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Numerical analysis of sheet pile wall structure considering soil-structure interaction

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Abstract. In this paper, a numerical study using finite element method with considering soil-structure interaction was conducted to investigate the stress and deformation behavior of a sheet pile wall structure. In numerical model, one of the nonlinear elastic material constitutive models, Duncan-Chang E-v model, is used for describing soil behavior. The hard contact constitutive model is used for simulating the behavior of interface between the sheet pile wall and soil. The construction process of excavation and backfill is simulated by the way of step loading. We also compare the present numerical method with the in-situ test results for verifying the numerical methods. The numerical analysis showed that the soil excavation in the lock chamber has a huge effect on the wall deflection and stress, pile deflection, and anchor force. With the increase of distance between anchored bars, the maximum wall deflection and anchor force increase, while the maximum wall stress decreases. At a low elevation of anchored bar, the maximum wall bending moment decreases, but the maximum wall deflection, pile deflection, and anchor force both increase. The construction procedure with first excavation and then backfill is quite favorable for decreasing pile deflection, wall deflection and stress, and anchor forces.

Keywords: anchored sheet pile wall; anchorage pile; anchored bar; soil-structure interaction; finite element analysis

1. Introduction

The sheet pile wall is a vertical wall formed by a series of platelike piles entering a certain depth to the foundation soil. Sheet pile walls used to provide lateral earth support can be either cantilever or anchored depending on the wall height. While relatively shorter sheet pile walls can be cantilever, higher walls require anchors. Sheet pile walls are widely used in port and wharf (Qiu and Grabe 2012, Tan *et al*. 2015, Ye *et al*. 2016), ship lock, dock (Santana *et al*. 2012), excavation support systems, slope reinforcement (Qu *et al*. 2017), and so on. The material for sheet piles contains mainly reinforced concrete, steel, and timber. The reinforced concrete sheet piles are the most common in anchored sheet pile wall.

The conventional design methods for anchored sheet pile walls are based on limit equilibrium approach. Due to complex mechanical characteristics of the sheet pile wall, conventional design computational methods cannot well reflect the soil-structure interaction problem. In the method, the soil-structure interaction only can be considered roughly by assuming the triangular active and passive lateral earth pressure distribution applied on the wall. Due to the limitation of the conventional design methods, it is thereby quite difficult to model the construction method and investigate the stress and deformation behavior of wall and surrounding soil throughout the construction process. Additionally, a study also indicated that the conventional methods may overestimate the wall bending moments and underestimated the anchor forces (Bilgin 2012).

Continuum mechanics numerical methods, such as finite element method, make it possible to incorporate the construction method during the analyses and design of sheet pile walls (Bilgin 2010). One of the earliest studies on anchored sheet pile walls using finite element method was performed by Bjerrum *et al.* (1972). KüÇÜKarslan and Banerjee (2004) analyzed inelastic pile-soil interaction by using a hybrid type of numerical method. The piles were modeled as linear finite elements and the soil half-space as boundary elements. The nonlinear spring model was used for modeling pile-soil interface behavior. They concluded that the numerical analysis could not only capable of predicting the general trend of pile group behavior, but also the general trend of pile settlement, which was of primary importance in the design of pile foundations. Mehdipour (2011) presented a series of 3D numerical analysis performed by the finite element method on sheet piles in a loose sandy soil, and investigated the effect of different length to height ratio of sheet piles on maximum bending moment, lateral earth pressure and sheet pile hinge point position. Liu *et al.* (2014) performed the numerical simulation of pile-anchor system composed of supporting piles and pre-stressed anchor cables by using finite difference method. By comparing monitoring data and numerical result, the result showed the numerical simulation was accurate and reliable by obtaining the reasonable

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parameters and considering the interaction effects of soil, cable and pile. Wu *et al.* (2014) investigated the soil-pile interaction in the pile vertical vibration by introducing the fictitious soil-pile model. By the method of on-site full-scale tests and the laboratory physical modeling of U-profile piles, Doubrovsky and Meshcheryakov (2015) studied the dependencies between the applied forces and friction in the interlocks during pressing-in regarding the pile-pile interaction and the soil properties, and developed an improved finite element calculation model for the design of sheet pile walls and applied to concrete structures. Guharay and Baidya (2015) presented an analytical study of a cantilever sheet pile wall considering the effects of uncertainty of soil properties using finite element methods. Based on the numerical analysis, they provided the design guidelines for penetration depth for both types of backfill and the design guidelines might quite useful to practitioners. Gazetas *et al*. (2016) conducted a seismic analysis of a tall anchored sheet-pile wall by two commercially available finite element codes, ABAQUS and PLAXIS, and concluded that the numerical finite element analyses can capture well the physical phenomena of complex interaction problem leading to reliable results. Qu *et al.* (2016) studied an approach of seismic design of sheet pile wall based on capacity spectrum method. All these studies indicate that the numerical analysis is an effective tool for capturing the deformation behaviors of the sheet pile wall structures with considering complex conditions, as well as for extending test conditions. Further, the numerical results can provide for designers and guide engineering design. However, few integral finite element model consisting of the anchorage pile, the sheet pile wall, the anchored bar and the soil exists. The soil-structure interface behavior are usually modeled by soft contact model, such as the nonlinear spring model (KüÇÜKarslan and Banerjee 2004), the spring-slider model (Liu *et al*. 2014). A fully geometric contact model may more fit for modeling the soil-structure interface behavior. Few in-site test and numerical simulation are carried out simultaneously for a practical engineering example. It is more reliable to verify the validity of the numerical methods by using the in-site testing data. The influence of a comprehensive multi factors on the pile deflection, wall deflection and stress, and anchor forces has not been studied in these literatures.

In this study, we will take a ship lock in China as example and the objective is to analyze the stress and deformation behavior of the anchored sheet pile wall by using finite element method with considering soil-structure interaction and the nonlinearity of the soil for improving design of similar engineering. An integral finite element model consisting of the anchorage pile, the sheet pile wall, the anchored bar and the soil will be established. The hard contact constitutive model will be used for simulating the behavior of interface between the sheet pile wall and soil. The in-site test and numerical simulation will be carried out simultaneously for the anchored sheet pile wall structure. Additionally, a detailed analysis will also cover to investigate the effect of these factors (i.e., the distance between anchored bars, the location of anchored bars, and the construction procedures) on the pile deflection, wall deflection and stress, and anchor forces.

The logic frame of this paper is considered organized as follows. Firstly, in Section 2, we introduce the numerical model in this study, including the finite element mesh of the sheet pile wall structure, material constitutive relations, contact constitutive relations for simulating the behavior of interface between the sheet pile wall and soil, and several typical construction stages when we concern the stress and deformation of the wall at these stages. Secondly, to verify the proposed numerical model, we compare the present numerical results with in-situ testing data in Section 3. And thirdly, after the validity of the numerical methods has been ensured, the proposed numerical model can be used to further analyze the stress and deformation of the wall in Section 4. The numerical simulation can show its huge advantages in extending test conditions. Thus, we give some detailed results and analysis. Finally, Section 5 summarises the major conclusions that can be drawn from this study.

2. Numerical model

2.1 Finite element model

The finite element methods were used for analyzing the stress and deformation behavior of sheet pile wall structure.

And analyses were carried out by using the business software ABAQUS. In this paper, we took a ship lock in China as example; see Fig. 1. The ship lock was named as

Fig. 1 A ship lock in China

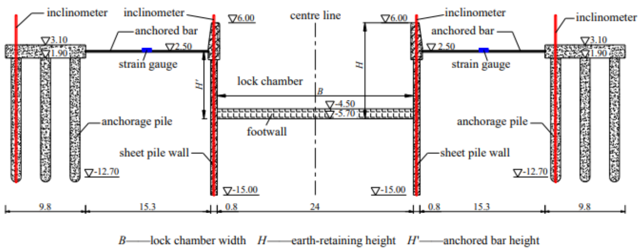


Fig. 2 A typical anchored sheet pile wall structure of a ship lock (Unit: m)

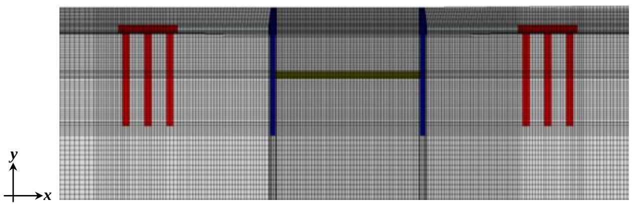


Fig. 3 Finite element mesh

Table 1 Linear elastic material parameters

Materials	Mass density ρ (kg/m^3)	Elastic modulus E (GPa)	Poisson ratio v
Anchorage pile	2400	28.0	0.167
Sheet pile wall	2500	28.0	0.2
Footwall	2500	30.0	0.2
Anchored bar	7800	200.0	0.3

the second line ship lock engineering of Taizhou irrigation channel Gaogang hydraulic schemes. The second line ship lock was located on the west side of the first ship lock. The center line along the flow direction of the second line ship lock was 70 m away from that of the first line ship lock. The upstream edge of the upper gate head of the second line ship lock was flush with that of the first line ship lock. The geometric dimension of the ship lock was 230 m length, and 23 m width. A reinforced concrete Hollywood structure was designed at the upper and lower gate heads. The footwall of the upper and lower gate heads is 29 m length, and 53.8 widths. A permeable footwall was designed at the chamber with the bottom elevation of -4.5 m. The anchored sheet pile wall structure was adopted for constructing the wall of ship lock. The height of the backfill in the wall was 6 m. The upper and lower guide walls also adopted the anchored sheet pile wall structure.

Fig. 2 showed a typical 2D anchored sheet pile wall structure of the ship lock. In numerical model, an integral finite element model consisting of the anchorage pile, the sheet pile wall, the anchored bar and the soil was established. The structure combined with its surrounding soil was discretized into several elements. The anchorage pile, the sheet pile wall, and the soil both were discretized into several plane 4-node quadrilateral isoparametric elements. The anchored bar was discretized into several 2-node bar elements. The depth of the numerical model boundary was extended to include two times the wall height below the bottom of the wall, and the model width also was extended two times the wall height from the left border of the left anchorage pile, as well as the right border of the right anchorage pile. As shown in Fig. 3, the finite element model contained 66573-node and 65606-element. The thickness of sheet pile wall was divided into 5 layers element, and the thickness of footwall was divided into 6 layers element. It should be noted that in Fig. 3, we cut down part of the figure border for display purpose.

2.2 Constitutive relations

2.2.1 Material constitutive relations

In numerical model, the linear elastic material constitutive models are used for these parts of the structure: anchorage pile, the sheet pile wall, footwall, and anchored bar. The material parameters of these parts are given in Table 1.

One of the nonlinear elastic material constitutive models, Duncan-Chang *E-v* model (Duncan and Chang 1970), is used for describing soil behavior. The Duncan-Chang is one of the typical representatives of nonlinear constitutive models and has been widely used for describing the behavior of the soil or rockfill materials (Chen *et al*. 2011, Li *et al*. 2016, Wang *et al*. 2017). Here, the Duncan-Chang *E-v* model has been developed by user subroutine UEL in ABAQUS.

Table 2 Duncan-Chang *E-v* model parameters

Parameters		Soil 1	Soil 2
Mass density ρ (kg/m^3)		1960	1910
Modulus number k		319.0	255.0
Modulus exponent n		0.423	0.542
Failure ratio R_f		0.823	0.822
Cohesion c(Pa)		30000	23700
Friction angle φ(°)		33.4	40.2
Lateral deformation coefficient	G	0.25	0.35
	F	0.158	0.108
	D	8.2	3.4
Modulus number in an unloading or reloading situation k_{ur}		957.0	765.0

Table 3 Soil layer

Soil layer	Elevation / m	Material
Backfill	6.00~2.00	Soil 1
Soil layer 1 (sandy loam soil)	2.00~1.00	Soil 1
Soil layer 2 (sandy soil)	1.00~-15.00	Soil 1
Soil layer 3	Below -15.00	Soil 2

Table 4 Construction process of excavation and backfill

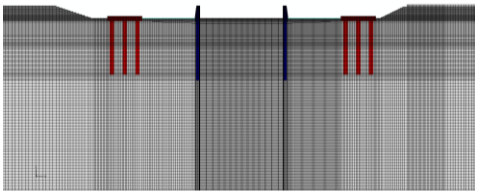
Case	Loading step	Construction process of excavation and backfill
Case 1	1st step	Initial geo-stress balance
Case 2	2nd ~ 3rd step	Backfill soil behind the sheet pile wall, and backfill to about 4.0 m
Case 3	4th ~ 12th step	Excavate soil in the lock chamber, and excavate to -5.7 m
Case 4	13th step	Construction the footwall with the thickness of 1.2 m in the lock chamber
Case 5	14th ~ 15th step	Continue to backfill soil behind the sheet pile wall, and backfill to about 6.0 m

The Duncan-Chang model parameters were obtained by the triaxial tests of in-situ soil samples; see Table 2. During construction, the soils were treated by mechanical rolling and manual ramming. Therefore, the mechanical properties of sandy loam soil and sandy soil may be very similar to that of backfill. In numerical modelling, the sandy loam soil, sandy soil and backfill were simulated for the same material. Table 3 shows the soil layer.

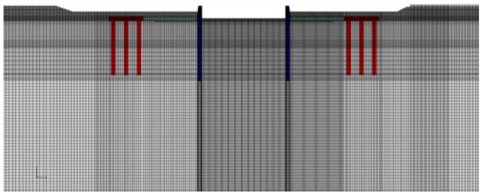
2.2.2 Contact constitutive relations

The hard contact constitutive model is used for simulating the behavior of interface between the sheet pile wall and soil. The contact constitutive relations can be expressed by

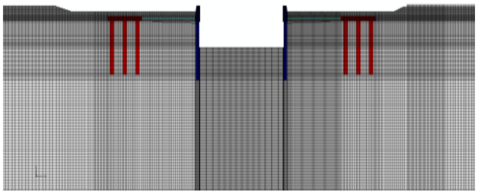
$$\begin{cases} p = 0, & h < 0 \\ h = 0, & p > 0 \end{cases} \tag{1}$$



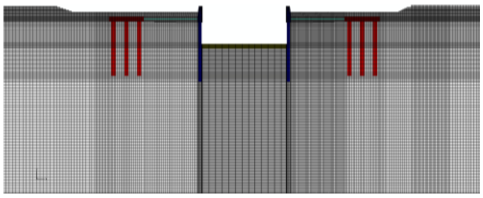
(a) Case 1



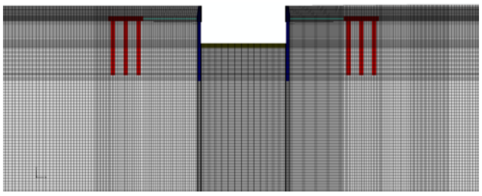
(b) Case 2



(c) Case 3



(d) Case 4



(e) Case 5

Fig. 4 Five typical construction processes of excavation and backfill

where, *h* is the clearance; *p* is the contact pressure.

The contact algorithm can minimize the penetration between two contact bodies at the constraint location. When the two surfaces are in contact, any contact pressure can be transmitted between them. Once the two surfaces separate, the contact pressure immediately decreases to zero. Separated surfaces come into contact again when the clearance between them is reduced to zero.

2.3 Construction process simulation

The construction process of excavation and backfill is simulated by the way of step loading. We investigate the stress and deformation of the sheet pile wall under five cases; see Table 4 and Fig. 4. In case 1 in Fig. 4(a), for the initial status of the simulation, the sheet pile wall and the anchorage pile has been finished pouring, and also the anchored bar has been finished fastening. But the soil behind the sheet pile wall still has not been filled. The elevation for the soil behind the sheet pile wall and in the lock chamber both are 2.5 m.

Fig. 5 Inclinometer

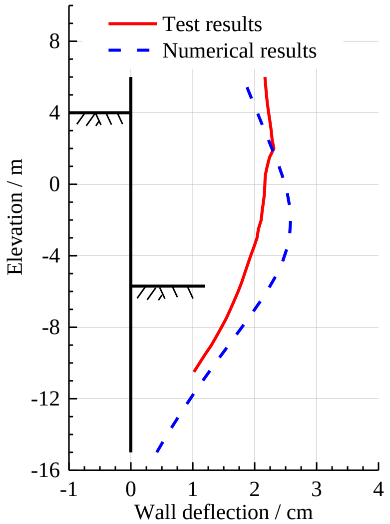
Fig. 6 Strain gauge installed on the anchored bar

3. Numerical verification

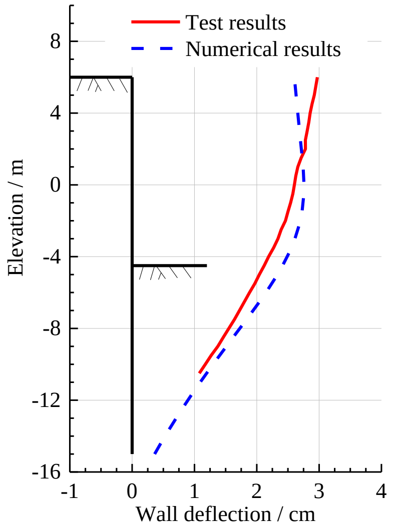
To real-time observe the deformation of the sheet pile wall and the anchorage pile during construction, some inclinometers in Fig. 5 were embedded previously, as well as some strain gauges in Fig. 6 were installed on the anchored bar for observing its internal force. The installation location of these instruments can be seen in Fig. 2.

As shown in Fig. 7, we compare the sheet pile wall deflection obtained by our present numerical results with that obtained from test results for cases 3 and 5. A fairly satisfactory agreement can be observed from the figure. The computed numerically maximum deflection value of the wall is 2.76 cm, while the testing maximum value is 2.97 cm.

As shown in Fig. 8, we compare the anchorage pile deflection obtained by our present numerical results with that obtained from test results for cases 3 and 5. A fairly satisfactory agreement for the deflection trend of the pile can be observed from the figure. Because the deflection tested by inclinometer reflects a relative quantity, the deflection at the bottom of the pile cannot be well reflected

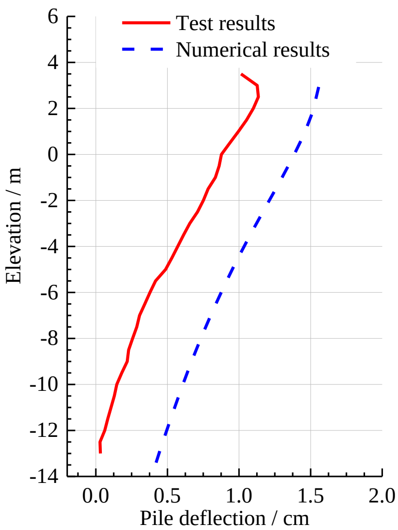


(a) Case 3



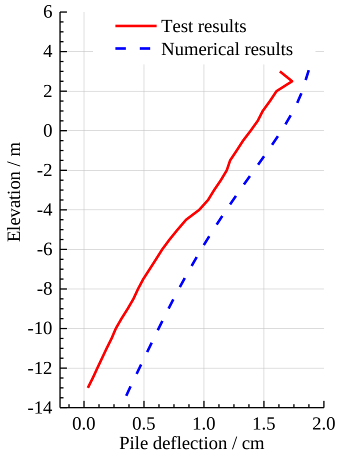
(b) Case 5

Fig. 7 Comparison of numerical results with test results for sheet pile wall deflection



(a) Case 3

Fig. 8 Comparison of numerical results with test results for anchorage pile deflection



(b) Case 5

Fig. 8 Continued

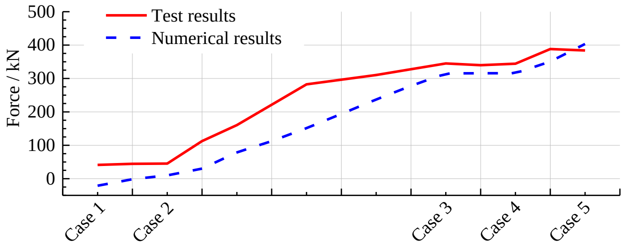


Fig. 9 Comparison of numerical results with test results for the internal force of the anchored bar

from test results. The computed numerically maximum deflection value of the pile is 1.88 cm, while the testing maximum value is 1.74 cm.

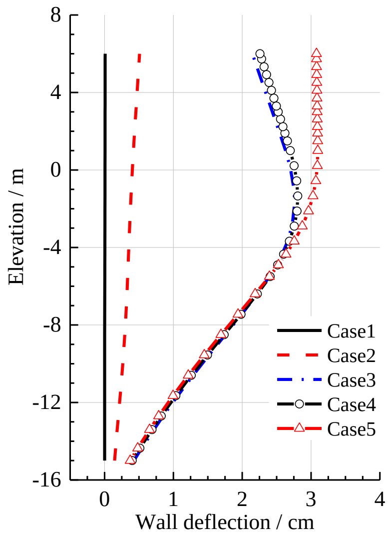
Fig. 9 shows the variation of the internal force of the anchored bar during construction. Comparing our present numerical results with test results, an excellent consistency over the variation trend of the internal force of the anchored bar can be found. The computed numerically maximum internal force value of the bar is 403.46 kN, while the testing maximum value is 388.25 kN.

It can be concluded that the present numerical method yields a satisfactory agreement with the test results. Therefore, the validity of the numerical methods can be ensured.

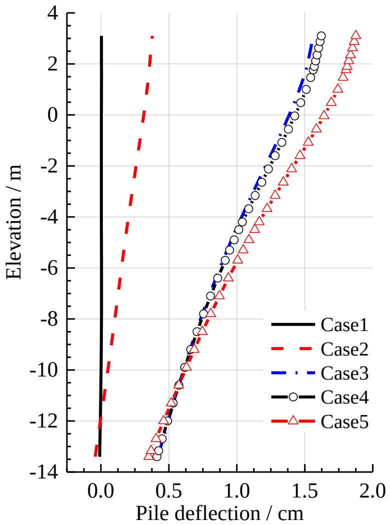
4. Results and analysis

4.1 Deformation of sheet pile wall and anchorage pile

Fig. 10(a) shows the deformation of sheet pile wall along elevation under five different cases. During soil backfill and excavation, the wall deforms toward the lock chamber side. Before the soil in the lock chamber is excavated, the wall approximates to deform linearly and the location of the maximum deflection lies in the top of the wall. After the soil in the lock chamber is excavated, the location of the maximum deflection transfers to the upper part of the wall with range from elevation -2.50 m to 1.00 m. While the soil backfill and excavation are finished in case 5, the deflection of the wall reaches to the maximum



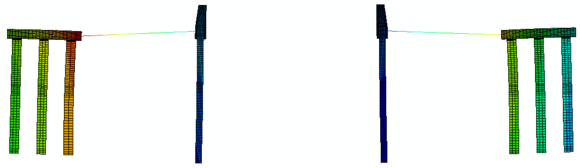
(a) Sheet pile wall



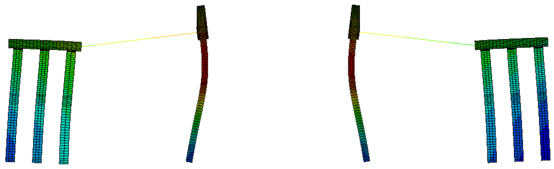
(b) Anchorage pile

Fig. 10 Deformation of sheet pile wall and anchorage pile under different cases

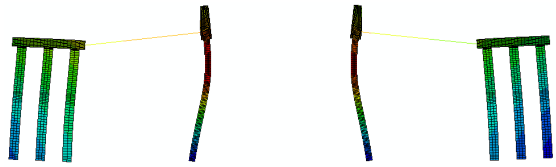
(a) Case 1



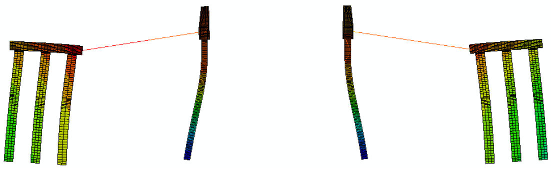
(b) Case 2



(c) Case 3



(d) Case 4



(e) Case 5

Fig. 11 Deformed wall-bar-pile structures (with 100 times magnified deformation)

value of 2.76 cm. The soil excavation in the lock chamber has a huge effect on the deflection of the wall. During the soil excavation in the lock chamber, the maximum deflection of the wall increases from 0.49 cm in case 2 to 2.58 cm in case 3. That is almost 76% of the final wall deformations occur during the soil excavation in the lock chamber.

Fig. 10(b) shows the deformation of anchorage pile along elevation under five different cases. During soil backfill and excavation, the pile also deforms toward the lock chamber side. The location of the maximum deflection lies in the top of the pile. While the soil backfill and excavation are finished in case 5, the deflection of the pile reaches to the maximum value of 1.88 cm. Similarly, the soil excavation in the lock chamber also has a huge effect on the deflection of the pile. During soil excavation in the lock chamber, the maximum deflection of the pile increases from 0.38 cm in case 2 to 1.56 cm in case 3. That is almost 63% of the final pile deformations occur during the soil excavation in the lock chamber.

Fig.11 shows the deformed diagrams of the wall-bar-pile structures under five different cases.

4.2 Bending moment and stress of sheet pile wall

Fig. 12 shows the bending moment of sheet pile wall along elevation under different cases. The bending moment of the wall reaches to the maximum value of 786.24 kN·m/m in case 3. In case 5, the maximum value of the bending moment of the wall is 600.00 kN·m/m.

Fig. 13 shows the principle tensile stress of sheet pile wall along elevation under different cases. The location of the maximum principle tensile stress lies in the upper part of the wall with range from elevation -4.00 m to -2.00 m. In case 4, the principle tensile stress of the wall reaches to the maximum value of 3.18 MPa. Fig.14 shows the maximum principle tensile stress variation of sheet pile wall during construction. From the figure, we can see that the stress has a significant increase from case 2 to case 3. The soil excavation in the lock chamber has a huge effect on the stress of the wall. From case 4 to case 5, the stress exhibits a somewhat resilient due to the soil backfill. Fig.15 shows the principle tensile stress distribution of sheet pile wall.

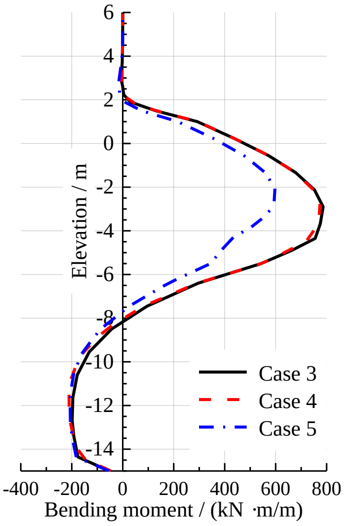


Fig. 12 Bending moment of sheet pile wall under different cases

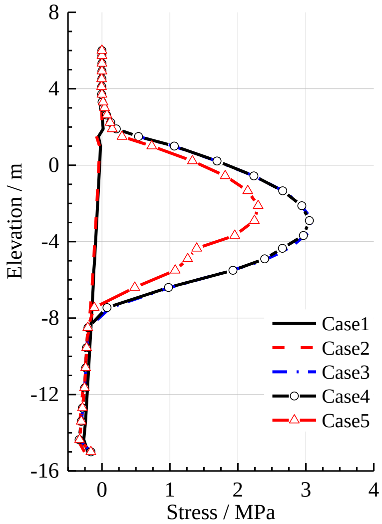


Fig. 13 Principle tensile stress of sheet pile wall under different cases

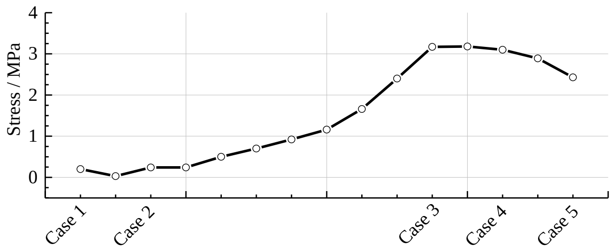


Fig. 14 Maximum principle tensile stress variation of sheet pile wall during construction

4.3 Internal force of anchored bar

Fig. 16 shows the internal force variation of anchored bar during construction. In case 5, the internal force of the bar reaches to the maximum value of 403.46 kN. The soil excavation in the lock chamber also has a huge effect on the internal force of the anchored bar. During soil excavation in the lock chamber, the maximum internal force of the bar

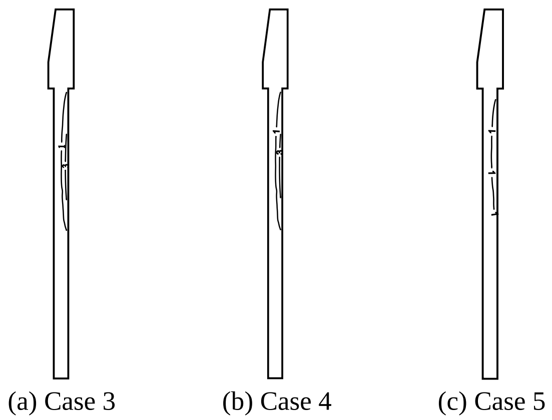


Fig. 15 Principle tensile stress distribution of sheet pile wall / MPa

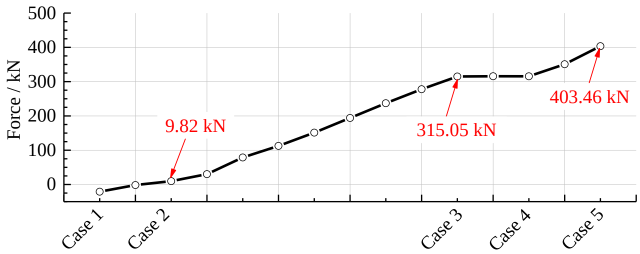


Fig. 16 Internal force variation of anchored bar during construction

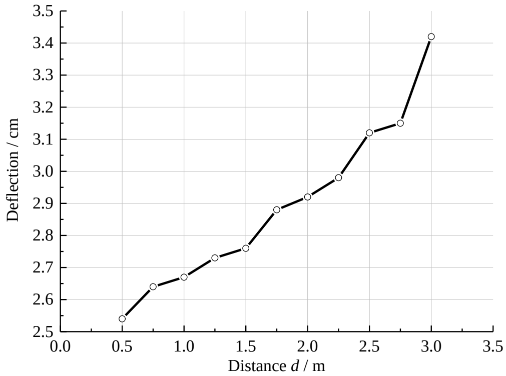
increases from 9.82 kN in case 2 to 315.05 kN in case 3. By comparison, the soil backfill has a slightly effect on the internal force of the bar. The maximum internal force of the bar increases from 315.52 kN in case 4 to 403.46 kN in case 5. That is almost 76% of the final anchor forces occur during the soil excavation in the lock chamber.

4.4 Effect of distance between anchored bars on wall deflection, wall stress, and anchor force

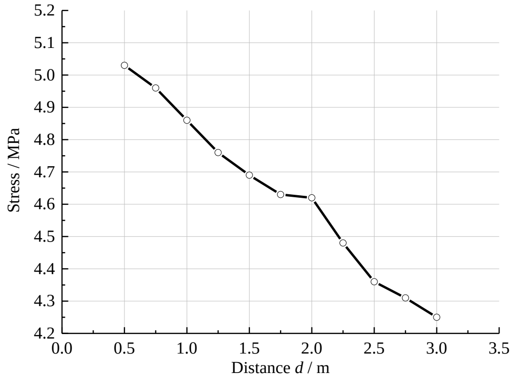
The anchored bar quantity has a significant influence on wall deflection and stress. Current China code stipulates the distance between anchored bars ranging from 1.0 m to 3.0 m (JTS 167-3-2009). For the anchored sheet pile wall structure, the actual distance between anchored bars is designed as 1.5 m.

Here, we investigate numerically the effect of distance between anchored bars on the maximum wall deflection, the maximum wall stress, and the maximum anchor force. As shown in Fig. 17, with the increase of distance between anchored bars, the maximum wall deflection and the maximum anchor force increases, while the maximum wall stress decreases.

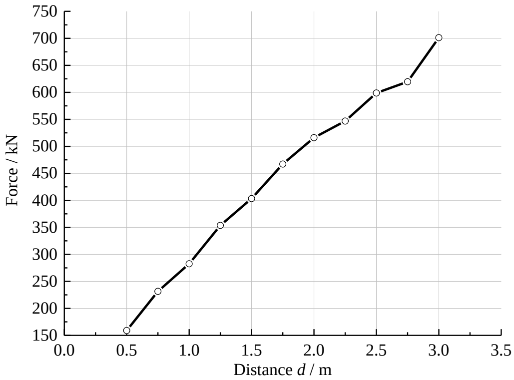
Fig. 18 shows the deformation of the sheet pile wall along elevation in case 5 under different distances between anchored bars, *d*=3.0 m case, *d*=1.5 m case, *d*=0.75 m case, as well as no bar case. From the figure, we can see that for no bar case, that is a cantilever sheet pile wall, the wall deflection has a rapid increase with the maximum deflection of 9.39 cm. Meanwhile, the location of the maximum deflection of the wall transfers to the top of the wall. The rapid increase of the wall deflection influences seriously the stability of the lock chamber.



(a) Wall deflection vs. distance curve



(b) Wall stress vs. distance curve



(c) Anchor force vs. distance curve

Fig. 17 Effect of distance between anchored bars on wall deflection, wall stress, and anchor force

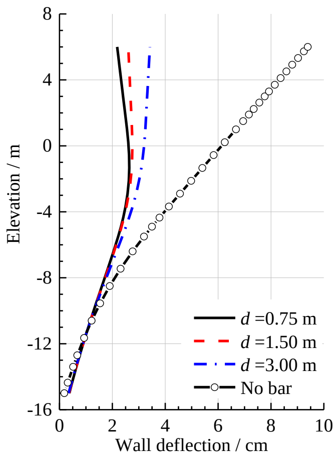


Fig. 18 Deformation of sheet pile wall along elevation in case 5 under different distances between anchored bars

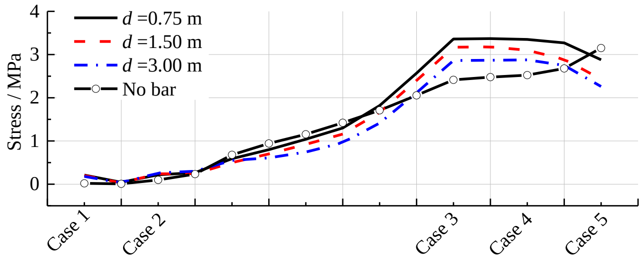


Fig. 19 Maximum wall stress variation during construction under different distances between anchored bars

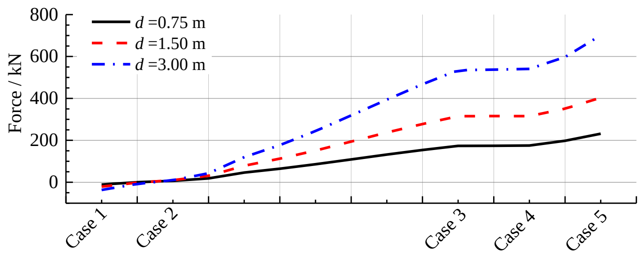
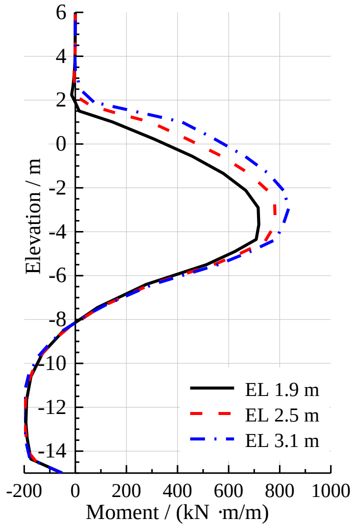


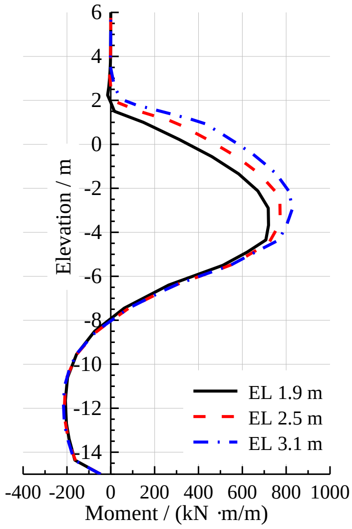
Fig. 20 Anchor force variation during construction under different distances between anchored bars

Fig. 19 shows the maximum wall stress variation during construction under different distances between anchored bars and Fig. 20 shows the anchor force variation during construction. For *d*=3.0 m case, the principle tensile stress of the wall reaches to the maximum value of 2.88 MPa in case 4. Compared with *d*=3.0 m case, the principle tensile stress of the wall reaches to the maximum value of 3.18 MPa for *d*=1.5 m case. The variation trends of the principle tensile stress during construction are quite identical both for *d*=3.0 m and *d*=1.5 m cases. However, for *d*=3.0 m case, the maximum anchor force reaches to 701.13 kN. For no bar case, the principle tensile stress of the wall constantly increases during construction, and in case the stress reaches to 3.15 MPa of the maximum value.

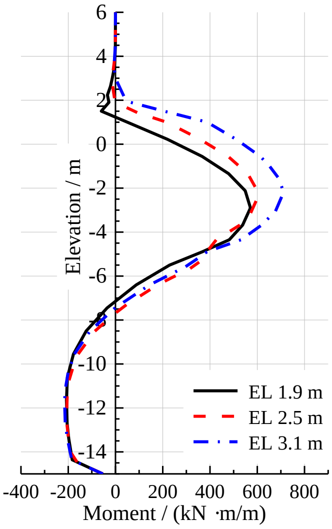
4.5 Effect of location of anchored bars on pile deflection, wall deflection and stress, anchor force, and wall bending moment



(a) Case 3



(b) Case 4



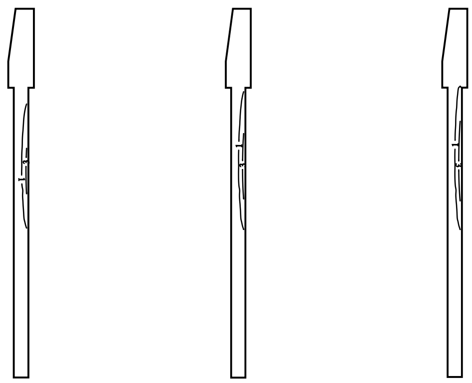
(c) Case 5

Fig. 21 Effect of location of anchored bars on wall bending moment

Table 5 Maximum pile deflection, wall deflection and stress, and anchor force under different locations of anchored bars

Anchored bars elevation	Maximum pile deflection/cm	Maximum wall deflection/cm	Maximum wall stress/MPa	Maximum anchor force/kN
1.90 m (0.65*H*)	1.96	2.87	2.90	434.18
2.50 m (0.70 *H*)	1.88	2.76	3.18	403.46
3.10 m (0.75 *H*)	1.85	2.84	3.38	379.67

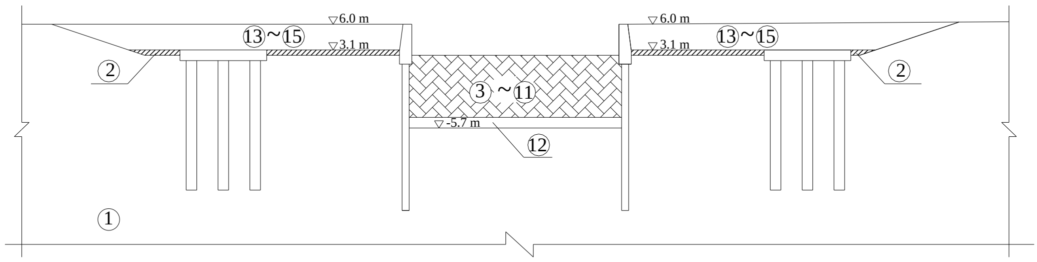
The actual elevation of anchored bar for the anchored sheet pile wall structure is designed as elevation 2.50 m, that is the anchored bar height H'=8.2 m, which accounts for 70% of earth-retaining height H (H=11.7 m). Here, we investigate numerically the effect of location of anchored bars on pile deflection, wall deflection and stress, and anchor force with H'=0.65H case, H'=0.70H case, and H'=0.75H case; see Table 5. Fig. 21 shows the effect of location of anchored bars on wall bending moment.



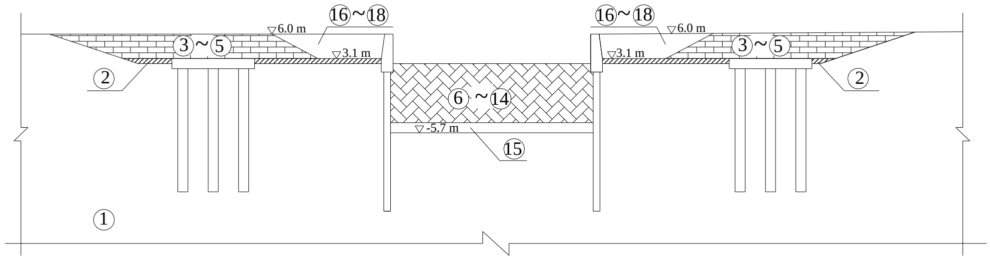
(a) Elevation 1.90 m (b) Elevation 2.50 m (c) Elevation 3.10 m

Fig. 22 Principle tensile stress distribution of sheet pile wall under different locations of anchored bars / MPa

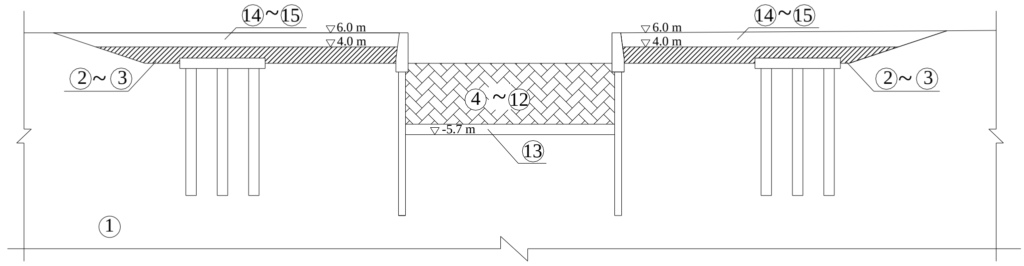
At a low elevation of anchored bar, the maximum bending moment of the wall decreases, but the maximum wall deflection, the maximum pile deflection, and the



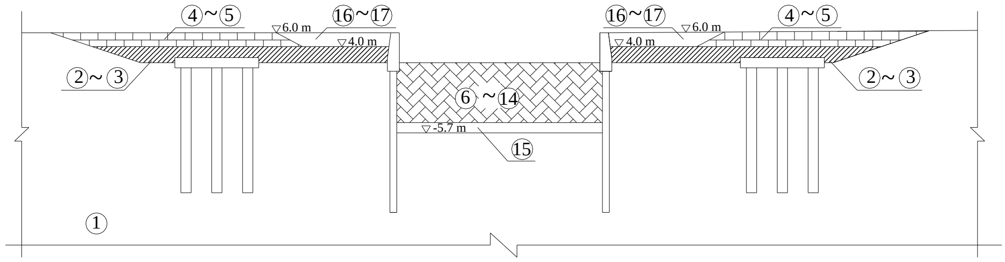
(a) Construction case 1



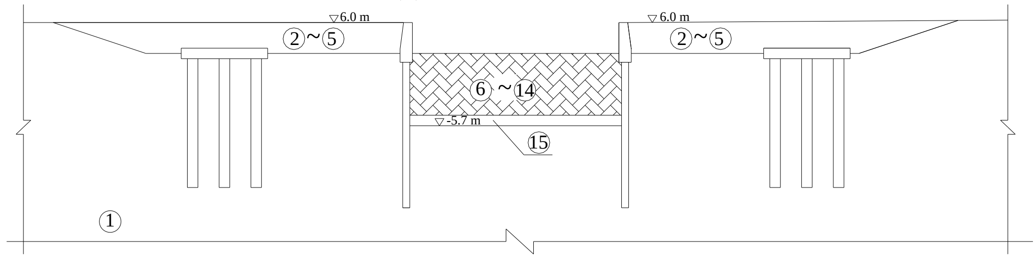
(b) Construction case 2



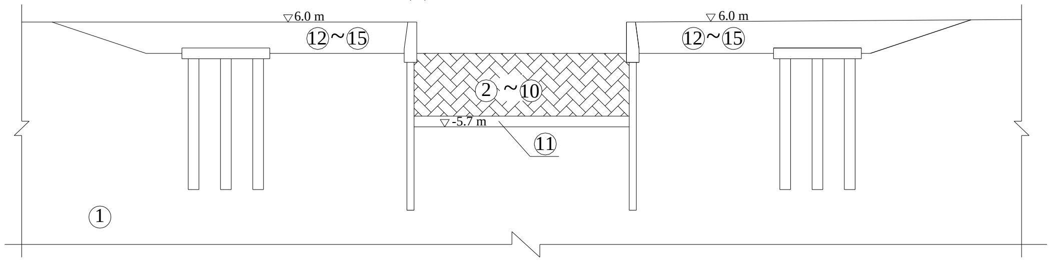
(c) Construction case 3



(d) Construction case 4



(e) Construction case 5



(f) Construction case 6

Fig. 23 Schemes for several different construction procedures

Table 6 Maximum pile deflection, wall deflection and stress, and anchor forces under different construction procedures

Construction procedures	Pile deflection /cm	Wall deflection /cm	Wall stress /MPa	Anchor forces /kN
Case 1	1.83	2.51	2.98	354.33
Case 2	2.09	2.90	3.30	382.43
Case 3	1.88	2.76	3.18	403.46
Case 4	2.26	3.13	3.38	419.87
Case 5	2.46	3.39	3.38	449.50
Case 6	1.72	2.47	2.64	317.50

maximum anchor force both increase. By comparison, the maximum bending moment of the wall has an evident increase at a high elevation of anchored bar. As shown in Fig. 22, we can see that for $H'=0.65H$ case, the tensile zone with the stress higher than 3.0 MPa has an obvious decrease.

4.6 Effect of construction procedures on pile deflection, wall deflection and stress, and anchor forces

To investigate the effect of construction procedures on pile deflection, wall deflection and stress, and anchor forces, several different construction procedures are analyzed in this section; see Fig. 23.

For construction case 1, as shown in Fig. 23(a), the symbol ① mean the initial geo-stress balance. The 2^{nd} step is to backfill soil behind the sheet pile wall, and backfill to elevation 3.1 m. The 3^{rd}-11^{th} is to excavate soil in the lock chamber, and excavate to -5.7 m. The 12^{th} is to construction the footwall with the thickness of 1.2 m in the lock chamber. At the 13^{th}~15^{th} step, continue to backfill soil behind the sheet pile wall, and backfill to about 6.0 m. The symbol in Fig.23(b)~(f) has a similar meaning with that in Fig.23(a). We do not explain again in detail.

We compare the maximum pile deflection, wall deflection and stress, and anchor forces with different construction procedures in Table 6. The results show that the construction procedure with first excavation and then backfill is quite favorable for decreasing pile deflection, wall deflection and stress, and anchor forces. However, according to some construction experiences, a small soil behind the sheet pile wall can be backfilled in advance to avoid the construction interference on anchorage pile and anchored bar.

5. Conclusions

A numerical study using finite element method with considering soil-structure interaction was conducted to investigate the stress and deformation behavior of a sheet pile wall structure. In numerical model, an integral finite element model consisting of the anchorage pile, the sheet pile wall, the anchored bar and the soil was established. The hard contact constitutive model is used for simulating the behavior of interface between the sheet pile wall and soil. The linear elastic material constitutive models are used for these parts of the structure: anchorage pile, the sheet pile wall, footwall, and anchored bar. One of the nonlinear elastic material constitutive models, Duncan-Chang *E-v* model, is used for describing soil behavior. The construction process of excavation and backfill is simulated by the way of step loading. Additionally, to real-time observe the deformation of the sheet pile wall and the anchorage pile during construction, some inclinometers were embedded previously, as well as some strain gauges were installed on the anchored bar for observing its internal force. By comparing the present numerical method with the in-situ test results, a satisfactory agreement can be observed. Therefore, the validity of the numerical methods can be ensured. By using finite element analysis, some valuable conclusions can be drawn from this study.

• The soil excavation in the lock chamber has a huge effect on the wall deflection and stress, pile deflection, and anchor force. Almost 76% of the final wall deformations and anchor force occur during this stage, while 63% of the final pile deformations occur.

• With the increase of distance between anchored bars, the maximum wall deflection and anchor force increase, while the maximum wall stress decreases.

• At a low elevation of anchored bar, the maximum wall bending moment decreases, but the maximum wall deflection, pile deflection, and anchor force both increase. By comparison, the maximum bending moment of the wall has an evident increase at a high elevation of anchored bar.

• The construction procedure with first excavation and then backfill is quite favorable for decreasing pile deflection, wall deflection and stress, and anchor forces. However, according to some construction experiences, a small soil behind the sheet pile wall can be backfilled in advance to avoid the construction interference on anchorage pile and anchored bar.

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