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Site Measurement Study on Mechanical Properties of SMW Piles of Building Structures in Sandy Soil Areas

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Abstract: SMW (soil mixing wall) piles have been widely used in soft soil areas such as Jiangsu, Shanghai, Tianjin and so on, and they have many advantages, such as retaining the structures of foundation pits. In order to promote the application of SMW piles in sandy soil areas such as Henan province, SMW piles were used in a deep foundation pit project of a high-rise building in Zhengzhou. Three SMW piles in the middle area of the foundation pit were selected for site measurement to determine the mechanical properties of SMW piles in sandy soil areas. Several typical test sections were determined along the height of the pile. The vibrating string type of the reinforcement dynamometers were set on the H-shaped steel of each test section, and the stress distribution of the H-shaped steel along the depth of the pit was obtained via testing. The axial force, bending moment and shearing force of the H-shaped steel were further calculated, and the affecting factors and development laws of the internal force distribution of the H-shaped steel were analyzed in detail. The research shows that, at the stage of foundation pit excavation, the overall stress of H-shaped steel increases gradually. The axial force of H-shaped steel in an SMW pile is mainly affected by such factors as the weight of the H-shaped steel, the weight of the crown beam and the first support system, the weight of the breast beam and the second support system, and the frictional resistance of the cemented soil. The bending moment and shearing force of H-shaped steel are mainly affected by such factors as the lateral soil pressure and the concentrated forces of the two support systems. When the foundation pit was excavated to the base, the development of and changes in the law of internal force with regard to the H-shaped steel was analyzed. When the overall internal force of the H-shaped steel is at its maximum, the maximum absolute values in terms of the axial force, bending moment and shearing force are −481 KN, 371 KN·m and 123 KN. In the process of foundation pit excavation and backfilling, the point of contraflexure of the H-shaped steel moves down gradually, and the fixed end of corresponding SMW pile also moves down and stabilizes below the base. These results may provide a reference for the design and construction of SMW piles of building structures in sandy soil areas.

Keywords: high-rise building; sandy soil area; Soil Mixing Wall pile; site measurement; mechanical property; H-shaped steel; internal force

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1. Introduction

The SMW (soil mixing wall) pile is a kind of composite support structure which is integrated with soil retaining and seepage prevention after H-shaped steel is inserted into a continuous lapping three-axis cemented soil mixing pile [1,2]. The SWM pile not only has a high strength, high stiffness and good anti-seepage effect, but also has the advantages of a small impact on the surrounding strata and environment, small construction space and speedy construction. After the supporting effect of SMW piles is achieved, the H-shaped steel can be pulled out and recycled according to requirements. This not only saves the steel, but it also achieves sustainable development. SMW piles are very suitable for deep foundation pit engineering in large and medium-sized cities with dense buildings. Therefore, SWM piles have been widely used in soft soil areas such as Jiangsu, Zhejiang, Shanghai and Tianjin. At the same time, there are also many studies on the mechanical characteristics of cemented soil based on soft soil and corresponding SMW piles [3–6].

As SWM piles have many advantages as foundation pit supporting structures, and in order to further promote their application to sandy soil areas such as Henan, SMW piles were adopted in the deep foundation pit supporting project of a high-rise building in Zhengzhou. According to the design requirements of the "Technical Specification for Soil Mixed Wall" (JGJ/T 199-2010) [7], the internal forces, such as the bending moment and shearing force, generated by the lateral soil and water pressure of the foundation pit are borne by the H-shaped steel in the SMW pile, while the cemented soil only plays the role of forming a sealing curtain [8–10].

In order to determine mechanical properties of H-shaped steel in SMW piles in sandy soil areas, the following works were carried out in the process of constructing a foundation pit supporting structure for the high-rise building. Firstly, three SMW piles with specific mechanical behaviors were selected, and the stress distribution for the H-shaped steel was monitored under different construction conditions by setting vibrating chord reinforcement dynamometers on several typical test sections of the H-shaped steel. Then, the measured normal stress of H-shaped steel was decomposed into uniform compressive stress and bending normal stress, and the axial pressure and bending moment of the H-shaped steel were calculated, respectively. The development of and variation in the distribution curves of axial force and bending moment of the H-shaped steel were discussed under different construction conditions, and the influencing factors were analyzed. Finally, the bending moment fitting curve was obtained using the polynomial fitting method, and the distribution curves for the shearing force were obtained under different construction conditions by derivation. The development trends for and influencing factors behind the shearing force curves were further analyzed.

The stress state of the H-shaped steel in the SMW piles was monitored on site, and the axial force, bending moment and shearing force of the H-shaped steel were analyzed and studied. Thus, the mechanical properties of SMW piles could be determined and used as a reliable basis for the design and construction of SMW piles in sandy soil areas.

2. Retaining Structures of the Foundation Pit

Concerning the foundation pit of the high-rise building, its north–south length is 48.04 m, its east–west width is 25.76 m, and the excavation depth is 11.46 m. Three SMW piles were selected for site measurement in the western edge of the pit [11,12]. There are six soil layers within a depth of 39.6 m below ground level at the proposed site. The name and burial depth of each soil layer are as follows. The first layer is miscellaneous fill, with a buried depth of 1.0–3.9 m; the second layer is clayey silt, with a buried depth of 2.1–6.7 m; the third layer is silt, with a buried depth of 4.0–5.7 m; the fourth layer is clayey silt, with a buried depth of 5.8–10.3 m; the fifth layer is fine sand, with a buried depth of 9.3–20.7 m; the sixth layer is medium sand, with a buried depth of 24.2–39.6 m. It can be seen that the six soil layers are mainly sandy soils. The upper five soil layers within the range of the pile length were directly involved in forming the cemented soil of the SMW piles.

The diameter of the SMW piles is 850 mm, their center distance is 600 mm, and there are two kinds of pile lengths of 15.55 m and 18.25 m. The H-shaped steel, H700 × 300 × 13 × 24, with the steel grade of Q235B, was inserted at intervals or partly but densely inserted, and the two H-shaped steel lengths corresponding to the pile lengths were 16.65 m and 19.35 m. Two layers of steel supports were set from top to bottom along SMW piles as inner supports to form the retaining structures of the foundation pit. The first layer of steel supports was set on the concrete crown beam at the top of the piles 1.61 m below the ground. The second layer of steel supports was set on the steel waist beam at 6.11 m below the ground. The steel supports were made of circular steel tubes and specific axial forces were applied in advance to reduce the lateral displacement of the SMW piles towards the foundation pit.

3. Site Measurement Design

3.1. Selection of Measured SMW Piles

The following two factors should be considered when selecting SMW piles measured on site. First, the piles should be located at the edge of the foundation pit where the mechanical behavior is relatively clear. Second, the piles corresponding to the support positions should be selected, if at all possible, to investigate the influence of the supports on the mechanical behavior of the piles. Therefore, in the middle of the west edge of the foundation pit, the three piles corresponding to the middle three steel supports were selected and measured. The piles were numbered Z1, Z2 and Z3 consecutively from north to south. The length of the three piles is 18.25 m, and the length of H-shaped steel inside is 19.35 m. There are two piles between Z1 and Z2 and between Z2 and Z3, so as to avoid the influence of mechanical behavior between the measured piles.

3.2. Layout of Stress Monitoring Points

To determine the stress of H-shaped steel in SMW piles, it is necessary to use vibrating chord type reinforcement dynamometers and a frequency reading instrument for monitoring. The vibration frequency of the vibrating string is obtained by the frequency reading instrument, and the stress of the measured structure can be obtained via calculations.

The SMW pile can be regarded as a compression-bending member, and the lower end of the pile is inserted into a certain depth below the base, which can be used as the fixed end. The upper end of the pile is connected by the crown beam, and the inner steel supports act on the crown beam, which can be used as the elastic support of the upper end. The middle of the pile is connected by the steel waist beam, and the internal steel supports act on the waist beam, which can be used as the intermediate elastic support. The soil and water pressure from the outside of the foundation pit can be considered as the distributed load acting on the pile, and the dead weight of the pile and the vertical force transmitted to the pile by the supporting system through the crown beam and the waist beam can be considered as the axial compression load. When considering the pile as a compression-bending member, the test sections need to be set in the following parts: the base elevation, which the intermediate steel support is acting on, and the junction of two adjacent soil layers. Additionally, the uniformity in terms of test section distribution should be considered to obtain more monitoring data.

As shown in Figure 1, a total of eight test sections were set along the measured pile from top to bottom, and the distance from each section to the ground is listed in Table 1. Two reinforcement dynamometers were arranged at the connections between one side of the web and the upper and lower flanges of the H-shaped steel in each section, and the measured stresses can be regarded as the stresses at the upper and lower ends of the web. A full length of steel strip was welded at the connection between the web and the flange of the H-shaped steel to protect the dynamometers and corresponding wires. The bottom of the steel strip was sealed to prevent the entry of cemented soil during the insertion of the H-shaped steel.

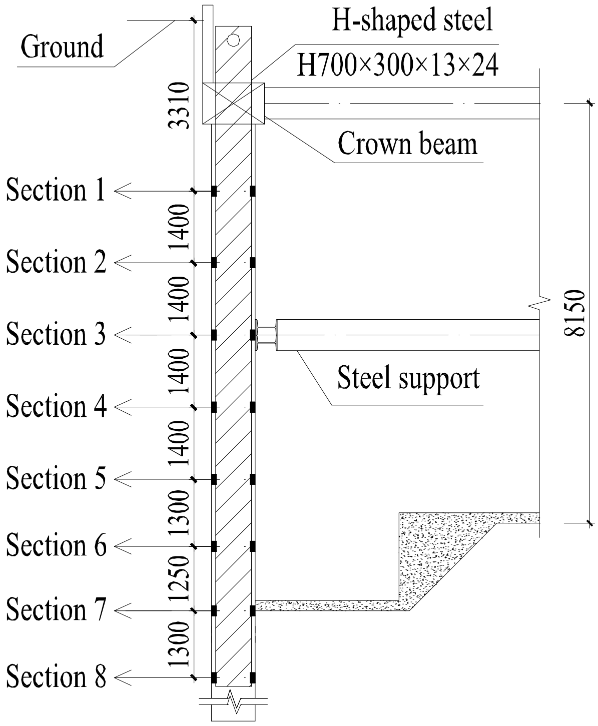


Figure 1. Test section layout.

Table 1. Position of test section.

Test Section	Distance to the Ground (m)
Section 1	3.31
Section 2	4.71
Section 3 (second layer of supports)	6.11
Section 4	7.51
Section 5	8.91
Section 6	10.21
Section 7 (the base)	11.46
Section 8	12.76

3.3. Main Construction Conditions

The stress frequency of the H-shaped steel in the measured pile was monitored as follows. The monitoring frequency was once a day during the excavation process of the foundation pit and once every two days during substructure construction and foundation pit backfilling, resulting in the obtainment of a large amount of measured data. In order to facilitate the analysis of the main mechanical characteristics of the piles, the following representative construction conditions were selected for research.

Construction condition 0: The foundation pit is excavated to 2.01 m below the ground and reaches the elevation of the bottom surface of the crown beam. This is the initial loading state when the initial value data for reinforcement dynamometers are collected.

Construction condition 1: On the basis of construction condition 0, pour the reinforced concrete crown beam, and set the first layer of steel supports.

Construction condition 2: Excavate the foundation pit to 6.41 m below the ground, install the steel waist beam, and set the second layer of steel supports.

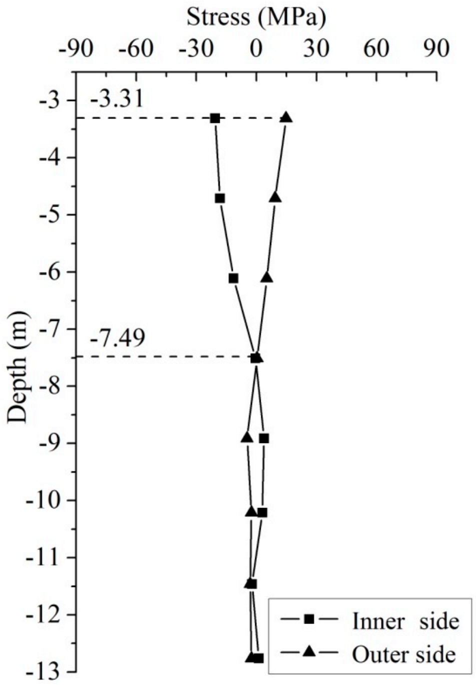
Construction condition 3: Excavate the foundation pit to 11.46 m below the ground and pour the concrete cushion of the base.

Construction condition 4: Build the foundation pit floor and the internal structure, backfill the foundation pit, and remove the second layer of steel supports.

Construction condition 5: Continue to construct the internal structure and the roof, backfill the foundation pit, and remove the first layer of steel supports.

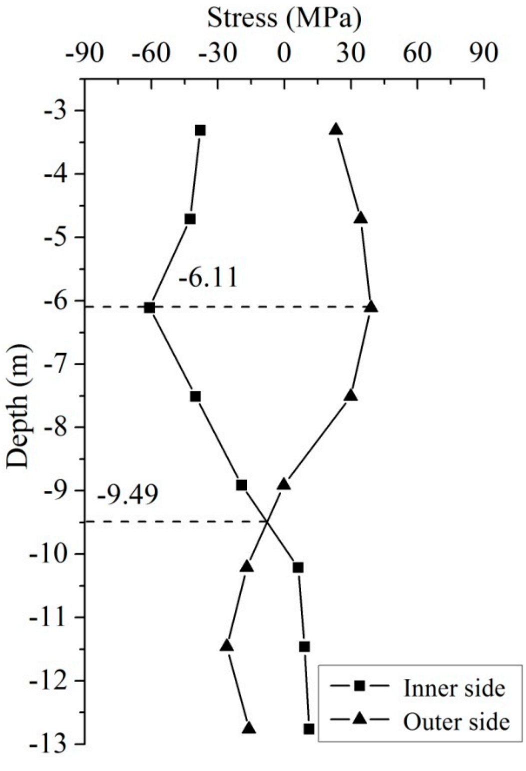
4. Stress Analysis of H-Shaped Steel in Measured SMW Piles

It can be seen from the analysis in Section 3.2 that the SMW pile is used as a compression-bending member and the internal forces of the H-shaped steel have both axial pressure and bending moment. The normal stress obtained by dynamometers is the superposition of uniform compressive stress corresponding to axial pressure and bending normal stress corresponding to bending moment. Figure 2 shows the stress distribution law for the H-shaped steel in the SMW pile Z1 along the depth of the foundation pit under five construction conditions. In the figure, the abscissa represents the section stress of the H-shaped steel. The tensile stress is positive, while the compressive stress is negative. The ordinate represents the depth of the foundation pit below the ground. The "inner side" in the legend indicates the stress measured by the dynamometer at the connection of the flange and web of the H-shaped steel near the foundation pit, while the "outer side" indicates the stress measured by the dynamometer on the section of the H-shaped steel at a distance from the foundation pit.



(**a**)

Figure 2. *Cont.*



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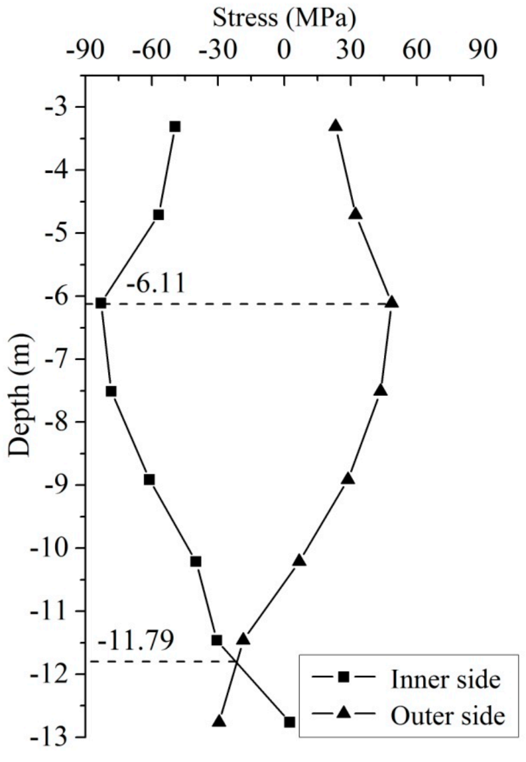
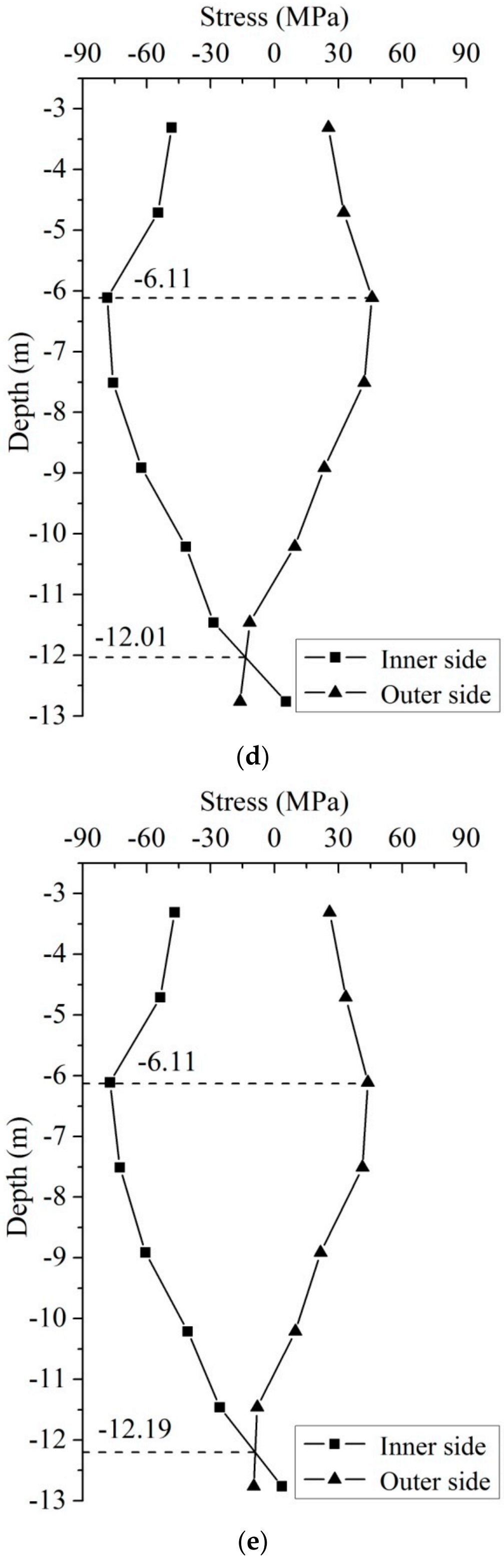


(**c**)

Figure 2. *Cont*.



(**d**)

(**e**)

Figure 2. The stress distribution characteristics of the H-shaped steel in the SMW pile Z1 under five construction conditions. (**a**) The stress distribution of the H-shaped steel under construction condition 1; (**b**) the stress distribution of the H-shaped steel under construction condition 2; (**c**) the stress distribution of the H-shaped steel under construction condition 3; (**d**) the stress distribution of the H-shaped steel under construction condition 4; and (**e**) the stress distribution of the H-shaped steel under construction condition 5.

The following stress analysis can be recognized from Figure 2:

(1) Under construction condition 1, the excavation depth of the foundation pit was only −2.01 m, and the first layer of supports was set. The lateral soil pressure was small, so the overall stress of the H-shaped steel was small. The maximum tensile and compressive stresses occurred in Section 1 at −3.31 m, and the stress values were 14.9 MPa and −20.1 MPa, respectively. The reason why the absolute value of compressive stress was larger is that in addition to the normal stress generated by the bending moment, the compressive stress generated by axial pressure was also superimposed on this section. The axial pressure can be considered to be mainly caused by the vertical force transmitted by the first supporting system to the SMW pile through the crown beam. At the section of −7.49 m, which is very close to Section 4 (−7.51 m), the inner and outer stress curves intersect at a point, and the compressive stress value was −0.11 MPa. It indicates that this section only had axial pressure and the bending moment was zero; thus, the section was the contraflexure point of the bending moment of H-shaped steel. According to the bending moment of the H-shaped steel, the outside of the H-shaped steel above this section was tensile, while the inside of the H-shaped steel below this section was tensile. The tensile and compressive stresses of the H-shaped steel below the contraflexure point were close to zero, indicating that this construction condition had little influence on mechanical performance of this part of the SMW pile.

(2) Under construction condition 2, the excavation depth of the foundation pit further increased to −6.41 m, and the second layer of supports was set. The lateral soil pressure was larger, so the overall stress of the H-shaped steel noticeably increased. The maximum tensile and compressive stresses occurred in Section 3 at −6.11 m, and the stress values were 39.3 MPa and −60.8 MPa, respectively. This section corresponds to the position of the second layer of supports, and there is a large difference between the algebraic values for tensile and compressive stresses, indicating that this section was subjected to a large bending moment. This is because the bending moment diagram of the H-shaped steel produced a turning point and the bending moment reached an extreme value under the action of the pre-added axial pressure of the second layer of supports. At the section −9.49 m, the inner and outer stress curves intersected, and the compressive stress value was −7.67 MPa, indicating that this section was the contraflexure point of the bending moment of the H-shaped steel. The increase in compressive stress indicates that the axial pressure of the H-shaped steel increased. This was caused by the vertical force further transmitted to the SMW pile through the waist beam by the second layer of the support system. Below the contraflexure point, there was still a difference between the tensile and compressive stresses, indicating that the H-shaped steel still bore a bending moment.

(3) Under construction condition 3, the excavation depth of the foundation pit increased to −11.46 m, the base was reached, and the concrete cushion of the base was poured. The lateral soil pressure was at its greatest at this stage, so the overall stress on the H-shaped steel was at its greatest. The greatest values in terms of tensile and compressive stresses also appeared in Section 3 at −6.11 m, with these being 48.6 MPa and −82.3 MPa, respectively, corresponding to the position of the second layer of supports. At this time, the difference between the tensile and compressive stresses was at its most significant, indicating that the bending moment of this section was also the largest. At the base section of −11.46 m, the outer and inner compressive stresses were −18.38 MPa and −29.97 MPa, respectively. The two stress values were different, but the difference was not large, indicating that the H-shaped steel also bore a bending moment, with the bending moment value being small. The contraflexure point appeared at the section −11.79 m, slightly downward, and the H-shaped steel below the contraflexure point still bore a bending moment. This part of the SMW pile can be used as the embedded end.

(4) Under construction conditions 4 and 5, the internal structure and the backfilling of the foundation pit were in the process of being constructed. Due to the offsetting

part of the soil and water pressure outside of the foundation pit, the shape of the inner and outer stress curves of the H-shaped steel was similar to that for construction condition 3, but the overall stress on the H-shaped steel was reduced. The maximum tensile and compressive stresses under construction condition 4 were 45.86 MPa and −78.01 MPa, respectively, which are lower than those under construction condition 3. The contraflexure point appeared at the section −12.01 m below the base, which is further down when compared with construction condition 3. The maximum tensile and compressive stresses under construction condition 5 were 43.76 MPa and −76.99 MPa, respectively, which show a continued decrease from the basis of construction condition 4. The contraflexure point appeared at the section −12.19 m below the base, which is further down when compared with construction condition 4.

A comparison of the stress distribution curves for the H-shaped steel in the SMW pile Z1 under five construction conditions in Figure 2 is shown in Figure 3. The comparative analysis shows that:

(1) Construction conditions 1 to 3 correspond to foundation pit excavation, and the overall stress of the H-shaped steel increased gradually under these conditions. With the exception of when the first layer of supports was set, the maximum tensile and compressive stresses of the H-shaped steel under construction condition 1 appeared at the uppermost Section 1. After setting the second layer of supports, the maximum tensile and compressive stresses of the H-shaped steel under construction conditions 2 and 3 appeared at Section 3, corresponding to the position of the second layer of supports.

(2) The excavation depths of the foundation pit from construction conditions 1 to 3 were 2.01 m, 6.41 m and 11.46 m (the base), respectively, and the corresponding contraflexure point depths of the H-shaped steel were −7.49 m, −9.49 m and −11.79 m, respectively. The contraflexure points were all below the excavation face, and it can be considered that the embedded end of the SMW pile gradually moved below the base.

(3) The SMW pile can be regarded as a compression-bending member. Taking construction condition 3 as an example, the bending moment at the base section was very small, and the SMW pile below the contraflexure point can be regarded as the embedded end. The first layer of supports can be used as the elastic support of the upper end. Because this section is still below the ground, there is a bending moment, but the value of that bending moment is not large. The second layer of supports can be used as an intermediate elastic support, and the pre-added axial pressure of the supports makes the bending moment produce an extreme value, which is also the maximum bending moment value. Even if the effect of axial pressure is further considered, the H-shaped steel at this section still produces maximum tensile and compressive stresses. The maximum tensile and compressive stresses were 48.6 MPa and −82.3 MPa, respectively. The steel grade used for the H-shaped steel was Q235 B. The maximum stress value was far less than the designed strength value for the steel, and the safety of the SMW pile met the requirements.

(4) Construction conditions 4 to 5 correspond to the construction of the internal structure and the backfilling of the foundation pit. Compared with construction condition 3, under these conditions, the overall stress of the H-shaped steel was reduced, the maximum tensile and compressive stresses were gradually reduce and the position of the contraflexure point was still within a small range below the base and gradually moved down, indicating that this stage had little influence on the mechanical performance of the SMW pile.

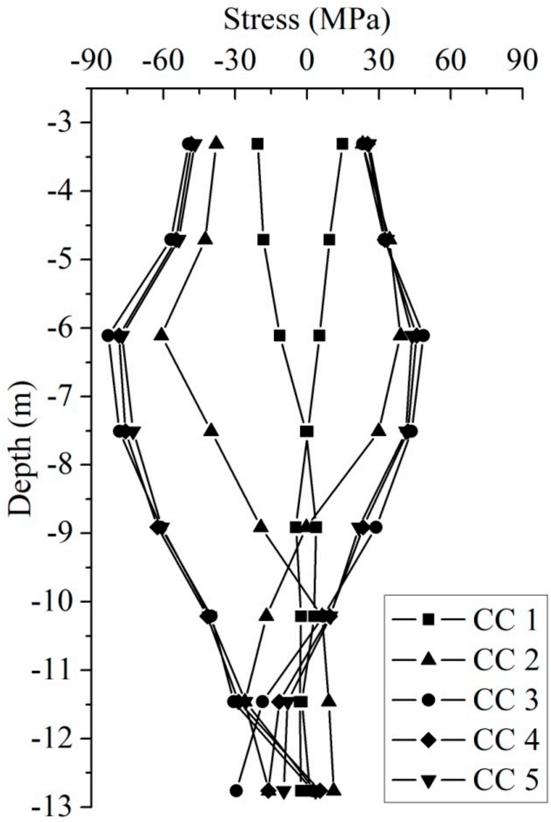


Figure 3. A comparison of the stress distribution of the H-shaped steel in the SMW pile Z1 under five construction conditions (construction condition is abbreviated as "CC").

The stress distribution curves of the H-shaped steel of the SMW piles Z2 and Z3 are approximately the same as that of the SMW pile Z1, and the mechanical properties are approximately the same. The corresponding curves are no longer given here.

5. Axial Force Analysis of H-Shaped Steel in SMW Piles

Since the SMW pile can be regarded as a compression-bending member, the measured normal stress of the H-shaped steel in Figure 3 can be decomposed into uniform compressive stress and bending normal stress. The axial pressure of the H-shaped steel can be calculated from the uniform compressive stress, and the bending moment can be calculated from the bending normal stress.

Figure 4 shows the calculation results for the axial forces of the H-shaped steel in the SMW pile Z1 under five construction conditions. The abscissa represents the axial force of the H-shaped steel, which was positive under tension and negative under compression. The ordinate represents the depth of the foundation pit. Each construction condition corresponds to an axial force distribution curve.

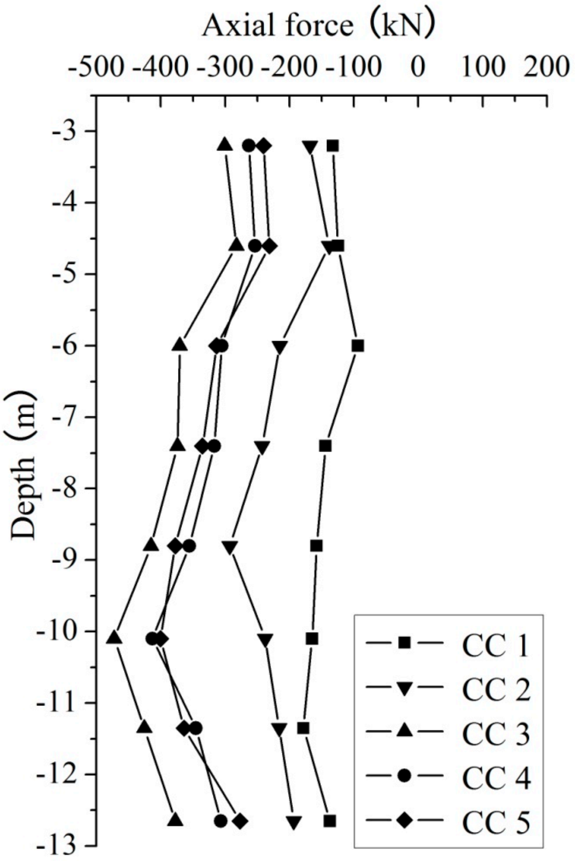


Figure 4. The axial force distribution curves of the H-shaped steel in the SMW pile Z1 under five construction conditions (construction condition is abbreviated "CC").

According to the analysis in Figure 4, it can be seen that:

(1) Under construction condition 1, the foundation pit was excavated to −2.01 m, the reinforced concrete crown beam was poured and the first layer of steel supports was set. All test sections, including Section 1 at −3.31 m, were below the first layer of supports. The axial pressure of the H-shaped steel was mainly generated by the dead weight of the SMW pile, crown beam and the first layer of supports. Since the dead weight of crown beam and supports was constant, and the dead weight of the SMW pile increased gradually with the increase in depth, the axial pressure had a trend of increasing gradually. The maximum axial pressure occurred in Section 7 at −11.46 m, and the axial force value was −176 KN.

(2) Under construction condition 2, the foundation pit was excavated to −6.41 m, a steel waist beam was installed and a second layer of steel supports was set. Section 3 and all the following test sections were below the second layer of supports. As the cemented soil at one side of the foundation pit was removed, the corresponding frictional resistance decreased. The axial pressure of Section 1 (−3.31 m) and Section 2 (−4.71 m) increased compared with that of construction condition 1. Due to the dead weight of the waist beam and corresponding supports, the axial pressure of Section 3 (−6.11 m) suddenly increased compared with that of Section 2. The axial pressure in the following sections gradually increased, and the maximum axial pressure occurred in Section 5 at −8.91 m, with the axial force value being −293 KN. The soil buried at a depth of 9.3 m to 13.6 m is fine sand. The frictional resistance of cemented soil formed by fine sand is relatively large, resulting in a decrease in the axial pressure of the H-shaped steel in the range of Section 6 (−10.21 m) to Section 8 (−12.76 m).

(3) Under construction condition 3, the foundation pit was excavated to −11.46 m, the base was reached and the concrete cushion was poured. The test sections, including

Section 7 and Section 8, were below the base. The frictional resistance provided by the cemented soil greatly reduced because all the cemented soil of the H-shaped steel at the side of the foundation pit was removed. Compared with construction condition 2, the axial pressure of all sections of H-shaped stee noticeably increased. The axial force of the H-shaped steel gradually increased with an increase of depth. The maximum axial pressure appeared in Section 6 at −10.21 m, and the axial force value was −481 kN. Due to the large frictional resistance provided by the cemented soil formed based on fine sand in the range of Section 7 (−11.46 m) to Section 8 (−12.76 m), the corresponding axial pressure of the H-shaped steel decreased.

(4) Construction conditions 4 and 5 correspond to the construction of the internal structure and the backfilling of the foundation pit. The second layer of supports and the first layer of supports were removed. The original weight of the two layers of supports passed through the waist beam and crown beam was eliminated. Compared with construction condition 3, the distribution law of axial force with depth remained unchanged, while the axial pressure value decreased to a certain extent. The maximum axial pressure occurred in Section 6 at −10.21 m under construction condition 4, and the axial force value was −413 kN. The change in the axial force of the H-shaped steel under construction conditions 4 and 5 was not obvious.

6. Bending Moment Analysis of H-Shaped Steel in SMW Piles

Based on the bending normal stress obtained from the measured normal stress decomposition in Figure 3, the calculation results for the bending moment of the H-shaped steel in the SMW pile Z1 under five construction conditions are given in Figure 5. The abscissa represents the bending moment of the H-shaped steel, which is positive when the flange of H-shaped steel away from the foundation pit is under tension. The ordinate represents the depth of the foundation pit. Each construction condition corresponds to a bending moment distribution curve.

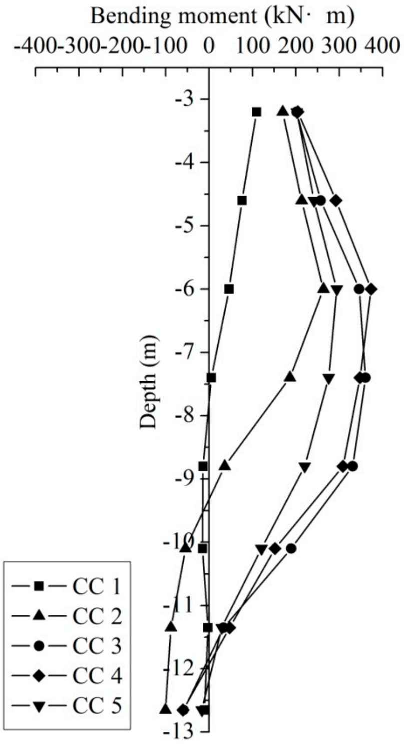


Figure 5. The bending moment distribution curves of the H-shaped steel in the SMW pile Z1 under five construction conditions (construction condition is abbreviated "CC").

According to the analysis in Figure 5, it can be seen that:

(1) Under construction condition 1, the excavation depth of the foundation pit was not large and only the first layer of supports was set. The corresponding lateral soil pressure was small, resulting in a small bending moment in the H-shaped steel along the height direction. The maximum positive bending moment occurred in Section 1 (−3.31 m), and the bending moment value was 111 KN·m. It can be considered that the H-shaped steel bent to the side of the foundation pit, and the bending moment of H-shaped steel below this section gradually decreased. The bending moment distribution curve intersected the vertical axis at a point adjacent to Section 4 (−7.51 m). The bending moment here was zero, which can be regarded as the contraflexure point of the H-shaped steel. In the portion below this point, the bending moment made the H-shaped steel bend to the outside of the foundation pit, and the bending moment value was close to zero, indicating that this construction condition had little influence on mechanical performance of this portion.

(2) Under construction condition 2, the excavation depth of the foundation pit was increased and the second layer of supports was further set. The corresponding lateral soil pressure increased, and the bending moment of the H-shaped steel noticeably increased. According to the distribution state of the bending moment curve, most of the upper range of the H-shaped steel bore a positive bending moment, and the H-shaped steel continued to bend to the inner side of the foundation pit. The maximum positive bending moment occurred in Section 3 (−6.11 m), with bending moment value of 261 KN·m. This is where the second layer of supports was set. The large axial pressure pre-added in the supports was the equivalent to a large, concentrated force applied to the H-shaped steel. The bending moment curve bent at this section, and the bending moment value reached its extreme value, which was the maximum value. At the depth of −9.49 m, the bending moment curve also intersected the vertical axis at a point. Here, the bending moment was zero, which was the contraflexure point of the H-shaped steel. Below this section, the bending moment caused the H-shaped steel to be strained at the inner side of the foundation pit. The H-shaped steel still bore a bending moment, and the bending moment gradually increased. At the bottom Section 8 (−12.76 m), the bending moment value reached −101 KN·m.

(3) Under construction condition 3, the foundation pit was excavated to the base. The lateral soil pressure reached its maximum, and the bending moment of the H-shaped steel also reached its maximum. In most of the above ranges, the H-shaped steel bears positive bending moments, and the bending moment values were large. The maximum positive bending moment still occurred in Section 3 (−6.11 m), where the second layer of supports is set, with a bending moment value of 371 KN·m. At the base, Section 7 (−11.46 m), the H-shaped steel still bore a positive bending moment, which was 49 KN·m. At its lower depth of −11.79 m, the bending moment curve intersected the longitudinal axis and the bending moment value was zero. This was the contraflexure point of H-shaped steel, and there was a certain of negative bending moment in the lower portion of the H-shaped steel.

(4) Under construction conditions 4 and 5, two layers of supports were removed successively from bottom to top in the process of foundation pit backfilling. The shape of the bending moment distribution curve is practically the same as that of construction condition 3, but the overall bending moment of the H-shaped steel decreased gradually. The maximum positive bending moments under construction conditions 4 and 5 were 340 KN·m and 287 KN·m, respectively, which were further reduced compared with construction condition 3. The positions of the contraflexure points under construction conditions 4 and 5 appeared at −12.01 m and −12.19 m below the base, which further gradually moved down compared with construction condition 3.

(5) From construction conditions 1 to 5, the positions of the contraflexure points of the H-shaped steel are −7.49 m, −9.49 m, −11.79 m, −12.01 m and −12.19 m, respectively. It can be seen that during the whole construction process, from foundation pit excavation to backfilling, the position of the contraflexure point gradually moves down. It can

be considered that the embedded end of the SMW pile gradually moves down and stabilizes below the base.

7. Shearing Force Analysis of H-Shaped Steel in SMW Piles

The axial force and bending moment of the H-shaped steel in the SMW pile Z1 are analyzed above. In order to further analyze the shearing force of the H-shaped steel, the distribution curve for the shearing force along the depth of foundation pit should be obtained first. According to the relationship between the bending moment and shearing force of the bending member in material mechanics, the derivative of the bending moment to the position coordinate of the member section is equal to the shearing force. In other words, the shearing force distribution curve can be obtained from the slope of the bending moment distribution curve. Figure 5 just shows the line between the bending moments of each test section under each construction condition. In order to facilitate the derivation, the fitting curve of each bending moment curve should be obtained.

Here, the method of polynomial fitting was adopted to determine the polynomial whose highest degree term is of degree 5 and whose form is $M(x) = ax^5 + bx^4 + cx^3 + dx^2 + ex + f$. Each bending moment curve shown in Figure 5 was fitted to obtain the bending moment fitting curve under each construction condition. By taking the derivative of each bending moment fitting curve, the shearing force distribution curve under each construction condition could be obtained. Figure 6 shows the shearing force distribution curves of the H-shaped steel in the SMW pile Z1 under five construction conditions. The abscissa represents the shearing force of the H-shaped steel, which was positive in the clockwise direction determined from the angle of view in Figure 1. The ordinate represents the depth of the foundation pit.

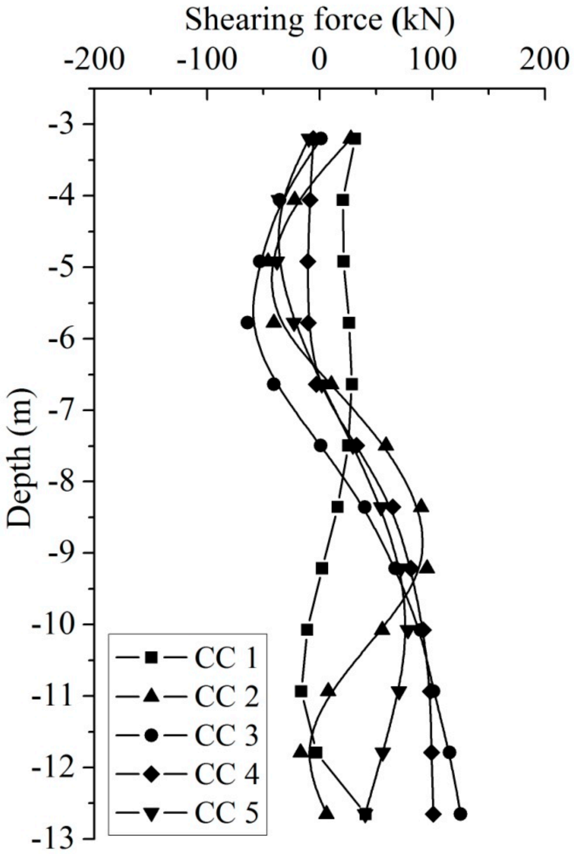


Figure 6. The shearing force distribution curves of the H-shaped steel in the SMW pile Z1 under five construction conditions (construction condition is abbreviated "CC").

According to the analysis in Figure 6, it can be seen that:

(1) Under construction condition 1, the first layer of supports was set and the overall shearing force of the H-shaped steel was small. The maximum positive shearing force occurred in Section 1 (−3.31 m), with a value of 32 KN. The shearing force below this section underwent changes, with the overall trend gradually decreasing. At a depth of −9.25 m, the shearing force decreased to zero. From this depth down, the shearing force was very small and changed little.

(2) Under construction condition 2, the second layer of supports was set and the shearing force of the H-shaped steel increased significantly. The upper portion of the H-shaped steel mainly bore the negative shearing force. The negative shearing force with the largest absolute value occurred at the depth of −5.25 m, with the value of −48 KN. The shearing force value was zero at the depth of −6.45 m, which is just near the position of the second layer of support (−6.11 m). Due to the concentrated force provided by the supports, the shape of the shearing force curve changed, with indications that the shearing force value changed both positively and negatively. If an ideal concentrated force is applied, the shearing force curve should be abrupt here. Considering that the shearing force curve is obtained by taking the derivative of the bending moment fitting curve, the shearing force curve slowly changed from the above negative shearing force to the below positive shearing force. The lower portion of the H-shaped steel mainly bore the positive shearing force. The maximum positive shearing force occurred at the depth of −8.82 m, with a value of 81 KN.

(3) Under construction condition 3, the foundation pit was excavated to the base and the shearing force of H-shaped steel reached its maximum. The upper portion of the H-shaped steel bore the negative shearing force. Compared with construction condition 2, the shearing force further increased. The negative shearing force with the largest absolute value occurred at the depth of −5.68 m, with a value of −63 KN. This is also the negative shearing force with the largest absolute value among the five construction conditions. The shearing force value was zero at the depth of −7.23 m, which is also near the position of the second layer of supports. The shearing force curve slowly changed, and the shearing force value changed from the above negative value to the below positive value. The lower portion of the H-shaped steel bore the positive shearing force, and the shearing force increased as the depth increased. In the bottom Section 8 (−12.76 m), the shearing force reached its maximum, with a value of 123 KN. This is the maximum positive shearing force among five construction conditions and also the shearing force with the largest absolute value.

(4) Under construction conditions 4 and 5, the second supporting system and the first supporting system were successively removed along the foundation pit depth from bottom to top. Compared with construction condition 3, the overall shearing force of the H-shaped steel was significantly reduced. The upper portion of the H-shaped steel still bore negative shearing force. The negative shearing force with the largest absolute value was −41 KN. The lower portion of the H-shaped steel still bore positive shearing force. The maximum positive shearing force was 99 KN.

8. Conclusions

Three SMW piles in the foundation pit supporting the structure of a high-rise building in Zhengzhou were monitored on site. The stress distribution law of the H-shaped steel under significant construction conditions was obtained. On this basis, the internal forces of the H-shaped steel, such as its axial force, bending moment and shearing force, were calculated and analyzed in detail. The mechanical properties of the SMW piles in sandy soil areas were discussed. The conclusions are as follows:

(1) Three SMW piles with clear mechanical properties were selected on site. Reinforcement dynamometers were arranged in several typical test sections along the H-shaped steel. The stress distribution state of the H-shaped steel with foundation pit depth and the development of and changes in the related laws according to the construction

process were monitored. These works laid the foundation for the subsequent internal force analysis of H-shaped steel in an SMW pile.

(2) The axial force of the H-shaped steel is mainly caused by the dead weight of the SMW pile, the dead weight of the crown beam and the first supporting system, the dead weight of waist beam and the second supporting system and the frictional resistance of the cemented soil, etc. Under several construction conditions, the H-shaped steel only bears axial pressure, which varies with the depth of foundation pit, the setting and removal of the two supporting systems and the frictional resistance of the cemented soil. The axial pressure generally increases with the increase in foundation pit depth under the influence of various factors. The maximum axial pressure appeared in Section 6 (-10.21 m) under construction condition 3, with an axial force value of -481 kN. The frictional resistance of cemented soil based on fine sand near the base is large and the axial pressure is small.

(3) The bending moment of the H-shaped steel is mainly caused by the lateral soil pressure and the concentrated forces provided by the first supporting system and the second supporting system. Under construction condition 3, the overall bending moment reached its maximum, and the upper most portion of the H-shaped steel bore positive bending moment. At the same time, the portion of the SMW pile below the contraflexure point slightly below the base can be regarded as the embedded end, which this bearing a small bending moment at the base section. The first supporting system can be used as the elastic support of the upper end, and there is still a bending moment at the corresponding section. The second supporting system can be used as the intermediate elastic support, with a maximum positive bending moment occurring in the corresponding section, with the value of 371 KN·m.

(4) With an increase in the excavation depth of the foundation pit, the contraflexure point of the bending moment of the H-shaped steel in the SMW pile gradually moves down. The contraflexure points are all below the excavation face. In the process of foundation pit backfilling, the contraflexure point continues to move down slightly. It can be considered that in the whole construction process, the embedded end of the SMW pile gradually moves down and stabilizes below the base.

(5) The shearing force of the H-shaped steel is mainly affected by the lateral soil pressure and the concentrated forces of the first and second supporting systems. The overall shearing force reaches its maximum under construction condition 3. At the same time, the upper portion of H-shaped steel bears a negative shearing force, which its largest absolute value being -63 KN. The lower portion of the H-shaped steel bears a positive shearing force, which produces a maximum positive shearing force value of 123 KN. Near the middle second supporting system, the shearing force is zero, the value changes from positive to negative and the shearing force curve is in a transition stage.

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