A Novel Approach to Use Soil-Cement Piles for Steel Sheet Pile Walls in Deep Excavations

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Abstract In recent years, owing to advances in technology, excavation pits have shown increased improvements. Taking advantage of advanced solutions combined with traditional ones has brought about considerable advantages for construction contractors and saves on expenses to carry out construction projects. Owing to their ability to analyze geotechnical problems, several calculation and simulation software, such as Plaxis, Bentley, along with many others, have grown in popularity. Among them, Midas is one such software, which is a set of solutions developed by the MIDAS IT company and is widely applied in many constructions. The authors evaluated the ability to use Midas software to calculate the stability of a wall in a deep excavation pit for the Ho Chi Minh City Water Environment Improvement Project. The results of these researches reveal that combining soil-cement piles and steel sheet piles decreases the internal forces in sheet steel pile walls. At the same time, this solution not only reduces horizontal displacement but also keeps the settlement of the soil around the excavation pit within the permissible range, which helps to ensure that the adjacent pavements are stable and will not crack. The results of this study can be applied to similar geological constructions.

Keywords Deep Excavation, FEM, Displacement, Deep Cement Mixing Columns, Stability

1. Introduction

Tunneling construction has become an indispensable trend for traffic systems by exploring underground space in modern cities. It is the case, however, that each project has different conditions of geology, hydrography, tunnel structure, etc [11]. So profound research is constantly needed to assess the influences of tunneling on adjacent buildings.

Deep cement mixing columns (DCMCs) comprise the soil at the construction site and cement, which is grouted to the ground using the injection grouting pump. The drill bit is drilled down to loosen the soil until it reaches the depth of the soil layer that needs to be reinforced. After that, the drill bit then comes back and moves up. In the process of moving up, cement is grouted into the ground. This is a new technology applied in flooded areas where other types of columns do not meet the requirements. [1,16,21]

In Ho Chi Minh City, the rapid pace of urban development has narrowed the construction area. The technical infrastructure systems are being upgraded and improved due to the rapid development of urban areas. As a result, the deep excavation of pits is frequent and inevitable. [2]

Owing to their versatility and usefulness, sheet steel pile combined with a bracing support to stabilize the pit is often applied as a solution; however, among other problems, at the joints of steel sheet piles, water can often

leak and spill into the excavation pit, thus causing difficulties during construction. [4]

The solution of soil-cement pile walls is also frequently used in the construction of basements; however, due to the limited horizontal shearing resistance, they are only applicable to pits that are not too deep. [13,19]

Currently, nobody has used soil-cement piles with steel sheet piles in a project; therefore, the authors proposed a simulation combining soil-cement piles with steel sheet piles to find a better solution.

Many authors have studied the factors affecting the horizontal displacement of the diaphragm wall in a deep excavation pit, including pre-stressing in the strut system, factors related to construction issues, and factors related to design issues. [14,17]

Chang Yu Ou et al. (1993) [5] studied the relationship between the depth of a pit and the horizontal displacement of the diaphragm wall in the deep excavation pit. According to the results of this study, the largest horizontal displacement of the diaphragm wall in the deep excavation pit varies between 0.2 and 0.5% of the depth of the pit, as shown in Fig.1.

Figure 1. Relationship between the maximum horizontal displacement of the diaphragm wall and depth of excavation pit [4]

Further, Chang Yu Ou (2006) mentioned the relationship between the depth of the diaphragm wall (H_p) and the displacement of the diaphragm wall, as shown in

Fig. 2 [5]. The authors analyzed the horizontal displacement of the diaphragm wall in a 20m deep excavation pit using FEM (Fig.3).

Figure 2. H_p wall depth, Chang Yu Ou (2006)

Figure 3. Correlation between fixed wall depth and horizontal displacement of a wall [5]

When the struts are not filled, the wall will move like a cantilever. When the struts are installed, the stiffness of the struts is large enough to allow the wall to move around the junction between the wall and the struts and the largest horizontal displacement of the wall, located near the bottom of the pit. The displacement type of a wall is shown in Fig. 4 and Fig. 5.

Figure 4. Displacement type of a wall in a case where the strut stiffness is large enough. (a) stage without struts, (b) stage with struts, (c) stage with multiple struts installed [5].

Figure 5. Displacement type of a wall in a case where the strut stiffness is not large enough. (a) stage without struts, (b) stage with struts, (c) stage with multiple struts installed [5].

Clough and O'Rourke (1990) discussed safety in a study of its effect on the horizontal displacement of the diaphragm wall in a deep excavation pit [6]. The researchers provided a correlation between the factor of safety against basal heave, the stiffness of the diaphragm wall, and the support system with the maximum horizontal displacement of the wall through Fig. 6.

In which F_b is the factor of safety against the basal heave.

In order for the model to be able to give reliable deformation and stress distributions, the modeling area limits also need to be rational. The rationality here is understood that the model area must be large enough to cover the interaction between the deep excavation pit and the surrounding ground. K.J. Bakker (2005) proposed limiting the model area when analyzing deep excavation pits through the Plaxis software [3]. According to Bakker, modeling area limits depend on the width of the pit, the depth of the pit, and the length of the diaphragm wall. Helmut F. Schweiger (2002) studied the effect of modeling area limits on the analysis results of the horizontal displacement of diaphragm walls. Helmut F. Schweiger analyzed a deep excavation pit with different

modeling area limits. From the research results, Helmut F. Schweiger commented that once the limit of the modeling area is reached, the expansion of the modeling area limit does not significantly affect the results of horizontal displacement analysis of the diaphragm wall in the excavation pit.

Figure 6. Correlation between the factor of safety against basal heave, the stiffness of the diaphragm wall and the support system with the maximum horizontal displacement of the wall [6].

B. Gebreselassie and H.G. Kempfert (2006) [8] conducted a sensitivity analysis of the parameters of the Hardening Soil model to the results of the behavior of a deep excavation pit in a normally consolidated clay foundation. The parameters that B. Gebreselassie and H.G. Kempfert conducted for sensitivity analysis were ν_{ur} , k_0^{nc} , E_{50}^{ref} , E_{ur}^{ref} , E_{oed}^{ref} , and R_f . Parameter sensitivity was analyzed changing one parameter while keeping the remaining parameters fixed. The analysis results in each case were compared to draw conclusions. According to B. Gebreselassie and H.G. Kempfert, the most sensitive parameter for the horizontal displacement analysis of the basement diaphragm wall is E_{50} . The largest horizontal displacement of the diaphragm wall changes from 45–24% in accordance with the range of E_{50} variation of $\pm 50\%$.

The factor k_0^{nc} also has a significant influence on the horizontal displacement of the diaphragm wall in a deep excavation pit. Trung, N.D. and Phan, V. (2011) [18] analyzed the sensitivity of loading and unloading module parameters in the Hardening Soil model to the horizontal displacement of the diaphragm wall. Value E_{ur} changes by $3E_{50}$, $4E_{50}$, $5E_{50}$ to analyze the horizontal displacement of the diaphragm wall during the excavation phase. The analysis results show that the effect of the value fluctuation of the horizontal displacement of the diaphragm wall is negligible.

Tan et al. (2001) [15] studied the correlation between the module E parameter in the Hardening Soil model of Plaxis and the SPT-N index by back analysis of some deep excavation works on the sedimentary foundation of Kenny Hill in Kuala Lumpur, Malaysia, and sea mud in western Malaysia.

According to the above studies, hardness parameters affect the analysis results of the basement wall horizontal displacement the most. However, determining the parameters for the ground models according to the model's theory is an impossible task because in reality the geological data as well as the results of laboratory and field experiments are not always complete and correct. Therefore, it is essential to determine the range of fluctuations for these parameters for each soil type or their correlation with other physical and mechanical parameters. This range of fluctuation and correlation was studied through the back analysis of deep excavation and the comparison of the monitoring results of some national and international authors.

An, C.N. (2009) [1] used the correlation between SPT-N and modulus E in the Mohr Coulomb model to analyze the simultaneous work between the ground and the diaphragm wall of the water pumping station at the Nhieu Loc - Thi Nghe wastewater treatment system in Ho Chi Minh City.

Hai, N.V. and Nghia, L.T. (2007) [7] analyzed a deep excavation pit and its diaphragm wall with soil-cement

piles and provided the variation of modulus E in the Mohr Coulomb model for the soft soil layer in District 7, Ho Chi Minh city, Vietnam.

This paper presents the application of steel sheet piles combined with soil-cement piles to stabilize a deep excavation pit's wall for the Ho Chi Minh City Water Environment Improvement Project.

2. Materials and Methods

2.1. Simple Method

The simple method is based on past cases that had produced graphs of the relationship between different factors and the horizontal displacement of the diaphragm wall. Ou et al. (1993) [5] established the relationship between the largest horizontal displacement and the depth of the excavation pit for clay and sandy soils. Clough and O'Rourke (1990) [6] also studied deep excavation in the Taipei area as a basis for developing a correlation diagram of the largest horizontal displacement of the diaphragm wall with the factor of safety against basal heave of the diaphragm wall and support system. The above charts can be used to predict an estimated displacement of the diaphragm wall in similar conditions.

2.2. Method of Dependent Pressures and FEM

The method of dependent pressures and FEM are two common methods for analyzing the horizontal displacement of diaphragm walls in deep excavation pits. The advantage of either methods is the simulation of nearly all factors affecting the horizontal displacement of the diaphragm wall in any deep excavation pits. On the other hand, these two methods can be applied in computer software to reduce the volume and calculation time with more accurate results. However, the basic theory of these two methods is not really simple, especially the FEM, so that the analyst must not only have a strong basic knowledge but also practical experience.

Figure 7. The method of dependent pressures

Application of the method of dependent pressures and FEM in analyzing the horizontal displacement of diaphragm wall in the deep excavation pit has been studied by some authors. M. Mitew (2006) [12] used the two methods to conduct horizontal displacement analysis of the diaphragm wall in the deep excavation pit (Fig.7).

Using Geo-FEM software, Masew calculated K_h following the methods of Terzaghi (1955), Menard and Bourdon (1964), and Monnet (1994). For FEM, Mitew used the Mohr Coulomb model and Plaxis 2D software. Mitew divided soil hardness into four cases: FEM 1, soil hardness based on Polish standards; FEM 2, soil hardness based on previous studies; FEM 3, soil hardness based on geological survey results; and FEM 4, soil hardness based on on-site stress measurements. The results are given in Table 1. The results of the analysis were compared with those collected in the field. Mitew reported that the dependent pressure method gave extremely variable results because it is highly dependent on how the coefficient of K_h is determined. Meanwhile, the results of FEM had little variation and were close to the monitoring results. However, Mitew also emphasized that the chosen background model and its parameters are crucial when using FEM.

Table 1. The largest horizontal displacement of the wall when analyzing by different methods compared to the observed results, M.Mitew (2005) [12]

Method of dependent pressures	Terzaghi	9.2 mm
	Menard and Bourdon	9.7 mm
	Monnet	18.9 mm
FEM	FEM1	12.1mm
	FEM2	12.8 mm
	FEM3	11.7 mm
	FEM4	11.1 mm
Monitor		12.3 mm

Krasinski and Urban (2011) conducted a deep excavation analysis using two methods [9]. The first method simulated the interaction between the foundation and the wall with a system of elastic springs, and the authors used Obudowy Głębokich Wykopów software (OGW) to improve on Winkler model. The second method was a FEM that used Plaxis 2D with the Hardening Soil model. Krasinski and Urban found significant differences between methods. For the first method, the authors discovered shortcomings when simulating the behavior of the wall and the foundation with a beam on elastic springs because these elastic springs did not fully describe the complex physical phenomena in the interaction between the wall and the soil. The authors also noted that both methods gave different results. To determine which method is more reliable, we must verify their results with actual monitoring data.

2.3. Engineering Geological Parameters

We analyzed the pits belonging to package G, located in SIP1. Our study was a part of the project on improving the water environment in Ho Chi Minh City. For the jacking pit SIP1-15, the physical and mechanical indicators of the soil layer in the study area are given in Table 2. Geological surveying was conducted by the Viet Nam Water, Sanitation, and Environment Joint Stock Company (VIWASE). The physical and mechanical characteristics of the soil layer and the cement-soil piles are collected in Tables 2–4.

Table 2. Physical and mechanical characteristics of the soil layer

Name of indicator	Layer 2	Layer 4
Type of soil	Clay	Sandy soil
Status	Fluid	Medium stiff
Thickness (m)	5.2	43.8
Unit weight γ_{unsat} (kN/m ³)	8.20	16.00
Saturated unit weight γ_{sat} (kN/m ³)	15.05	20.05
Vertical permeability k_x (m/day)	0.103	0.0347
Horizontal permeability k_y (m/day)	0.0637	0.00694
Effective secant modulus E_{50} (kN/m ²)	5670	11200
Effective oedometer modulus E_{oed} (kN/m ²)	5670	11200
Effective unloading/reloading modulus E_{ur} (kN/m ²)	17010	33600
Cohesion c' (kN/m ²)	8.10	16.00
Internal frictional angle ϕ (degree)	3.22	18.82
Intensity reduction coefficient R_{inter}	0.65	0.65
m	1	1
Dilatation angle ψ (degree)	0	0
Poisson's ratio ν	0.30	0.30
Material model	H-S	H-S
Behavior of materials	Drained	Drained

Table 3. Physical and mechanical parameters of the cement-soil piles of the equivalent foundation model

Name of indicators	Soil-cement pile (Layer 2)	Soil-cement pile (Layer 4)
γ_{unsat} (kN/m ³)	8.79	16.20
γ_{sat} (kN/m ³)	15.40	20.15
k_x (m/day)	0.102	0.0373
k_y (m/day)	0.0648	0.0109
E_{50} (kN/m ²)	15387	20640
E_{oed} (kN/m ²)	15387	20640
E_{ur} (kN/m ²)	36160	61920
c' (kN/m ²)	22.70	40.20
ϕ (degree)	4.81	19.63
R_{inter}	0	0
m	0.9	1
ψ (degree)	0.97	0.97
Poisson's ratio ν	0.30	0.25
Material model	H-S	H-S
Behavior of materials	Drained	Drained

Table 4. Physical and mechanical parameters of the soil-cement piles of cylinder models working as piles

Element	Parameter	Value	Unit
Model type	Material type	Elastic	-
Elastic modulus	E	2.00E+05	kN/m ²
Horizontal cross-sectional area	A	0.785	m ²
Hardness along the axis	EA	1.57E+05	kN/m
Distance	L	1	m

2.4. Simulation of Steel Sheet Piles Combined with Soil-Cement Piles to Stabilize a Deep Excavation Pit Wall

2.4.1. Construction sequence of an excavation pit

The construction sequence of an excavation pit is shown in Table 5.

Table 5. Construction sequence of an excavation pit

Step	Works to be done
0	The initial state of the soil (+ 0.0m)
1	Construction of the Larsen diaphragm wall
2	Construction of soil-cement wall
3	Construction of bouchon with 2m soil-cement piles (-22.0m to -20.0m)
4	Construction of the first strut floor (+ 0.0m).
5	Lowering the underground water level, construction of the first excavation (3m of soil) to the elevation of -3.0m
6	Construction of the second strut floor (-3.0m).
7	Lowering the underground water level, construction of the second excavation (3m of soil) to the elevation of -6.0m
8	Construction of the third strut floor (-6.0m).
9	Lowering the underground water level, construction of the third excavation (3m of soil) to the elevation of -9.0m
10	Construction of the fourth strut floor (-9.0m).
11	Lowering the underground water level, construction of the fourth excavation (3m of soil) to the elevation of -12.0m
12	Construction of the fifth strut floor (-12.0m).
13	Lowering the underground water level, construction of the fifth excavation (3m of soil) to the elevation of -15.0m
14	Construction of the sixth strut floor (-15.0m).
15	Lowering the underground water level, construction of the sixth excavation (3m of soil) to the elevation of -18.0m
16	Construction of the seventh strut floor (-18.0m).
17	Lowering the underground water level, construction of the seventh excavation (3m of soil) to the elevation of -20.0m

2.4.2. Simulations using Midas GTS NX software

The Larsen sheet piles diaphragm wall was pressed down to a depth of 30m. Cross and longitudinal sections of the strut in the excavation pit are shown in Figs. 8-11. Details on the steel sheet piles reinforcing the excavation pit wall and the parameters of the struts are displayed in Tables 6-7.

Figure 8. Cross section of the strut in the excavation pit **Figure 9.** Cross section of the strut in the excavation pit combined with Larsen sheet piles **Figure 10.** Cross section of the bottom of the excavation pit

Figure 11. Longitudinal section of the excavation pit

Table 6. Specification of steel sheet piles reinforcing the excavation pit's wall

Element	Parameter	Larsen sheet piles	Unit
Model type	Material type	Elastic	-
Elastic modulus	E	21E+07	kN/m ²
Horizontal cross-sectional area	A	242.50	cm ²
Moment of inertia	$I = (b \cdot d^3) / 12$	38600	cm ⁴
Thickness	d	1.55	cm
Height	H	17.00	cm
Weight	w	7.6	kN/m/m
Poisson's ratio	v	0.2	-

Table 7. Parameters of the struts: pits were constructed with struts H400*400*13*21

Element	Parameter	Value	Unit
Model type	Material type	Elastic	-
Elastic modulus	E	2.10E+08	kN/m ²
Horizontal cross-sectional area	A	2.187E-02	m ²
Stiffness along the axis	EA	4.59E+06	kN
Distance	L	3	m

3. Results and Discussion

3.1. Results

The results of using the Equivalent Material Simulation method (EMS) method on the Larssen sheet piles wall are illustrated in Figs. 12-14. The results of using the Real Allocation Simulation method (RAS) to determine the internal forces acting on a Larssen sheet piles wall are shown in Figs 15-17.

Figure 12. Moment diagram of the longitudinal aspect of Larsen sheet pile's diaphragm wall according to Mohr Coulomb model and Hardening Soil model

Figure 13. Shear force diagram of the longitudinal aspect of Larsen sheet piles' diaphragm wall according to Mohr Coulomb model and Hardening Soil model

Figure 14. Displacement diagram of the longitudinal aspect of Larsen sheet piles' diaphragm wall according to Mohr Coulomb model and Hardening Soil model

Figure 15. Moment diagram of the longitudinal aspect of Larsen sheet piles' diaphragm wall according to Mohr Coulomb model and Hardening Soil model

Figs. 18-19 illustrate the effects of ground surface displacement when the excavation pit wall has not been reinforced by soil-cement piles. Figs. 20-21 demonstrate the effects of ground surface displacement when the excavation pit wall has been reinforced by soil-cement piles that comply with EMS. Figs. 22-23 show the effects of foundation-surface displacement when the excavation pit wall has been reinforced with soil-cement piles following the RAS method.

Figure 16. Shear force diagram of the longitudinal aspect of Larsen sheet piles' diaphragm wall according to Mohr Coulomb model and Hardening Soil model

Figure 17. Displacement diagram of longitudinal aspect of Larsen sheet piles' diaphragm wall according to Mohr Coulomb model and Hardening Soil model

Figure 18. Longitudinal section of the excavation pit

Figure 19. The result of vertical displacement of the foundation according to the MC model when the excavation pit's wall has not been reinforced by soil-cement piles

Figure 20. The result of vertical displacement of the foundation according to the HS model when the excavation pit's wall has been reinforced with soil-cement piles

Figure 21. The result of vertical displacement of the foundation according to the MC model when the excavation pit's wall has been reinforced with soil-cement piles

Figure 22. The result of vertical displacement of the foundation according to the HS model when the excavation pit's wall has been reinforced with soil-cement piles

Figure 23. The result of vertical displacement of the foundation according to the MC model when the excavation pit's wall has been reinforced with soil-cement piles

3.2. Discussion

3.2.1. The internal force of Larsen sheet piles' wall

When a wall was not reinforced by soil-cement piles 800mm in diameter (D800), the Mohr-Coulomb model gave the following result for the maximum moment in the wall: $M = 131.241 \text{ kN}\cdot\text{m/m}$ $< [M] = 476.70 \text{ kN}\cdot\text{m/m}$. The moment is within the permitted range. In contrast, the analytical method gave the following result: $M = 140.35 \text{ kN}\cdot\text{m/m}$ (difference of 6.94%). Therefore, we concluded that the ground simulated by the Mohr-Coulomb model has results similar to those of the analytical model. The Hardening Soil model gave the highest equal value for the shear force in the unreinforced pile wall: $Q = 277.74 \text{ kN/m}$. In comparison, the analytical method gave the following result: $Q = 286.10 \text{ kN/m}$ (difference of 3%). Based on these results, we determined that the results of the finite element model using Midas GTS NX software are equivalent those of analytical methods.

We also tested models on the excavation pit stabilized by soil-cement and steel piles. We modeled the problem of combining soil-cement and steel sheet piles to stabilize the excavation pit using the EMS method. The Mohr Coulomb model gave the maximum moment in the sheet-steel pile wall, $M = 88.657 \text{ kN}\cdot\text{m/m}$, while the Hardening Soil model delivered a lower value, $M = 24.083 \text{ kN}\cdot\text{m/m}$. This difference indicates that a sheet steel pile wall is most dangerous when the Mohr Coulomb model is used as its soil model. Shear forces in reinforced walls

have the same value in Mohr-Coulomb model as $Q = 265.492 \text{ kN/m}$, and Hardening Soil $Q = 283.25 \text{ kN/m}$.

- When modeling a combination of soil-cement piles and steel sheet piles to stabilize the excavation pit by the RAS method, it can be found that the Mohr-Coulomb model gives the maximum moment in the sheet steel pile's wall, $M = 48.754 \text{ kN}\cdot\text{m/m}$, while the Hardening Soil model delivers $M = 43.437 \text{ kN}\cdot\text{m/m}$. This difference shows that the sheet steel pile's wall is the most dangerous when the soil model is Mohr-Coulomb. Shear forces in reinforced walls have the same value for the Mohr-Coulomb model as $Q = 194.02 \text{ kN/m}$ and Hardening Soil $Q = 196.679 \text{ kN/m}$.

3.2.2. The displacement in Larsen sheet piles' wall

- When the excavation pit's wall has not been reinforced by soil-cement piles through comparison between the two models of MC, HS and monitoring results, it was found that the HS model gives results closer to the monitoring results (the most displacement position above the distance from the bottom of the pit of 2-3 m). When the excavation pit's wall has been reinforced by soil-cement piles, the displacement of steel sheet piles will decrease.

3.2.3. Ground surface displacement

When the bottom of the excavation pit has been reinforced, but the excavation pit's wall has not been reinforced, the settlement of the outer edge and the inside edges of the reinforced soil-cement piles' walls have a large and uneven difference. When combining soil-cement piles and steel sheet piles, the settlement is reduced and uniformly distributed, while the settlement within the zone of reinforced soil-cement piles increases because the soil layer has been reinforced with cement; thus the self-load is larger, with $\gamma = 21 \text{ kN/m}^3$, compared to the existing layer 2 with $\gamma = 14.8 \text{ kN/m}^3$ and layer 4 with $\gamma = 20.5 \text{ kN/m}^3$.

4. Conclusions

Through this research and analysis, the author gave a general conclusion about the research content, evaluation of the application of sheet piles combined with soil-cement piles to stabilize a deep excavation pit's wall in the Ho Chi Minh City water environment improvement project as below.

- 1) Combination of soil-cement piles and steel sheet piles reduces the horizontal displacement of steel sheet piles' walls.
 - By EMS method: The Mohr-Coulomb model has the largest horizontal displacement when the excavation pit's wall has not been reinforced by soil-cement piles D800 with T_y value equal

0.018 m, decreasing by 38.89% to $T_y = 0.011 \text{ m}$ (17 m from the excavation pit mouth). The Hardening Soil model has the largest horizontal displacement when the excavation pit's wall has not been reinforced by D800 cement soil piles, with the T_y value of 0.008 m decreasing by 62.25%, compared to $T_y = 0.003 \text{ m}$ (17 m from the excavation pit mouth).

- By RAS method: The Mohr-Coulomb (MC) model has the largest horizontal displacement when the wall of the excavation pit has not been reinforced by D800 soil-cement piles. The T_y value = 0.018 m, which decreases by 61.11% to $T_y = 0.007 \text{ m}$ (16.95 m from the excavation pit mouth). The hardening soil (HS) model has the largest horizontal displacement when the wall of the excavation pit has not been reinforced by D800 soil-cement piles. The T_y value of 0.008 m decreases by 50% to $T_y = 0.004 \text{ m}$ (17.25 m from the excavation pit mouth).
- 2) A combination of soil-cement piles and steel sheet piles not only reduces horizontal displacement but also keeps the settlement of the soil around the excavation pit within the permissible range. This ensures the stability of the surrounding pavement and therefore prevents cracks.
 - By EMS method: In the MC model, the maximum surface settlement of $T_z = 0.019 \text{ m}$ decreases by 47.36% to $T_z = 0.010 \text{ m}$ (located far from the outer edge of the soil-cement piles). The HS model has the largest surface settlement of $T_z = 0.004 \text{ m}$, which decreases by 47.5% to $T_z = 0.0021 \text{ m}$ (located at the outer edge of the soil-cement piles).
 - By RAS method: In the MC model, the maximum surface settlement of $T_z = 0.022 \text{ m}$ decreases by 34.09% to $T_z = 0.0145 \text{ m}$ (located far from the outer edge of the soil-cement piles). The HS model has the largest surface settlement of $T_z = 0.005 \text{ m}$, which decreases by 36% to $T_z = 0.0032 \text{ m}$ (located at the outer edge of the soil-cement piles).
 - 3) A combination of soil-cement piles and steel sheet piles reduces the internal force of the steel sheet pile walls.
 - By EMS method: In the MC model, the maximum moment in the steel sheet pile walls is $M = 88.657 \text{ kN}\cdot\text{m/m}$, which decreases by 32.44%. The shear force $Q = 265.492 \text{ kN/m}$, which decreases by 1.93%. In the HS model, $M = 24.083 \text{ kN}\cdot\text{m/m}$, which decreases by 79.10%. The shear force $Q = 283.25 \text{ kN/m}$, which increases by 1.98%.
 - By RAS method: In the MC model, the maximum moment in the steel sheet pile walls is

$M = 48.754 \text{ kN}\cdot\text{m/m}$, which decreases by 62.85%. The shear force $Q = 194.04 \text{ kN/m}$, which decreases by 28.32%. In the HS model, $M = 43.437 \text{ kN}\cdot\text{m/m}$, which decreases by 62.32%. The shear force $Q = 196.679 \text{ kN/m}$, which increases by 29.18%

In addition, the wall of soil-cement piles has a horizontal waterproofing effect on the excavation pit (preventing water from flowing into the pit), with a permeability coefficient of $k = 0.0864 \text{ m/day}$. Therefore, it is used extensively in irrigation, infrastructure, and construction works for waterproofing of dike banks and diaphragm walls.

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