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Evaluation method for elastic foundation coefficient of finite downslope soil against loading segment of stabilizing piles

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Abstract: In order to determine the lateral elastic foundation coefficient of the finite soil mass against the loading pile segment, based on the proportion coefficient of the foundation coefficient of the infinite soil mass, the laterally loaded beam-on-elastic-foundation method for a stabilizing pile is adopted in combination with the upper bound limit analysis method under the consideration of the internal forces and deformation continuity of the whole pile element. Thus, a method to calculate the proportion coefficient of the lateral elastic foundation coefficient of the finite soil mass is provided. The relationship between the proportion coefficient and the slope angle of the finite soil mass is determined. The proposed method is verified by a numerical simulation of a practical example. A series of numerical simulations with various physical and mechanical parameters of soil mass and stabilizing pile have been conducted to study their effect on the proportion coefficient. Analysis results of the example show that the proportion coefficient decreases nonlinearly with the increase in the slope angle of the local soil. In addition, the length of embedded segment (below the slip surface) and the size of cross section of stabilizing piles, cohesion, internal friction angle, and unit weight of the local soil also affect the proportion coefficient. The influence of the unit weight is slight, while other factors have significant positive correlations with the proportion coefficient.

Keywords: stabilizing pile; loading segment of a pile; finite soil mass; elastic foundation coefficient; limit analysis

1 Introduction

Stabilizing pile is one of the common methods to prevent landslides. The finite soil mass (local soil slopes) often exists in front of the piles. Therefore, a reasonable estimation of the resistance of the finite soil mass is significant for the analysis of the internal force of the pile. This resistance can generally be taken as the minimum value of passive earth pressure, residual sliding resistance, and elastic resistance[1]. The former two can be determined by the limit equilibrium theory, and the latter is restricted by the lateral elastic foundation coefficient of the finite soil mass. Therefore, the determination of the proportion coefficient m against the lateral elastic foundation coefficient is an essential to make a reasonable analysis of the forces and deformation of the pile. Among all the methods to calculate the value of m, the field horizontal load test of a pile is the most reliable one in practice [2]. The test usually yields the value of m under infinite soil (the soil mass is large enough). However, in some cases, the lateral pile (loading segment) often has very limited local soil. In the absence of test conditions, its m value is often approximated from the Table[2] of m values based on infinite downslope soil tests, which obviously has irrationality. Therefore, it is necessary to discuss the method of calculating the proportion coefficient of the lateral elastic foundation coefficient of the finite soil mass.

Xing et al. [3] analyzed the CPT data of Tianjin area using statistical method, and obtained the relationship between the CPT readings and the value of m. The empirical relationship between m and the readings was revealed, but m was not directly determined. In order to solve the problem of calculating m value of the horizontally loaded piles in multi-layer foundation, Dai et al.[4] proposed the finite element method and the finite element method of the elastic foundation rod system to calculate the displacement and stress, which provides a reference for calculating the displacement and stress of the pile in practice. Wu et al.[5] found that the value of m has an exponential relationship with the displacement of pile based on field measured data. Based on the experimental results of the horizontal bearing capacity load of group piles, Huang et al. [6] proposed a method to calculate m along the depth of the pile based on the diameter of the pile, the displacement of the pile, the undrained shear strength. Lou et al.[7] provided a method at a given allowable level to determine the value of m according to the pile diameter, the undrained shear strength of the foundation and its distribution pattern along the depth under displacement. But this method is only applicable to soils under certain conditions. Yu et al.[8] studied group bearing characteristics through laboratory tests, and the result show that the value of m decreases with increasing slope. But due to the limited test data, the curve cannot determine the specific variations. Yin et al.[9] designed and conducted a series of model tests on horizontal bearing capacity of rigid piles on slope foundations, in which

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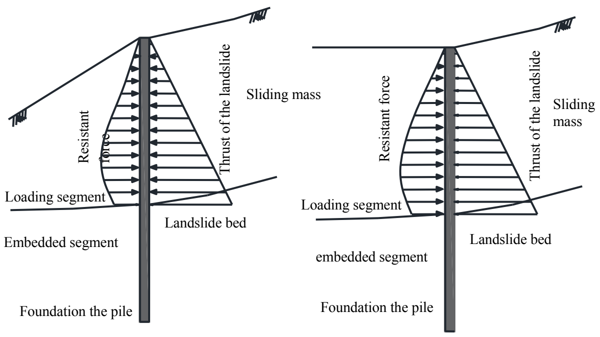
they measured m values under different slope gradients and horizontal load angles, and explored the effects of slope gradients and horizontal load effects on m values. Unfortunately, the model only considers the relationship between the displacement at the top of the pile and m, and lacks the analysis of the displacement of the whole pile.

In summary, there have been extensive studies on the proportion coefficient m of the elastic foundation coefficient on a flat ground (infinite soil). But studies on the value of the proportion coefficient of the elastic foundation coefficient with a finite soil mass in front of the pile are still lacking, particularly in theory. For this reason, based on the foundation coefficient method of the stabilizing pile, combined with plastic limit analysis, the method to calculate the proportion coefficient m of piles with finite soil mass is proposed in which the flat ground foundation coefficient (determined by experiments) is used as a reference. In addition, sensitivity analysis is conducted to evaluate the influence of the slope of the local soil of the pile, rock and soil and pile parameters on m, which provides a reference for the corresponding m value under the condition of finite soil mass of the stabilizing pile.

2 Theoretical analysis

As shown in Fig.1 (a), there is a stabilizing pile model to analyze the local soil in front of the pile. While the stabilizing pile is subjected the thrust of the landslide, the front side of the pile is also affected by the soil resistant force. It should be noted that this resistant force is different from the infinite soil situation (Fig.1 (b)).



(a) Finite soil condition (b) Infinite soil condition

Fig.1 Analysis models of stabilizing piles

For the latter case, the foundation coefficient method can be used to analyze the stabilizing piles in which the foundation coefficient of soil in front of the pile is the proportion coefficient m of the resistance coefficient of the flat ground foundation. The m value is given in table form in many literatures according to the soil type. But for the case in Fig.1(a) (limited soil in front of the pile), the following general steps can be used:

(1) In the case of an infinitely long slope on the horizontal ground in front of the pile, the stabilizing pile is analyzed with the full-length foundation coefficient method with the two-segment (loaded segment and embedded segment), and the elastic resistant combined force R_{e0} of the soil in front of the pile is obtained by the power series method[10].

(2) The upper limit method of plastic limit analysis[11] can used to solve the passive ultimate resistance of the soil in front of the pile in the loaded segment, and its value was R_{u0}.

(3) Assume that the foundation coefficient in front of the pile in the load segment is linearly related with depth, the ratio of coefficient and depth is a constant.

(4) The power series method[10] is used to solve the elastic resistant combined force when the finite soil is in front of a pile.

(5) The limit analysis method[11] is used to solve the passive limit resistant force of the finite soil mass in front of the pile.

(6) It is assumed that in the case of finite soil mass the relative relationship between its elastic resistant force $R_{e\beta}$ and passive ultimate resistant force $R_{u\beta}$ is the same as in the case of an infinitely long slope on the horizontal ground in front of the pile, that is, $R_{e\beta} / R_{u\beta} = R_{e0}/R_{u0}$, and the value m_β can be determined.

The following analyzes and explains the calculation methods of each key step.

2.1 Power series method for elastic resistant force in front of the pile

In order to facilitate the analysis of the problem, the soil-like sliding body is taken as the research object here. The landslide thrust can be considered as a triangle distribution [12]. The bottom of the pile is considered to as the free end. The bending moment is positive when the left side of the pile is subjected to tensile stress, and the positive shear stress is defined with clockwise direction [13]. The pile top does not bear any vertical load, and vertical stress is not considered in the analysis. The pile body microelement analysis model is shown in Fig.2.

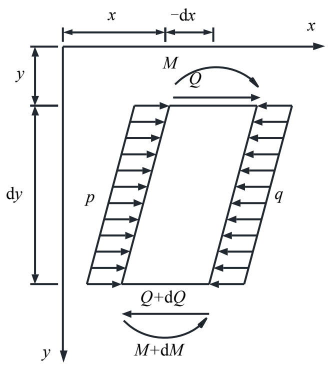


Fig.2 Analysis model of a pile element

According to the equilibrium condition of the force of the differential element, the differential equation of the pile deflection can be obtained as[10]

$$EI\frac{d^4 x}{d y^4} = p - q \quad (1)$$

where x is the horizontal displacement of the pile; y is the depth from the top of the pile; p is the landslide thrust of the slope; q

is the resistant force of the rock and soil; EI is the bending stiffness of the stabilizing pile; E is the elastic modulus of the pile; and I is the moment of inertia of the pile section.

By simplifying Eq. (1), we get

$$\frac{\mathrm{d}^4 x}{\mathrm{d}y^4}=\frac{2E_{\mathrm{n}}}{EI\cdot H_1^2}y-\frac{m_\beta B_{\mathrm{p}}}{EI}xy \tag{2}$$

where E_{n} is the combined thrust acting on the back side of the stabilizing pile; H_1 is the length of the embedded segment; B_{p} is the calculated width of the stabilizing pile.

Assume that the power series solution of the displacement of the pile is: $x=\sum_{i=0}^{\infty}a_i y^i$, where a_i is the coefficient of the term, i represents the number of power series expansion terms, and takes a non-negative integer.

According to Euler-Bernoulli beam theory and boundary bars at the top of the pile, let $\delta=\frac{2E_{\mathrm{n}}}{EI\cdot H_1^2}$, $\alpha^5=\frac{m_\beta B_{\mathrm{p}}}{EI}$. Where δ is the simplification coefficient and α is the lateral deformation coefficient of the pile, then Eq. (2) can be sorted as

$$\sum_{i=4}^{\infty}i(i-1)(i-2)(i-3)a_i y^{i-4}=\delta y-\alpha^5\sum_{i-0}^{\infty}a_i y^{i+1} \tag{3}$$

According to the identity condition of Eq. (3), the coefficient a_0 - a_i is

$$\left.\begin{aligned}&a_0=x_0,\ a_1=x_1=\varphi_0,\ a_2=\frac{M_0}{2EI}=0\\&a_3=\frac{Q_0}{6EI}=0,\ a_4=0,\ a_5=\frac{1}{5!}(\beta-\alpha^5 a_0)\\&a_i=-\frac{\alpha^5}{i(i-1)(i-2)(i-3)}a_{i-5}\end{aligned}\right\} \tag{4}$$

In the equation: x_0, φ_0 , M_0 and Q_0 are the horizontal displacement, corner, bending moment and shear force at the top of the pile, respectively.

Let $a_i=c_{1,i}x_0+c_{2,i}\varphi_0+c_{3,i}$, then

$$c_{n,i}=-\frac{\alpha^5}{i(i-1)(i-2)(i-3)}c_{n,i-5}\ (n=1,2,3;\ i\geqslant 6) \tag{5}$$

In the equation: $c_{n,i}$ is the calculation coefficient of a_i.

Furthermore, the calculation equations for the displacement and internal force of the arbitrary section of the loading pile are

$$\left.\begin{aligned}x(y)&=A_{1,1}x_0+A_{2,1}\varphi_0+A_{3,1}\\\varphi(y)&=A_{1,2}x_0+A_{2,2}\varphi_0+A_{3,2}\\M(y)&=EI(A_{1,3}x_0+A_{2,3}\varphi_0+A_{3,3})\\Q(y)&=EI(A_{1,4}x_0+A_{2,4}\varphi_0+A_{3,4})\end{aligned}\right\} \tag{6}$$

The calculation coefficients $A_{n,j}$ (n=1,2,3; j=1,2,3,4) of horizontal displacement $x(y)$, corner $\varphi(y)$, bending moment $M(y)$ and shear force $Q(y)$ are

$$\left.\begin{aligned}&A_{n,1}=\sum_{i=0}^{\infty}c_{n,i}y^i,\ A_{n,2}=\sum_{i=1}^{\infty}ic_{n,i}y^{i-1}\\&A_{n,3}=\sum_{i=2}^{\infty}i(i-1)c_{n,i}y^{i-2}\\&A_{n,4}=\sum_{i=3}^{\infty}i(i-1)(i-2)c_{n,i}y^{i-3}\\&(n=1,\ 2,\ 3;\ i\geqslant 6)\end{aligned}\right\} \tag{7}$$

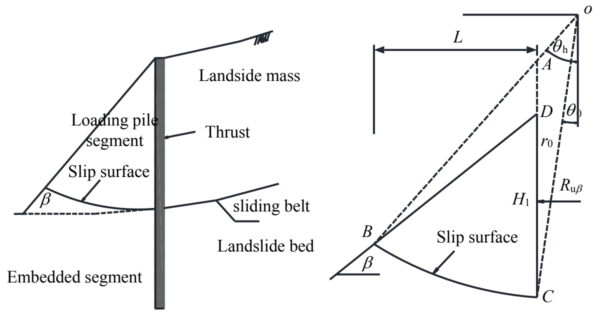
The above-mentioned method is used to calculate the bending moment M_A and shear force Q_A of the pile at sliding surface A, and then the method of m and K is used to calculate the internal force of the structure at the embedded segment according to the lithology of the stratum [14]. Then, according to the continuity conditions of the internal force and displacement of the pile at the sliding surface and the boundary conditions at the bottom of the pile, various coefficients a_i can be obtained (limited to the length of the space, and this process will not be described).

According to the determined horizontal displacement of the pile, the horizontal resistant combined force $R_{\mathrm{e}\beta}$ in front of the pile at the loading segment can be obtained by integration

$$R_{\mathrm{e}\beta}=\int_0^{H_1}m_\beta yx\,\mathrm{d}y=m_\beta\sum_{i=0}^{\infty}\int_0^{H_1}a_i y^{i+1}\mathrm{d}y=m_\beta\sum_{i=0}^{\infty}\frac{a_i}{i+2}H_1^{i+2} \tag{8}$$

2.2 Upper limit method for solving ultimate resistant force in front of the pile

The ultimate resistant force analysis model of the soil in front of the stabilizing pile is shown in Fig.3, where β is the slope angle in front of the pile. The ultimate resistant force is solved according to analyse of the upper limit method with plastic limit, using logarithmic spiral surface failure mechanism[11].



(a) Schematic diagram of failure mechanism (b) Analysis model of failure mechanism

Fig.3 Failure mechanism of downslope soil against loading pile segment

The equation for the logarithmic spiral BC is

$$r(\theta)=r_0\exp[(\theta-\theta_0)\tan\varphi] \tag{9}$$

In the equation: r_0 is the distance from the centre of rotation O to the starting point C of the sliding surface; θ_0 is the angle between OC and the vertical direction; φ is the friction angle in the soil.

By derivation, the external power W can be obtained as

$$W=W_4-(W_1-W_2-W_3) \tag{10}$$

$$\left.\begin{aligned}&W_1=\frac{1}{3}\gamma\Omega\int_{\theta_0}^{\theta_{\mathrm{h}}}r^3\cos\theta\,\mathrm{d}\theta\\&W_2=\frac{\gamma}{2}\left(r_0\cos\theta_0-\frac{r_0\sin\theta_0}{\tan\theta_{\mathrm{h}}}\right)r_0\sin\theta_0\cdot\frac{2}{3}r_0\sin\theta_0\Omega\\&W_3=\frac{\gamma\Omega L}{2}\left(r_0\cos\theta_0-\frac{r_0\sin\theta_0}{\tan\theta_{\mathrm{h}}}-H_1\right)\left(r_0\sin\theta_0+\frac{L}{3}\right)\\&W_4=R_{\mathrm{u}\beta}(r_0\cos\theta_0-\xi H_1)\Omega\end{aligned}\right\} \tag{11}$$

In the equation: W_1, W_2, and W_3 are the power of soil gravity in the logarithmic spiral area OBC, triangular area OAC, and triangular area ABD, respectively; W_4 is the power of thrust $R_{u\beta}$ (equal to the ultimate resistant force of the soil in front of the loading pile segment); γ is soil weight; Ω is the angular velocity of the soil in front of the loading pile segment around point *O*; *L* is the horizontal distance between the exit point *B* of the sliding surface shear and the pile; θ_h is the angle between *OB* and the vertical direction; ξ is the ratio of the height from the action point of thrust $R_{u\beta}$ to the point *C* to H_1.

The internal energy loss occurs on the surface of speed discontinuity, i.e. *BC*, and the energy loss rate is

$$E = \int_{\theta_0}^{\theta_h} c(V\cos\varphi)\frac{r}{\cos\varphi}\mathrm{d}\theta = c\int_{\theta_0}^{\theta_h} r^2\,\mathrm{d}\theta\cdot\Omega \qquad (12)$$

In the equation: *c* is the cohesion of the soil; *V* is the linear velocity of each point on the sliding surface *BC*, which is equal to the product of the pole diameter *r* and Ω at each point.

According to the upper bound theorem [11], from the external force power and the internal energy loss rate is equal to, so

$$W_4 - (W_1 - W_2 - W_3) = c\int_{\theta_0}^{\theta_h} r^2\,\mathrm{d}\theta\cdot\Omega \qquad (13)$$

Substituting Eq. (11) into Eq. (13), we can get

$$R_{u\beta} = f(\theta_h, \theta_0) = \frac{c\int_{\theta_0}^{\theta_h} r^2\,\mathrm{d}\theta\cdot\Omega + W_1 - W_2 - W_3}{(r_0\cos\theta_0 - \xi H_1)\Omega} \qquad (14)$$

During the changes of θ_h and θ_0, the condition for the minimum value of the passive ultimate resistant force function $f(\theta_h,\ \theta_0)$ is

$$\frac{\partial f}{\partial\theta_h} = 0 \text{ and } \frac{\partial f}{\partial\theta_0} = 0 \qquad (15)$$

Solving the two equations simultaneously, we can get the minimum passive resistance $R_{u\beta}$ when the slope angle is β.

2.3 Determination of the proportion coefficient of the foundation resistant force coefficient

According to the foregoing general analysis step (6), we obtain

$$R_{e\beta} = \frac{R_{e0}}{R_{u0}}\cdot R_{u\beta} \qquad (16)$$

Therefore, the steps of calculating m_β can be briefly summarized as

(1) calculate $R_{u\beta}$ according to Eq. (14);

(2) calculate $R_{e\beta}$ according to Eq. (16);

(3) calculate the value of m_β is based on Eq. (8) in which the relationship between the proportion coefficients m_β and $R_{e\beta}$ of the foundation resistant force coefficient is provided.

3 Case study

The cutting slope of a construction site of the Guangba Expressway is shown in Fig.4. The sliding body is gravel soil and the sliding bed is weak weathered silt mudstone. The main parameters of the stratum are shown in Table 1. The angle of the slope in front of the pile is 30°, and the proportion coefficient m_0 of the foundation resistant force coefficient, when the slope in front of the pile is horizontal, is 5 000 kPa/m^2. Coefficient of horizontal elastic resistant force of sliding bed *k* is 100 MPa / m. The stabilizing piles are cast with C30 concrete. In addition, the size of the cross section is 2 m×3 m; the total length of the pile is *H* =18 m; the length of the loading segment is H_1 = 9 m; the length of the embedded segment is H_2 =9 m; the distance between the anti-sliding piles is *L* =6 m; and the calculated width b_0=*b*+1= 3 m. Based on the transfer coefficient method[14], the design safety factor is chosen as 1.35 which yields the design landslide thrust E_n of 1 300 kN/m. Then the landslide thrust, which has a triangular distribution, acting on each pile is given by $E_T = E_n \cdot L$= 1 300×6=7 800 kN. The bottom end of the pile is considered as the free end.

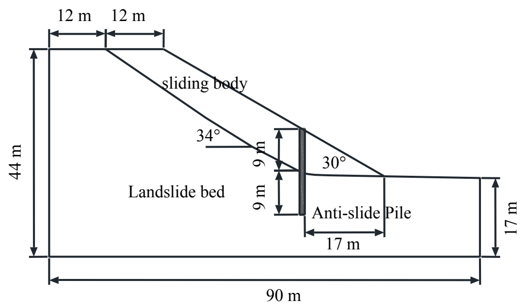


Fig.4 Sketch map of a practical pile-reinforced slope

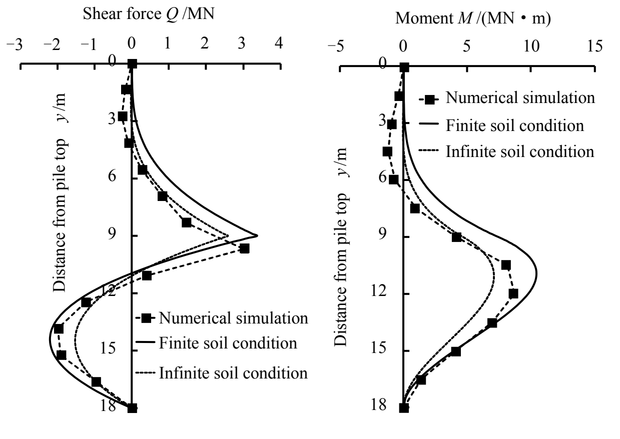
Table 1 Physical and mechanical parameters of slope

Material of slope	Young's modulus	Poisson's ratio	Unit weight /(kN • m^{-3})	Cohesion /kPa	Friction angle /(°)
Sliding body	40	0.18	19	10	25
Sliding bed	400	0.25	22	1 000	45

According to the foregoing calculation method proposed in this paper, the proportion coefficient of the slope foundation resistant force coefficient in front of the pile is 3 045 kPa/m^2, which is 0.61 times of that in the horizontal foundation. The result of the internal force of the pile is shown in Fig.5, and the result is also shown in Fig.5 when the proportion coefficient of the infinite foundation resistant force coefficient is used. It can be seen that, compared with the horizontal infinite foundation condition, the maximum bending moment of the pile is increased by 47.1% and the maximum shear force is increased by 30.6% under the limited foundation of the slope in front of the pile. In other words, in the case of limited foundation of the slope in front of the pile, if the reduction of the foundation resistant force coefficient is not considered, the internal force of the pile will be greatly underestimated, which is on the unsafe side.

In addition, FLAC^{3D} numerical simulation method was used in this study. The mesh and boundary conditions of the numerical model are shown in Fig.6. The soil adopts the ideal elastoplastic constitutive model and Mohr-Coulomb strength criterion, and the stabilizing pile adopts structural elements[15]. The numerical model has a total number of 25 776 nodes and

22 860 elements.



(a) shear force (b) moment

Fig.5 Calculation results of pile internal forces in the example

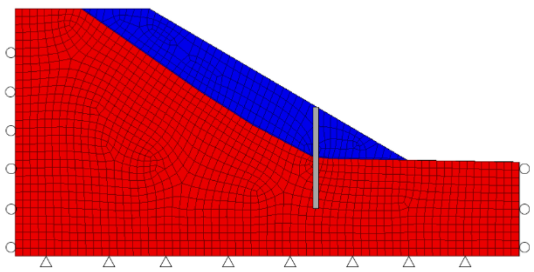


Fig.6 Numerical simulation model of the pile-reinforced slope example

Because FLAC^{3D} and the theoretical calculation of the foundation coefficient method use different parameter systems, the parameter systems of the two methods need to be correlated and coordinated with each other for the same soil mass. Here, a numerical simulation of the plate load test method[16] is adopted, in which the deformation parameters of the soil in the numerical simulation are continuously adjusted until a linear relationship between the lateral stress and the lateral displacement of the pile is achieved. And the value of the proportionality coefficient between the stress and the displacement should be close to the value of the proportionality coefficient of the foundation resistance coefficient adopted in the theoretical calculation of the internal force of the anti-slide pile. The adjusted soil deformation parameters on the side of the pile are used as the final parameters for FLAC^{3D} numerical simulations.

With this method, the internal force of the pile obtained by numerical simulation is shown in Fig.5. It can be seen that the numerical simulation value is slightly smaller than the calculated value of the proportion coefficient method considering the resistant force coefficient of the slope foundation (finite soil), but both are larger than the result calculated using the proportion coefficient of the infinite foundation resistant force coefficient.

4 Discussion

4.1 Effect of the slope of the soil on the foundation coefficient

Still using the foregoing example, the slope angle in front of the pile is changed, and the proportion coefficient of the foundation resistant force coefficient is calculated, as shown in Fig.7. It can be seen that the proportion coefficient of the foundation resistant force coefficient decreases with the increase of the slope. In the range of 0°-15°, the curve is relatively gentle and the rate of change is low; when it exceeds 15°, its value decreases sharply; when it exceeds 50°, its value decreases gradually.

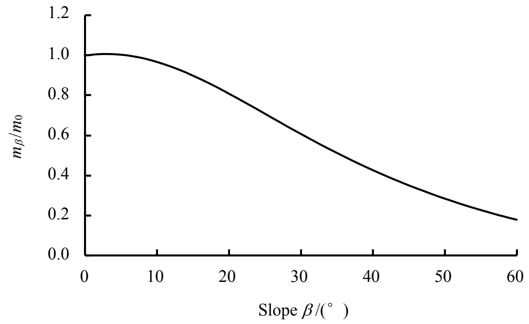


Fig.7 Relationship between m_β/m_0 and β

4.2 Effect of the slope of the soil on the internal force of the pile

When the slope of the soil in front of the pile is 30°, 45°, and 60°, the mechanical response of the pile are shown in Fig.8.

It can be seen that as the slope of the soil in front of the pile increases, the proportion coefficient of the foundation resistant force coefficient gradually decreases, which means that the soil resistant force decreases. As a result, the displacement, shear force, bending moment, and resistant force of the pile increase.

4.3 Effect of different parameters on m_β-β curve

In order to explore the effect of different parameters on the m_β - β curve, the control variates method was used to evaluate the effect of the depth of the embedded segment, the cross-section size of the pile, the cohesion of the soil in front of the pile, the internal friction angle, and the gravity. The results of m_β / m_0 - β with different parameters are shown in Fig.9.

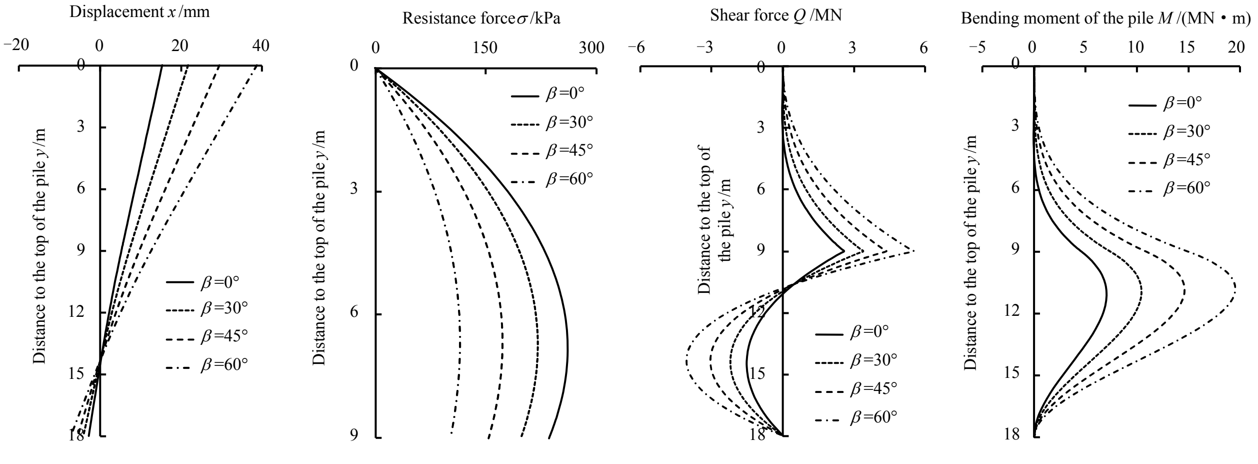
It can be seen from Fig.9(a) that when the slope of the soil in front of the pile is less than 10°, the proportion coefficient of the foundation resistant force coefficient is slightly affected by the embedded depth of the pile. When the slope exceeds 10°, the proportion coefficient of the foundation resistant force coefficient increases with the embedded depth, and the maximum difference of the m_β / m_0 happens within the range of 20°～40°. When the depth of the embedded section reaches a certain value, the m_β - β curve gradually stabilizes.

It can be seen from Fig.9(b) that when the slope of the soil in front of the pile is less than 15°, the size of the cross-section has a minor impact on the proportion coefficient of the foundation resistant force coefficient. When the slope is greater than 20°, the proportion coefficient increases with the increase of the size of cross-section.

It can be seen from Fig.9(c) that the proportion coefficient of the foundation resistant force coefficient increases as the cohesion of the soil increases. The effect of the cohesion has the most significant when the slope of the soil in front of the pile is 10°-30 °.

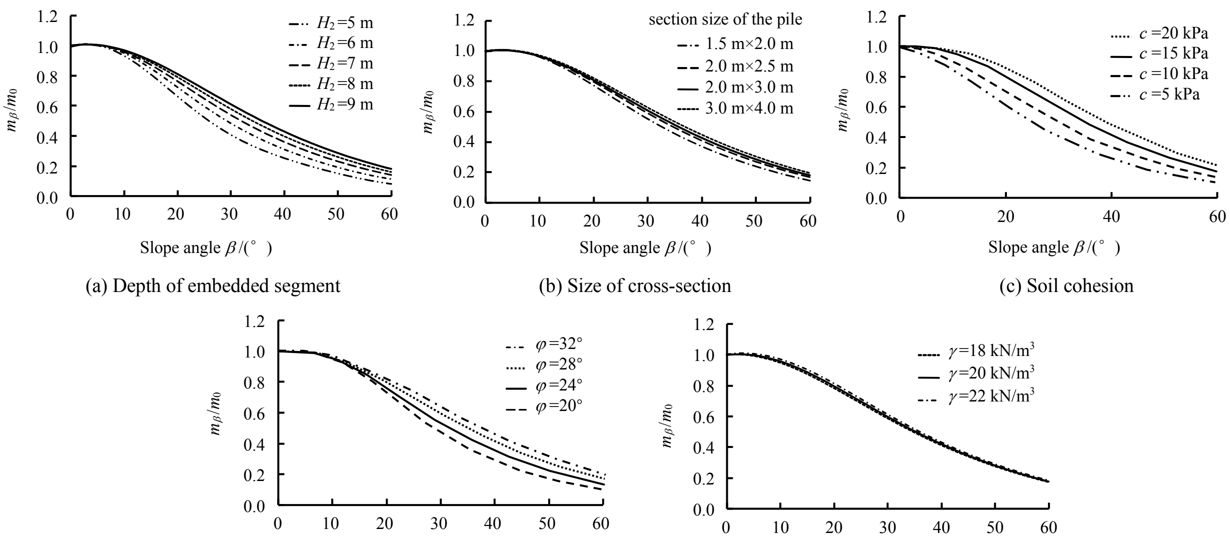
Fig.9(d) shows that when the slope of the soil in front of the pile is in the range of 15° to 35 °, the proportion coefficient of the foundation resistant force coefficient increases significantly with the increase of friction angle. Thereafter, as the internal friction angle continuous to increase, the increase of the proportionality coefficient gradually becomes slight.

Fig.9(e) shows that the influence of the soil unit weight on the m_β - β curve is mainly occurs when the slope is between 10° and 30°. And its influence is not significant compared with other parameters.



(a) Displacement (b) Resistance force (c) Shear force (d) Moment

Fig.8 Mechanical responses of loading pile segment interacted with finite soil of various slope angles



(a) Depth of embedded segment (b) Size of cross-section (c) Soil cohesion

(d) Friction angle (e) Soil unit weight

Fig.9 Relationships between m_β/m_0 and β for pile and finite soil with various parameters

5 Conclusions

(1) A method to calculate the proportion coefficient of the foundation resistant force coefficient with the condition of the finite soil mass was proposed. The foundation coefficient of the stabilizing pile and the upper limit method in the plastic limit analysis were adopted in this method, and the proportion coefficient value of the foundation resistant force coefficient under the infinite soil condition in the front of the loading segment was used as a reference value. In addition, a quantitative relationship between the proportion coefficient and the slope of the soil in front of the loading segment was obtained.

(2) The proportion coefficient of the foundation resistant force coefficient decreases with the increase of the slope angle of the soil in front of the loading segment. When the slope angle

is in the range of 20° to 40°, the proportion coefficient experiences the most rapid decrease. The curve is smoother in the range of 0° to 10°, the change of proportion coefficient is slight.

(3) The embedded depth, size of the cross-section of the pile, soil cohesion, internal friction angle, and unit weight of the soil have effects on the proportion coefficient of the foundation resistant force coefficient of the soil in front of the pile. The influence of the soil weight is slight, while other factors are more significant. The proportion coefficient of the foundation resistant force coefficient increases with the increase of the depth of the embedded segment, the size of the cross-section of the pile and the strength parameters of the soil.

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