Journal of Civil Engineering Research 2016, 6(2): 23-31
DOI: 10.5923/j.jce.20160602.01

Reliability Analysis of Bearing Capacity of Inclined Prestressed Concrete Pipe Pile

Li-Yun Tang*, Jie Wang, Geng-She Yang, Yan-Jun Shen, Pei-Yong Qiu, Hui Liu

Xi'an University of Science & Technology, School of Architecture and Civil Engineering, Xi'an, China

Abstract The incline of a prestressed concrete pipe pile induced by the incorrect excavation and incorrect heap of soil will change pile behavior and thus present a problem for determining the bearing capacity of the inclined pile. Aiming to solve this problem by analyzing the failure mechanism of inclined piles, the failure modes of inclined prestressed concrete pipe piles are divided into flexure failure and shear failure to establish the limit state equations accordingly. Based on structural reliability theory, by introducing JC-Method, a new method to calculate the reliability index of bearing capacity of inclined pile is proposed by MATLAB programming and the bearing feature of inclined pile is discussed. Combining with practical engineering, it's concluded that the main factors affecting the reliability index of inclined pile bearing capacity are pile side resistance, pile declination and external diameter. Also, there exists specific thresholds of wall thickness and prestress that allows the reliability index of an inclined pile bearing capacity to change acutely when wall thickness or prestress is less than the specific threshold. In particular, the side resistance and tip resistance most obviously affects the reliability index of inclined pile bearing capacity when the slope of the line is smaller than 0.04. The main factor that affects bearing capacity of an inclined pile is the cracking bending moment when the load is lower than 1300kN.

Keywords Inclined pile, Concrete pipe pile, Bearing capacity, Reliability index

1. Introduction

In recent years, the prestressed concrete pipe pile has been widely used in the construction of railway, highway, port and other structures. At the same time, the incline of the pile induced by the incorrect excavation and incorrect heap of soil will even exceed the upper limit of 1% stipulated in the specification [1]. Economic losses can be significant when the piles having inclines exceeding 1% are treated as discarded piles. In addition, the stress mechanism of inclined piles is very complicated with influences resulting from the vertical load, horizontal load or inclined load simultaneously. There is no unified method to assess the bearing capacity of piles where inclination exceeds 1%, thus it is important to study the behaviors of pile bearing capacity and contribute to the theoretical research for inclined pile design.

The laboratory test and numerical analysis are the most widely used methods to analyze the inclined pile bearing capacity. Meyethof and Sastry [2] analyzed the deformation of piles with the influence of inclined loads and eccentric loads, and established an empirical formula for the relationship between ultimate shear and ultimate moment. Meyethof and Yalcin [3] also conducted tests to analyze the deformation characteristics of inclined piles when considering the influence of inclined load. Characteristic curves reflecting the change of the horizontal displacement of the pile tops with the change of the loads were obtained for when the piles are in different conditions of inclination. By conducting physical model tests. Long-qi Li et al. [4] concluded that the angle of the inclined pile is the main factor to change the pile bearing capacity, meanwhile Chandra Shekhar Goit et al. [5] and Nikos Gerolymos et al. [6] found that the Horizontal impedance functions of inclined single piles are smaller than the vertical pile and the values decrease as the angle of the pile inclination increases by Model tests and numerical analyses. Gang Zheng et al. [7] presented model test results studying the bearing capacity behaviors of inclined piles with different inclinations under vertical load and concluded that the bending failure of piles will occur when the degree of the pile inclination exceeds 8 degrees. Ashraf Nazir et al. [8] proposed that under the same inclination situations observed in modeling tests that the circular pile is more resistant to pullout forces than the square and rectangular pile shapes. The effect of inclination on the dynamic response of pile was analyzed by L. A. Padrón et al. [9, 10] and Cristina Medina et al. [11] and the settlement of a

* Corresponding author:
tangly@xust.edu.cn (Li-Yun Tang)
Published online at http://journal.sapub.org/jce

partially inclined pile was analyzed using finite element software by Li Wang et al. [12]. In addition, inclination is the most effective parameter in interaction factors of piles group with inclined piles [13, 14]. In conclusion, these studies have mainly focused on the effect of declination on the capacity of the pile, and few research are found reporting analyses of the influence from other factors, such as soil properties, load effect, pile material and diameter. Moreover, it's well known that these factors do not function independently, but work synergistically [15]. The probabilistic method is introduced to analyze the effect of these factors on the capacity of inclined pile using reliability theory.

At present, many researchers mainly focus on the vertical piles to analyze the reliability index of bearing capacity. Zi-fu Zhang et al. [16] has analyzed the influences of the pile side resistance, load effect on the reliability index, and proposes that the reliability degree meets the needs of the present codes when the coefficient of variation is within 0.2. Garland L et al. [17] and Niandou et al. [18] and ZHANG L M et al. [19, 20] propose that the ratio of test data to design data for bearing capacity have an obvious effect on the capacity reliability of inclined pile. The effect of soil properties on the capacity reliability has been study by Hai jian Fan et al. [21] and Ana Teixeiraa et al. [22], In addition, other researchers (Zhao et al. [23]; Zhao et al. [24]; Xu and Zhang [25]; Xu et al. [26]; Bian et al. [27] and Peter Friis Hansen [28]) have investigated the reliability index of the capacity of vertical piles through different computation methods by considering the failure criterion and load effects. However, there are few investigations about the reliability index of bearing capacity for an inclined pile, mainly because the bearing capacity formula for an inclined pile has not been consistently stipulated, and the limit state equations are difficult to establish when calculating the reliability of inclined pile. Additionally, little information has been found in the literature on estimating the reliability of inclined pile capacity. That is not surprising since the formulas of bearing capacity are not stipulated in the specification and the limit state equation of reliability theory is difficult to establish. This has thus caused the reliability analysis of bearing capacity of inclined pile to be difficult to achieve.

Aiming to solve this problem by analyzing the failure mechanism of inclined piles, the failure modes of inclined prestressed concrete pipe pile are divided into flexure failure mode and shear failure mode, and the limit state equations are established accordingly. Based on structural reliability theory, by introducing JC-Method, a new method to calculate the reliability index of bearing capacity of inclined pile is proposed by MATLAB programming. The effect of the main factors on the bearing capacity with different inclinations and different loads is discussed, and this research makes a reference to the safety assessment of the inclined pile.

2. Failure Mode and Influential Factors of Inclined Piles

2.1. Failure Mechanism of Inclined Piles

The limit state equations of JC-Method are established based on the pile bearing capacity, however, the forced mechanism of inclined piles is so complex that there specific approaches do not exist for defining the formula to calculate the pile bearing capacity in the specification. It's necessary to analyze the failure modes of inclined piles and confirm the pile failure mode. However, the inclined pile failure mode is different from that of the vertical piles. The vertical load P on the top of the pile is divided into an axial load P_y and a lateral load P_x. The bearing capacity of inclined pile mainly then depends on two aspects: the shear failure and the flexural failure modes in the inclined pile. The shear failure will be observed due to a load larger than pile capacity which includes the side resistance Q_{sk} and tip resistance Q_{pk}, as shown in figure 1(a). The flexural failure is usually observed in the inclined pile when the cracking bending moment Mcr is lower than the bending moment M, which is produced by the lateral loads P_x and the horizontal resisting force S_x due to soil, as shown in figure 1(b).

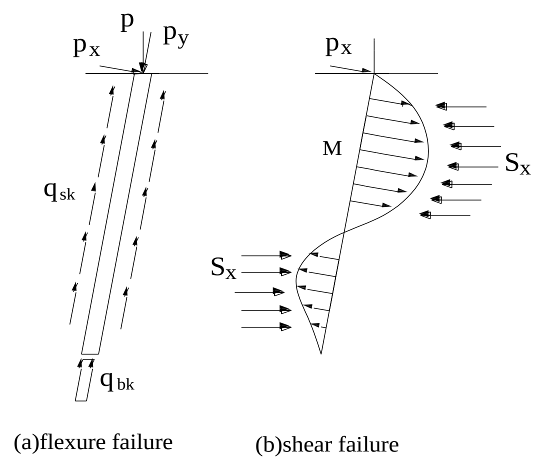

Figure 1. Two kinds of failure pattern of batter pile

2.2. Influential Factors of Inclined Piles

The shear failure of an inclined prestressed concrete pipe pile is mainly due to the axial capacity being lower than the pile's top axial loads. The axial capacity of single pile includes the side resistance and the tip resistance. The pile diameter affects the side resistance of pile, which is influenced by the surrounding soil properties. The primary factors affecting the pile shear failure include the side resistance, the tip resistance, the pile diameter and the pile's top axial load.

The flexural failure of inclined prestressed concrete pipe pile is mainly due to the cracking bending moment M_{cr} when it is lower than the bending moment M. The bending moment that is produced by the pile's top lateral loads and the horizontal resisting force induced by the soil is affected by the declination and the lateral load. The cracking bending moment is determined by concrete strength and prestress conditions. Thus, the primary factors effecting flexural failure of an inclined pile include pile's top lateral load, inclination, concrete strength and prestress conditions.

3. Reliability Theory of a Single Inclined Pile

3.1. Limit State Equations of Two Failure Modes

It's assumed that the performance function is only related to pile's top load effect *S* and pile bearing capacity *R*. The performance function of an inclined pile can be written as

$$Z = g\left(R,S\right) = R - S \tag{1}$$

When Z=0, the limit state equations of single pile can be formulated as

$$R - S = 0 \tag{2}$$

The limit state equations under the flexure failure mode and the shear failure mode, respectively, can also be derived.

3.1.1. Limit State Equations of Flexure Failure Mode

Considering that the pile can become inclined after piling, the tips of inclined pile and straight pile are in the same bearing stratum, so the design value of axial capacity of inclined pile can be written as:

$$Q_k^{'} = Q_k \cos\theta \tag{3}$$

Where Q_k is the vertical bearing capacity of pile; θ is the inclination.

Then the limit state equations can be expressed as:

$$Z = (S_L + S_G)\cos\theta - \left(\mu \sum q_{sik} l_i + p_{sk} A_p\right)\cos\theta = 0 \tag{4}$$

Where S_L and S_G are the live and dead loads, respectively; q_{sik} is a standard value of the ultimate side resistance; μ is the pile circumference; l_i is the thickness resistance of the soil layer; p_{sk} is a standard value of ultimate tip resistance ; A_D is the area of the pile bottom.

3.1.2. Limit State Equations of Shear Failure Mode

The maximum bending moment under a vertical load and considering the $p-\Delta$ effect has been proposed by Ning [29] as follows:

$$M_m = dbPn_m / a \tag{5}$$

Where *d* is the amplifying coefficient of internal force and horizontal displacement, $d = (1 - n_x P / 4a^2 EI)^{-1}$; n_x is the coefficient of the lateral deformation of the pile top, n_x = 2.441 (pile length>a/4); *P* is the working load; *a* is the coefficient of pile horizontal deformation with $a = \sqrt[5]{mb_0 / EI}$; *m* is the proportional coefficient of side resistance and *m* can be defined as $10\,MN/m^2$ when the soil is a cohesive soil or dense silt; b_0 is the calculated width of single pile; *E* is the elastic modulus of concrete; *I* is the inertia moment of the pile section; *b* is the declination; *P* is the vertical load; n_m is the coefficient of the pile's maximum bending moment and n_m = 0.78 (pile length>a/4).

The cracking bending moment of a steel pipe pile can be expressed as

$$M_{cr} = (\sigma_{pc} + f_{tk})W_o \tag{6}$$

Where, W_0 is the elastic resistance moment of the tensile edge of the conversed section of the pipe pile; σ_{pc} is the pipe pile prestress; f_{tk} is the standard values of the tensile strength of concrete; *d*, *D* are the inside diameter and outside diameter, respectively, of the pipe pile.

Then the limit state equations can be expressed as

$$Z = M_\mu - M_{cr} = 0 \tag{7}$$

3.2. Random Variables of Two Limit State Equations

The random variables include the length of pile, the sectional area of piles soil properties *etc*. which affect the reliability of inclined pile. In this article, the random variables are divided into resistance random variables and load random variables and each of random variables is analyzed.

3.2.1. Resistance Random Variables

The parameters in the limit state equations, including the standard values of ultimate side resistance q_{sik} , the standard values of ultimate tip resistance p_{sk} , the pipe pile prestress σ_{pc}, the standard values of the tensile strength of concrete f_{tk} , the *i* layer of soil l_i , the area of pile bottom A_D, the pile diameter μ and the outside diameter of pile *D* are all considered as resistance random variables. q_{sik} and p_{sk} follow a normal distribution and the variation coefficient is between 0.1 and 0.3 [30]; the variation coefficient of σ_{pc} is 0.21; the variation coefficient of f_{tk} is 0.18. μ, l_i , A_D and *D* are considered as constants because the changes occurring with each of them is considered insignificant.

3.2.2. Load Random Variables

The parameters in the limit state equations of the two failure modes including live load S_L, dead load S_G, amplifying coefficient of internal force and horizontal displacement *d* and declination *b* are considered as load random variables. Live load follows a normal distribution and dead load follows a logarithmic normal distribution. For convenience, the live and dead load effect is not considered individually, and the distribution characteristics of live load effect is equivalent to the distribution characteristics of pile's top working load, namely the pile's top load effect follows an approximate normal distribution and the coefficient of variation is 0.07 [31]. The amplifying coefficient of internal force and horizontal displacement *d*, the coefficient of the lateral deformation of pile top n_x , the proportional coefficient of side resistance m, the calculative width of single pile b_0 and the declination b are all considered as constants while the elastic modulus of concrete E and vertical load P are considered as random variables.

3.3. Reliability Calculation of Inclined Piles

Based on limit state equations of inclined piles and statistics distribution of random variables, the JC method is introduced to analyze the reliability of the pile capacity. The linearization of functions is expanded on the structural failure hyperplane through a Taylor expansion by the JC method. The actual distribution of the random variables can be also considered by JC method.

3.3.1. Reliability Calculation under Flexure Failure Mode

(1) q_{sik1}, q_{sik2}, q_{sik3}, q_{sk} and S follow a normal distribution. It is assumed that the checking points are known and the first order expansion of the performance function can be expressed as

$$Z_L = g_X(q_{sik1}^*, q_{sik2}^*, q_{sik3}^*, q_{sk}^*, s^*) + \sum_{i=1}^{n} \frac{\partial_{g_X}(x^*)}{\partial X_i}(X_i - x_i^*) \quad (8)$$

Where q_{sik1}, q_{sik2}, q_{sik3} are the standard values of ultimate side resistance for the three soil layers, respectively; q_{sk} is the standard value of ultimate tip resistance; and S is the load effect.

(2) The mean and standard deviation can be formulated as

$$\mu_{Z_L} = g_X(q_{sik1}^*, q_{sik2}^*, q_{sik3}^*, s^*) + \sum_{i=1}^{4} \frac{\partial_{g_x}(x^*)}{\partial X_i}(\mu_{x_i} - x^*) \quad (9)$$

$$\sigma_{Z_L}^2 = E(Z_L - \mu_{Z_L})^2 \quad (10)$$

Where μ_{Z_L} is the mean; σ_{Z_L} is the standard deviation.

The reliability index can be formulated as

$$\beta = \frac{g(q_{sik1}^*, q_{sik2}^*, q_{sik3}^*, s^*) + \sum_{i=1}^{4} \frac{\partial_{g_X}(x^*)}{\partial X_i}(\mu_{X_i} - x_i^*)}{\sqrt{\sum_{i=1}^{4} \left[\frac{\partial_{g(x^*)}}{\partial X_i}\right]^2 \sigma_{X_i}^2}} \quad (11)$$

(3) The direction cosines $\cos\theta$ of coordinate vector corresponding to the normal of checking point P* in the limit state surface can be formulated as:

$$\cos\theta_{X_i} = \cos\theta_{Y_i} = -\frac{\frac{\partial_{g_X}(x^*)}{\partial X_i}\sigma_{X_i}}{\sqrt{\sum_{i=1}^{n}\left[\frac{\partial g_X(x^*)}{\partial X_i}\right]^2 \sigma_{X_i}^2}} \quad (12)$$

(4) The new coordinates of the checking point calculated by the checking point formula can be expressed as

$$x_i^* = \mu_{X_i} + \beta\sigma_{X_i}\cos\theta_{X_i} \quad (13)$$

(5) By inserting the new checking point into the limit equation, the reliability index can be calculated by a trial-and-error method. The calculated reliability index is named β_1;

(6) When $|\beta_1 - \beta_0| \le \varepsilon$ (tolerable error), the iteration is complete and the β_1 is the ultimate reliability index; when $|\beta_1 - \beta_0| > \varepsilon$, the iteration continues by returning to step(3).

3.3.2. Reliability Calculation under Bending Failure Mode

(1) σ_{pc},f_{tk}, S follow a normal distribution. It's assumed that the checking points are known and the first order expansion of performance function can be expressed as:

$$Z_L = g_X(\sigma_{pc}, f_{tk}, s^*) + \sum_{i=1}^{n} \frac{\partial_{g_X}(x^*)}{\partial X_i}(X_i - x_i^*) \quad (14)$$

(2) The mean and standard deviation can be formulated as:

$$\mu_{Z_L} = g_X(\sigma_{pc}, f_{tk}, s^*) + \sum_{i=1}^{4} \frac{\partial_{g_x}(x^*)}{\partial X_i}(\mu_{x_i} - x^*) \quad (15)$$

$$\sigma_{Z_L}^2 = E\left(Z_L - \mu_{Z_L}\right)^2 \quad (16)$$

Where μ_{Z_L} is the mean; $\sigma_{Z_L}^2$ is the standard deviation.

The reliability index can be formulated as:

$$\beta = \frac{g(\sigma_{pc}, f_{tk}, s^*) + \sum_{i=1}^{4} \frac{\partial_{g_X}(x^*)}{\partial X_i}(\mu_{X_i} - x_i^*)}{\sqrt{\sum_{i=1}^{4} \left[\frac{\partial_{g(x^*)}}{\partial X_i}\right]^2 \sigma_{X_i}^2}} \quad (17)$$

(3) The direction cosines $\cos\theta$ of coordinate vector corresponding to the normal of checking point P* in the limit state surface can be formulated as:

$$\cos\theta_{X_i} = \cos\theta_{Y_i} = -\frac{\frac{\partial_{g_X}(x^*)}{\partial X_i}\sigma_{X_i}}{\sqrt{\sum_{i=1}^{n}\left[\frac{\partial g_X(x^*)}{\partial X_i}\right]^2 \sigma_{X_i}^2}} \quad (18)$$

(4) The new coordinates of the checking point calculated by the checking point formula can be expressed as

$$x_i^* = \mu_{X_i} + \beta\sigma_{X_i}\cos\theta_{X_i} \quad (19)$$

(5) By inserting the new checking point into the limit equation, the reliability index can be calculated by a trial-and-error method. The calculated reliability index is named β_1;

(6) When $|\beta_1 - \beta_0| \leq \varepsilon$ (margin for error), the iteration is complete and the β_1 is the ultimate reliability index; when $|\beta_1 - \beta_0| > \varepsilon$, the iteration continues by returning to step(3).

4. Validation by Practical Engineering

4.1. Engineering Situation

The above-ground building of 1# building of Xi'an Beibuwan project is a reinforced concrete shear wall structure with a pile-raft foundation used in the infrastructure. High strength pre-stressing concrete piles (PHC) are used in the foundation. The diameter of the pile is 600mm; the pile length is 21m; the wall thickness of the pile is 110mm; the concrete strength grade is C50, and the prestress is 6 MPa. According to the geological data, the physical and mechanical parameters of the soil are shown in table 1.

Table 1. Soil properties

Soil layer	Thickness (m)	Unit weight (kN/m^3)	Modulus of Compression (Mpa)	Pile side resistance (Kpa)	Pile limit tip resistance (Kpa)
Plain fill	4	19.1	-	-	-
loess	7	19.4	0.27	80	
Silty clay	6	22.5	0.15	60	
Medium sand	8	21.85	0.1	85	2050

Based on conditions of an incorrect excavation where the declination is 0.01 and the initial load is 2000kN, the limit state equations for the two kinds of failure mode allow the effect of various factors on the bearing capacity reliability of inclined pile to be analyzed by using a MATLAB programming approach.

4.2. Random Variables Influence on Reliability Index

Since changes in the random variables will cause changes in the reliability index during reliability analysis, controlling variables is the method used to analyze the random variables, including the influence that variable coefficient of pile side resistance and tip resistance has on the reliability index, as well as declination, wall thickness, load effect, etc. The influence of the random variables on the reliability index is also analyzed.

4.2.1. Effect of Variable Coefficient of Pile Side Resistance and Tip Resistance on Reliability Index

In shear failure mode, there is a significant influence of the pile side resistance and tip resistance on the pile axial bearing capacity. In this project the first soil layer is a plain fill so the pile side resistance can be neglected. Keeping other random variables unchanged, when the variable coefficients of pile side resistance and tip resistance in the different soil layers change from 0.05 to 0.25, the pile reliability indexes are calculated and the results are shown in figure 2.

As shown in figure 2, the reliability index decrease gradually as the variable coefficients of pile side resistance and tip resistance increase. Moreover, the change of the variable coefficient of pile side resistance in the medium sand layer has the most significant effect on the reliability index. The main reason for this is that the lower sand layer is more compacted than the upper layer and the pile side resistance is greater in the lower layer causing the change of variable coefficient to have a more obvious effect on the pile side resistance. In addition, the change of variable coefficient of pile tip resistance has less effect on the reliability index than the change of the variable coefficient of pile side resistance. This is because the pile tip resistance is not totally functional in this process and the load is mainly shared by the pile side resistance causing the pile tip resistance to have little influence on pile bearing capacity.

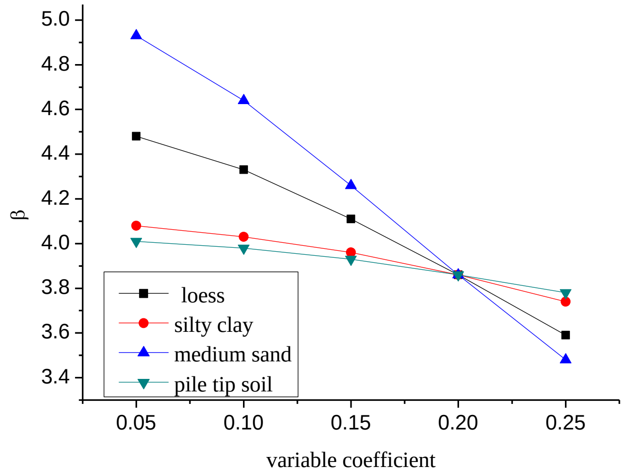

Figure 2. Effect of variable coefficient of pile side resistance and tip resistance on reliability index

4.2.2. Effect of Pile Declination on Reliability Index

Declination has a significant effect on the reliability index of an inclined pile. Keeping all other random variables unchanged, the influence of declinations ranging from 0.01 to 0.08 on the reliability indexes of inclined piles are analyzed and shown in table 2.

Table 2. Effect of pile declination on reliability index

Declination	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08
Reliability index	5.74	5.15	4.54	3.94	3.34	2.71	2.04	1.32

As shown in table 2, the reliability index decreases from 5.74 to 1.32 when the pile declination increases from 0.01 to 0.08. It is obvious that the reliability index decreases with the increase of declination. This is due to the bending moment caused by the lateral load, which increases as the declination increases, and it is concluded that the increase of declination will immensely decrease the stability of the inclined pile.

4.2.3. Effect of Prestress on Reliability Index

Keeping other random variables unchanged, when the prestress ranges from 1MPa to 10MPa, the reliability indexes for the declination at 0.02 and 0.03 respectively, can be seen in figure 3.

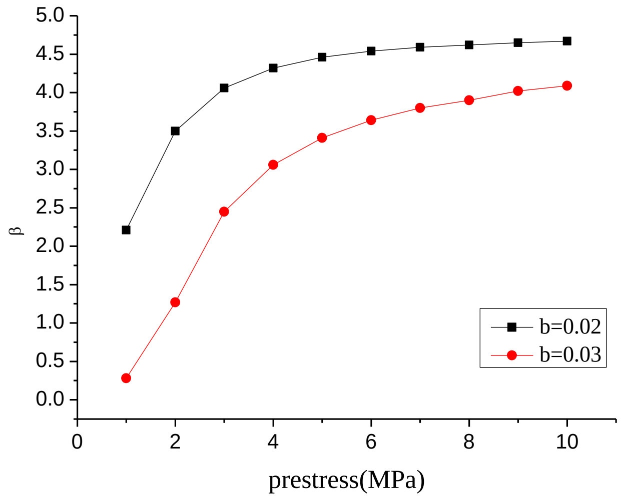

Figure 3. Effect of prestress on reliability index

As shown in figure 3, with the pile inclining by 0.02, the reliability index will increase rapidly with the increase of prestress for prestress values lower than 4MPa, while for prestress values exceeding 4MPa the reliability index will increase more slowly, Similarly, with the pile inclining by 0.03, the reliability index will increase rapidly with the increase of prestress for prestress values lower than 5MPa and then increases more slowly when the prestress values exceeds 5MPa. It can be concluded that there exists a threshold value of prestress: when the prestress is lower than the threshold value of prestress, the reliability index will increase rapidly as prestress increases and when the the prestress is higher than the threshold value of prestress the reliability index will increase more slowly.

4.2.4. Effect of Concrete Strength on Reliability Index

Standard values of tensile strength of concrete will affect both the cracking bending moment of pipe pile, and the reliability index of an inclined pile. Usually C50~C80 concrete is used for steel pipe piles. Keeping other random variables unchanged, the influence of concrete strength ranging from C50 to C80 on the reliability indexes of inclined piles are analyzed and shown in table 3.

Table 3. Effect of concrete strength on reliability index

Concrete strength (MPa)	2.64	2.74	2.85	2.93	2.99	3.05	3.12
Reliability index	5.74	5.78	5.83	5.87	5.9	5.92	5.94

As shown in table 3, there is a minor amount of increase in the reliability index with the increase of concrete strength. As the concrete strength increases from 2.64 MPa to 3.12 MPa, the reliability index increases from 5.74 to 5.94, respectively. By comparing this effect with the effect shown in figure 3, it can be concluded that the effect of concrete strength on the reliability index is less than the effect of prestress on the reliability index.

4.2.5. Effect of Wall Thickness on Reliability Index

The wall thickness of the pipe pile will affect the elastic resistance moment of the tensile edge of conversed section of the pipe pile, and the reliability index as well. The influence of pipe pile wall thickness on the reliability index, is analyzed for piles with the declinations of 0.01, 0.03 and 0.06. Keeping other random variables unchanged, the effect on the reliability indexes is analyzed separately for wall thickness ranging from 70mm to 130mm, and is shown in figure 4.

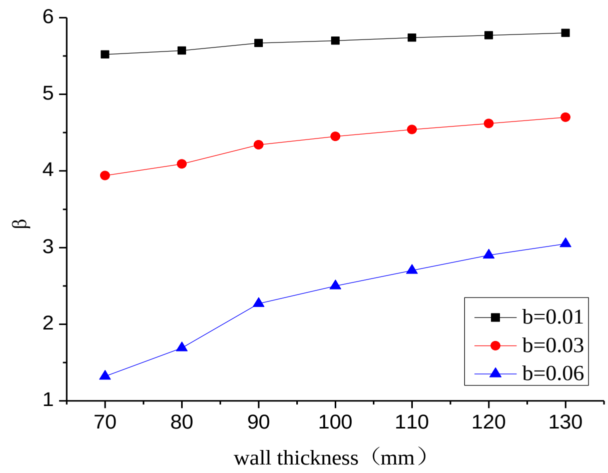

Figure 4. Effect of wall thickness on reliability index

As shown in figure 4, the reliability index of the three different pile declinations will increase to a certain extent with the increase of a certain wall thickness, and the trend for this change can be divided into two stages: for a pile inclining by 0.02, when the wall thickness is less than 90mm the reliability index increases quickly with an increase of wall thickness; when wall thickness is greater than 90mm, the reliability index increases more slowly as wall thickness increases.

From the analysis above, it can be concluded that there is a threshold value of wall thickness (the threshold value of wall thickness is 90mm in this case): when the wall thickness is less than the threshold value of wall thickness, the reliability index increases rapid with wall thickness and when the wall thickness is greater than the threshold value of wall thickness, the reliability index increase more slowly with wall thickness.

4.2.6. Effect of External Diameter on Reliability Index

Keeping other random variables unchanged, the reliability indexes of the two kinds of failure modes are obtained for when the external diameter ranges from 500 mm to 800 mm, and are shown in figure 5.

As seen in figure 5, the reliability indexes for both the shear failure mode and flexural failure mode increase with the increase of external diameter. In this study, the reliability indexes of pile for the two failure modes are analyzed for when the external diameter increases from 500mm to 800mm. In the condition of shear failure mode, as the external diameter increases from 500mm to 800mm, the reliability index increases from 2.67 to 5.3 respectively, increasing overall by about 2.63. In the condition of flexural failure mode, the reliability index increase from 4.26 to 5.7, increasing overall by about 1.48. It can be seen from these results that as the external diameter changes, the flexural failure condition has a greater effect on the reliability index in than the shear failure condition.

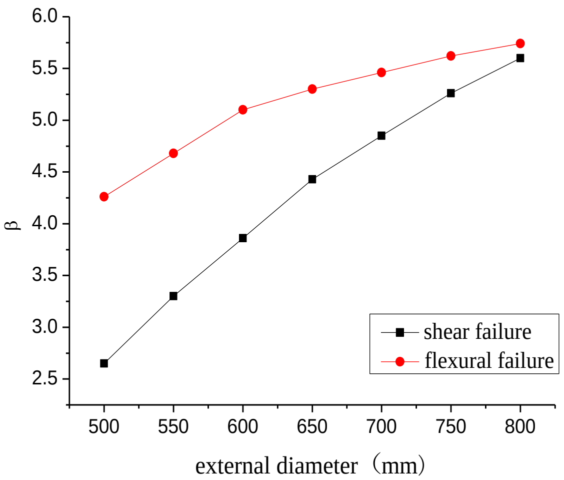

Figure 5. Effect of external diameter on reliability index

In addition, since a change in the declination will influence the effect that external diameter has on the reliability index, the influence of the external diameter on the reliability index under different declinations is also analyzed. With pile declinations of 0.01, 0.02 and 0.03 respectively, the characteristics of reliability index changes under different external diameters are shown in figure 6.

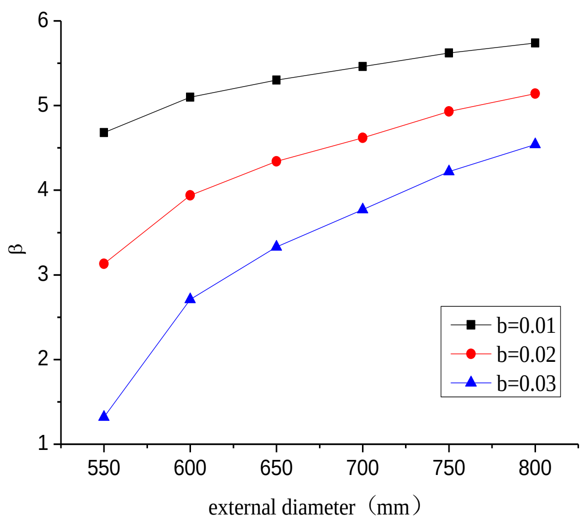

Figure 6. Effect of external diameter on reliability index

Figure 6 shows the results of analyzing the reliability indexes of piles inclined by 0.01, 0.02, and 0.03 for pile external diameters ranging from 550 mm to 800 mm. The reliability index increases observed are from 4.68 to 5.74 for the pile inclined by 0.01, from 3.13 to 5.14 for the pile inclined by 0.02, and from 1.32 to 4.54 for the pile inclined by 0.03. It can be concluded that the effect of external diameter on the reliability index becomes more and more obvious as the pile declination increases.

4.2.7. Effect of Load Effect on Reliability Index

Keeping other random variables unchanged, when external loads range from 1000kN to 3000kN, the reliability index for the shear failure and the reliability indexes of piles for when the declination changes from 0.01 to 0.05 in the flexural failure mode are analyzed and shown in figure 7.

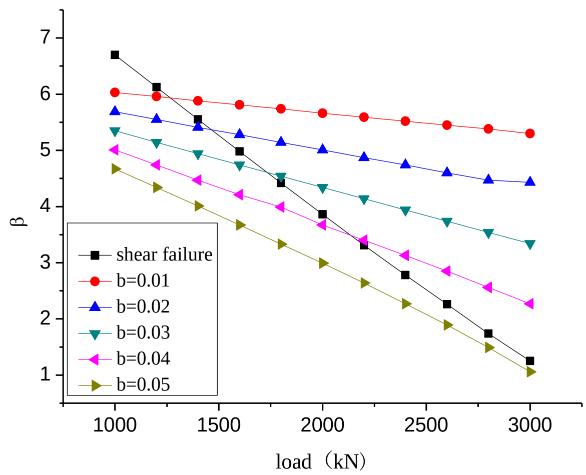

Figure 7. Effect of load on reliability index

The reliability indexes for both shear failure mode and flexural failure mode will decrease with the increase of load. In addition, there exists a critical load of 1300kN in this analysis: when the working load is lower than this critical load of 1300 kN, the reliability index of the flexural failure mode is less than the reliability index of the shear failure mode and when the working load is greater than this critical load of 1300kN, the reliability index of the flexural failure mode is higher than that of the shear failure mode. It can be concluded that the cracking bending moment has an obvious effect on the reliability index when the working load is lower than the critical load, otherwise, the effect of pile side resistance and tip resistance on the reliability index is more obvious.

Comparing the reliability index occurring under the same load, it can be found that there also exists a critical declination where, when the declination is lower than the critical declination, the reliability index of the flexural failure mode is higher than that of the shear failure mode, and where when the declination is greater than the critical declination the reliability index of the flexural failure mode is lower than that of the shear failure mode. It can be concluded that the pile side resistance and tip resistance have an obvious effect on the reliability index when the declination is lower than the critical declination and that the effect of the cracking bending moment on the reliability index is more obvious when the declination is greater than the critical declination. In this working condition, the critical declination is 0.04.

5. Conclusions

Based on the JC method and the MATLAB programming approach used, a new method to calculate the reliability index of an inclined pile is proposed, where the results may give a reference for use in following research studies of inclined pile reliability. According to the practical engineering project and analysis, the following conclusions were obtained:

The effect of the variable coefficient of pile side resistance, declination and external diameter on the reliability index is more obvious, with the effect of external diameter on the reliability index in the flexural failure mode being more acute than that in shear failure mode.

There exist threshold values of wall thickness and prestress. When the wall thickness or prestress is lower than the threshold value, the reliability index increases rapidly with the increase of the wall thickness or prestress respectively. When the wall thickness or prestress is greater than the threshold value, the reliability index slowly increases as the respective increase in wall thickness or prestress.

There exists a critical declination which causes the pile side resistance and tip resistance to have a more obvious effect on the reliability index when the declination is lower than the critical declination. When the declination exceeds the critical declination, the effect of the cracking bending moment on the reliability index becomes more obvious.

There exists a critical load which makes the cracking bending moment have a more obvious effect on the reliability index when the working load is lower than this critical load. When the working load exceeds the critical load the effect of pile side resistance and tip resistance on the reliability index becomes more obvious.

From the conclusion above, some advice which is useful in the actual projects could be got:

The effect of the external diameter on the reliability index is more obvious, so the bearing capacity of the inclined pile can be improved by appropriately increasing the external diameter of pile in the actual projects

The researches provide reference for the security of the inclined pile. From the research work above, the security of the inclined pile will not be impacted when the declination is lower than 0.04.

On the basis of ensuring the project quality, the project budget can be reduced by using the threshold values of wall thickness and prestress in the actual projects according to the algorithm in this paper.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (No. 41502298), Shaanxi province science and technology innovation team project (No.2014KCT-30) and the Overall Innovation Projects of Science and Technology of Shanxi Province of China (No.2011KTZ03-02-01).

REFERENCES

[1] General Administration of Quality Supervision Inspection and Quarantine of the People's Republic of China. (2009) Pretensioned spun concrete piles. Beijing: Standards Press of China.

[2] V.V.R.N. Sastry & Meyerhof G G. (1995). Behaviour of flexible piles in layered clays under eccentric and inclined loads. *Canadian Geotechnical Journal*, 32(3), pp: 387-396.

[3] Meyerhof G G, Yalcinas. (1993). Behaviour of flexible batter piles under inclined loads in layered soil. *Canadian Geotechnical Journal*, 30(2), pp: 247-256.

[4] Long-qi Li, Shu-xue Luo. (2012). A simulation test study of vertical bearing capacity of inclined pile foundation in inhomogeneous strata. Rock and Soil Mechanics, 33(5): 1300-1305.

[5] Chandra Shekhar Goit, Masato Saitoh. (2013). Model tests and numerical analyses on horizontal impedance functions of inclined single piles embedded in cohesionless soil. *Earthquake engineering & engineering vibration*, 12(1),pp: 143-154.

[6] Nikos Gerolymos, Amalia Giannakou. (2008). Evidence of beneficial role of inclined piles: observations and summary of numerical analyses.*Bulletin of Earthquake Engineering*, 6(4), pp: 705–722.

[7] Gang Zheng, Shuai Li, Yi-ming Du. (2012). Bearing Capacity Behaviors of Inclined Pile Under Vertical Load. Journal of tian Jin university, 45(7): 567-576.

[8] Ashraf Nazir, Ahmed Nasr. (2012). Pullout capacity of batter pile in sand. *Journal of Advanced Research*,4(1),pp：147-154.

[9] L.A. Padrón, J. J. Aznárez. (2010). Dynamic stiffness of deep foundations with inclined piles. *Earthquake Engineering & Structure Dynamic*, 39(12), pp: 1343-1367.

[10] L. A. Padrón, J. J. Aznárez. (2012). Impedance functions of end-bearing inclined piles. *Soil Dynamics & Earthquake Engineering*, 38, pp: 97-108.

[11] Cristina Medina, Luis A. Padrón. (2015). Influence of pile inclination angle on the dynamic properties and seismic response of piled structures.*Soil Dynamics & Earthquake Engineering*, 69, pp: 196-206.

[12] Gang Zheng, Li Wang. (2009). Research on vertical bearing capacity of partially inclined pile with finite element method. Rock and Soil Mechanics, 30(11): 3533-3538.

[13] Mahmoud Ghazavi, Pedram Ravanshenas. (2014). Analytical

and numerical solution for interaction between batter pile group. *Ksce Journal of Civil Engineering*, 18(7), pp: 2051-2063.

[14] Hasan Ghasemzadeh, Mehrnaz Alibeikloo. (2011). Pile-soil-pile interaction in pile groups with batter piles under dynamic loads. Soil Dynamics and Earthquake Engineering, 31, pp: 1159– 1170.

[15] Kok-Kwang Phoon. (2008). Reliability-Based Design in Geotechnical Engineering: Computations and Applications. New York: Taylor and Francis.

[16] Zi-fu Zhang, Wen-zhi Yang, Hai-tao Zhu. (2015). Reliability Analysis of Bearing-Capacity of Tower Foundations Designed for Ultra High Voltage Transmission Lines. Journal of Tianjin University, 48(Suup.): 142-146.

[17] Garland L. (2004). Current Practices and Future Trends in Deep Foundation. Geotechnical Special Publication, ASCE,: 239-252.

[18] Niandouh, Breyssed. (2007). Reliability analysis of a piled raft accounting for soil horizontal varability. Computers and Geotechnics, 34(2): 71-80.

[19] L ZHANG. (2014). Reliability verification using proof pile load tests. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(11): 1203-1213.

[20] LM ZHANG, DQ LI, WH TANG. (2006) .Impact of routine quality assurance on reliability of bored piles. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(5): 622-630.

[21] Haijian Fan, Qindan Huang, Robert Liang. (2014). Reliability analysis of piles in spatially varying soils considering multiple failure modes. *Computers and Geotechnics*, 57: 97-104.

[22] Ana Teixeiraa, Yusuke Honjob. (2012). Sensitivity analysis of vertically loaded pile reliability. *Soils and Foundations*, 52(6): 1118-1129.

[23] Xin-ming ZHAO, Xiao-wei WANG, Chun-run ZHAO. (2008) Reliability analysis of vertical bearing capacity of PHC piles at north bank of Yangtze River, Nanjing. *Rock and Soil Mechanics*, 29(3): 785-789.

[24] Ming-hua Zhao, Zhao-yu Zeng, Xiao-ming Liu. (2005). Reliability of pile foundation under vertical and lateral loads. Journal of Architecture and Civil Engineering, 22(2): 57-60.

[25] Zhi-jun XU, Jun-jie ZHENG, Yong LIU. (2010). Reliability analysis for vertical bearing capacity of piles based on the maximum entropy principle. Chinese Journal of Geotechnical Engineering, 32(11):1643-1647.

[26] Zhi-jun XU, Jun-jie ZHENG, Xiao-ya BIAN. (2012). Reliability analysis of pile groups based on different failur criteria. Chinese Journal of Geotechnical Engineering 34(5): 819-825.

[27] Xiao-ya BIAN, Zhi-jun XU, Jun-jie ZHENG. (2013). Reliability analysis of bearing capacity of foundation piles considering pile foundation design approach. Chinese Journal of Geotechnical Engineering, 35(2):1099-1102.

[28] Peter Friis Hansen, Henrik O. Madsen. (1995). Reliability analysis of a pile design.Marine Structures, 8(2):171-198.

[29] Pan-fang Ning, Wei-hong Hu, 2006, The theoretical calculation of bearing capacity of batter pile. Guang dong Architechure Civil Engineering, 11: 3-5.

[30] Wu-ming Leng, 2000, Reliability analysis and design of foundation engineering. Chang Sha: Central South University press.

[31] Ministry of Construction, 2001, GB50068-2001. Reliability Design of Building Structures. Beijing: China Building Industry Pres.