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Impact Study of Deep Foundations Construction of Inclined and Straight Combined Support Piles on Adjacent Pile Foundations

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Abstract: An inclined straight combination support pile can play a better role in deep foundation pit support, especially for the protection of adjacent structural pile foundations. We take a section of the construction of a deep foundation pit project in Wuhan City, Hubei Province as the research object. This paper studies the influence of inclined and straight combination support piles on the bending moment and displacement behavior of adjacent pile foundations during the construction of foundation pits under the influence of different factors such as distance from the excavation surface, pit angle effect, inclined pile tilt angle, pit depth to width ratio, and construction conditions on the adjacent pile foundation using a three-dimensional finite element model. According to the research results, as the distance from the excavation surface increases, the bending moment of the adjacent pile foundation decreases, and the closer the pile is to the foundation pit, the greater the horizontal displacement of the pile; the bending moment and displacement of the pile foundation are supported by the pit angle effect. Moreover, the pile bending moment increases with the increase of the pit depth–width ratio, and the maximum displacement point of the pile body gradually moves down from the middle of the pile body to the bottom of the pile foundation as the excavation depth of the pit increases. In addition, the minimum displacement of the adjacent pile foundation is at the top of the pile, and the maximum displacement is at the middle of the pile. Finally, compared with the static analysis, the whole process of dynamic simulation can reflect the dangerous working conditions in the project construction process, and make a more complete safety control construction plan for the project construction process.

Keywords: inclined straight combination pile; deep foundation construction; pile foundation; bending moment; three-dimensional finite element model

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1. Introduction

At present, with the development of urbanization in China, urban land resources have become increasingly large along with the continuous development of high-rise buildings and underground space. Even though deep excavation is temporary, underestimating its significance has unfavorable effects. As a result, more and more projects in urban construction require a large area, and deep foundation pit construction; however, the traditional pile bracing or wall bracing support method is not only complicated in construction, covering a large area, and repeated removal and replacement of bracing construction operations are very likely to cause delays and waste of resources.

On the other hand, deep excavation causes both vertical and lateral ground movements, which result in surface subsidence, inclination, discontinuous deformation, and curvature change. These changes have an impact on the stability and safety of nearby existing buildings within the settlement range of strata, potentially posing a threat to their structural safety [1–6].

It is widely accepted that the soil movement that takes place during the process of deep excavation has a substantial impact in this regard. Increased soil movement causes excessive settlement of nearby structures, which can result in a variety of damages [7–9].

Recently, many experts and scholars point out that compared with vertical pile support technology, inclined pile support technology has good advantages in pile displacement control and out-of-pit settlement control [10]. However, ref. [11] pointed out that in soft soil pits, the overturning resistance of inclined piles with the same inclination angle is stronger than that of single inclined piles; the settlement of the soil around the pit and the maximum displacement of the pile are inversely proportional to the inclination angle, by comparing and analyzing the finite element simulation results of purely inclined piles and inclined-straight combination piles. In addition, ref. [12] carried out that the internal force and deformation of the inclined-straight combination pile are less than the former and the stability is superior compared with the straight and purely inclined pile.

On the other hand, Diao et al. [13] derived the deformation control mechanism of the actively inclined pile by finite element simulation and confirmed that the use of active control technique in inclined and straight combined inclined pile support can well control the deformation of the soil body and effectively reduce the deformation and displacement of the soil body. However, pit construction can affect the pile foundations of adjacent structures, therefore it is necessary to analyze the impact of foundation construction on the pile foundations of adjacent structures. In addition, ref. [14] studied the effects of excavation distance, pit size, excavation depth, number of pits, and construction process on adjacent elevated subway structures.

Along the same line, ref. [15] used finite element software to analyze the damage and effects of pit excavation on adjacent pile foundations. They found that the maximum pile lateral deformations observed at the site after excavation depths of 6.71 and 15.24 m are 38 and 63 mm. Poulos et al. [16] concluded that the absence of support measures for the pit support structure would lead to increased deformation of the surrounding pile foundations. Moreover, ref. [17] used centrifugal tests combined with the effect of deep pit excavation on the deformation of the surrounding pile foundations that was studied by Leung using centrifugal tests combined with 3D numerical simulation software. Ref. [18] used 3D numerical analysis software for analysis and concluded that there is a close relationship between soil deformation and pile foundation deformation.

Although the aforementioned previous studies examined the impact of foundation pit excavation on the deformation of pile foundations, a great deal of expertise has been gained in foundation pit design and construction. Hence, an understanding of the influence of inclined and straight combination support piles on the bending moment and displacement behavior of adjacent pile foundations during the construction of foundation pits is a necessary basis for the design of deformation control measures. In the present literature, the analysis of inclined piles in the supporting structure appears to be limited, and there is a lack of discussion on the responses of the inclined piles. In this regard, this paper selects a deep foundation pit project in Wuhan City, Hubei Province, to conduct a field test of the inclined pile support structure and combines the finite element simulation and analysis to discuss the bending moment and displacement variation effect of the pile foundation adjacent to the foundation pit under the influence of different factors such as distance from the excavation surface, pit angle effect, inclined pile tilt angle, pit depth to width ratio, and construction conditions on the adjacent pile foundation using a three-dimensional finite element model.

2. Analysis of Inclined Pile Selection

According to the existing research results and comparing with the actual engineering data, under the same geological conditions, different row pile support methods are selected for construction, and there are displacement change diagrams of row piles under different working conditions, as shown in Figure 1 [19].

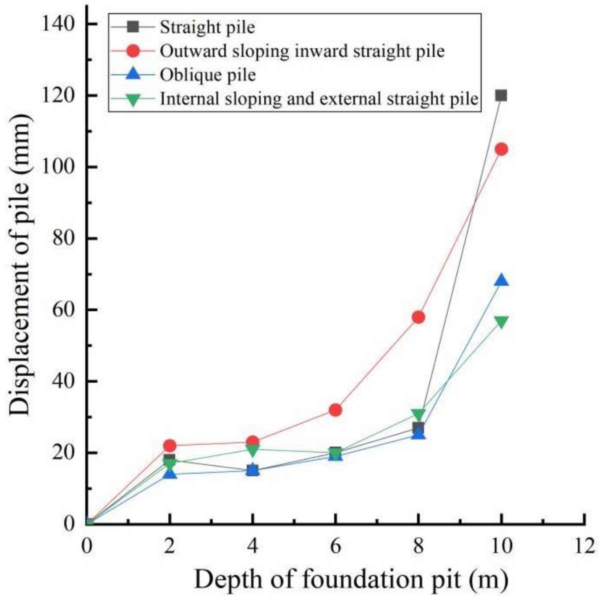

Figure 1. Variation of displacement of row pile under different working conditions.

Compared with straight piles, rear-slanting front-straight piles, and slanting piles, the pile displacement is smaller when using front-slanting rear-straight piles for pit support, resulting in the smaller displacement of the soil outside the pit, and the pile displacement gap is more obvious when the excavation depth of the pit reaches 10 m. It can be concluded that compared with the three support methods of the pure straight pile, backward sloping front straight pile, and pure sloping pile, front-row supporting sloping pile can play a better role in deep foundation pit construction support, especially for the effective protection of adjacent structure pile foundation in deep foundation pit construction with significant effect. Therefore, this paper adopts the combination of inclined and straight supporting pile support methods, combined with the construction example of a deep foundation pit project in Wuhan City, Hubei Province, to study the influence of pit depth to width ratio, distance from excavation surface, inclined pile support structure tilt angle, pit angle effect, and construction process on the bending moment and displacement of pile foundation near the foundation pit.

Overview of Geological Conditions and Site Construction Plan

The construction site is located in a deep foundation pit project in Wuhan City, Hubei Province, and the landform is a river impact plain. The foundation pit is excavated 10 m, and the stratum of the support area is the 1st layer of plain fill (Qml), the 2nd layer of clayey clay of the Quaternary Holocene alluvium (Q4 al), the 3rd layer of thicker silty clay of the Quaternary Holocene alluvium (Q4 al+l), and the 4th layer of Quaternary Holocene alluvial sand (Q4 al) [19].

According to the construction requirements, the excavation depth of the foundation pit is 10 m. One side is supported by the inclined and straight combination of inclined piles with the front row of inclined piles plus the back row of straight piles, and the support methods are shown in Figures 2 and 3. The remaining three sides are supported by a slope release slope. The angle of the inclined pile in the front row is 15°, and the bored piles with a diameter of 1 m and a length of 30 m are used in the front row inclined pile and the back row straight pile with a spacing of 1.5 m. The center spacing of the front row inclined pile and the back row straight pile is 3 m, and the top of the pile is equipped with a 1.2×0.9 m crown beam and connected by a 0.9×0.9 m connecting beam.

Figure 2. Sketch of the double-row pile.

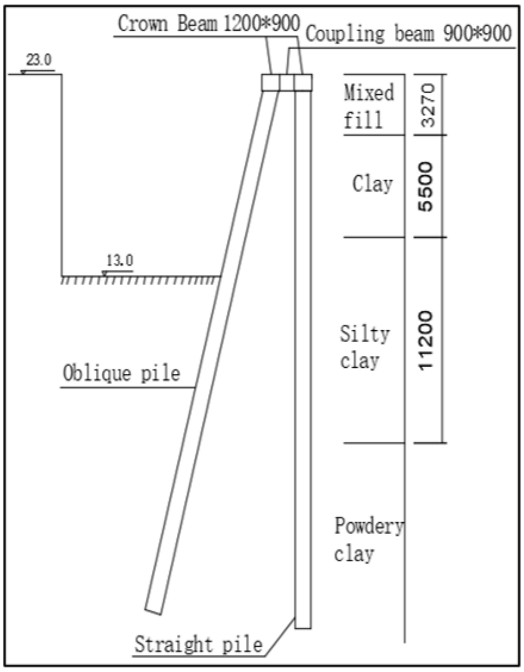

Figure 3. Layout of Foundation pit section. (unit: mm).

3. Numerical Analysis Modelling

3.1. Finite Element Model

In this study, finite element analysis was conducted using the Midas Gts Nx program. A three-dimensional model is established to study the influence of inclined and straight combination support piles on the bending moment and displacement of adjacent pile foundations during the construction of foundation pits. Considering the boundary effect on the accuracy of the numerical results, the influence of excavation of the foundation pit on adjacent pile foundations is chosen to establish a 3D finite element model. Hence, the accuracy of the analysis was significantly impacted by the mesh density inside the excavation, while the mesh density outside the excavation seemed to have less of an impact [20]. Therefore, a fine mesh was used near the pile and around the excavation zone.

Meanwhile, a coarser mesh was used outside these zones. In this study, the numerical model is shown in Figure 4. The dimensions of the foundation pit are 45 × 45 m and the mesh dimensions are 130 m (about three times the width of the pit) width in a transverse direction, 130 m (about 3 times the width of the pit) in a longitudinal direction, and 70 m (equal to seven times the excavation depth) depth in the vertical direction. Therefore, these dimensions are suitably large to reduce boundary effects in the numerical analysis because the massive increase in mesh size does not affect the analysis results. The boundary conditions are set as follows: the bottom surfaces are constrained in all directions while the top surface is free. In addition, the four sides of the model are restrained in the normal direction only without considering the influence of groundwater.

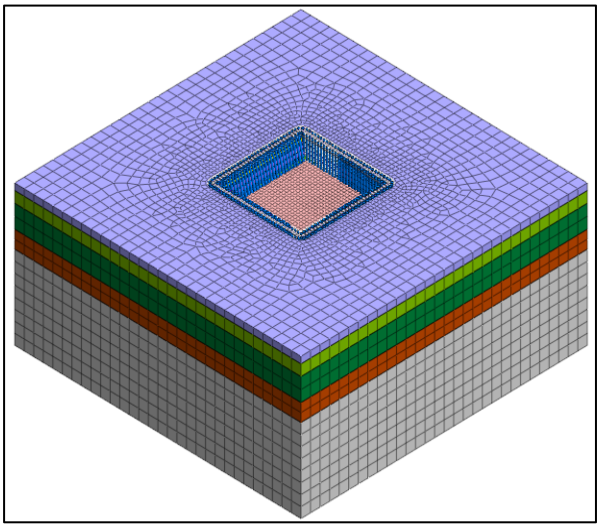

Figure 4. 3D finite element model.

The constitutive model type is very important, and it affects the accuracy of the numerical analysis results. Many authors, such as [21–25] show that the Modified Mohr-Coulomb (MMC) is suitable to simulate all soil types (both stiff and soft soils). In addition, in the case of excavation of the foundation pit, the loading and unloading behavior of the soil must be simulated [26,27]. Moreover, the MMC model is considered more accurate because it depends on the three soil stiffness parameters, which correspond to three loading conditions: triaxial loading stiffness, oedometer loading stiffness, and unloading-reloading modulus. Therefore, the soil strata adopt the Modified Mohr–Coulomb model. The required parameters are shown in Table 1. On the other hand, the linear elastic model is based on Hooke's law. Therefore, it is very suitable for simulating stiff structures in the soil. Hence, the pile body and the crown of the connecting beam have C50 high-strength concrete. So, the linear elastic constitutive model was chosen.

Table 1. Structural properties adopted in the numerical analysis.

Soil Layer / Parameter	Mixed Fill	Clay	Silty Clay	Powdery Clay
Thickness/m	4.4	4.52	12.3	7
Poisson ratio	0.2	0.2	0.2	0.2
$\gamma/\left(\mathrm{kN/m^{-3}}\right)$	18.5	19.4	18.0	20.3
E_{50}^{ref}/Mpa	5	8.6	3	10.6
E_{oed}^{ref}/Mpa	6	10.32	3.6	12.72
E_{ur}^{ref}/Mpa	45	77.4	27	95.4
g_0^{ref}/Mpa	121.5	209	72.9	257.6
c/(kpa)	5	15	1	1
$\varphi/(^\circ)$	24	31	10	26

3.2. Numerical Analysis Procedure

According to the actual construction sequence, Figure 5 shows the construction stages flowchart, and the excavation process is divided into the following working conditions.

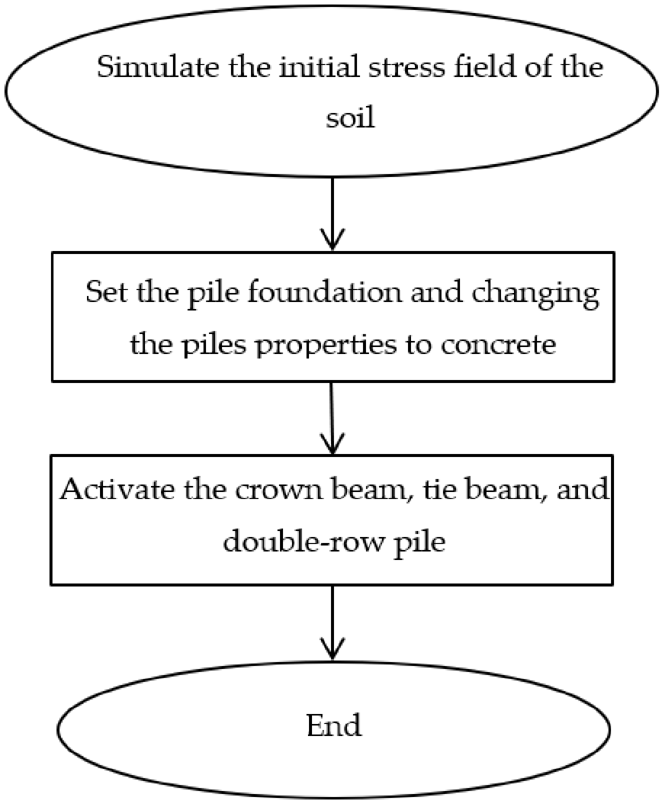

Figure 5. Construction stages flowchart.

(1) Set up the soil model, apply constraints to the other faces of the soil except for the upper surface, apply gravity load to the soil, simulate the initial stress field of the soil, and eliminate the settlement displacement generated by the self-weight of the soil;

(2) Activate the pile foundation, and the model calculates the stress field which is added to the pile foundation after eliminating the displacement caused by the construction of the pile foundation;

(3) In this stage, the crown beam, tie beam, and double-row piles are activated; and

(4) Every 2 m excavation is a working condition, simulating the bending moment and displacement of the support structure and adjacent pile foundation when excavating 2, 4, 6, 8, and 10 m.

3.3. Displacement Calculation and Analysis

According to the calculation structure of the finite element model, the displacement of the front row inclined pile and back row straight pile in excavation 2, 4, 6, 8 and 10 m is plotted as shown in Figures 6 and 7, respectively.

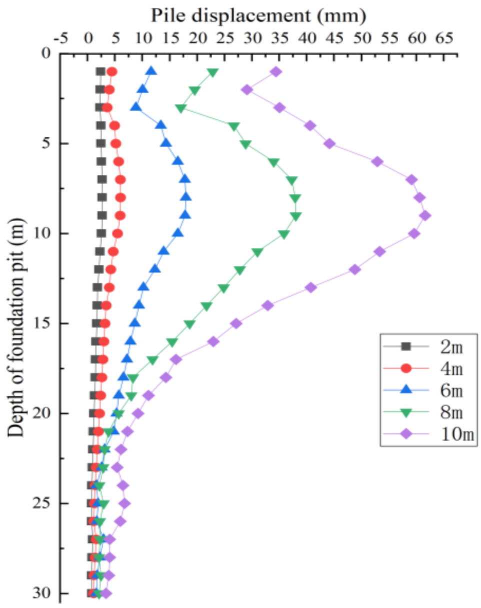

Figure 6. Horizontal displacement of front row inclined pile.

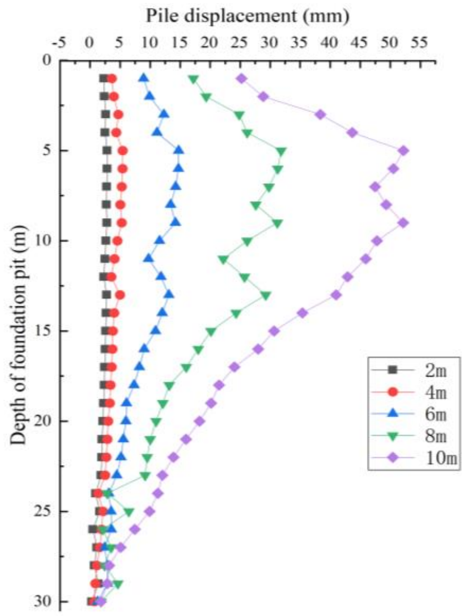

Figure 7. Horizontal displacement of rear straight pile.

3.4. Comparison of Monitoring Results

According to the monitoring plan of pile displacement before the construction of double-row piles, measurement points are arranged at an interval of 1 m along the vertical direction of the piles for monitoring the horizontal displacement of the piles. During the construction of the foundation pit, the monitoring data were read at intervals of one day, and the oblique and straight combined support pile deep foundation pit was excavated 10 m later according to the on-site monitoring data. The horizontal displacement monitoring structure of the front row of the inclined pile and the back row of the straight pile of No. 20 pile position is drawn as shown in Figures 8 and 9, respectively.

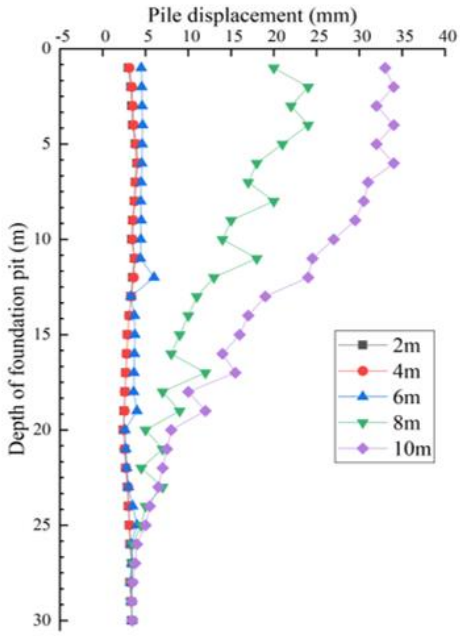

Figure 8. Horizontal displacement of rear straight pile.

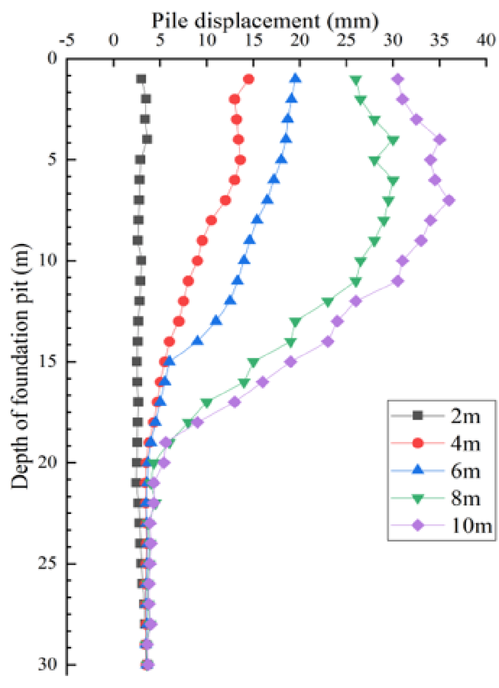

Figure 9. Horizontal displacement of front row inclined pile.

Comparing the model analysis results with the actual testing results on the surface, the pile displacement tends to increase first and then decrease with the depth of the pile row; the greater the excavation depth, the greater the rate of pile displacement increase and the maximum pile displacement occurs at 8 m from the top of the pile (0.27 times the pile length). Compared with the actual monitoring results, the changing trend of finite element simulation results is consistent with the actual results, but the monitored displacement is smaller than the simulated displacement. The reason for this is that the construction speed at the site is fast, the internal stress of the soil is not yet balanced when the monitoring results are read, and the soil deformation is still continuing. However, the finite element simulation results can still be considered reliable.

4. Analysis of the Force of the Inclined-Straight Combination Pile

The displacement diagram of the front and rear rows of piles when the excavation reaches 10 m is shown in Figure 10. The results indicated that when the deep foundation pit is excavated by inclined and straight combination pile support, the difference between the horizontal displacement of the front and rear rows of piles at the same depth is small, and they are all within the error range. That is, it can be considered that when the deep foundation pit is excavated by inclined and straight combination piles, the relative displacement between the soil and the pile body does not occur, and the pile side frictional resistance only appears in the front and rear rows of piles near the soil side outside the pile. Gang et al. [28] used indoor experiments to simulate the sliding surface of the inclined pile-supported foundation pit when it is close to the overturning damage, and the simulation results showed that for the inclined straight combination pile support structure with an inclination angle $\leq 20°$, there is no damage to the sliding surface of the soil between the piles when the overturning damage occurs. Therefore, when conducting force analysis, the support structure and the soil between the piles can be analyzed as a whole. The force analysis behavior of the support structure can be drawn as shown in Figure 11.

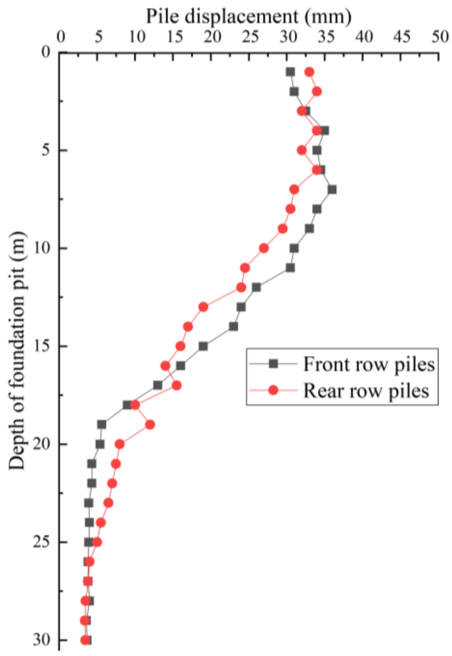

Figure 10. Horizontal displacement of front and rear rows of piles.

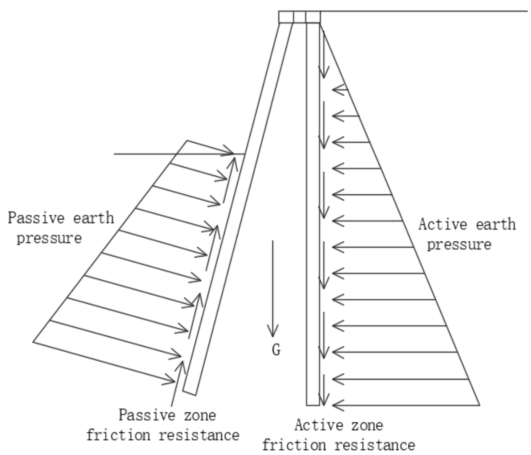

Figure 11. The behavior of force analysis of inclined-straight pile. Where, (G is the gravity of soil between combined piles).

For the force analysis of the inclined straight combination pile, the overturning rotation point can be approximated at the foot of the front row of inclined piles. Then, the moment of overturning rotation point should be taken:

$$E_a b_a \leq E_p b_p + F_n b_n + G \quad (1)$$

From the force analysis, compared with the straight pile, when the inclined pile support structure is tilted to the pit, the overturning force distance consisting of the active soil pressure outside the pit will be balanced with the overturning force distance consisting of the passive soil pressure, active zone frictional resistance and the gravity of the soil between the piles and the gravity of the combined pile. In addition, the larger the inclination angle of the front pile, the larger the overturning resistance distance is, so the stability of the inclined straight combination pile is greatly improved compared with the straight pile. However, when the inclination angle is $\geq 20°$, the soil between the piles will have a sliding damage surface, and the back row of straight piles will have upward frictional resistance near the side between the piles, and the stability of the support structure may be reduced instead.

Therefore, in the actual project, a suitable inclined pile inclination angle should be selected with the geological condition and other factors, so that the stability of the support structure can be optimized. At the same time, because the overturning resistance of the inclined pile is greatly improved compared with that of the straight pile, the soil deformation and horizontal displacement outside the pit is smaller when the deep foundation excavation of inclined and straight combined supporting pile is carried out, and the influence on the pile foundation of the adjacent structure outside the pit is also smaller.

5. Analysis of the Influence of Different Factors on the Adjacent Pile Foundation

5.1. Analysis of the Influence of the Distance from the Excavation Surface on the Adjacent Pile Foundation

The foundation pit is 45 width and 10 m depth, with a depth to width ratio of 2/9. The piles are inclined at an angle of 15°, buried at a depth of 30 m, and the beam is 3 m long. The pile bending moments and displacements are drawn at 5, 10, 15, 20, 25, and 30 m from the pile as shown in Figures 12 and 13, respectively.

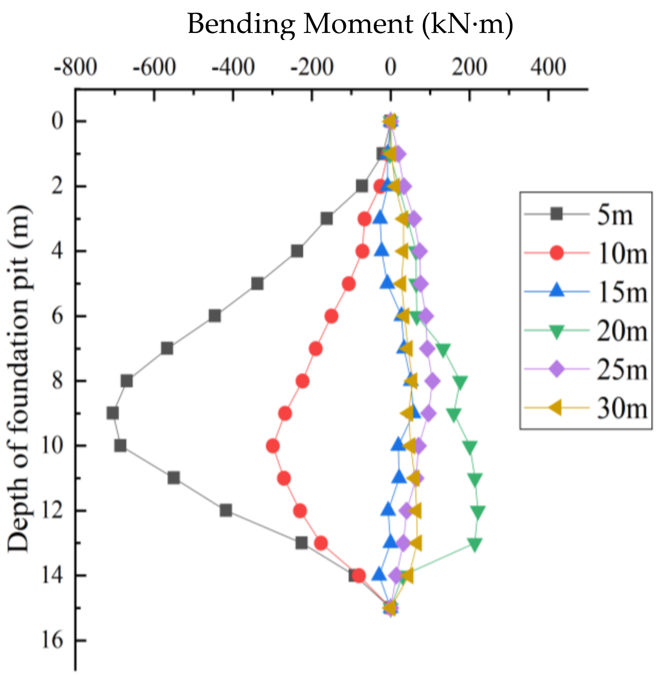

Figure 12. Pile bending moments.

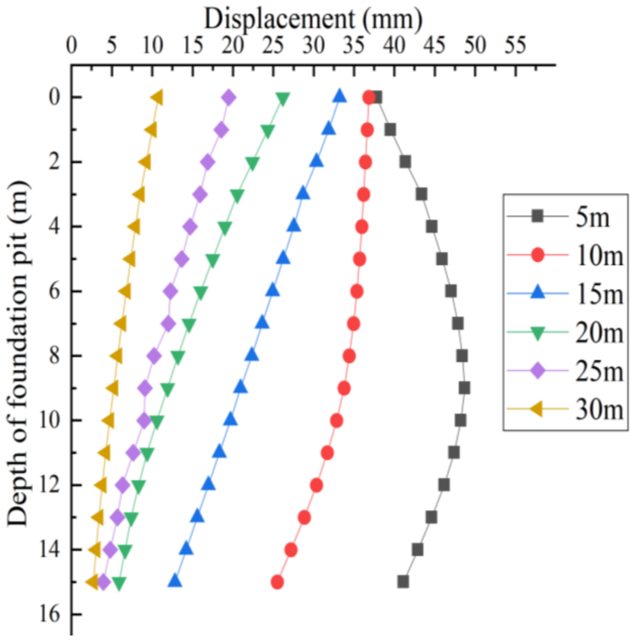

Figure 13. Pile displacement behavior.

From Figure 12, it can be seen that the bending moments of the vertical pile at 5 and 10 m from the excavation face are negative, while at 20, 25, and 30 m are positive. On the other hand, the bending moments of the vertical pile at 15 m from the excavation face show a negative and then positive change pattern. The maximum bending moments of the vertical pile at 5, 10, 15, 20, 25, and 30 m from the excavation face are −705.004, −298.936, 57.625, 221.537, 106.089, 67.533, respectively. It can be seen that as the distance from the excavation face increases, the maximum bending moment of the pile decreases first and then increases after changing the direction, the further the distance from the excavation face the slower the rate of change of the bending moment. The reason is that as the distance from the excavation surface increases, the active earth pressure of the sliding soil on the pile foundation decreases. In the passive area inside the pit, the reverse force of the spatial rigid frame structure consisting of the crown beam, straight pile, and inclined pile is generated on the soil and finally acts on the pile foundation and balances with the active soil pressure. At the same time, the maximum displacement of the support structure appears in the part of the support pile near the bottom of the pit when using the inclined and straight combined pile support structure, the displacement of the soil outside the pile at a deeper level is generally greater than the upper part of the soil, the soil pressure acting on the lower part of the adjacent pile foundation is greater than the upper part of the pile foundation, and the maximum pile bending moment appears in the lower part of the pile body. Therefore, attention should be paid to the bending moment in the middle and lower part of the adjacent pile foundation when designing the construction drawings, and increase the safety reserve to prevent pressure-bending damage for safety control.

On the other hand, from Figure 13, it can be seen that the displacement of the vertical pile at 5 m from the excavation surface shows the same trend as the support structure of tilted piles in the foundation pit, and the maximum displacement appears in the pile body. The maximum displacement of the remaining piles appears at the top of the pile, and the maximum displacement of the vertical pile at 5, 10, 15, 20, 25, and 30 m from the excavation surface is 51.43, 36.32, 33.25, 28.36, 17.92 and 11.03 mm, respectively. As expected, the nearest pile to the foundation pit has a larger horizontal displacement. Meanwhile, with the increase of distance from the excavation surface of the pit, the horizontal displacement of the pile decreases. In addition, with the increase of soil depth, the pile displacement decreases, and the distance from the top surface of the pile foundation is larger, the pile displacement changes more slowly.

5.2. Analysis of the Influence of the Pit Angle Effect on the Adjacent Pile Foundation

As mentioned in the previous section, the piles are inclined at an angle of 15°, buried at a depth of 30 m, and the beam connection is 3 m long. Therefore, Figures 14 and 15 show the vertical pile bending moments and the pile displacement behavior at 5 m from the excavation surface, and the distance D from the pit angle is 1.75, 6.75, 11.75, 16.75, and 21.75 m, respectively.

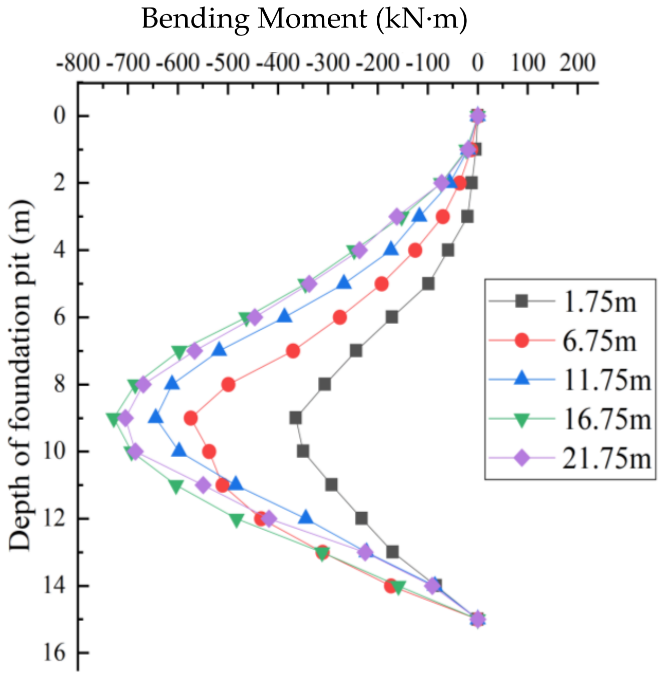

Figure 14. Pile bending moments.

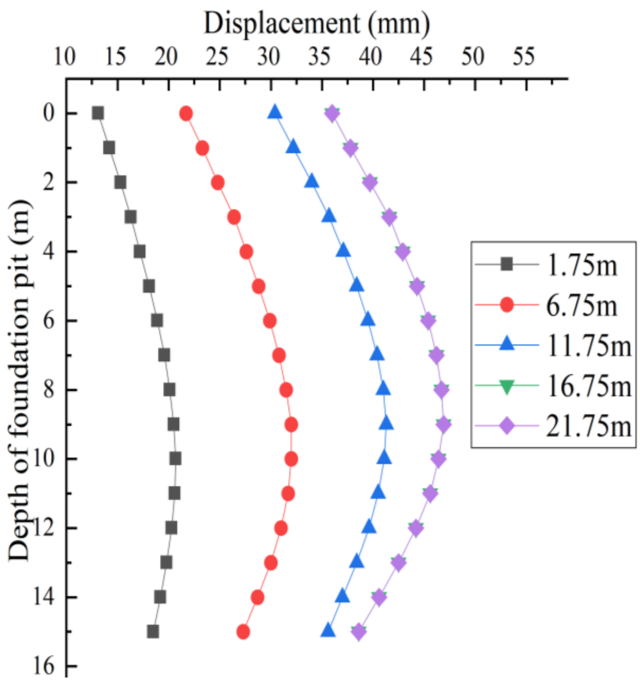

Figure 15. Pile displacement behavior.

From Figure 14, it can be noted that the behavior of the bending moment for the pile is the same at different distances from the pit angle. In addition, the maximum bending moments are: −352.789, −568.963, −561.947, −563.931, and −671.931, and the maximum bending moment appears on the pile foundation at D = 16.75 m. Furthermore, the pile closer to the pit corner, the smaller the pile bending moment, except for the piles near the pit corner and the centerline of the pit, the variation of the pile bending moment is small. Finally, the maximum bending moment increases by 61.28% from D = 1.75 m to D = 6.75 m and by 19.16% from D = 16.75 m to D = 21.75 m.

Additionally, from Figure 15, it can be seen that the maximum pile displacement is 21.01, 32.93, 43.10, 49.33, and 51.43 mm respectively. Also, the maximum pile displacement occurs in the middle and lower part of the pile, and the further away from the pit angle, the greater the pile displacement and the smaller the displacement variation. The maximum pile displacement increases by 56.67% from D = 1.75 m to D = 6.75 m, and by 4.26% from D = 16.75 m to D = 21.75 m.

Finally, it can be concluded that the bending moment and displacement of the adjacent pile foundation are all significantly influenced by the pit angle effect. The reason for this is that the support structures at the corner of the pit are perpendicular to each other to provide additional constraints, compared with the rest of the location, the stiffness of the support structure at the corner of the pit is greater, which can better resist the deformation of the soil outside the pit, and the area of deformation of the soil outside the pit is smaller compared with other locations, the closer to the corner of the pit, the smaller the bending moment and displacement of the adjacent structure pile foundation by the excavation of the pit. Therefore, when designing a large area of deep foundation excavation, the pit angle can be pointed to the adjacent structure for safety reasons.

5.3. Analysis of the Influence of Inclined Pile Tilt Angle on the Adjacent Pile Foundation

In order to understand the effect of the inclined pile tilt angle on the adjacent pile foundation, the vertical pile bending moment and the pile displacement behavior at 5 m from the excavation surface are investigated at 21.75 m from the pit angle, with different angles of the inclined pile as shown in Figures 16 and 17, respectively.

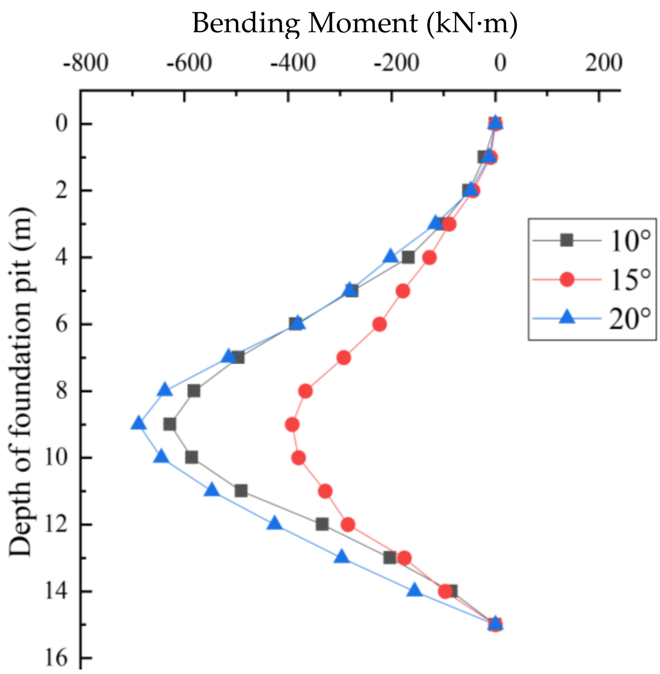

Figure 16. Pile bending moments.

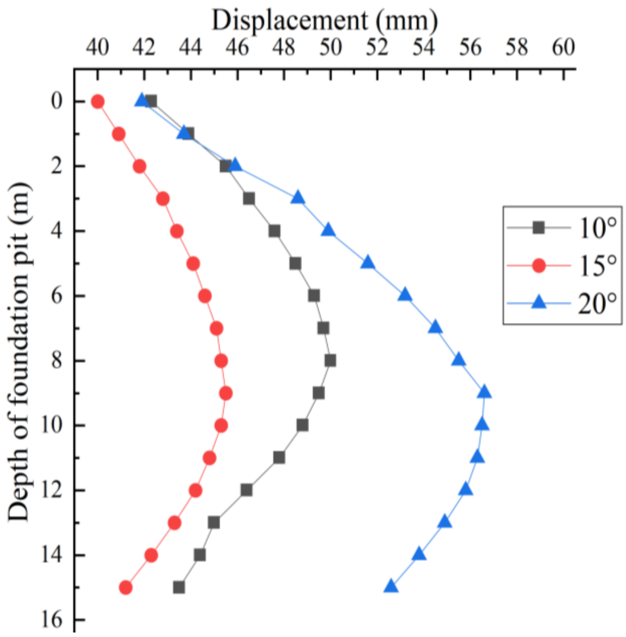

Figure 17. Pile displacement diagram.

From Figure 16, it can be noted that the pile foundation reaches the maximum bending moment at 9 m for different inclination angles, and the bending moment shows a trend of increasing and then decreasing with the increase of soil depth. In addition, the maximum bending moment is −672.38, −391.84, and −688.11 when the inclination angle of the inclined pile is 10°, 15°, and 20°, respectively. Finally, when the inclination angle increases from 10° to 15° the maximum bending moment decreases by 71.6% and by 75.6% when the inclination angle increases to 20°.

According to Figure 17, it can be concluded that under different inclination angles, the pile foundation reaches the maximum horizontal displacement at 8, 9, and 10 m, respectively. In addition, the minimum pile displacement occurs at the pile head and the pile displacement shows a trend of increasing and then decreasing with the increase of soil depth. The maximum horizontal displacement of the pile body is 49.5, 45.3, and 55.5 mm, respectively, when the inclination angle of the inclined pile is 10°, 15°, and 20°. With the increase of inclination angle of the supporting structure, the displacement of the pile body near the pile foundation also shows the trend of decreasing first and then increasing. Also, when the inclination angle increases from 10° to 15°, the maximum pile displacement decreases by 9.3%, and by 22.5% when the inclination angle increases to 20°. Lastly, it can be seen that under the same change of inclination angle, the larger the inclination angle of the support structure, the larger the change of horizontal displacement of the adjacent pile foundation. Since the top of the pile near the pile foundation is the least change of horizontal displacement when using the inclined and straight combined pile support structure, attention should be paid to the displacement below the top of the pile near the pile foundation in the actual process. When safety control is carried out in the construction stage, the displacement of the pile top cannot be used as the criterion for judging whether the deformation of the adjacent pile foundation is safe or not.

5.4. Analysis of the Influence of Pit Depth to Width Ratio on the Adjacent Pile Foundation

A case of pit depth-to-width ratio on the adjacent pile foundation was evaluated. As stated before, the foundation pit with 45 × 10 m dimensions has supported by the tilted pile at an angle of 15°. In this study, the depth-to-width ratio of the pit is 8/45, 10/45, 12/45, 14/45, and 15/45, respectively are taken. Therefore, Figures 18 and 19 show the vertical pile bending moments and the pile displacement behavior at 5 m from the excavation surface, and the distance D from the pit angle is 21.75 m.

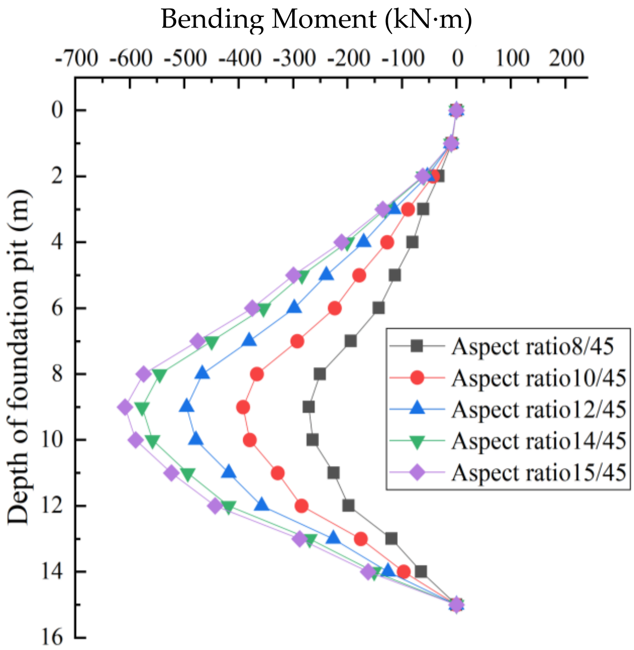

Figure 18. Pile bending moments.

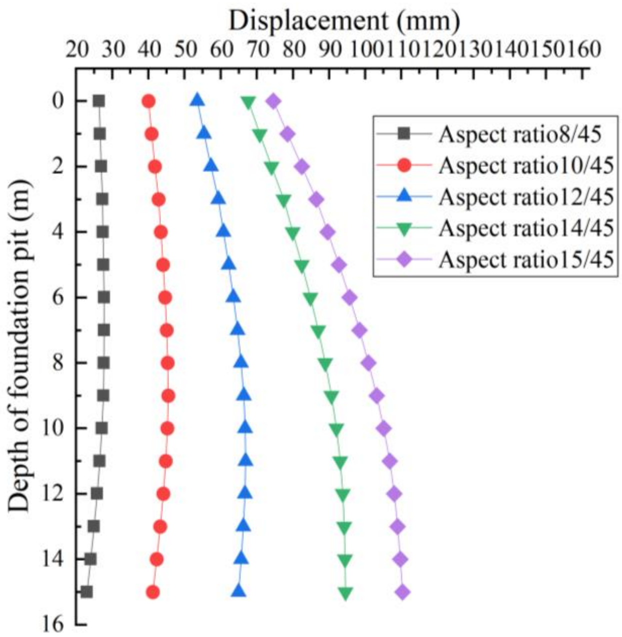

Figure 19. Pile displacement behavior.

As shown in Figure 18, it can be noted that the pile foundations reach the maximum bending moment at 9 m for different depth-to-width ratios, and the pile bending moment shows a trend of increasing and then decreasing with the increase of distance from the top of the pile. The maximum pile bending moment is −270.96, −391.84, −495.32, −577.31, and −608.62 when the depth-to-width ratio is 8/45, 10/45, 12/45, 14/45, and 15/45, respectively. Therefore, the larger the depth-to-width ratio, the larger the base bending moment.

As can be seen from Figure 19, when the depth of the pit is small, the maximum displacement of the pile appears in the middle of the pile, such as when the depth–width ratio is 8/45 and 10/45, the maximum displacement of the pile is 27.78 and 45.52 mm, which appear at 7 and 9 m from the top of the pile, respectively. The variation trend is the same as that of the pile displacement of the inclined and straight combination pile support structure. The reason is that in the inclined and straight combined pile support structure, the continuous beam, straight pile, and inclined pile work together to form a spatial frame structure, and the support structure is transformed from cantilevered force to internal bracing force, forming a self-stabilizing and self-supporting system, and the self-supporting effect of the support structure reduces the deformation and internal force of the pile near the foundation pit. At the same time, compared with other support methods, the inclined pile support provides additional restraint at the top of the pile, which increases the system stiffness of the support structure and reduces the deformation of the support structure and the top of the adjacent pile foundation, so that the maximum point of displacement is shifted down and does not appear at the top of the pile. Meanwhile, as the excavation depth increases, the maximum displacement of the pile increases, and the pile also shows a downward trend at the place where the maximum displacement occurs.

5.5. Analysis of the Influence of Construction Conditions on the Adjacent Pile Foundation

In order to explain the effect of construction conditions on adjacent pile foundations, Figure 20 shows the behavior of pile displacement at 5 m from the foundation pit with a depth-to-width ratio of 2/9.

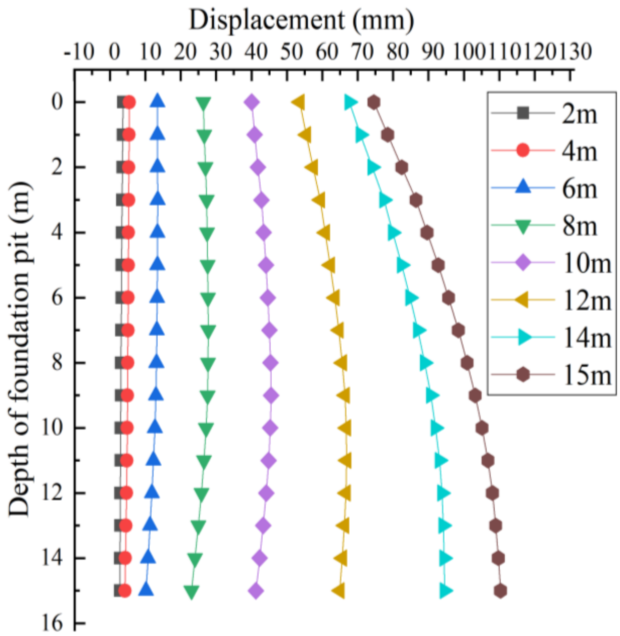

Figure 20. Pile displacement behavior.

From Figure 20, it can be seen that the distance of the maximum displacement point of the pile from the top of the pile increases with the increase of the excavation depth. When excavating to 2, 4, 6, 8, 10, 12, 14, and 15 m, the maximum displacement of the pile body appears at 0, 3, 7, 9, 11, 15, and 15 m from the top of the pile with the maximum displacement of 3.75, 5.49, 13.49, 27.78, 45.51, 66.90, 94.53, and 110.32 mm, with increases of 46.28%, 145.82%, 105.93%, 63.84%, 46.99%, 41.303%, and 16.70%, respectively. A comprehensive analysis of the maximum displacement size and the maximum displacement growth rate concluded that the excavation process of this deep foundation pit project is more prone to safety accidents due to the rapid growth of pile displacement in the rest of the working conditions compared with the excavation 14–15 m for working condition.

The traditional static analysis only focuses on the final deformation of the structure, which cannot reflect the dangerous nodes and conditions during the construction process and cannot make a comprehensive safety assessment of the actual construction process. Therefore, in the design process, the whole construction process should be simulated dynamically according to the actual construction plan, pointing out the dangerous conditions and making a more complete safety control construction plan for the project construction process.

6. Conclusions

In this paper, combining with a construction example of a deep foundation pit project in Wuhan City, Hubei Province, Midas GTS NX had been used to simulate and analyze the change of the bending moment and the displacement of the pile foundation near the foundation pit under the influence of different factors. Therefore, the following conclusions have been drawn from the research:

1. As the distance from the excavation surface increases, the maximum pile moment first decreases and then increases after changing direction, and the farther the distance from the excavation surface, the smaller the rate of moment change. The closer the pile foundation is to the pit, the greater the horizontal displacement of the pile, and with the increase of the distance from the excavation surface of the pit, the horizontal displacement of the pile decreases. In addition, as the distance from the top of the pile increases, the pile displacement decreases, and the greater the distance from the top of the pile, the slower the change on pile displacement. The maximum point of bending moment near the pile foundation appears in the middle and lower parts of the pile body. When carrying out the design of construction drawings, in consideration of safety control, attention should be paid to the bending moment in the middle and lower part of the pile foundation of the adjacent building to increase the safety reserve and prevent bending damage;
2. An inclined straight combination pile support structure has an obvious pit angle effect, the bending moment and displacement of the pile foundation near the pit are also affected by the pit angle, and the closer the pile foundation is to the pit angle, the more it is affected by the excavation of the pit. Therefore, when designing a large area of deep foundation excavation, the pit angle can be pointed toward the adjacent structure for safety reasons;
3. With the increase of the tilting angle of the tilting pile support structure, the bending moment and displacement of the adjacent pile base with the same distance from the top of the pile show a trend of decreasing and then increasing, so it is appropriate to use 15° of tilting pile support structure in actual construction design when the bending moment and displacement of the adjacent pile base are the smallest;
4. When excavating foundation pits with a different depth-to-width ratio of inclined and straight combination piles, the pile bending moment increases and then decreases with the increase of the distance from the top of the pile. Under the same conditions, the greater the depth-to-width ratio of the pit, the greater the pile bending moment. When the depth of the pit is small, the maximum displacement of the pile body appears in the middle of the pile body, and with the increase of the excavation depth of the pit, the maximum displacement point of the pile body gradually moves down;
5. When using an inclined pile support structure, the maximum displacement of the adjacent pile foundation appears in the middle of the pile body, and the top of the pile is the minimum displacement. In the construction of safety control, attention should be paid to monitoring the displacement change of the adjacent pile foundation, and the displacement of the top of the pile should not be used as the monitoring index; and
6. The traditional static analysis only focuses on the final deformation of the structure, which cannot reflect the dangerous nodes and dangerous working conditions in the construction process, and the safety assessment made on the actual construction process is often not comprehensive. Therefore, in the design process, the whole construction process should be simulated dynamically in accordance with the actual construction plan, pointing out where the dangerous conditions are, and making a more complete safety construction plan for the project construction process.

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