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Research Article

A Simplified Nonlinear Method for a Laterally Loaded Pile in Sloping Ground

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A simplified nonlinear method was proposed to evaluate lateral behavior of a pile located in or nearby a slope, based on the traditional *p-y* method. This method was validated with field test results of a steel pipe pile in clay and model tests of piles in sand slopes. The comparison indicated that the calculated horizontal displacement and bending moment of piles agree well with experimental results. Then, parametric studies were performed, and it shows that horizontal displacement, rotation, bending moment, and shear force increase along with increasing slope angles; the depth of maximum moment locates at about 1.6 D below ground surface for horizontal ground, while this value turns to be about 3.6 D and 5.6 D for sloping ground of 30° and 60°, respectively. The study clearly shows that slope angle has a significant effect on the deflection and lateral capacity of piles.

1. Introduction

The urban infrastructure development in China increases the possibility to construct piles in or nearby slopes, to support bridges, high-rise buildings, transmission towers, off-shore structures, retaining walls, etc. [1–5]. The lateral bearing behavior of these piles is extremely complicated due to sloping ground [6–8]. Compared to conventional piles, they may undergo severe reduction in horizontal bearing behavior. Although conventional laterally loaded piles have been studied by many researchers [9–15], limited literature can be found for piles in sloping ground [16–23]. In the past, the lateral behavior of piles could be evaluated with assumed earth pressure distribution, which can also be determined from field or model tests. This method usually assumes linearly increasing subgrade reaction modulus and cannot account for the influence of sloping ground. Thus, further studies have to be carried out to fill this gap.

This paper presented a simplified *p-y* method of laterally loaded piles located in or nearby slopes. A field test result of a steel pipe pile in clay and small-scale pile tests in sand slopes were employed to verify the proposed method and to assess the influence of slope angles on the maximum deflection and required length of a pile.

2. The *p-y* Analysis for Sloping Ground

For a laterally loaded pile, the *p-y* method is a simple and practical way to account for the relationship between soil reaction p and pile deflection y along pile shaft. The *p-y* curve can be measured in field, by loading cells installed on pile-soil interface, or stress meters installed on steel cages as proposed by McClelland and Focht [24].

2.1. The p-y Curve of Clay Slopes. According to field test results, a *p-y* curve of Houston soft clay was proposed by Matlock, as shown in Figure 1, and has been adopted by the American Petroleum Institute (API). It can be expressed as follows [9, 10, 25]:

$$\frac{p}{p_{\text{ult}}} = \begin{cases} 0.5\left(\dfrac{y}{y_{50}}\right)^{1/3}, & (y \le 8y_{50}) \\ 1, & (y > 8y_{50}), \end{cases} \tag{1}$$

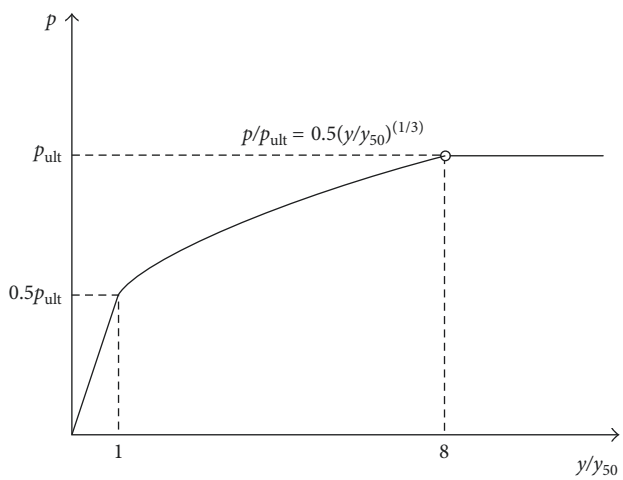


Figure 1: The p-y curve proposed by Matlock [9].

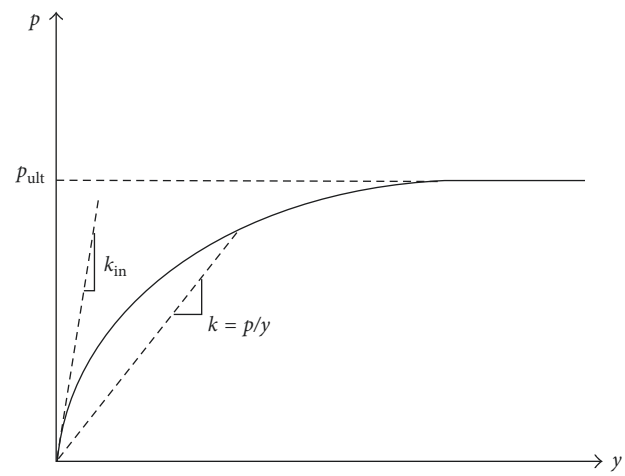


Figure 2: Hyperbolic p-y model.

where p is the soil reaction; y is the pile deflection; p_{ult} is the ultimate soil resistance; p/p_{ult} is the ratio of soil resistance; y/y_{50} is the ratio of pile deflection; and y_{50} is the pile deflection when soil resistance reaches 50% of its ultimate value, and it can be evaluated by the following equation:

$$y_{50} = 2.5\varepsilon_{50}d, \tag{2}$$

where ε_{50} is the strain when the soil resistance reaches a half of its ultimate value and d is the pile diameter.

When a laterally loaded pile locates in a clay slope of a slope angle θ, the ultimate soil resistance in front of a pile can be computed by the following equation [24, 26]:

$$p_{ult} = \begin{cases} (2c_u d + \gamma d z + 2.83 c_u z)\dfrac{1}{1+\tan\theta}, & z < z_r \\ 9dc_u, & z \geq z_r, \end{cases} \tag{3}$$

where c_u is the average undrained shear strength; γ is the average unit weight of soil; z is the depth from ground surface to a studied point on the pile; θ is the slope angle; and z_r can be computed by the following equation:

$$z_r = \frac{(7 + 9\tan\theta)c_u d}{\gamma d + 2.83c_u}. \tag{4}$$

2.2. The p-y Curve of Sand Slopes. A hyperbolic model was proposed to best-fit normalized p-y curves for laterally loaded piles in sand ground, as shown in Figure 2. This p-y curve is featured with an initial stiffness k_{in} and the relevant equation is as follows [27–32]:

$$p = \frac{y}{(1/k_{in}) + (y/p_{ult})}, \tag{5}$$

where k_{in} is the initial stiffness, which depends on the soil stiffness, the pile stiffness, and the pile diameter. The initial stiffness, k_{in}, can be assumed to increase linearly with depth in sands as [33–35]:

$$k_{in} = n_h z, \tag{6}$$

where n_h is the coefficient of horizontal subgrade reaction, which is related to the internal friction angle, the relative density, etc. n_h can be determined according to internal angle and relative density of sands [26].

The ultimate soil resistance in front of a pile located in sand slope can be described by the following equation [24, 26]:

$$\begin{aligned} p_{fult} = {} & \gamma z\left[\frac{K_0 z\tan\phi\sin\beta}{\tan(\beta-\phi)\cos\alpha}\left(4D_1^3 - 3D_1^2 + 1\right)\right] \\ & + \gamma z\left[\frac{\tan\beta\left(dD_2 + z\tan\beta\tan\alpha D_2^2\right)}{\tan(\beta-\phi)}\right] \\ & + \gamma z\left[K_0 z\tan\beta(\tan\phi\sin\beta - \tan\alpha)\left(4D_1^3 - 3D_1^2 + 1\right)\right. \\ & \left. - K_a d\right], \end{aligned} \tag{7}$$

where

$$\begin{aligned} D_1 &= \frac{\tan\beta\tan\theta}{\tan\beta\tan\theta + 1}, \\ D_2 &= 1 - D_1 = 1 - \frac{\tan\beta\tan\theta}{\tan\beta\tan\theta + 1}, \\ K_a &= \cos\theta\frac{\cos\theta - \sqrt{\cos^2\theta - \cos^2\phi}}{\cos\theta + \sqrt{\cos^2\theta - \cos^2\phi}}, \end{aligned} \tag{8}$$

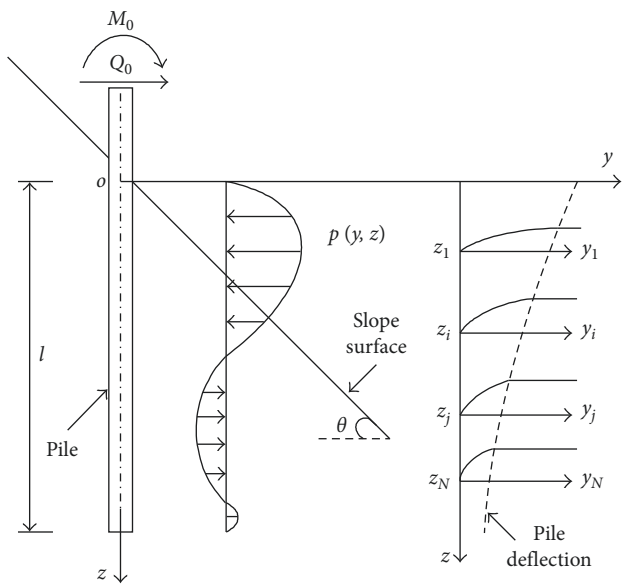


Figure 3: Simplified p-y model of laterally loaded piles in sloping ground.

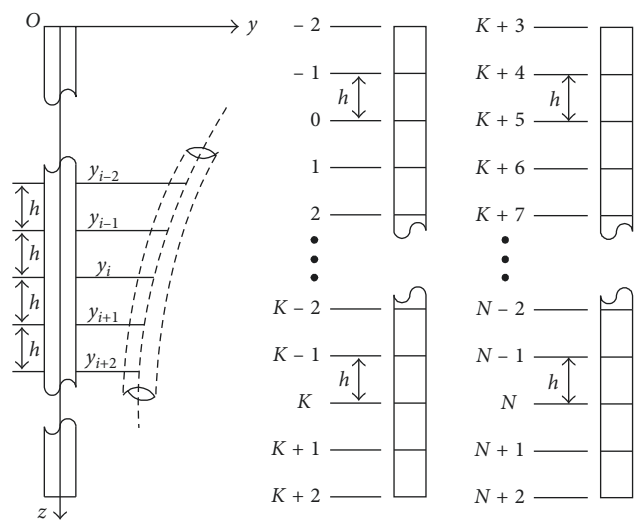


Figure 4: Deflection and differential points of the pile.

where K_0 is the coefficient of static earth pressure; ϕ is the internal friction angle; $\beta = 45^\circ + (\phi/2)$; and α is the angle of the wedge. Bowman [36] suggested that $\alpha = \phi/3 \sim \phi/2$ for loose sand and $\phi/2 \sim \phi$ for dense sand; K_a is the coefficient of active earth pressure.

3. Simplified *p-y* Method of Laterally Loaded Pile in Sloping Ground

3.1. Basic Equations. Assuming that the slope is stable and ignoring friction on the pile, a simplified method for laterally loaded piles in sloping ground can be established as shown in Figure 3. This yields to the differential equation as follows [20, 26]:

$$\mathrm{EI}\frac{d^4 y}{dz^4} + dp_i(y, z) = 0, \tag{9}$$

where EI is the flexural stiffness of a pile and $p_i(y, z)$ is the soil resistance of sloping ground.

3.2. Boundary Conditions. The boundary condition at pile top can be free, hinged, and partially or fully fixed, while that at pile toe can be fixed or hinged [20, 26]. In this paper, a bending moment M_0 and a shear force Q_0 are considered as external load on the pile head, and the pile toe is fixed, which yields to the following boundary conditions:

Free pile top:

$$\begin{aligned} \mathrm{EI}Y''\big|_{z=0} &= M_0, \\ \mathrm{EI}y'''\big|_{z=0} &= Q_0. \end{aligned} \tag{10}$$

Fixed pile toe:

$$\begin{aligned} y\big|_{z=l} &= 0, \\ y'\big|_{z=l} &= 0. \end{aligned} \tag{11}$$

3.3. Finite Difference Solution. Subdividing the pile into N sections, the length of each section is $h = l/N$, as shown in Figure 4. According to the principle of the central difference method, two virtual nodes are added at the pile head and toe, respectively. Thus, there are $N+1$ nodes on the pile shaft (node number: from 0 to N), 2 virtual nodes at the top (node number: −2 and −1), and another 2 virtual nodes at the toe (node number: $N+1$ and $N+2$).

Let the horizontal displacement at each node be y_i (where $i = 0 \sim n$), then (9) can be rewritten as

$$y_{i-2} - 4y_{i-1} + 6y_i - 4y_{i+1} + y_{i+2} + \frac{h^4 dp_i(y, z)}{\mathrm{EI}} = 0. \tag{12}$$

The slope, φ_i, the moment, M_i, and the shear force, Q_i, along the pile shaft can be obtained by using the difference method:

$$\begin{aligned} \varphi_i &= \frac{(y_{i+1} - y_{i-1})}{2h}, \\ M_i &= \frac{(y_{i-1} - 2y_i + y_{i+1})\mathrm{EI}}{h^2}, \\ Q_i &= \frac{(-y_{i-2} + 2y_{i-1} - 2y_{i+1} + y_{i+2})\mathrm{EI}}{2h^3}. \end{aligned} \tag{13}$$

The boundary conditions of the pile, namely, (10) and (11), can also be rewritten as follows:

$$\begin{aligned} y_1 - 2y_0 + y_{-1} &= \frac{M_0 h^2}{EI}, \\ y_2 - 2y_1 + 2y_{-1} - y_{-2} &= \frac{2Q_0 h^3}{EI}, \end{aligned} \tag{14}$$

$$\begin{aligned} y_n &= 0, \\ y_{N+1} - y_{N-1} &= 0. \end{aligned} \tag{15}$$

Then, we can establish the basic equation of the pile as

$$[K]\{y\} = \{F\}, \tag{16}$$

where $\{F\}$ is the matrix of load at pile nodes and $[K]$ is the horizontal stiffness matrix. These two matrices are as follows:

$$\{F\} = \left[\frac{2Q_0h^3}{\mathrm{EI}}, \frac{M_0h^2}{\mathrm{EI}}, 0, \ldots, 0, \ldots, 0\right]^T,$$

$$[K] = \begin{bmatrix} -1 & 2 & 0 & -2 & 1 & & & & \\ 0 & 1 & -2 & 1 & 0 & & & & 0 \\ 1 & -4 & 6+\lambda A_0 & -4 & 1 & & & & \\ 0 & 1 & -4 & 6+\lambda A_1 & -4 & 1 & & & \\ & & 1 & -4 & 6+\lambda A_2 & -4 & 1 & & \\ & & & & \vdots & \vdots & \vdots & & \\ & & & & 1 & -4 & 6+\lambda A_N & -4 & 1 \\ & 0 & & & 0 & -1 & 0 & 1 & 0 \\ & & & & & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{17}$$

where

$$\begin{aligned} A_0 &= 2 + \frac{\lambda}{1/k_0 + y_0/p_{\mathrm{ult}_0}}, \\ A_1 &= 5 + \frac{\lambda}{1/k_1 + y_1/p_{\mathrm{ult}_1}}, \\ A_i &= 6 + \frac{\lambda}{1/k_i + y_i/p_{\mathrm{ult}_i}}, \\ A_{N-1} &= 5 + \frac{\lambda}{1/k_{N-1} + y_{N-1}/p_{\mathrm{ult}_{N-1}}}, \\ A_N &= 2 + \frac{\lambda}{1/k_N + y_N/p_{\mathrm{ult}_N}}, \\ \lambda &= \frac{dh^4}{EI}, \quad i = 0 \sim N. \end{aligned} \tag{18}$$

Then, (16) can be rewritten as

$$\begin{bmatrix} -1 & 2 & 0 & -2 & 1 & & & & \\ 0 & 1 & -2 & 1 & 0 & & & & 0 \\ 1 & -4 & 6+\lambda A_0 & -4 & 1 & & & & \\ 0 & 1 & -4 & 6+\lambda A_1 & -4 & 1 & & & \\ & & 1 & -4 & 6+\lambda A_2 & -4 & 1 & & \\ & & & & \vdots & \vdots & \vdots & & \\ & & & & 1 & -4 & 6+\lambda A_N & -4 & 1 \\ & 0 & & & 0 & -1 & 0 & 1 & 0 \\ & & & & & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} y_{-2} \\ y_{-1} \\ y_0 \\ \vdots \\ \vdots \\ \vdots \\ y_N \\ y_{N+1} \\ y_{N+2} \end{bmatrix} = \begin{bmatrix} \frac{2H_0h^3}{\mathrm{EI}} \\ \frac{M_0h^2}{\mathrm{EI}} \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{19}$$

The horizontal displacement, y_i, slope, φ_i, bending moment, M_i, and shear, Q_i, at each pile node can be solved by (19) by using an iteration process as shown in Figure 5. The iteration criterion is indicated as ε in the process.

4. Case Studies

4.1. Field Test in Clay. The field test result of a steel pipe pile in clay by Matlock [9] was used to verify the proposed method. Parameters adopted in this analysis are as follows: the diameter, $d = 0.324$ m; the wall thickness of the pipe, $t = 12.7$ mm; the bending rigidity, $\mathrm{EI} = 31.28\ \mathrm{MN{\cdot}m^2}$; the length, $l = 12.81$ m; the average unit weight of soils,

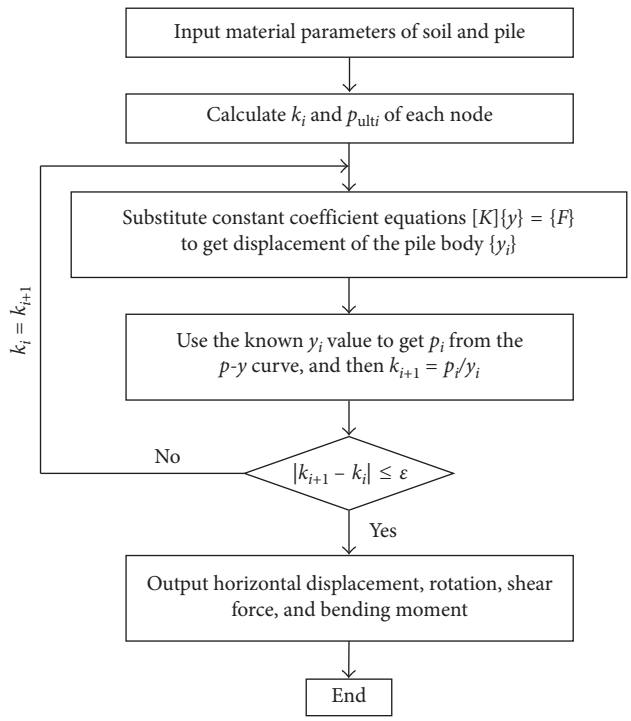


Figure 5: Iteration flowchart.

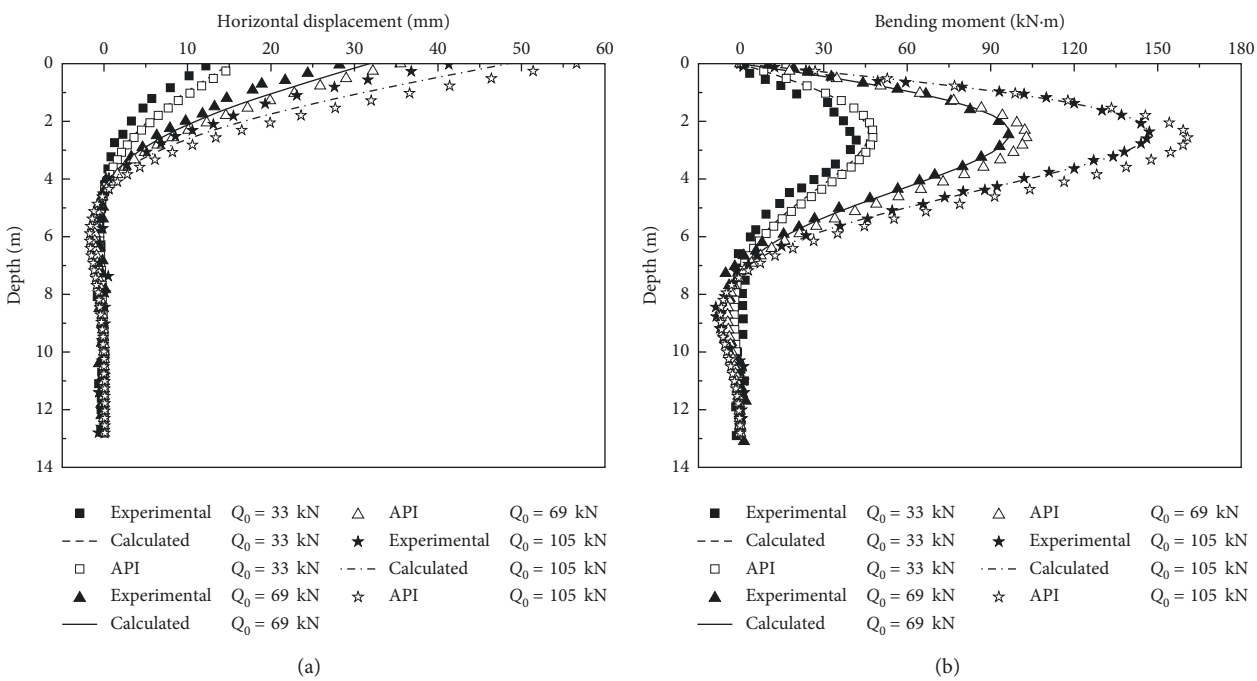
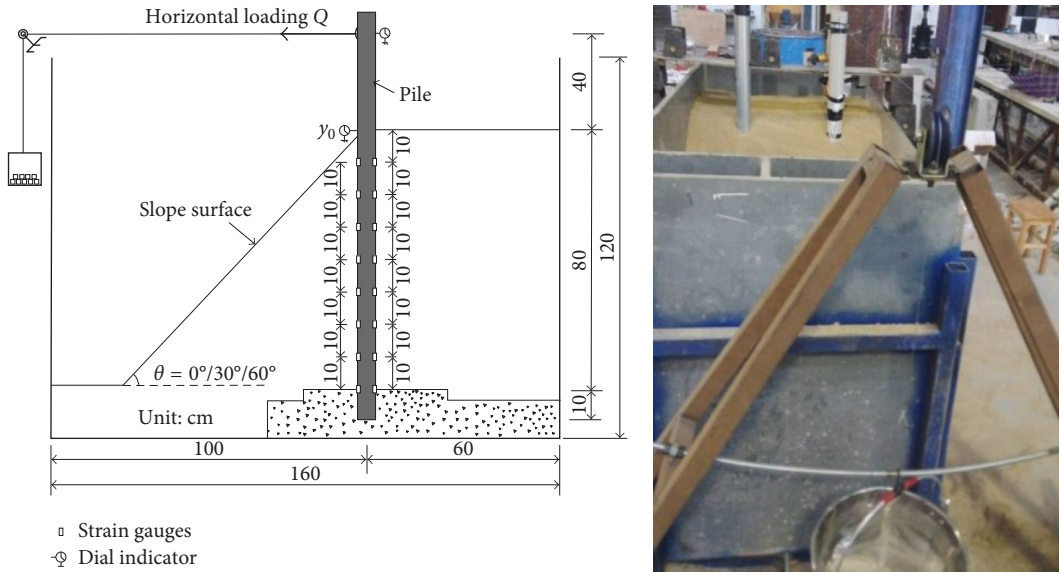


Figure 6: The comparison of the horizontal displacement (a) and bending moment (b).

$\gamma = 18\,\text{kN/m}^3$; the undrained strength of soils, $c_u = 39.1$ kPa; $\varepsilon_{50} = 0.012$; and the slope angle, $\theta = 0^\circ$. The comparison between the calculated and measured pile deflection and the bending moment is plotted in Figure 6.

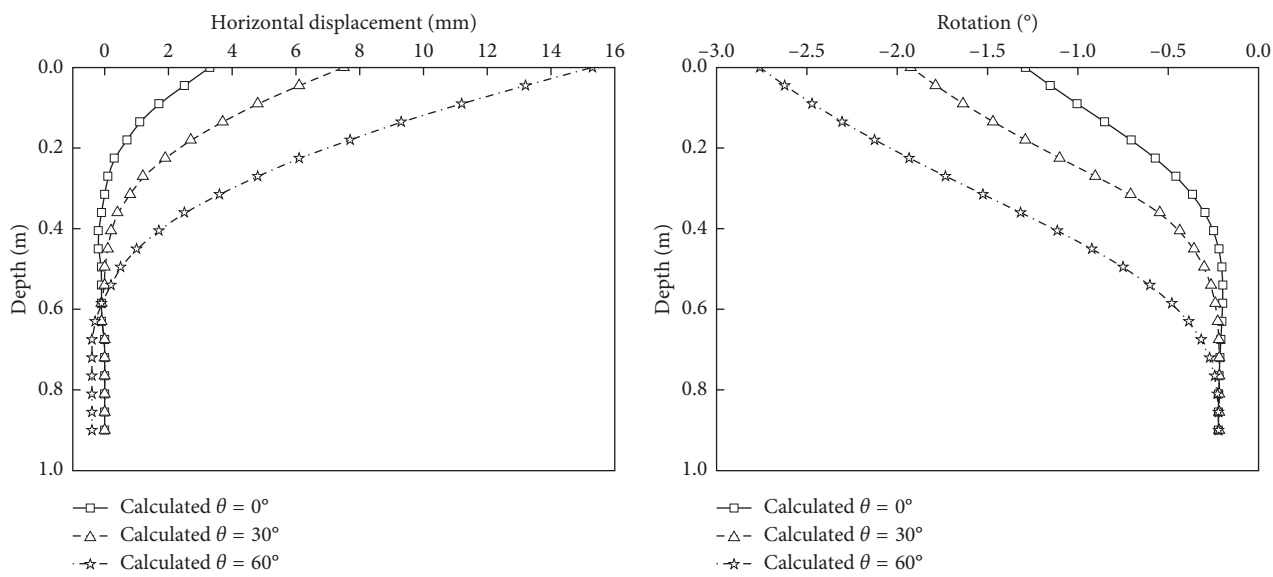
It is clear in Figure 6 that the calculated horizontal displacement and bending moment agree well with the measured and API method.

4.2. Model Tests of Piles in Sand Slopes. The objective of the model tests is to verify the proposed method. The model piles were made by the PPR (polypropylene random) pipe, which is of 63 mm in outside diameter, 58 mm in inner diameter, and 1680 MPa in elastic modulus. The total length of piles is 1200 mm, and the embedded depth is 900 mm, as shown in Figure 7. The model slope was filled by sand using



(a) (b)

Figure 7: Layout of model tests: (a) profile of the model tests; (b) loading frame.



(a) (b)

Figure 8: Continued.

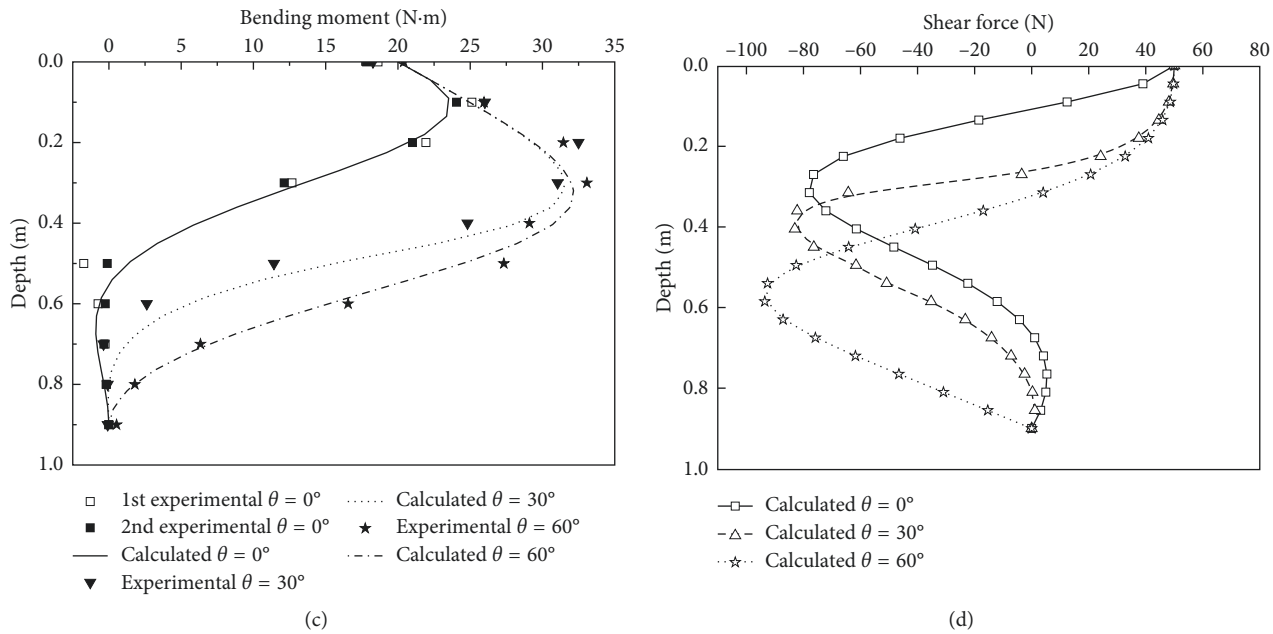


Figure 8: Pile behavior under the horizontal load, $Q_0 = 50$ N: (a) horizontal displacement; (b) rotation; (c) bending moment; (d) shear force.

Table 1: Comparison of pile behavior between the proposed method and the model tests.

Method	Horizontal displacement y_0 (mm)			Maximum bending moment M_{max} (N·m)		
Slope angle θ (°)	0	30	60	0	30	60
Experimental	3.2	7.6	18.2	24.1	32.5	33.1
Calculated	3.3	7.5	15.3	23.5	31.6	32.2
Absolute error (%)	3.1	1.3	15.9	2.5	2.7	2.7

the rainfall method. The physical and mechanical properties of the sand were tested in laboratory, including the moisture content, $w = 2.43\%$; the internal friction angle, $\phi = 39^\circ$; the unit weight of sand, $\gamma = 15.65\,\text{kN/m}^3$; the relative density, $D_r = 0.81$; and the coefficient of horizontal subgrade reaction, $n_h = 70\,\text{MN/m}^3$. The laboratory test carried out and the details of the model test preparation have been presented in the reference [37]. The predicted horizontal displacement and bending moment of piles are compared to the measured in Figure 8 and Table 1.

We can learn from Figure 8 and Table 1 that the pile head deflection and bending moment predicted by the proposed method agree well with the measured in the model tests, and the discrepancy is 2.7% for bending moment and 15.9% for pile head deflection.

As we can learn from Figure 8, the depth of the maximum moment increases from about 10 cm (1.6 D, D is the pile diameter) below ground level in even ground ($\theta = 0^\circ$) to 22.5 cm (3.6 D) and 36 cm (5.6 D) below ground level in sloping ground of 30° and 60° in slope angle, respectively.

The results also show that the pile head deflection on slope surface rises from 3.3 mm in even ground ($\theta = 0^\circ$) to 7.5 mm (127%) and 15.3 mm (364%) in sloping ground of 30° and 60° in angle, respectively; the rotation at the top of the pile rises from −1.15° in even ground ($\theta = 0^\circ$) to −1.84° ($\theta = 30^\circ$) and −2.74° ($\theta = 60^\circ$) in sloping ground; the maximum bending moment increases from 23.5 N·m in even ground ($\theta = 0^\circ$) to 31.6 N·m ($\theta = 30^\circ$) and 32.2 N·m ($\theta = 60^\circ$) in sloping ground, which are 34% and 37% increase, respectively; the maximum shear force increases from −78 N in even ground to −83 N ($\theta = 30^\circ$) and −93 N ($\theta = 60^\circ$) in sloping ground.

5. Conclusion

A simplified p-y method of piles located in slopes was proposed and solved using difference method in this paper. The proposed method was verified by the field tests of a steel pipe pile in clay and the model tests of piles in sand slopes. The main influence factor, namely, the slope angle, was discussed by parametric study. The results indicate that the horizontal displacement, rotation, bending moment, and shear force increase with increasing slope angle; the depth of maximum moment is about 1.6 D below ground level for even ground and about 3.6 D and 5.6 D for sloping ground of 30° and 60°, respectively. It is suggested that steep slope should be avoided when designing a laterally loaded pile in sloping ground.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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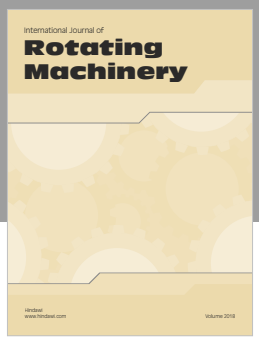

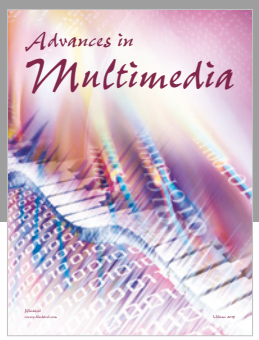

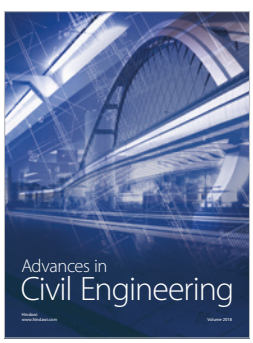

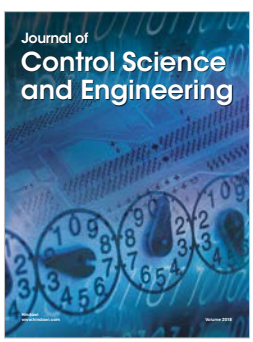

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