Lateral response characteristics of single pile in the inclined soil surface under lateral loads

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Abstract: The existing methods to evaluate the lateral bearing capacity of single pile foundation is based on the assumption that the soil surface is level. However, no mature evaluation method is available for the lateral bearing capacity of the pile in the inclined soil surface now. In this study, the lateral response characteristics of pile under lateral loads are studied via laboratory model test. Based on the effect of slope gradient study, a correction formula is proposed for the calculation of the displacements of soil surface and pile head, and the value/location of maximum bending moment along the pile length. The formula can provide a theoretical reference for single pile foundation design and calculation in the inclined soil surface.

Key words: pile foundation; inclined soil surface; lateral bearing capacity; model test

1 Introduction

Piles mainly withstand lateral loads in many engineering applications, such as wharf, foundation pit and slope supporting. The loading effect of the pile under lateral loading results from the interaction of pile and soil. The horizontal movement and bending caused by lateral loading transfer a part of the loading to the soil beside pile. Consequently, the soil is squeezed. When the soils reach the maximum shear strength with the increase of the lateral loading, the surface soil will fail. The failure of the soil will progressively develop from the surface to the underground with the increasing loading.

In the early 1970s, a model test was conducted by Davission [1] using aluminum alloy tube in the dry standard sand to simulate the lateral mechanical characteristic of pile. And the laboratory model test utilizing organic glass model, the steel pipe and the wood model was also conducted by Mayne [2], Caliendo [3] and Pan [4]. Through analyzing a large number of model tests results, a simple and reasonable calculation method for single pile under lateral loading was proposed by Wang and Lou [5]. The calculation results can consider the influence of the nonlinearity of a single pile. Zhao et al. [6] investigated the mechanical characteristic of pile under the combined axial and lateral loading by using alloy aluminum tubes as a model pile. Model test on the lateral bearing properties of caisson-pile foundation was simulated by Gong et al. [7]. Lee [8] estimated the ultimate lateral loading capacity of piles in sand using calibration chamber tests. Ma [9] researched the deformation characteristics such as displacement and bending moment of cast-in-situ concrete pipe piles under lateral loading by using the model test system.

By using centrifuge model, the pile group in sand with different pile spacing was studied by Michael [10]. The characteristic of pile in the sand under monotonic lateral loading was analyzed by Dyson and Randolph [11]. Brant [12] researched the behavior of tubular steel piles embedded within dry or saturated soil and subjected to varied rates of lateral loading. Zhang [13] studied the cyclic lateral responses of a rigid pile in the soft clay by the centrifuge model.


Some theories and methods of pile under lateral loading have been proposed, such as ultimate subgrade reaction method, P-Y curve method [16], NL method [17], and elastic subgrade reaction method. However, these methods are based on the assumption of level soil surface and fail to address the issue of the lateral bearing characteristic of pile foundations in an inclined soil surface. In the design of high-piled wharf on the inclined soil surface, high-piled wharf bending is calculated according to the Design and Construction Code of High-piled Wharf [18], when calculating the pile bearing capacity in the vertical and horizontal directions, the position of imaginary ground surface in the pile axis can be assumed as 1/2 of the intersection point position of wharf apron soil surface and the actual slope (fig. 1). The design and calculation will be carried out according to the imaginary fixing point method in the hypothetical soil surface.
This method was first adopted in the code of Japanese port in 1973. In that time, the scale of the port was small and the span was as short as approximately 20 m in length. Therefore, the method can satisfy the requirement of engineering design. With the development of container transport in the waterway engineering, the pier span has considerably exceeded 20m. The width of large-span high-piled wharf can even reach more than 40m. If this method was employed, the rear pile would be severely affected. Assuming that the hypothetical soil surface can reach certain position higher than the pile, the calculation of the imaginary fixing points will deviate significantly. The so-called imaginary fixing point does not actually exist since the displacement and angle of fixing point should be zero and the bending moment should be maximum.

In this study, the mechanical characteristics of single pile foundation under lateral loading in inclined ground surfaces with different incline angles were investigated using the laboratory model tests. The influence of the slope of soil surface on bending moment of pile and displacements at the soil surface and the pile head are analyzed, and the correction equations are proposed. The influence of the slope of soil surface on other mechanical characteristics of single pile foundation is also analyzed.

2 Test equipment and method
2.1 Test design

The model test is conducted in a rectangular container, which is made of steel plate and organic glass. The container has internal dimensions of 2000mm in length, 1000mm in width, and 2000mm in height, as shown in fig.2. There are two fasteners at the height of 1000mm and 1500mm for fixing the model pile.

In the present study, 5 model tests are carried out. The test scheme is summarized in Table 1. By changing the slope angle and loading direction, the influence of different soil surface slope on the behavior of piles subjected to lateral loading is studied, the correlation between the slope angle and key design parameter of laterally loaded piles is established, and the mechanical characteristics of piles in different soil surface slope is analyzed. The pile head is free. There are 12 loading levels with each level of 100N.
Table 1 The test scheme

<table>
<thead>
<tr>
<th>Test number</th>
<th>Slope gradient</th>
<th>Load direction</th>
<th>( \tan \theta )</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>0</td>
<td>lateral loading</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1:4</td>
<td>uphill loading</td>
<td>-1/4</td>
</tr>
<tr>
<td>3</td>
<td>1:4</td>
<td>downhill loading</td>
<td>1/4</td>
</tr>
<tr>
<td>4</td>
<td>1:3</td>
<td>uphill loading</td>
<td>-1/3</td>
</tr>
<tr>
<td>5</td>
<td>1:3</td>
<td>downhill loading</td>
<td>1/3</td>
</tr>
</tbody>
</table>

Note: \( \theta \) is the angle of slope, the value of which is positive under downhill loading.

2.2 Equipments

The experimental equipment consists of the model tank, loading module and measurement device, as shown in fig. 3. The test loading device is composed of pulley and weight. The steel wire and pulley will transfer the dead load of the weight to the horizontal concentrated loading on the pile head. The magnitude of the horizontal loading can be adjusted through increasing or decreasing the number of weights. During the testing, the magnitude of the horizontal loading applied on the pile head, the displacements of the soil surface and the pile head, and the strain of the pile body are measured. The displacements of the soil surface and the pile head are measured by a micrometer. The strain of pile body is measured by the strain gauges attached on the pile.

Circular hollow aluminum tubes are used in the experiment with a diameter of 40mm and wall thickness of 3mm. The total length of the model pile is 1800mm with a 1600mm penetration below the ground surface. 28 pairs of strain gauges are glued on the pile with a vertical interval of 5mm or 10mm to measure the bending moments along the pile shaft. The flexural rigidity \( EI \) of model pile is 4029.13 N \( \cdot \) m². The distance between pile and the boundary of soil is more than 10 D (D is the pile diameter). The size of container was designed large enough to minimize the influence of the container boundaries.

Due to the internal cohesive stress in the viscous soil, it is difficult to assure the homogeneity of the material, which will induce great error into the testing. Since the homogeneity of the filling soil can be ensured with adding the sand, coarse sand is selected as the material of the soil referring to many other domestic and international indoor tests. The soil parameters are as follows: the specific gravity is 2.67, the water content is 6.8%, the maximum and minimum dry density is 1.7g/cm³ and 1.43g/cm³, respectively, the maximum and minimum void ratio is 0.87 and 0.57, respectively, the relative density is 0.17, the d60, d30 and d10 is 0.43mm, 0.28mm and 0.16mm, respectively, the non-uniform coefficient is 2.688, the coefficient of curvature is 1.140. And according to some references [20], the stress-strain behavior of sands is time-independent.

The test is prepared in the following manner. A 100-mm-thick sand layer is filled into the model container every time and compacted twice using vibrator with a time interval of 30 minutes. The model pile is fixed at the predetermined position with fasteners after two layers of sand filling. We dismantle the lower fastener when the height of sand reaches 900mm, and dismantle the upper one when the height of sand reaches 1450mm. While the ground surface is inclined, filling up the container entirely and then cutting the surface to the desired slope angle.

The lateral bearing capacity of single pile is discrepant due to the difference of the slope angle. It is difficult to form a unified standard regarding displacement as the loading control factor. Thus, we adopt the pile stress as the control parameter to stop loading. According to the preliminary test results, the lateral bearing capacity of pile in horizontal soil surface is 1200 N, and the corresponding maximum pile strain is 1923 \( \mu \varepsilon \). In the present study, the test is stopped when the maximum pile strain is greater than or equal to \((1-10\%)-1923\mu\varepsilon\), i.e. 1730 \( \mu \varepsilon \).

3 Test result and discussion

3.1 Mechanical characteristics of pile in level soil surface

Fig. 4 shows the variation of the bending moment of the pile in the level soil surface under lateral loading. As shown in the figure, the bending moment of pile primarily arises in the upper part of pile. The position of maximum bending moment varies between 2.5~5 D below the soil surface. The position of the zero-moment point moves downward with the increase of loading and is about 12.3~19.3 D below the soil surface. The test results show that the pile in the model test is an elastic long pile. Fig. 5 shows the horizontal displacement variation of pile at different depths under lateral loading. The position of first zero-displacement point of pile varies between 10~11.3 D below the soil surface. The displacement of the pile in the lower part is very small.
The lower fastener is 20 D below the soil surface, so it does not impact the lateral response characteristics of pile.

In general, the maximum horizontal displacement of the pile arises at the top of the pile under the lateral loading. The displacements of the soil surface reflect the soil constraint conditions against the pile displacement. The relationships between loading and displacements at pile head and soil surface is of vital important for the pile under lateral loading with the horizontal displacement as the design parameter. Fig. 6 shows the displacements at pile head and soil surface under different loading. As shown in the figure, the relationships of lateral loading and the horizontal displacements at pile head and soil surface shows an obvious nonlinearity.

The resistance of soil beside the pile is obtained by double differentiating the measured pile bending moment [19], and the distribution of resistance of soil beside pile side is shown in Fig.7. The reaction force increases first and subsequently decreases along with the depth, where the maximum value is at a certain depth below the soil surface. The maximum point moves downward and varies between 2.5–5 D below the soil surface with the increase of the loading. The first zero-resistance point also moves downward as the loading increases, which varies between 7–11 D below the soil surface. The trend of the soil surface resistance reflects a process of the topsoil from elasticity to plasticity, and finally failure with the increase of loading.

![Fig. 3 Horizontal loading test](image)

![Fig. 4 The bending moment of pile in the level soil surface](image)

![Fig. 5 The displacement of pile in the level soil surface](image)
3.2 Mechanical characteristics of pile in the soil surface of slope 1:4 under uphill and downhill loading

3.2.1 Bending moment of pile

Fig. 8 shows the variation of the bending moment of pile in soil surface of slope 1:4 under uphill and downhill loading. Under the uphill loading, the position of maximum bending moment varies between 2.1~4.7 D below the soil surface. The position of the first zero-moment point is about 12.3~19.3 D below the soil surface, which moves downward with the increase of loading. Under the downhill loading, the position of maximum bending moment varies between 3.4~5.9 D below the soil surface. The position of the first zero-moment point is about 13.4~19.5 D below the soil surface, which also moves downward with the increase of loading.
3.2.2 Horizontal displacement of pile

Fig. 9 shows the variation of the horizontal displacement of pile at different depths in soil surface of slope 1:4 under lateral loading, which is reduced significantly relative to the level soil surface. Under the uphill loading, the position of the first zero displacement point is about 10 D below the soil surface. Under the downhill loading, the position of the first zero displacement point is about 11~12 D below the soil surface.

![Displacement of pile in soil surface of slope 1:4](image)

(a) Uphill loading  (b) Downhill loading

Fig. 9 The displacement of pile in soil surface of slope 1:4

3.2.3 Horizontal displacement of pile head and soil surface

Fig. 10 shows the horizontal displacement at pile head and soil surface in soil surface of slope 1:4 under lateral loading. As shown in the figure, the relationship of lateral loading and the horizontal displacements at pile head and soil surface shows nonlinear.

![Displacements at pile head and soil surface](image)

Fig. 10 The displacements at pile head and soil surface

3.2.4 Horizontal soil resistance of the pile side

Fig. 11 shows the resistance of soil beside the pile in soil surface of slope 1:4 under lateral loading, which increased with the increase of loading. The position of maximum soil resistance point also moves deeper.

![Resistance of soil beside the pile](image)
the uphill loading, the position of maximum soil resistance point first is located at the soil surface and then moves to 4.7 D below the soil surface. The first zero-resistance point also moves deeper with the increase of loading and varies between 6.8–10.3 D below the soil surface. The resistance of soil surface appears that the topsoil changes from elastic to plastic, and finally destruction as the loading changes as well. Under the downhill loading, the position of maximum soil resistance point varies between 2.1–5.9 D below the soil surface. The first zero-resistance point also moves deeper with the increase of loading and varies between 7.2–12 D below the soil surface. The soil surface resistance increases first and subsequently decreases which reflects the changing process of the topsoil with the changing of the loading.

![Graphs showing soil resistance under uphill and downhill loading](image)

Fig. 11 The distribution of soil resistance beside the pile in soil surface of slope 1:4

3.3 Mechanical characteristics of pile in the soil surface of slope 1:3 under uphill and downhill loading

3.3.1 Bending moment of pile

Fig. 12 shows the variation of the bending moment of pile in soil surface of slope 1:3 under uphill and downhill loading. Under the uphill loading, the position of maximum bending moment of pile varies between 2.1–4.6 D below the soil surface. The position of the first zero-moment point is about 12.1–16.9 D below the soil surface, which moves downward with the increase of loading. Under the downhill loading, the position of maximum bending moment of pile varies between 3.4–7.1 D below the soil surface. The position of the first zero-moment point is about 13.1–19.7 D below the soil surface, which also moves downward with the increase of loading.

3.3.2 Horizontal displacement of pile

Fig. 13 shows the variation of the horizontal displacement of pile at different depths in soil surface of slope 1:3 under lateral loading. As shown in the figure, the displacements of pile are significantly different compared to the other tests. The reverse displacement of the pile appears more obviously and increases with the increases of loading. Under the uphill loading, the position of the first zero-displacement point moves up obviously compared to the other tests and varies between 7–8 D below the soil surface. Under the downhill loading, the position of the first zero-displacement point moves downward and is about 11 D below the soil surface.

3.3.3 Horizontal displacement of pile head and soil surface

Fig. 14 shows the horizontal displacement at pile head and soil surface in soil surface of slope 1:3 under lateral loading. As shown in the figure, the relationship of lateral loading and the horizontal displacements at pile head and soil surface also shows nonlinear.

3.3.4 Horizontal soil resistance of the pile side

Fig. 15 shows the resistance of soil beside the pile in soil surface of slope 1:3 under lateral loading. Under the uphill loading, the position of the maximum soil resistance point is first located at the soil surface and then moves to 4.7 D below the soil surface. The first zero-resistance point also moves deeper with the increase of loading and varies between 6.8–10.3 D below the soil surface. The resistance of soil surface appears that the topsoil changes from elastic to plastic, and finally destruction as the loading changes as well. Under the downhill loading, the position of maximum soil resistance point varies between 2.1–5.9 D below the soil surface. The first zero-resistance point also moves deeper with the increase of loading and varies between 7.2–12 D below the soil surface. The soil surface resistance increases first and subsequently decreases which reflects the changing process of the topsoil with the changing of the loading.
moves to 4.6 D below the soil surface. The first zero-resistance point also moves deeper with the increases of loading and varies between 6.3~12.8 D below the soil surface. The resistance of soil surface increases gradually with the increases of loading. However, the growth rate gradually decreases, which reflects that the topsoil changes from an elastic state to the elastic-plastic state. Under the downhill loading, the position of maximum soil resistance point varies between 3.4~7.1 D below the soil surface. The first zero-resistance point also moves deeper with the increases of loading and varies between 8.3~12.7 D below the soil surface.

![Bending moment and Displacement diagrams](image-url)
4 Effect of slope of soil surface on the horizontal bearing capacity of pile

Some basic changing rules can be understood from the above model test with different slopes. Under the same lateral loading in the downhill direction, when the slope increases, the bending moment of pile increases and the position of maximum bending moment point moves downward. The displacements at pile head and soil surface both increase. Under the same lateral loading in the uphill direction, when the slope increases, the maximum bending moment of pile decreases and the position of maximum bending moment point moves upward. The displacements at pile head and soil surface also decrease. Through the numerical fitting of the measured data in the model tests, the influence of slope of soil surface on some critical design parameters of pile, such as the maximum bending moment of pile, the position of maximum bending moment point, the displacement at pile head, the displacement at soil surface, and the soil resistance beside pile, will be analyzed in this section.

4.1 The influence of slope of soil surface on bending moment of pile

Bending moment of pile is one of the important parameters of pile foundation design under the lateral loading. The data including the value and position of maximum bending moment, and the position of the first
zero-bending moment point are summarized. The data with different slopes are normalized by the data in level soil surface and then fitted to study the influence of slope of soil surface on bending moment of pile.

4.1.1 Maximum bending moment of pile

Because of the differences between the test data and data in practice, the values of maximum bending moment of pile under different slopes and loading are normalized by the maximum bending moment in the level soil surface, we set the value of maximum bending moment of pile in level soil surface, as listed in Table 2.

<table>
<thead>
<tr>
<th>H (N)</th>
<th>tan θ = 0</th>
<th>tan θ = −1/4</th>
<th>tan θ = 1/4</th>
<th>tan θ = −1/3</th>
<th>tan θ = 1/3</th>
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</thead>
<tbody>
<tr>
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<td>0.98111</td>
<td>0.98531</td>
<td>0.97271</td>
<td>1.1377</td>
</tr>
<tr>
<td>200</td>
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<td>1.14531</td>
</tr>
<tr>
<td>300</td>
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</tr>
<tr>
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<td>0.93798</td>
<td>1.16222</td>
</tr>
<tr>
<td>500</td>
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<tr>
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<td>0.92785</td>
<td>1.17625</td>
</tr>
<tr>
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<td>0.97881</td>
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<td>0.92041</td>
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</tr>
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</table>

The exponential, hyperbolic and logarithmic functions have been used to fit the bearing capacity of single pile foundation. These functions all have their advantages and disadvantages. In this study, it was found that the exponential function can fit the bearing capacity well. The fitting equation is as following:

\[
\frac{M_{\text{max},\varphi}}{M_{\text{max},0}} = \frac{2 + e^{\tan\theta}}{3}
\]

where: \( M_{\text{max},\varphi} \) is the maximum bending moment of pile in inclined surface with slope \( \varphi \), \( M_{\text{max},0} \) is the maximum bending moment of pile in level soil surface.

Fig. 16 shows the fitting curve and the measured data points. The fitting results are in good agreement with the measured data. The correlation coefficient is 0.952.

4.1.2 Position of maximum bending moment of pile

Based on the state of the level soil surface, we express The position of maximum bending moment of pile under different slopes of inclined surface and loading are normalized by the data in the horizontal ground surface. The fitting equation with the slope \( \varphi \) is as following:

![Fig. 16 The fitting curve of the maximum bending moment of pile](image-url)
\[
\frac{z_{M,\theta}}{z_{M,0}} = 1 + 0.75 \tan \theta
\]  \hspace{1cm} (2)

where: \( z_{M,\theta} \) is the position of maximum bending moment of pile in inclined surface with slope \( \theta \), \( z_{M,0} \) is the position of maximum bending moment of pile in level soil surface.

Fig. 17 shows the fitting curve and the measured data points. The fitting results are in good agreement with the measured data. The correlation coefficient is 0.962.

\[\tan \theta = 0.75 \tan \theta_0 + 0.06 \] \hspace{1cm} (3)

where: \( z_{M,\theta} \) is the position of maximum bending moment of pile in inclined surface with slope \( \theta \), \( z_{M,0} \) is the position of maximum bending moment of pile in level soil surface.

Fig. 17 The fitting curve of the position of maximum bending moment of pile

4.1.3 Position of the first zero bending moment of pile under the soil surface

According to the position of juncture at the positive and negative bending moment of pile in the bending moment diagram, we can approximately calculate the position of the first zero-bending moment point under different soil surface slopes and loading levels through linear interpolation. The position is also converted into the dimensionless form. The fitting formula with the slope \( \theta \) is as following:

\[\frac{z_{M0,\theta}}{z_{M0,0}} = 1.06 - 0.06e^{-3\tan \theta} \]  \hspace{1cm} (4)

where: \( z_{M0,\theta} \) is the position of the first zero-bending moment point of pile in inclined surface with slope \( \theta \), \( z_{M0,0} \) is the position of the first zero-bending moment point of pile in level soil surface.

Fig. 18 shows the fitting curve and the measured data points. The fitting results are in good agreement with the measured data. The correlation coefficient is 0.891.

Fig. 18 The fitting curve of the position of the first zero bending moment point of pile

4.2 The influence of slope of soil surface on displacement of pile

Displacement of pile is also an important parameter of single pile foundation design under the lateral loading. The data including the displacements at pile head and soil surface, and the position of the first-zero displacement point. Those data are fitted with the change of slope based on the corresponding state of the level soil surface. The influence of soil surface slope on displacement of pile is studied.
4.2.1 Displacement at pile head
As shown in the fig. 6, 10 and 14, the influence of soil surface slope on displacement at pile head is very clear. We convert the displacement of pile head under different soil surface slopes and loading levels to the dimensionless form. The fitting formula with the soil surface slope $\theta$ is as following:

$$\frac{y_{H,\theta}}{y_{H,0}} = \frac{1 + 4e^{tan\theta}}{5}$$  \hspace{1cm} (4)

where: $y_{H,\theta}$ is the displacement at pile head in inclined surface with slope $\theta$, $y_{H,0}$ is the displacement at pile head in level soil surface.

Fig. 19 shows the fitting curve and the measured data points. The fitting results are in good agreement with the measured data. The correlation coefficient is 0.935.

![Fig. 19 The fitting curve of the displacement of pile head](image1)

4.2.2 Displacement at soil surface
The change rule of displacement at soil surface with the slope is consistent with the displacement at pile head. The influence of soil surface slope on the displacement at soil surface is very obvious as well. We convert the displacement at soil surface under different soil surface slopes and loading levels to the dimensionless form. The fitting formula with the soil surface slope $\theta$ is as following:

$$\frac{y_{0,\theta}}{y_{0,0}} = \frac{-1 + 6e^{tan\theta}}{5}$$  \hspace{1cm} (5)

where $y_{0,\theta}$ is the displacement at soil surface in inclined surface with slope $\theta$, $y_{0,0}$ is the displacement at soil surface in level soil surface.

Fig. 20 shows the fitting curve and the measured data points. The fitting results are in good agreement with the measured data. The correlation coefficient is 0.946.

![Fig. 20 The fitting curve of the displacement of soil surface](image2)
5 Conclusions and recommendations

Through the model test of the horizontal bearing capacity of the single pile foundation in the soils with different gradients, the mechanical characteristics of the pile are systematically investigated. A correction formula is developed in this paper, based on the level soil surface about the displacement at soil surface and pile head, and the maximum bending moment. The proposed correction formula is based on the test values about the same pile and soil in the level soil surface, so the soil classification or properties, the friction etc. are coincident and needn’t be considered. The formula can provide a theoretical reference for single pile foundation design and calculation in the actual project. Some preliminary works have been conducted and discussed.

Some problems remain further investigated, including:

1. The indoor model test needs to be further improved. We have studied the horizontal mechanical characteristics of single pile in the slope surface of homogeneous sand soil only. The clay has not been complemented. Due to the limitation of test conditions, we only analyze the state of free pile head surface and the state of the fixed pile head. A hinged one should be considered in the future. In addition, we have analyzed the state of pile with specific length and diameter. Parametric study on the length or diameter needs to be performed.

2. We have investigated the horizontal mechanical characteristics of a single pile in the inclined surface only. However, the pile foundation in practice is mainly in the form of pile group. The mechanical characteristics of the pile in a pile group are different from that of a single pile because of the group effect, which is worth further investigating.

References: