Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 5204372, 8 pages
https://doi.org/10.1155/2019/5204372

*Research Article*

# Reliability Design of Soft Soil Foundation Preloading Method for Airport Runway

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Received 17 December 2018; Accepted 15 February 2019; Published 3 March 2019

Academic Editor: Hossein Moayedi

Focusing on the rapid assessment of the reliability of airport runway soft soil foundation, taking the soft soil foundation preloading method as the research object, we established the corresponding settlement calculation model and studied the soil parameters and how they affect the settlement values, and the reliability of the soft soil foundation preloading method was obtained by the checking point method (JC). In order to realize the fast calculation of reliability, Visual Studio 2010 is used to design the visual reliability calculation program of the airport runway soft soil foundation preloading method. The analysis results showed that the soil index with the greatest influence on the final consolidation settlement was the compression coefficient, followed by the soil layer thickness, the compression modulus, the void ratio, and the consolidation coefficient. On the basis of the limit state equation, we got the final failure probability formula. Combined with an airport project example, the reliability calculation results showed that the longer the preloading time was, the more reliable the treatment plan was, and the less the probability of failure was; the larger the preloading pressure was, the more reliable the treatment plan was, and the less the probability of failure was. In the engineering example, it can be found that the treatment plan with the preloading of 100 kPa and the stacking time of 150 days is the best solution.

## 1. Introduction

With the rapid development of the country's economic construction, the role of air transport is becoming more and more prominent. In particular, in recent years, more and more airports have been rebuilt and expanded. In fact, the airport occupies a large area, but the urban land is limited, so most of the airports are located in poor soil and wasteland, and the contradiction is particularly prominent in the coastal areas. Then, how to effectively evaluate the reliability of airport construction in soft soil area has become an important issue for airport design and engineering personnel.

Some scholars have carried out fruitful work on the reliability of ground base. Cherubini [1] obtained the general probability distribution of shallow foundation and calculated the cumulative distribution curve. Based on Cherubini's research results, Easa [2] got the rough probability distribution of shallow foundation, obtained the cumulative distribution curve by calculation, and compared with those results obtained by the Monte Carlo method. Qidong and Gao [3] carried out relatively systematically reliability research on the bearing capacity of natural foundation according to the bearing capacity calculation method proposed by Hansen and conducted sensitivity analysis. Ding et al. [4] established a random field model under the condition of inclined additional stress and studied the reliability sensitivity of the soil index according to the actual engineering conditions. The first-order second-moment method is employed to calculate the reliability of bearing capacity of foundation under inclined additional stress condition, combined with the bearing capacity calculation method proposed by Hansen [5]. Taking into account the uncertainties of the calculation model of bearing capacity and the load, with the reliability analysis method and the theory of probability and statistics, Bian et al. obtained respectively the calculation formulas of reliability indices for ultimate limit state (ULS) and serviceability limit state (SLS). Meanwhile, the linear relationship between reliability indices for ULS and SLS was presented. Finally, the impact of stochastic behaviors of limiting tolerable settlement of pile head (slt) on reliability analysis for SLS was studied. The following conclusions could be drawn from this study. First, the influences of soil type and pile type on the model factor for SLS were slight. Second, the reliability index for SLS decreased with an increase of the uncertainties from the bearing capacity calculation model and the load, although the decrease rate gradually diminished. And the total variation in the reliability index for SLS was limited, which means that it is reasonable to ignore the influences of the uncertainties from the bearing capacity calculation model and the load on the reliability analysis for SLS in engineering practice. Third, the stochastic behaviors of slt had a significant effect on reliability analysis for SLS [6]. The reliability of the bearing capacity of the CFG pile composite foundation was studied by Zhang and Zheng, and the sensitivity analysis of the influence factors was also carried out [7]. In Zhang et al. [8], based on the uncertainty analysis to calculation model of settlement, the formula of reliability index of foundation pile was derived; based on this formula, the influence of different parameters on reliability was analyzed; the results indicated that the high-reliability index could be obtained by increasing the safety coefficient; reliability index would be reduced with increasing of the mean value of the calculation model coefficient and coefficient of variation of the permissible limit of settlement; the reliability index would not always monotonically increase or decrease with increasing of coefficient of variation of the calculated settlement and coefficient of variation of the calculation model coefficient. The reliability calculation method of multipile composite foundation was proposed by Ding et al., and the reliability was solved by the checking point method [9].

Based on the aforementioned research, we find that there is no research on the reliability of airport soft soil foundation. In this paper, we focus on the rapid evaluation of the reliability of the airport runway soft soil foundation, taking the treatment technology of preloading method soft soil foundation as the research object; combined with an airport construction example, a corresponding settlement calculation model is established, and the sensitivity of the soil parameters affecting the settlement calculation model is studied, and then the JC method is used to get the reliability of the soft soil foundation preloading method treatment plan. In order to realize the fast calculation of the reliability, Visual Studio 2010 is used to design the visual program interface, and the reliability calculation program of the airport runway soft soil foundation preloading method treatment plan is written, which provides a simple and convenient way for the airport design and construction.

## 2. Reliability Theory

*2.1. Limit State Equation.* If the engineering structure can achieve the desired function, we call it a reliable state. If the engineering structure cannot achieve the expected function, we call it a failure state. In the middle state of reliability and failure, we call it the limit state, expressed as follows:

$$Z = g(X_1, X_2, \ldots, X_n). \tag{1}$$

*2.2. Reliability Index.* Let $X_1, X_2, \ldots, X_n$ be a random variable in the limit state equation, and $f_x(x_1, x_2, \ldots, x_n)$ is a corresponding probability density function. Then, the failure probability of the engineering structure can be expressed as follows:

$$P_f = P(Z < 0) = \iint_{Z<0} \cdots \int f_X(x_1, x_2, \ldots, x_n) dx_1 dx_2 \cdots dx_n. \tag{2}$$

Suppose that $Z$ is related to the two random variables $R$ and $S$, both $R$ and $S$ satisfy the normal distribution, the mean value is $\mu_R$, $\mu_S$, and the standard deviation is $\sigma_R$, $\sigma_S$. Then, the function can be expressed as $Z = R - S$ by $R$ and $S$ and also satisfies the normal distribution, with the mean value $Z = R - S$ and standard deviation $\sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2}$.

As shown in Figure 1, $Z < 0$ means the probability of failure and can be written as $P_f = P(Z < 0)$, that is, the shaded area shown in Figure 1. The distance from 0 to the mean value $\mu_Z$ can be expressed as $\mu_Z = \beta\sigma_Z$. It is not difficult to find that when $\beta$ is smaller, $P_f$ is larger, when $\beta$ is larger, $P_f$ is smaller. Since there is such a negative correlation between the probability of failure $P_f$ and the value $\beta$, we can refer to $\beta$ as the reliability index. Then, the failure probability can be expressed as follows:

$$P_f = P(Z < 0) = F_Z(0) = \int_{-\infty}^{0} \frac{1}{\sqrt{2\pi}\sigma_Z} \exp\left[-\frac{(z-\mu_Z)^2}{2\sigma_Z^2}\right] dZ. \tag{3}$$

To normalize equation (3) (i.e., $\mu_t = 0$, $\sigma_t = 1$), then

$$P_f = \int_{-\infty}^{-(\mu_z/\sigma_Z)} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{t^2}{2}\right] dt = \Phi(-\beta). \tag{4}$$

The reliability index $\beta$ can be expressed as follows:

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}. \tag{5}$$

*2.3. Calculation of Reliability Index by JC Method.* Before solving the reliability index $\beta$, we must standardize the data $X_i$ first, namely,

$$\overline{X_i} = \frac{X_i - \mu_{X_i}}{\sigma_{X_i}}, \quad (i = 1, 2, \ldots, n), \tag{6}$$

where $\mu_{X_i}$ is the mean value and $\sigma_{X_i}$ is the standard deviation. Then, in the coordinate space $\overline{O}\overline{X_1}\overline{X_2}\cdots\overline{X_n}$, the following equation can be used to express the limit state:

$$Z = g\left(\overline{X_1}\sigma_{X_1} + \mu_{X_1}, \overline{X_2}\sigma_{X_2} + \mu_{X_2}, \ldots, \overline{X_n}\sigma_{X_n} + \mu_{X_n}\right) = 0. \tag{7}$$

Equation (7) can be understood as the shortest distance from the limit state surface in the standard normal space

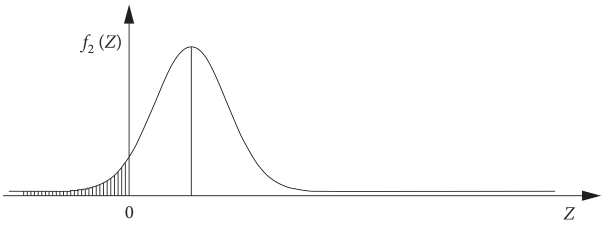


Figure 1: Probability density curve of performance function.

coordinate system $\overline{O}\overline{X_1}\,\overline{X_2}\cdots\overline{X_n}$ to the origin $\overline{O}$, which is regarded as the reliability index $\beta$. The limit state surface of the three normal random variables is shown in Figure 2, and the perpendicular point $P^*$ of the shortest point-to-surface distance is the "design checking point."

As shown in Figure 2, the direction cosine of the normal line $\overline{O}P^*$ relative to the coordinate vector is

$$\cos\theta_{\overline{x_i}} = \cos\theta_{x_i} = \frac{-(\partial g/\partial X_i)\big|_{p^8}\sigma_{X_i}}{\left[\sum_{i=1}^{n}\left((\partial g/\partial X_i)\big|_{p^*}\sigma_{X_i}\right)^2\right]^{1/2}}, \tag{8}$$

where $(\partial g/\partial X_i)|_{P^*}$ is the partial derivative at the point $P^*$.

By the definition of the direction cosine, we can see

$$\overline{X_i^*} = \overline{\overline{O}P^*}\cos\theta_{\overline{X_i}} = \overline{\overline{O}P^*}\cos\theta_{X_i} = \beta\cos\theta_{X_i}, \quad (i = 1, 2, \ldots, n). \tag{9}$$

It can be obtained by Formula (6):

$$\overline{X_i^*} = \frac{X_i^* - \mu_{X_i}}{\sigma_{X_i}} = \beta\cos\theta_{X_i}. \tag{10}$$

So, in the coordinate space $\overline{O}\overline{X_1}\,\overline{X_2}\cdots\overline{X_n}$, the coordinates of $P^*$ are

$$X_i^* = \mu_{X_i} + \beta\sigma_{X_i}\cos\theta_{X_i}, \quad (i = 1, 2, \ldots, n). \tag{11}$$

Since $P^*$ is on the limit state surface, there must be the following equation:

$$g\left(X_1^*, X_2^*, \ldots, X_n^*\right) = 0. \tag{12}$$

From equations (9) to (11) to form an equation system, we can solve $\beta$ and $X_i^*$ $(i = 1, 2, \ldots, n)$.

After the random variables are equivalently normalized, the reliability index $\beta$ can be solved by equations (9)–(11). However, $\mu_{X_i'}$ and $\sigma_{X_i'}$ are done by the checking point $x_i^*$, but the value of the checking point is unknown. It can be seen that the conditions of "equivalent normalization" and equations (9)–(11) are related to each other, and the iterative method is usually used to solve $\beta$.

## 3. Research on the Reliability of Preloading Method Treatment Plan

In this paper, the foundation settlement is taken as an index to study the reliability of the soft soil foundation treatment plan. According to the reliability theory, the limit state is designed and the limit state equation is constructed. Due to the large area of the airport, when the preloading method is used, a large area will be covered. Under these circumstances, the final vertical deformation of the runway foundation can be obtained by the stratified summation method.

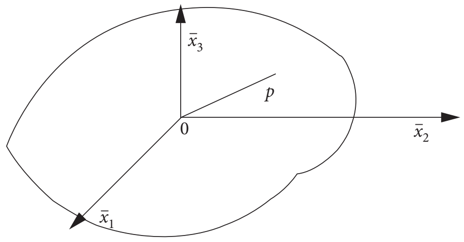


Figure 2: The curved surface of limit state.

*3.1. Preloading Method Foundation Settlement Calculation Model and Method.* According to the stratified summation method proposed by Terzaghi [10], under the condition of preloading, the final vertical deformation can be obtained by the following equation:

$$\begin{aligned} S_{\mathrm{t}} = SU_{\mathrm{t}} &= \left(N\sum_{i=1}^{n}\frac{a_{\mathrm{v}i}}{1+e_{\mathrm{o}i}}\Delta Ph_i\right) \\ &\quad\cdot\left(1-\frac{8}{\pi^2}e^{-\left(\left(8C_{\mathrm{h}}/F(n)\mathrm{de}^2\right)+\left(\pi^2C_{\mathrm{v}}/4H^2\right)\right)t}\right) \\ &= \left(N\sum_{i=1}^{n}\frac{1}{E_{\mathrm{s}i}}\Delta Ph_i\right)\left(1-\frac{8}{\pi^2}e^{-\left(\left(8C_{\mathrm{h}}/F(n)\mathrm{de}^2\right)+\left(\pi^2C_{\mathrm{v}}/4H^2\right)\right)t}\right), \end{aligned} \tag{13}$$

where $S_{\mathrm{t}}$ is the vertical deformation after treatment; $S$ is the foundation ultimate vertical deformation; $U_{\mathrm{t}}$ is the average consolidation degree of sand well drainage (excluding the influence of well resistance and smearing); $N$ is the correction coefficient; $a_{\mathrm{v}i}$ is the compressibility coefficient of soil; $e_{\mathrm{o}i}$ is the void ratio of the soil layer; $C_{\mathrm{v}}$ is the vertical drainage consolidation coefficient; $C_{\mathrm{h}}$ is the horizontal drainage consolidation coefficient; $a_{\mathrm{v}i}$ is the compressive modulus of the soil layer; $e_{\mathrm{o}i}$ is the void ratio of soil layer; $C_{\mathrm{v}}$ is the vertical drainage consolidation coefficient; $C_{\mathrm{h}}$ is the horizontal drainage consolidation coefficient; $E_{\mathrm{s}i}$ is the compressive modulus of the soil layer; $\Delta P$ is the additional stress, which is set as the constant; $h_i$ is the thickness of the $i$th compression layer; $H$ is the sand well longest drainage path length; de is the effective drainage diameter of the sand well; $n$ is the well diameter ratio; $F(n)$ is a function related to the well diameter ratio.

*3.2. Research on the Sensitivity of Soil Index.* For the settlement calculation model of preloading method foundation treatment plan, the final consolidation settlement of foundation is affected by many soil indexes [11], and the degree of influence is still different. In order to clarify the degree of influence of each index on the final consolidation settlement, so as to simplify the actual calculation model, it is necessary to conduct a sensitivity study of the soil index. According to the preloading method settlement calculation model, the final consolidation settlement is affected by the void ratio $e$, the consolidation coefficient $C_v$, the compression modulus $E_s$, the compression coefficient $a_v$, and the soil thickness $h$.

According to the engineering geological investigation report of an airport, silt clay is taken as the research object to study the degree of influence of each soil index on the final consolidation settlement. The results of the sensitivity study are as follows:

$$\begin{aligned} S_t = SU_t &= \left(\frac{a_v}{1+e}\right)\Delta Ph\left(1-\frac{8}{\pi^2}e^{-\left(\left(8C_h/F(n)\mathrm{de}^2\right)+\left(\pi^2C_v/4H^2\right)\right)t}\right) \\ &= \frac{1}{E_s}\Delta Ph\left(1-\frac{8}{\pi^2}e^{-\left(\left(8C_h/F(n)\mathrm{de}^2\right)+\left(\pi^2C_v/4H^2\right)\right)t}\right), \end{aligned} \tag{14}$$

where $S_t$ is the vertical deformation after the treatment; $S$ is the final foundation vertical deformation; and $U_t$ is the sand drainage average consolidation degree (excluding well resistance and smear effects).

Among them, the preloading load $\Delta P$ is assumed as 100 kPa, the well diameter ratio $n = \mathrm{de}/\mathrm{dw} = 1.47/0.07 = 21$, $F(n) = (n^2/(n^2-1))\ln(n) - ((3n^2-1)/(4n^2)) = 2.3$, the sand well effective drainage cylinder diameter $\mathrm{de} = 1.05l = 1.05 \times 0.4 = 1.47$ m, the maximum drainage path length of sand well $H = 15$ m, and the stacking time $t$ is 150 d. The soil index values are shown in Table 1.

TABLE 1: The statistics of soil parameter.

| Silt clay | $e$ | $a_v$ | $E_s$ | $C_v$ | $h$ |
|---|---|---|---|---|---|
| Mean value | 1.317 | 0.941 | 2.593 | 2.51E-04 | 3.900 |
| Standard deviation | 0.737 | 0.081 | 0.392 | 1.95E-05 | 0.792 |

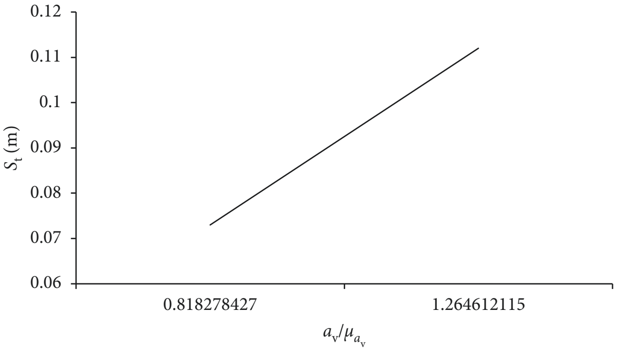


FIGURE 3: Effect of compression coefficient on final consolidation settlement.

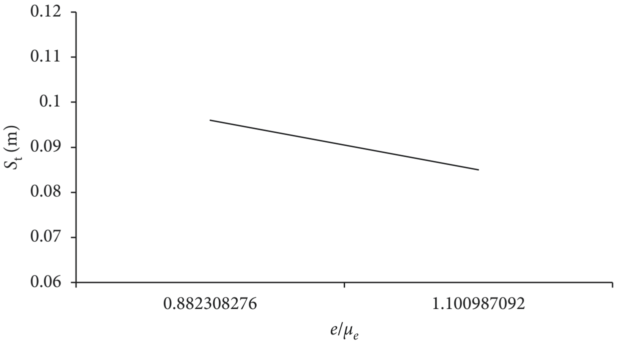


FIGURE 4: Effect of void ratio on final consolidation settlement.

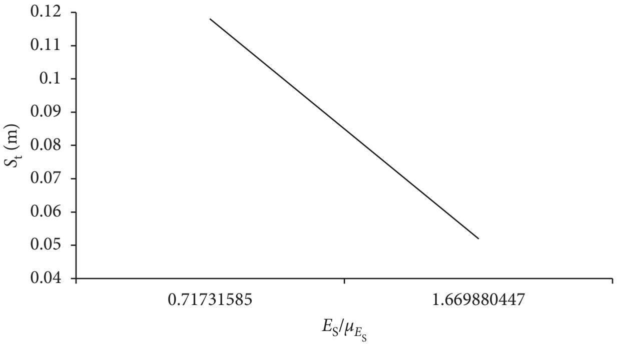


FIGURE 5: Effect of compressive modulus on final consolidation settlement.

(1) Calculation of the slope of the final consolidation settlement by the compression coefficient.

$a_v \sim \Phi(\mu_{a_v}, \sigma^2_{a_v})$, $\mu_{a_v} = 0.941$ MPa$^{-1}$, $\sigma_{a_v} = 0.081$, the changing range of $a_v$ is 0.770~1.190 MPa$^{-1}$, the slope is $|l_1|$, $|l_1| = ((S_{t\max} - S_{t\min})/((a_{v\max} - a_{v\min})/\mu_{a_v})) = 0.090$, as shown in Figure 3.

(2) Calculation of the slope of the final consolidation settlement by the void ratio.

$e \sim \Phi(\mu_e, \sigma_e^2)$, $\mu_e = 1.317$, $\sigma_e = 0.737$, the changing range of $e$ is 1.162~1.450, the slope is $|l_2|$, $|l_2| = ((S_{t\max} - S_{t\min})/((e_{\max} - e_{\min})/\mu_e)) = 0.052$, as shown in Figure 4.

(3) Calculation of the slope of the final consolidation settlement by the compression modulus.

$E_s \sim \Phi(\mu_{E_s}, \sigma^2_{E_s})$, $\mu_{E_s} = 2.593$ MPa, $\sigma_{E_s} = 0.392$, the changing range of $E_s$ is 1.860~4.330 MPa, the slope is $|l_3|$, $|l_3| = ((S_{t\max} - S_{t\min})/((E_{s\max} - E_{s\min})/E_s)) = 0.071$, as shown in Figure 5.

(4) Calculation of the slope of the final consolidation settlement by the soil thickness.

$h \sim \Phi(\mu_h, \sigma_h^2)$, $\mu_h = 3.9$, $\sigma_h = 0.792$, the changing range of $h$ is 3.6~4.3 m, the slope is $|l_4|$, $|l_4| = ((S_{t\max} - S_{t\min})/((h_{\max} - h_{\min})/\mu_h)) = 0.078$, as shown in Figure 6.

(5) Calculation of the slope of the final consolidation settlement by the consolidation coefficient.

$C_v \sim \Phi(\mu_{C_v}, \sigma^2_{C_v})$, $\mu_{C_v} = 2.5 \times 10^{-4}$ cm/s$^2$, $\sigma_{C_v} = 1.95 \times 10^{-5}$, the changing range of $C_v$ is 0.0002~0.0003 cm/s$^2$, the slope is $|l_5|$, $|l_5| = (S_{t\max} - S_{t\min}/(C_{v\max} - C_{v\min}/\mu_{C_v})) = 0.040$, as shown in Figure 7.

As Figures 3–7 show, $|l_1| > |l_4| > |l_3| > |l_2| > |l_5|$. The results show that the soil index which has the most influence on the final consolidation settlement is the compression

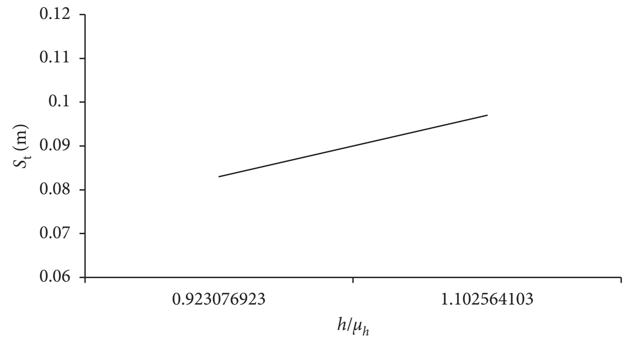


FIGURE 6: Effect of soil thickness on the final consolidation settlement.

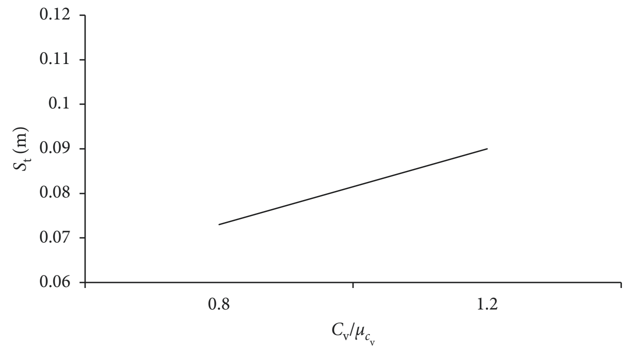


FIGURE 7: Effect of consolidation coefficient on the final consolidation settlement.

coefficient, and then the soil thickness, compression modulus, void ratio, and consolidation coefficient.

*3.3. Reliability Calculation of Preloading Method Soft Soil Foundation Treatment Plan.* The limit state is analyzed [12], and the limit state equation is determined as follows:

$$g(x) = \left(N\sum_{i=1}^{n}\frac{1}{E_{si}}\Delta Ph_i\right)\left(1-\frac{8}{\pi^2}e^{-\left(\left(8C_{\mathrm{h}}/F(n)\mathrm{de}^2\right)+\left(\pi^2C_{\mathrm{v}}/4H^2\right)\right)t}\right) - S' = 0, \tag{15}$$

where $S'$ refers to the foundation settlement in the construction period.

As for the judgment of the compressive soil layer, for the soft clay, it is judged by the principle that the prestress at a certain depth is equal to 0.1 times of the soil self-weight, that is, when $\sum_{i=1}^{N}\gamma h_i \geq 10\Delta P$, $h_i$ is the $i$-layer compressive soil thickness. And the effect of consolidation coefficient on foundation final consolidation settlement is very small, so it can be assumed that the consolidation coefficients of all the soil layers are the same, and the consolidation coefficients are the same in the transverse and vertical direction.

Assuming $C_{\mathrm{v}} = C_{\mathrm{h}}$, the statistics of $E_{si}$, $h_i$, $C_{\mathrm{v}}$ are shown in Table 2.

TABLE 2: The statistics of $E_{si}$, $h_i$, $C_{\mathrm{v}}$.

| Random variables | Mean value | Standard derivation | Variation coefficient |
|---|---|---|---|
| $E_{si}$ | $\mu_{E_{si}}$ | $\sigma_{E_{si}}$ | $\delta_{E_{si}}$ |
| $h_i$ | $\mu_{h_i}$ | $\sigma_{h_i}$ | $\delta_{h_i}$ |
| $C_{\mathrm{v}}$ | $\mu_{C_{\mathrm{v}}}$ | $\sigma_{C_{\mathrm{v}}}$ | $\delta_{C_{\mathrm{v}}}$ |

Then, you can use the iterative method to calculate the reliability $\beta$ and failure probability $P_{\mathrm{f}}$; the calculation steps are as follows [13]:

(1) Calculate the derivative of each variable.

$$\begin{aligned}
\left(\frac{\partial g}{\partial E_{si}}\right)_* &= \left(\frac{\partial g}{\partial E_{si}}\right)\Bigg|_{E_{si}^*}\sigma_{E_{si}} = \left(-N\frac{1}{E_{si}^{*2}}\Delta Ph_i^*\sigma_{E_{si}}\right) \\
&\quad\cdot\left(1-\frac{8}{\pi^2}e^{-\left(\left(8C_{\mathrm{h}}^*/F(n)\mathrm{de}^2\right)+\left(\pi^2C_{\mathrm{v}}^*/4H^2\right)\right)t}\right), \\
\left(\frac{\partial g}{\partial h_i}\right)_* &= \left(\frac{\partial g}{\partial h_i}\right)\Bigg|_{h_i^*}\sigma_{h_i} = \left(N\frac{1}{E_{si}^*}\Delta P\sigma_{h_i}\right) \\
&\quad\cdot\left(1-\frac{8}{\pi^2}e^{-\left(\left(8C_{\mathrm{h}}^*/F(n)\mathrm{de}^2\right)+\left(\pi^2C_{\mathrm{v}}^*/4H^2\right)\right)t}\right), \\
\left(\frac{\partial g}{\partial C_{\mathrm{v}}}\right)_* &= \left(\frac{\partial g}{\partial C_{\mathrm{v}}}\right)\Bigg|_{C_{\mathrm{v}}^*}\sigma_{C_{\mathrm{v}}} = \left(N\sum_{i=1}^{n}\frac{1}{E_{si}^*}\Delta Ph_i^*\sigma_{C_{\mathrm{v}}}\right) \\
&\quad\cdot\left(\frac{8}{\pi^2}\left(\frac{8t}{F(n)\mathrm{de}^2}+\frac{\pi^2t}{4H^2}\right)\right)e^{-\left(\left(8C_{\mathrm{h}}^*/F(n)\mathrm{de}^2\right)+\left(\pi^2C_{\mathrm{v}}^*/4H^2\right)\right)t}.
\end{aligned} \tag{16}$$

(2) Iterative method to solve the result: take $E_{si}^* = \mu_{E_{si}}$, $h_i^* = \mu_{h_i}$, and $C_{\mathrm{v}}^* = \mu_{C_{\mathrm{v}}}$, and the iterative solution is shown in Table 3.

Then, we put the new checking point back into the limit equation $g(x_1^*, x_2^*, \ldots, x_j^*) = 0$ and repeat the calculation. Finally, the value of $\beta$ can be obtained by the iteration method. And the probability of failure can be written as follows [14]:

$$P_{\mathrm{f}} = \Phi(-\beta) = 1 - \Phi(\beta). \tag{17}$$

*3.4. Engineering Example Analysis.* According to the engineering geological investigation report of an airport, in accordance with the preloading method soft soil foundation treatment plan requirements, the settlement generated in the construction time is $S'$. Assuming that sand wells' effective drainage cylinder diameter $\mathrm{de} = 1.47$ m, well diameter ratio $n = \mathrm{de}/\mathrm{dw} = 1.47/0.07 = 21$, $F(n) = (n^2/(n^2-1))\ln(n) - ((3n^2-1)/4n^2) = 2.3$, the longest drainage path length in a sand well $H = 66$ m, and take $\mu_{C_{\mathrm{v}}} = 0.001$, $\sigma_{C_{\mathrm{v}}} = 0.001$.

In this engineering example, the engineering technicians have designed three sets of plans:

Table 3: Iterative solution.

| Iteration number | $x_j$ | $x_j^*$ | $(\partial g/\partial x_j)_*$ | $\cos\theta_j$ | $x_j^{'*}$ |
|---|---|---|---|---|---|
| 1 | $E_{si}$<br>$h_i$<br>$C_\mathrm{v}$ | $\mu_{E_{si}}$<br>$\mu_{h_i}$<br>$\mu_{C_\mathrm{v}}$ | $(\partial g/\partial x_j)\vert_{x_j^*}\sigma_{x_j}$ | $-\left((\partial g/\partial x_j)_*/\sqrt{\sum(\partial g/\partial x_j)_*^2}\right)$ | $x_j^* + \beta\sigma_{x_j}\cos\theta_j$ |

(1) Preloading pressure is 80 kPa, stacking time is 150 d

(2) Preloading pressure is 80 kPa, stacking time is 180 d

(3) Preloading pressure is 100 kPa, stacking time is 150 d

By the iterative method, solve the reliability $\beta$ of different plans:

(1) Preloading pressure is 80 kPa, stacking time is 150 d.

Determine the thickness of soft soil layer. Because $\sum_{i=1}^{n}\gamma_i' h_i < 10\Delta P$, the thickness of the compressive layer is equal to the entire thickness of the soft soil layer.

Solve the value of $S'$ ($N$ value is 1.0) by equations (13) and (14):

$$S_\mathrm{t} = SU_\mathrm{t} = \left(N\sum_{i=1}^{n}\frac{1}{E_{si}}\Delta P h_i\right) \cdot \left(1-\frac{8}{\pi^2}e^{-\left(\left(8C_\mathrm{h}/F(n)\mathrm{de}^2\right)+\left(\pi^2 C_\mathrm{v}/4H^2\right)\right)t}\right) = 0.623\ \mathrm{m}. \tag{18}$$

From equation (14), make $S' = 0.6$ m, the result obtained by the JC method is as follows:

$$P_\mathrm{f} = 1-\Phi(\beta) = 1-\Phi(0.125) = 0.450. \tag{19}$$

(2) Preloading pressure is 80 kPa, stacking time is 180 days.

Take $S' = 0.6$ m, the result obtained by the JC method is as follows:

$$P_\mathrm{f} = 1-\Phi(\beta) = 1-\Phi(0.273) = 0.392. \tag{20}$$

(3) Preloading pressure is 100 kPa, stacking time is 150 days.

Take $S' = S_\mathrm{t} = 0.78$ m, the result obtained by the JC method is as follows:

$$P_\mathrm{f} = 1-\Phi(\beta) = 1-\Phi(0.535) = 0.294. \tag{21}$$

It is not difficult to find that the degree of reliability index affected by different parameters is not the same: the longer the stacking time, the more reliable the design plan is, the less likely the failure; the greater the preloading pressure, the more reliable the design plan is, the less likely the failure. In the engineering example, we adopted the third solution of which the failure probability is the least.

## 4. Reliability Calculation Program Design of Soft Soil Foundation Preloading Method Treatment

*4.1. Interface Design.* This program uses C # to realize the fast reliability calculation of the soft ground treatment plan, builds the development environment by using Visual Studio 2010, and creates the project file of "Reliability Calculation." The design of the login interface is shown in Figure 8. After completing the setting and making of the login form, we need to implement the login form selection processing technology and link to the interface of the corresponding processing technology. Then, the processing technology interface of the preloading method is designed, as shown in Figure 9. Finally, the code of the reliability calculation program is implemented according to the algorithm of reliability calculation.

### *4.2. Reliability Algorithm Programming*

#### *4.2.1. Reliability Algorithm*

(1) Input each random variable and constant

Constant: $n$, de, $F(n)$, $H$, $N$, $\Delta P$, $S'$, $t$:

Variable: $X_j$ ($j = 1,\ldots,n,n+1,\ldots,2n,2n+1$) means the average of each soil index; $Y_j$ ($j = 1,\ldots,n,n+1,\ldots,2n,2n+1$) means the standard deviation of each soil index.

(2) Calculate $(\partial g/\partial x_j)_*$

Let $X_j^* = X_j$,

When $j = 1,\ldots,n$, $Z_j = (-N(1/X_j^{*2})\Delta P X_{j+n}^* Y_j)(1-(8/\pi^2)e^{-((8/F(n)\mathrm{de}^2)+(\pi^2/4H^2))X_{2n+1}^* t})$

When $j = n+1,\ldots,2n$, $Z_j = (N(1/X_{j-n}^*)\Delta P Y_j)(1-(8/\pi^2)e^{-((8/F(n)\mathrm{de}^2)+(\pi^2/4H^2))X_{2n+1}^* t})$

When $j = 2n+1$, $Z_j = (N\sum_{i=1}^{n}(1/X_i^*)\Delta P X_{i+n}^* Y_j)((8/\pi^2)((8/F(n)\mathrm{de}^2)+(\pi^2/4H^2)))e^{-((8/F(n)\mathrm{de}^2)+(\pi^2/4H^2))X_j^* t}$

(3) Calculate $\cos\theta_j$

$$\cos\theta_j = -\frac{Z_j}{\sqrt{\sum Z_j^2}}, \quad j = 1,\ldots,n,n+1,\ldots,2n,2n+1. \tag{22}$$

(4) Calculate the new checking point $X_j^{'*}$

$$X_j^{'*} = X_j + \beta Y_j W_j, \quad j = 1,\ldots,n,n+1,\ldots,2n,2n+1. \tag{23}$$

(5) Take $X_j^{'*}$ into the equation $g(X_j^{'*}) = 0$, and solve $\beta$.

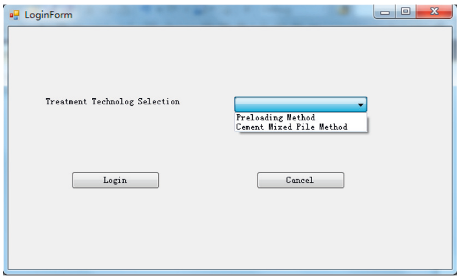


FIGURE 8: The login form.

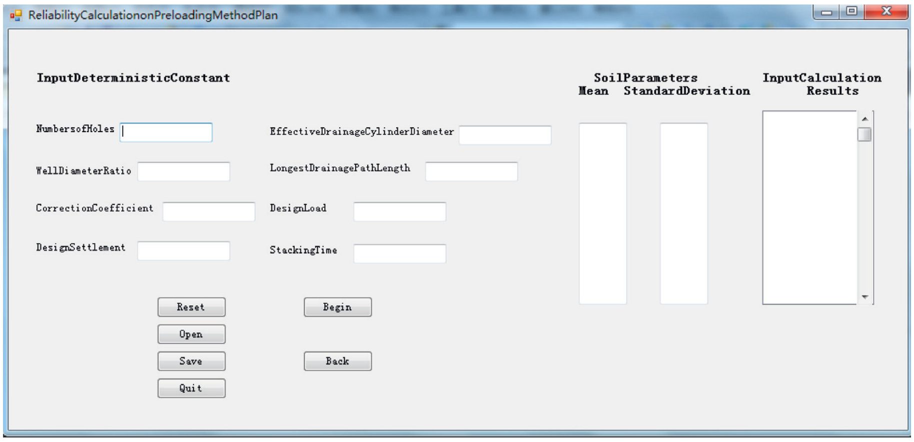
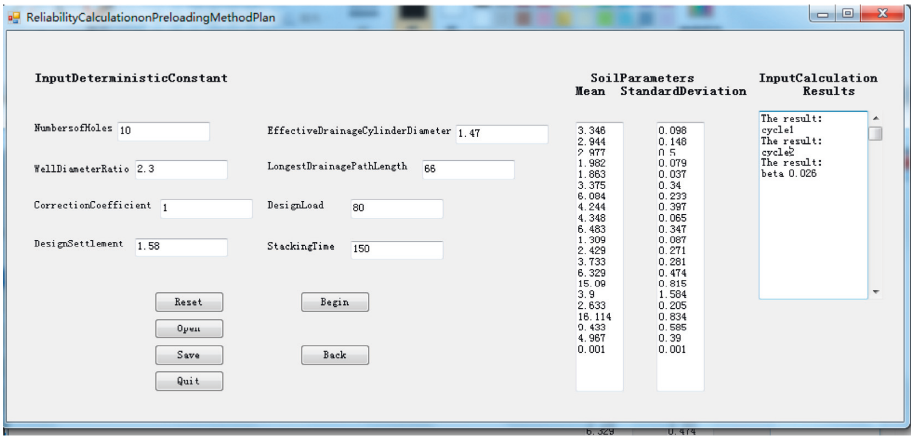


FIGURE 9: Preloading method reliability calculation interface.



NumbersofHoles 10
WellDiameterRatio 2.3
CorrectionCoefficient 1
DesignSettlement 1.58
EffectiveDrainageCylinderDiameter 1.47
LongestDrainagePathLength 66
DesignLoad 80
StackingTime 150

```
Mean    StandardDeviation
3.346   0.098
2.944   0.148
2.977   0.5
1.982   0.079
1.863   0.037
3.375   0.34
6.084   0.233
4.244   0.397
4.348   0.065
6.483   0.347
1.309   0.087
2.429   0.271
3.733   0.281
6.329   0.474
15.09   0.815
3.9     1.584
2.633   0.205
16.114  0.834
0.433   0.585
4.967   0.39
0.001   0.001
```

```
The result:
cycle1
The result:
cycle2
The result:
beta 0.026
```

FIGURE 10: The test result of the preloading method reliability calculation.

Let $\beta = 0$ $g\left(X_j^{'*}\right) = \left(N \sum_{j=1}^{n} \frac{1}{X_j^{'*}} \Delta P X_{j+n}^{'*}\right)$

$$\cdot \left(1 - \frac{8}{\pi^2} e^{-\left(\left(8/F(n)\mathrm{d}e^2\right) + \left(\pi^2/4H^2\right)\right) X_{2n+1}^{'*} t}\right) - S'. \quad (24)$$

Determine whether $|g(X_j^{'*})| < \varepsilon$, if yes, then export $\beta_1 = \beta$; if no, then let $\beta = \beta + \Delta\beta$, $\Delta\beta = 10^{-3}$, replace $\beta$ in $g(X_j^{'*}) = 0$, iterate until $|g(X_j^{'*})| < \varepsilon$, and export $\beta_1 = \beta$.

(6) Take $\beta = \beta_1$, $X_j^* = X_j^{'*}$, repeat Step 2 to Step 5, and then export $\beta_2 = \beta$.

(7) Iterate until $|\beta_{i+1} - \beta_i| \leq 10^{-3}$ and then export $\beta = \beta_{i+1}$.

*4.2.2. Program Implementation.* After the program design is completed, the program needs to be tested so as to observe whether the program can successfully realize its proper function. In the engineering example in this paper, the preloading method test results are shown in Figure 10.

The result of the program is correct, the fast calculation is realized, and the efficiency of work is improved.

## 5. Conclusions

In this paper, we take the airport runway soft soil foundation as the research object and research on the reliability of preloading method soft ground plans by means of theoretical analysis, numerical simulation, and engineering example analysis and program design. According to the settlement calculation model, the influence degree of each soil parameter on the final consolidation settlement is analyzed. Moreover, we find the relationship between the stacking time and the reliability, and the preloading pressure and the reliability that the longer the stacking time is, the more reliable the design plan is, and the less likely the failure possibility is; the larger the preloading pressure is, the more reliable the design plan is, and the less likely the failure possibility is. Finally, we solve the complicated problem of reliability calculation and write the calculation program. The reliability calculation program is much faster than the manual calculation, which can save time and reduce the workload. According to the engineering example of an airport runway soft soil foundation, we carry out the reliability calculation; the theoretical calculation result is consistent with the practical application, which shows the feasibility of the reliability calculation method. In the next step, we can consider other foundation treatment technology reliability calculation programss and gradually form a set of reliability research system.

## Data Availability

All data included in this study are available upon request from the corresponding author.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Authors' Contributions

Qingkun Yu designed models and wrote the manuscript, Liangcai Cai analyzed the results, and Xiang Shi conducted data collection and statistics.

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