Research Article

Active and Passive Earth Pressure Calculation Method for Double-Row Piles considering the Nonlinear Pile Deformation

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The double-row pile supporting structure has been widely used in foundation pit excavations. When analyzing the effect of earth pressure on the pile structure, previous research only considered the double-row piles as the rigid body and the pile-soil interaction has not been examined. In this study, a theoretical model was developed based on Duncan-Chang’s hyperbolic theory to calculate earth pressures in the active and passive zones of the double-row pile supporting structure. The model considered the nonlinear effect of the pile deformation on the active and passive earth pressures. The macroscopic pile-soil interaction was converted into a microscopic stress-strain relationship at a certain point in the soil body, reflecting the nonlinear effect of pile deformation on earth pressure. Numerical simulation and large-scale field tests have been conducted to verify the proposed model. The results show that the average values of the parameters obtained by numerical simulation are \( a = 0.38 \), \( b = -0.253 \) for the active zone and \( a = 0.00612 \), \( b = -0.729 \) for the passive zone. Based on the values of \( a \) and \( b \), the predicted active and passive earth pressures stemming from the developed model agreed well with those obtained from field tests. The developed model in this study can be used to predict the distribution of active and passive earth pressures for double-row pile supporting structures.

1. Introduction

Rapid urbanization, in recent years, accelerates the construction of a bunch of tall buildings and subways in large cities [1]. The construction of deep foundation pits in tall building projects might have a significant impact on the surrounding infrastructures, such as metro lines and buildings. Various types of piles have been developed to ensure the stability of the foundation pit during excavation, including the cantilever single-row pile wall, the anchored single-row pile wall, and the double-row pile supporting structure.

In the construction of coal mine towers, the piles also play an important role, which can transfer the upper load to the foundation soil through the piles. The main principle is to transfer the upper load to the soil layer through the pile side friction resistance and the pile end resistance, so as to reduce the possibility of coal mine damage caused by excessive concentrated load. Especially in areas with abundant groundwater, choosing appropriate piles can effectively resist the effect of buoyancy in the soil, thereby improving the safety of the coal mine.

Various types of piles with strong constraints continue to appear, and the double-row pile support structure is one of them. Compared with the cantilever single-row piles, the double-row pile supporting structure has the characteristics of large lateral rigidity and strong overturning resistance. Compared with the anchored single-row piles, the double-row pile supporting structure has strong restraint ability and saves construction space [2].

The double-row pile supporting structure is mainly composed of front-row piles, rear-row piles, connecting beams, and crown beams (Figure 1). It is flexible and diverse in layout. As shown in Figure 2, various types of double piles have been developed, such as plum blossom, rectangular lattice, and zigzag [3]. To date, the design of double-row piles in actual projects relies heavily on empirical methods.
However, because of the complex formation, the empirical methods produce variation more or less. The existing research on double-row piles mainly focuses on structural optimizations, pile deformation mechanisms, and design parameter improvements [4–9]. The study on the effects of earth pressure on the stability of the double-row pile supporting system is not insufficient.

During the excavation of the foundation pit, the pile body deforms due to soil pressure and the soil and pile interact with each other. Considering the pile-soil interaction, the magnitude and distribution of earth pressure undergo complex changes with the deformation of the supporting structure to reach a new equilibrium. Some scholars have studied the impacts of earth pressure on the double-row pile supporting structure based on the finite soil theory [10–14]. The finite soil theory is the earth pressure value calculated according to the actual stress state of the soil body not the semi-infinite state of space. The earth pressure value is in line with the actual situation. In addition, soil arching effects on the double-row piles were investigated, when they were applied on stabilizing slopes [15–19].

However, previous research only considered the double-row pile model to be the rigid body when calculating the earth pressure. The pile-soil interaction during the excavation of foundation pits has not been examined [20–27]. Several limitations of previous works are summarized as follows. (1) Soils are assumed as ideal elastic materials and subjected to the Mohr-Coulomb strength theory [28]. (2) In terms of the limit equilibrium method for analyzing earth pressure, the earth pressure is distributed in a triangle shape from top to bottom along the pile body. However, the earth pressure distributed is not in a triangle shape in the actual engineering; it is just a simplifying assumption. (3) When considering the effect of earth pressure on the supporting structure, the structure is always regarded as a rigid body. In other words, the supporting structure only moves in translation or rotation corresponding to the variations of earth pressure and the pile-soil interaction is not considered. (4) The calculation method adopted in Chinese Standard JG120-2012, “Technical Specification for Building Foundation Pit Support,” is based on Winkler’s elastic foundation beam theory. That is, when calculating the earth pressure in the passive zone in front of the front row of piles, the passive earth pressure coefficient \((K_p)\) of the soil is simplified as the stiffness coefficient of the soil spring. However, the method in the standard only considers the linear effect of the deformation of the retaining wall when calculating the earth pressure for the retaining structure [29].

Based on the Duncan-Zhang hyperbolic model, this study focuses on the influence of the deformation of the double-row piles on the earth pressure in the active and passive areas during the excavation of the foundation pit. In this study, the macroscopic pile-soil interaction is transformed into the microscopic stress-strain relationship at a certain point in the soil. Subsequently, a calculation model of the earth pressure in the active and passive areas of the double-row pile supporting structure considering the influence of the pile body deformation was established; the proposed model is verified by using field test data.

2. Materials and Methods

2.1. Duncan-Chang Hyperbolic Model under the Unloading State of the Foundation Pit

2.1.1. Stress-Strain Relationship of Soil in the Unloaded State of the Foundation Pit. To adapt to the new equilibrium relationship, the double-row pile supporting structure will have a complex interaction with the surrounding soil, during the excavation of the foundation pit. With the excavation of the foundation pit, below the excavation surface, the stress change trend of a certain point in the soil in front of the front row piles is as follows: the vertical stress decreases, and the horizontal stress continues to increase. The stress change trend of a certain point in the soil behind the back row piles with the excavation of the foundation pit is as follows: the vertical stress remains unchanged, and the horizontal stress continues to decrease. This is similar to the stress path unloading test. The axial pressure of the former decreases and the confining pressure increases, and the axial pressure of the latter does not change but the confining pressure decreases. It is worth mentioning that through a series of model test studies, Yang and Lu found that the soil outside the slip surface of the foundation pit is slightly affected by the deformation of the supporting structure [30]. It can be considered that the deformation of the supporting structure only affects the soil within the slip surface. Therefore, this article assumes that during the excavation of the foundation pit, the deformation of the pile body of the double-row pile supporting structure only affects the earth.
pressure of the soil within the slip surface. The soil in front of the front row of piles is called the passive earth pressure area, the soil behind the back row of piles is called the active earth pressure area, and their interface is the Rankine slip surface. Then, the soil in the passive zone can be called the disturbed zone and the soil in the active zone is called the nondisturbed zone. This work assumes that the pile deformation only affects the soil in the disturbance zone.

2.1.2. Duncan-Chang Hyperbolic Model Application. The Duncan-Chang hyperbolic model can not only reflect the nonlinearity of soil deformation but also reflect the elastoplastic characteristics of the soil to a certain extent. This model was proposed by Conner in 1963 through a large number of triaxial stress tests. This curve is about \( \sigma_1 - \sigma_3 \)~\( \varepsilon_1 \) and can be applied to most soils. The curve is shown in Figure 3(a), and its expression is as follows:

\[
\sigma_1 - \sigma_3 = \frac{\varepsilon_a}{a + b\varepsilon_a}.
\]

In the formula, \( \sigma_1 \) and \( \sigma_3 \) are the maximum principal stress and the minimum principal stress, respectively. \( \varepsilon_a \) is the strain in the common condition, and \( \varepsilon_1 \) is the maximum principal strain. The unit is kPa, while \( a \) and \( b \) are the test constants. In the conventional triaxial compression test, because \( \varepsilon_a = \varepsilon_1 \), formula (1) can also be deformed as follows:

\[
\frac{\varepsilon_1}{\sigma_1 - \sigma_3} = a + b\varepsilon_1.
\]

Sorting and simplifying according to the form of \( (\varepsilon_1/(\sigma_1 - \sigma_3)) \sim \varepsilon_1 \), they are linearly distributed, as shown in Figure 3(b).

2.2. Earth Pressure Calculation in the Passive Zone

2.2.1. Establishment of a Calculation Model. The calculation model adopts a conventional cantilever double-row pile supporting structure. The area below the excavation surface of the foundation pit is regarded as the passive zone, and the earth pressure calculation model of the passive zone is established as shown in Figure 4.

\( z \) is the calculated depth of a certain point of the soil in the disturbance zone below the excavation surface; \( d \) and \( h \) are the pile length and the excavation depth of the foundation pit, respectively; \( \beta \) is the angle between Rankine’s passive slip surface and the horizontal plane; \( L \) is the horizontal distance from the slip surface at depth \( z \) to the front row of piles; \( \eta(z) \) is the horizontal displacement of the pile at depth \( z \).

2.3. Force Analysis. According to the Moore-Coulomb strength failure criterion, the angle \( \beta \) between the passive slip surface and the horizontal plane is \( 45^\circ - \varphi/2 \) and \( \varphi \) is the internal friction angle of the soil in the passive zone. The displacement (\( \eta(z) \)) of the pile body at depth \( z \) mainly affects the horizontal deformation of the soil between the pile body and the slip surface. Assume that the displacement \( \eta(z) \) of the pile body is equal to the deformation of the soil in the disturbance zone at the same depth and the strain of the soil between the pile body and the slip surface shows a linearly decreasing trend. Then, the strain of the soil at any point in the disturbance zone from the horizontal distance of the pile body can be expressed as follows:

\[
\varepsilon = \frac{2(L-x)\eta(z)}{L^2}.
\]

Establish equation (4) according to equation (3):

\[
\int_0^L \frac{2(L-x)\eta(z)}{L^2} \, dx = \eta(z).
\]

When the pile body does not move, it can be assumed that the soil at any point in the passive zone is in a state of isobaric consolidation stress. In other words, the stresses in the three main axis directions are equal at this time, as shown in equation (5). Since the soil is in a state of isobaric consolidation, the horizontal direction can be regarded as the direction of the maximum principal stress. At this time,
the maximum principal stress is the earth pressure value in the passive zone.

\[ \sigma_m = \frac{1}{3} (1 + 2K_0)rz. \]  

(5)

In equation (5), \( \sigma_m \) is the average consolidation pressure (unit: kPa); \( K_0 \) is the coefficient of earth pressure at rest; \( r \) is the gravity of the soil (unit: kN/m^3); \( z \) is the depth of the calculation point (unit: m).

With the excavation of the foundation pit, the horizontal stress of the soil in the passive zone continues to increase. Therefore, the earth pressure \( p_p \) in the passive zone is the maximum principal stress \( \sigma_1 = \sigma_m \). The strain of the soil at the retaining wall position \((x = 0)\) is \( \varepsilon = 2\eta(z)/L \).

Put the above parameters into equation (1), and we can get equation (6):

\[ p_p - \frac{1}{3} (1 + 2K_0)rz = \frac{2\eta(z)/L}{a + 2b\eta(z)/L}. \]  

(6)

It can be seen from the geometric relationship in Figure 4 that \( L = \tan(45^\circ + \varphi/2)(d - z) = \sqrt{K_p^*}(d - z). \) Substitute this geometric relationship into equation (6).

\[ p_p = \frac{1}{3} (1 + 2K_0)rz + \frac{2\eta(z)}{a\sqrt{K_p^*}(d - z) + 2b\eta(z)}. \]  

(7)

Equation (7) is the calculation formula for the earth pressure in the passive zone below the excavation surface of the foundation pit, which takes the influence of pile deformation into account. The test constants \( a \) and \( b \) in equation (7) can be obtained by the following four approaches.

1. Carry out the indoor routine triaxial test, fit a straight line according to the relationship of \( \varepsilon/\sigma_1 - \sigma_3 \sim \varepsilon_1 \), and get the values of \( a \) and \( b \)

2. Derive \( a \) and \( b \) values through indoor model tests

3. Derive the values of \( a \) and \( b \) based on the measured earth pressure on site

4. Derive \( a \) and \( b \) values through numerical simulation

### 2.4. Earth Pressure Calculation in the Active Zone

#### 2.4.1. Establishment of a Calculation Model

The earth pressure calculation model in the active zone is established, as shown in Figure 5. \( z \) is the calculation point depth of the soil in the disturbance zone behind the double-row piles. \( d \) and \( h \) are the pile length and the excavation depth of the foundation pit, respectively. \( \gamma \) is the angle between Rankine's active slip surface and the horizontal plane. \( L' \) is the horizontal distance from the slip surface at depth \( z \) to the rear row of piles.

#### 2.5. Force Analysis

Liu and Hou used the stress path triaxial tester to test the stress-strain relationship of the excavation and unloading of the soft soil foundation pit [31–41]. The
Table 1: The parameter of strata.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Dry weight (kN/m³)</th>
<th>Cohesion (kPa)</th>
<th>Internal friction angle (°)</th>
<th>Elastic modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Stratum thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miscellaneous fill</td>
<td>16.5</td>
<td>0</td>
<td>13</td>
<td>10</td>
<td>0.34</td>
<td>2.4</td>
</tr>
<tr>
<td>Silt</td>
<td>19.7</td>
<td>21</td>
<td>17</td>
<td>21</td>
<td>0.36</td>
<td>5.6</td>
</tr>
<tr>
<td>Silty fine sand</td>
<td>20.8</td>
<td>0</td>
<td>38</td>
<td>30</td>
<td>0.29</td>
<td>4.0</td>
</tr>
<tr>
<td>Granular pebbles</td>
<td>21.5</td>
<td>0</td>
<td>40</td>
<td>70</td>
<td>0.28</td>
<td>4.0</td>
</tr>
<tr>
<td>Silty clay</td>
<td>19.8</td>
<td>29</td>
<td>25</td>
<td>40</td>
<td>0.35</td>
<td>8.0</td>
</tr>
<tr>
<td>Sandy pebble</td>
<td>21.5</td>
<td>0</td>
<td>45</td>
<td>100</td>
<td>0.26</td>
<td>16</td>
</tr>
</tbody>
</table>

Figure 7: Excavation model of the foundation pit.
results show that the stress-strain relationship of the soil during the unloading process can be normalized by the average consolidation stress \( \sigma_m \). Therefore, the soil unloading stress-strain formula represented by the Duncan-Chang hyperbolic function can also be normalized. Equation (2) can be written as follows:

\[
\frac{\sigma_m \varepsilon_1}{(\sigma_1 - \sigma_3) - (\sigma_{1c} - \sigma_{3c})} = a + b \varepsilon_1. \tag{8}
\]

In equation (8), \( \sigma_1 \), \( \sigma_3 \), and \( \sigma_{1c} \) are the vertical stress and horizontal stress when the soil is consolidated (unit: kPa). \( \varepsilon_1 \) is the strain corresponding to \( \sigma_1 \), \( \sigma_m \) is the average consolidation stress (unit: kPa). \( a \) and \( b \) are test constants.

Equation (8) is applicable to the stress-strain relationship of the soil in the unloaded state. For the soil in the active area behind the double-row piles, due to the excavation of the foundation pit, the vertical stress of the soil in the active area behind the rear-row piles remains unchanged, while the horizontal stress becomes smaller. Therefore, we have \( \sigma_1 = \sigma_{1c} = rz \), \( \sigma_{3c} = k_0rz \). That is to say, \( \sigma_3 \) is the strength of earth pressure in the active area behind the back row of piles and its value is \( P_a \). It is assumed that the horizontal strain of the soil in the active zone and the axial strain becomes a linear relationship. That is \( \varepsilon_3/\varepsilon_1 = \nu \), then, we have \( \varepsilon_1 = 2\eta(z)/L'\nu \) and \( L' = \tan(45^\circ - \varphi/2) \cdot (d - z) = \sqrt{K_a} \cdot (d - z) \), \( \nu \) is the Poisson’s ratio of the soil.

Simplify equation (8) to obtain the calculation formula of earth pressure strength in the active zone behind the double-row piles:

\[
P_a = k_0rz - \frac{2\eta(z)(1 + 2k_0)rz}{3av\sqrt{k_a(d - z) + 6b\eta(z)}}. \tag{9}
\]

In equation (9), \( k_0 \) is the coefficient of earth pressure at rest; \( k_a \) is the active earth pressure coefficient; \( \eta(z) \) is the horizontal displacement of the pile at depth \( z \) (unit: m).

2.6. Engineering Verification. Numerical simulation and field test methods are used to verify the applicability of the calculation model obtained. First, the values of parameters \( a \) and \( b \) in the earth pressure formula are derived through numerical simulation, and secondly, the actual earth pressure values are measured through field tests and compared with the theoretical formula results.

2.6.1. Engineering Background. A deep foundation pit project of an underground comprehensive pipeline gallery in Beijing was selected for the field test. The project is located in Yufa town and Lixian town, Daxing district, Beijing, and Guanyang district, Langfang city, Hebei province. The location is shown in Figure 6. The formation parameters are shown in Table 1.

2.6.2. Numerical Model Establishment and Analysis. The finite difference software FLAC 3D is used for simulation. The stratum parameters, construction sequence, and pile geometry parameters are consistent with the field test. The excavation sequence of the foundation pit is shown in Figure 7, and the supporting structure parameters are shown in Tables 2 and 3. To make the calculation simple and easy to solve, the following assumptions are made on the model:

1. The top of the pile is rigidly connected to the crown beam. That is, only the bending moment is generated here without deformation
2. Since precipitation has already been carried out before construction, the impact of groundwater seepage is not considered
3. The supporting structure satisfies the basic assumption of the plane strain problem

The FLAC 3D modeling and excavation process are shown in Figure 8.

Derive the values of \( a \) and \( b \) in the previous equation through the results of numerical simulation. Take the pile displacement value \( \eta(z) \) corresponding to different depth \( z \) to calculate the \( a \) and \( b \) values of the passive zone and the active zone. The calculation results are shown in Tables 4 and 5.

It can be seen in Tables 4 and 5 that the derivation of \( a \) and \( b \) values fluctuates slightly. The average values of \( a \) and \( b \) in the passive zone are \( \bar{a} = 0.00612 \) and \( \bar{b} = -0.729 \), respectively. In the same way, the values of \( a \) and \( b \) in the active zone are \( \bar{a} = 0.38 \) and \( \bar{b} = -0.253 \), respectively.

<p>| Table 2: Geometrical parameters of the supporting structure. |</p>
<table>
<thead>
<tr>
<th>Foundation pit depth (m)</th>
<th>Pile diameter (m)</th>
<th>Pile distance (m)</th>
<th>Row spacing (m)</th>
<th>Embedded depth (m)</th>
<th>Pile length (m)</th>
<th>Beam section size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.2</td>
<td>0.8</td>
<td>1.6</td>
<td>2.4</td>
<td>11.2</td>
<td>25.6</td>
<td>0.8 × 0.8</td>
</tr>
</tbody>
</table>

<p>| Table 3: Calculation parameters of the supporting structure. |</p>
<table>
<thead>
<tr>
<th>Concrete power level of pile and beam (E/GPa)</th>
<th>Elastic modulus of pile and beam (E/GPa)</th>
<th>Poisson’s ratio of pile (( \mu ))</th>
<th>Elastic modulus of pile and steel bar (E/GPa)</th>
<th>Rebar diameter (DS/m)</th>
<th>Number of longitudinal bars in piles and beams (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C30</td>
<td>24</td>
<td>0.2</td>
<td>200</td>
<td>0.028</td>
<td>18/24</td>
</tr>
</tbody>
</table>
(a) Meshing of solid elements

(b) Pile element and beam element

Figure 8: Continued.
(c) First step of excavation

(d) The second step of excavation

Figure 8: Continued.
(e) The third step of excavation

(f) The fourth step of excavation

Figure 8: Continued.
(g) The fifth step of excavation

(h) The sixth step of excavation

**Figure 8:** Continued.
FLAC3D 3.00
Step: 90267 Model Perspective
22:12:01 Thu Feb 16 2017

Center: X: 5.000e+001 Y: 0.000 Z: 2.001e+01
Rot: X: 0.000 Y: 0.000 Z: 0.000
Dis: 3.258e+002 Ang: 1

Plane Origin: X: 0.000e+000 Y: 1.000e+000 Z: 0.000e+000
Plane Normal: X: 0.000e+000 Y: 0.000e+000 Z: 0.000e+000

Contour of X Displacement
Plane: on
-1.393e-002 to -1.000e-002
-1.000e-002 to -8.000e-003
-6.000e-003 to -4.000e-003
-4.000e-003 to -2.000e-003
-2.000e-003 to 0.000e+000
0.000e+000 to 2.000e-003
2.000e-003 to 2.316e-003
Interval: 2.0e-003

Axis
Landscape Consulting Group, Inc.
Minneapolis, MN, USA

(i) The seventh step of excavation

FLAC3D 3.00
Step: 90267 Model Perspective
22:15:40 Thu Feb 16 2017

Center: X: 5.000e+001 Y: 0.000 Z: 2.001e+01
Rot: X: 0.000 Y: 0.000 Z: 0.000
Dis: 3.258e+002 Ang: 1

Plane Origin: X: 0.000e+000 Y: 1.000e+000 Z: 0.000e+000
Plane Normal: X: 0.000e+000 Y: 0.000e+000 Z: 0.000e+000

Contour of X Displacement
Plane: on
-1.393e-002 to -1.000e-002
-1.000e-002 to -8.000e-003
-6.000e-003 to -4.000e-003
-4.000e-003 to -2.000e-003
-2.000e-003 to 0.000e+000
0.000e+000 to 2.000e-003
2.000e-003 to 2.316e-003
Interval: 2.0e-003

Axis
Landscape Consulting Group, Inc.
Minneapolis, MN, USA

(j) The eighth step of excavation

**Figure 8:** Continued.
2.6.3. Field Test and Analysis. In this field test, the soil pressure and horizontal displacement on the pile body during the excavation of the foundation pit were measured. Earth pressure box, inclinometer tube, and corresponding data acquisition equipment are used for measurement. The monitoring instrument is shown in Figure 9, the layout of the monitoring points is shown in Figure 10, and the field test process is shown in Figure 11.

Table 4: Values of $a$ and $b$ at each depth of the passive zone.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>$\eta(z)$ (mm)</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>11.46</td>
<td>0.005812</td>
<td>-0.841</td>
</tr>
<tr>
<td>18</td>
<td>10.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>10.31</td>
<td>0.006334</td>
<td>-0.711</td>
</tr>
<tr>
<td>20</td>
<td>10.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>10.28</td>
<td>0.006215</td>
<td>-0.636</td>
</tr>
<tr>
<td>22</td>
<td>10.15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Values of $a$ and $b$ at each depth of the active zone.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>$\eta(z)$ (mm)</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>16.97</td>
<td>0.461</td>
<td>-0.22</td>
</tr>
<tr>
<td>5</td>
<td>16.54</td>
<td></td>
<td>-0.18</td>
</tr>
<tr>
<td>7</td>
<td>16.2</td>
<td>0.354</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>15.68</td>
<td>0.325</td>
<td>-0.36</td>
</tr>
<tr>
<td>11</td>
<td>15.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>13.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Results

According to the earth pressure value measured in the field test, the applicability of the theoretical formula in this study is verified. As shown in Figure 12, the theoretical earth pressure value is basically the same as the field measured earth pressure value along the pile body. Their numerical changes are relatively close, and the earth pressure values gradually
Figure 9: Monitoring equipment.

Figure 10: Monitoring point layout map.
Figure 11: Field test construction process.
increase as the depth increases. It can be seen that the monitoring point is 20 meters deep in the active zone. The theoretical value here is 121.2 kPa and the measured value here is 132.5 kPa. As for the 22-meter depth monitoring point in the passive zone, the theoretical value here is 172.5 kPa and the actual value here is 188.3 kPa. As a whole, the earth pressure in the active zone is less than the earth pressure in the passive zone.

4. Conclusions

Numerical simulation and field measurement had been used in this study to theoretically derive the earth pressure on the double-row piles during the excavation of the foundation pit, relying on a deep foundation pit project in Beijing area.

During the excavation of the foundation pit, due to the influence of the deformation of the double-row pile supporting structure, the stress state of the soil in the active zone and the passive zone is different. During the excavation process of the foundation pit, the horizontal stress of the soil in the active area (soils after the rear row of piles) continuously decreases, while the vertical stress is basically unchanged. The horizontal stress of the soil in the passive zone increases continuously, and the vertical stress decreases with the excavation of the foundation pit.

This study considers the nonlinear effects of soil deformation. Based on the Duncan-Chang hyperbola theory, a calculation model of earth pressure after excavation of a foundation pit supported by double-row piles is established. Subsequently, the calculation formula of earth pressure in the active and passive zones is proposed. The values of parameters $a$ and $b$ are derived through numerical simulation. The sequence of the numerical simulation working conditions is consistent with the field experiment. The average values of parameters $a$ and $b$ in the active zone are 0.38 and $-0.253$, respectively, and the average values of parameters $a$ and $b$ in the passive zone are $0.00612$ and $-0.729$, respectively.

The large-scale field test is used to verify the theoretical calculation formula derived in this paper and then compares the earth pressure values of two points in the active zone and the passive zone, which are a 20-meter-depth monitoring point in the active zone and 22-meter-depth monitoring point in the passive zone. The theoretical earth pressure value is basically the same as the field measured earth pressure value along the pile body, and the numerical change is relatively close. This result shows that the theoretical earth pressure calculation formula deduced in this study is reasonable and correct.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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