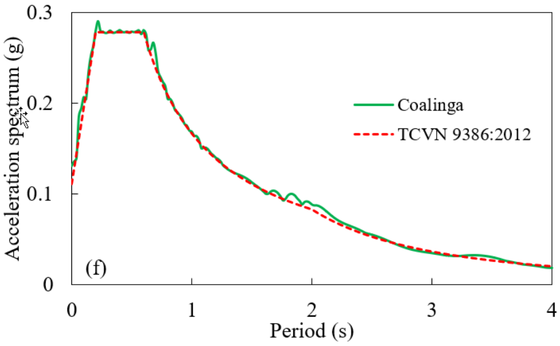


Figure 4. Outcrop rock acceleration response spectra of the earthquake motions after matching with the Vietnamese standard design spectrum for the target PGA of 0.11g

4. RESULTS AND DISCUSSION

4.1. Deformation and bending moment of the sheet pile wall

Figure 5 (a) and (b) compare the deformed shape of the quay walls between two models at the end of the earthquake (Scaled up ten times). In the case without improvement, a large bending occurred, especially in the middle of the sheet pile. The soil in front of the wall was also deformed and raised. In the case of improvement, the strength of the subsoil area in front of the wall increased. The curvature of

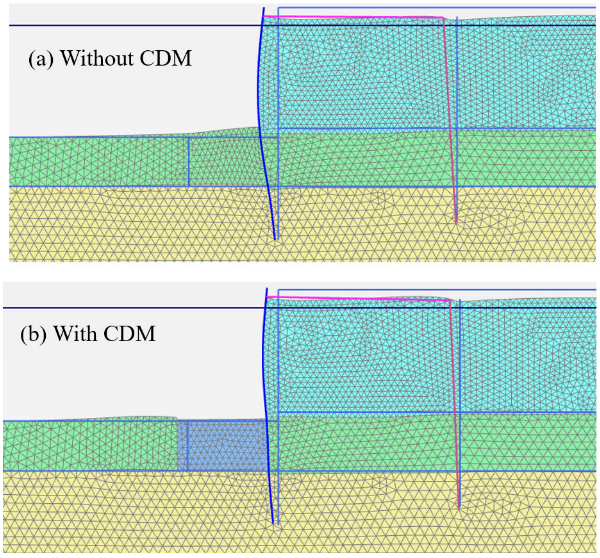


Figure 5. Overall deformed shape of the quay walls after earthquake

the sheet pile wall decreased significantly, and the dredge surface was flat.

The horizontal displacement and bending moment of the sheet pile along the depth are depicted in Figure 6. It can be seen that the improvement using the CDM sharply reduced both the horizontal displacement and bending moment of the sheet pile. The maximum displacement of the sheet pile for the case without improvement was 22.78 cm, which was higher than that of the improvement case at 17.17 cm. The standards [16, 23] suggested that the allowable displacement for the quay wall was 1.5%H (H was the height of the wall from the dredge level to the top). In this study, the height of the wall was 14.5 m; thus, the calculated allowable displacement was 21.75 cm. As shown in Figure 6, if the quay wall did not improve, the maximum displacement exceeded the allowable limit. In contrast, the improvement reduced displacement lower than the criteria value. Similarly, both positive and negative bending moments of the sheet pile wall in the improvement quay wall were significantly lower than those in the case without improvement. In the improvement case, the maximum positive and negative bending moments were 986.73 and 302.72 kNm, while the values for the without improvement case were 1102.53 and 615.62 kNm.

The comparison of horizontal displacements at Point A (top of the sheet pile) between the quay wall dredged with and without CDM is depicted in Figure 7. The results indicated that the displacement sharply decreased if the quay wall was improved using the CDM. The maximum and residual displacements at point A were 16.79 and 13.78 cm for the quay walls without CDM, while these values

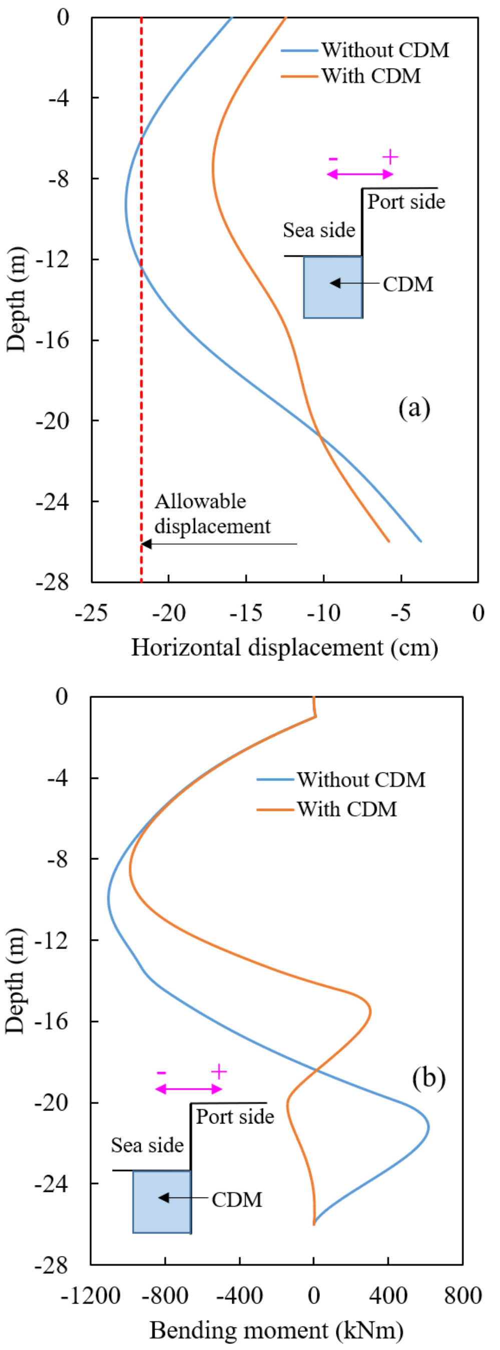


Figure 6. Horizontal displacement and bending moment versus the depth of the sheet pile at the end of the earthquake

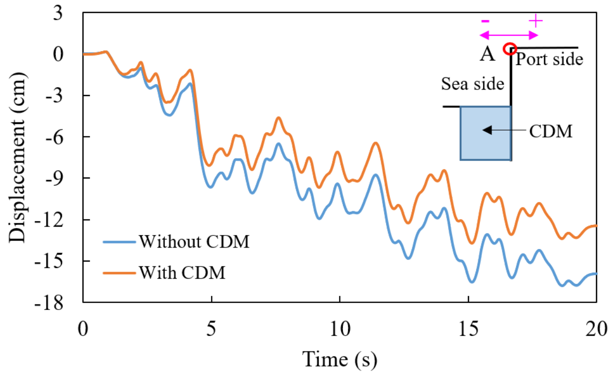


Figure 7. Horizontal displacement at point A

for the quay wall with CDM were 15.92 and 12.45 cm, respectively.

4.2. Effect of the improvement area

To consider the influence of improvement area on the behavior of the quay wall, various cases with different area of the CDM was analyzed. The improvement area was changed by increasing the CDM width, B, from 0 to 15 m, while the improvement depth was kept constant at 5.5 m. Figure 8 compares the horizontal displacement of the sheet pile along with the depth with different CDM widths, while Figure 9 shows the decrease of displacement at the sheet pile top and maximum displacement with respect to the width of CDM. It can be seen that the displacement of the sheet pile decreased with increasing improvement area. When the CDM width, B, increased from 0 to 10 m, the maximum horizontal displacement decreased significantly from 22.78 to 17.17 cm, while the displacement at the top pile reduced from 15.92 cm to 12.45 cm, respectively. After that, even though the CDM width continuously increased, the sheet pile displacement increased slightly. It follows from Figure 9 that the sheet pile displacement decreased with increasing improvement area until it reached a certain area. Particularly, when the ratio B/D equaled or over 2 (B was the width and D was the depth of CDM area, respectively), the displacement of the sheet pile was mostly constant.

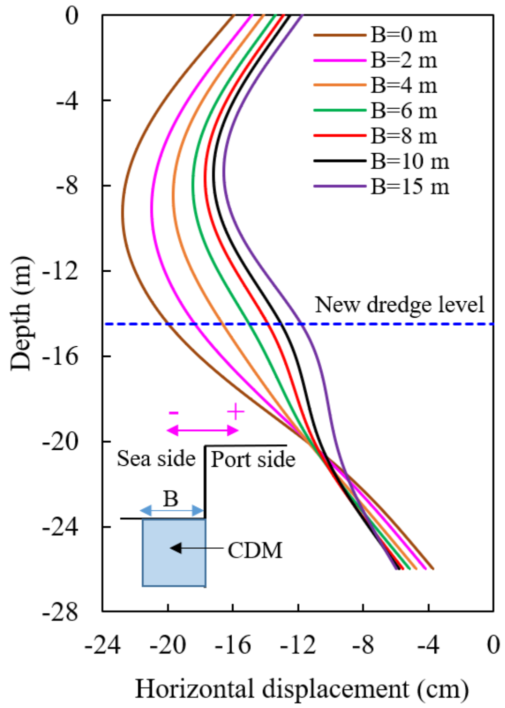


Figure 8. Horizontal displacement of the sheet pile with different improvement areas

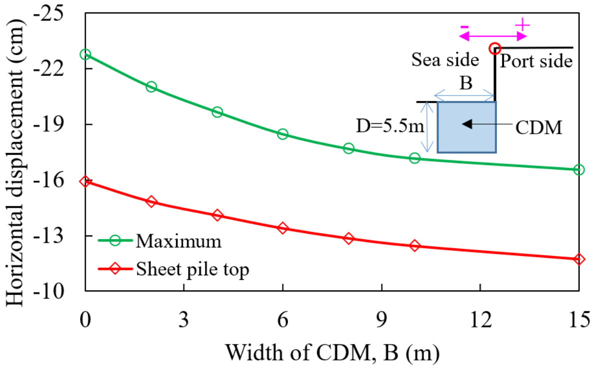


Figure 9. Change of horizontal displacement with the width of CDM

4.3. Effect of the CDM strength

In this section, the effect of CDM strength was investigated by analyzing several cases of changing the undrained shear strength (S_u) of CDM from 100 to 700 kPa. The range of CDM was determined based on the standard TCVN 9906:2014 [24]. The input motion used in the analysis was the Coalinga motion, and the area of the CDM was 10 × 5.5 m. The horizontal displacement, along with the dept at the end of the earthquake, was depicted in Figure 10. The summary for the displacement at the wall top and maximum displacement of the sheet pile depended on the undrained shear strength is illustrated in Figure 11. The results indicated that the CDM strength increase, the decrease the horizontal displacement decreased. However, when S_u reached 500 kPa or over, the displacements were almost constant.

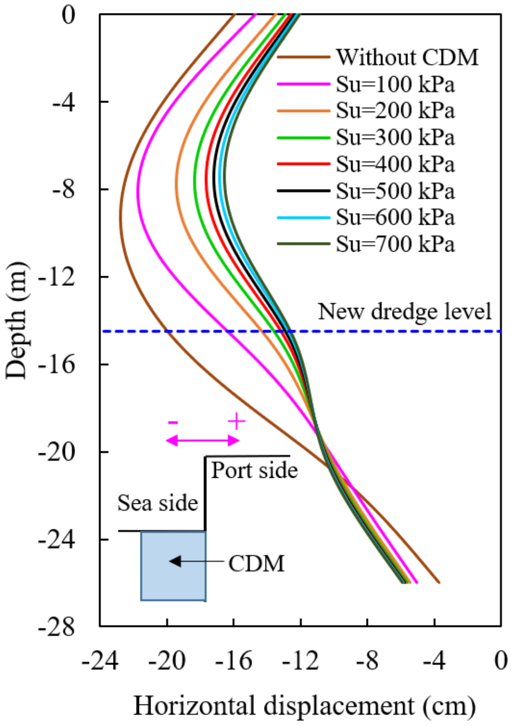


Figure 10. Horizontal displacement of the sheet pile wall with the different undrained shear strength of CDM

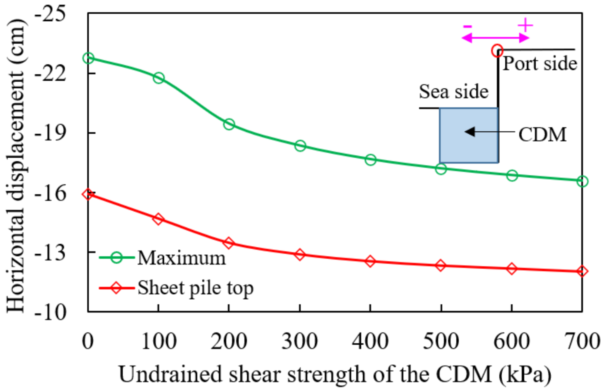


Figure 11. Change of horizontal displacement with the strength of CDM

5. CONCLUSIONS

Based on the analysis results, the following main conclusions were reached:

(1) Compared to the case without improvement, the CDM changed in favor of the deformed shape of the sheet pile. The curvature of the sheet pile wall decreased significantly, and the upwelling of the soil in front of the wall did not occur. The improvement decreased the horizontal displacement of the sheet pile by approximately 25% and the bending moment by approximately 10%.

(2) The horizontal displacement of the sheet pile wall decreased with increasing improvement area. However, it decreased to a certain value, and after that, it remained constant regardless of the increasing improvement area. In this study, with the constant of the CDM depth, when the ratio between the width and depth of the CDM zone reached 2, the horizontal displacement almost did not change.

(3) When the undrained shear strength of CDM increased from 100 to 500 kPa, the horizontal displacement of the sheet pile decreased significantly. After that, although it increased over 500 kPa, the horizontal displacements remained stable.

(4) The numerical simulation was conducted to evaluate the dynamic resistance of the sheet pile quay wall dredged and improved seaside subsoil using cement deep mixing. The results proved that the suggested technology was technically feasible. Based on these results, further studies, such as shaking table tests or testbeds, will be peformed before applying in practice.

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