Monitoring Data Analysis and Structural Reliability of Foundation Pit During Construction: A Case Study

Guowang Meng

Guangxi University

Hongbin Qiu (✉ 1039273208@qq.com)

Guangxi University

Yajie ZHao

Jinan Rail Transit Group Co., Ltd

Bo Wu

Guangxi University

Da Gao

Jinan Rail Transit Group Co., Ltd

Wei Huang

Guangxi University

Guixiang Liu

China Railway Beijing Engineering Group Co., Ltd

Research Article

Keywords: Ground settlement, Reliability evaluation, Foundation pit, Reliability level, Structure deformation

Posted Date: September 15th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-877543/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Monitoring data analysis and structural reliability of foundation pit during construction: a case study

Guowang Meng^{1,2}, Hongbin Qiu^{1,*}, Yajie ZHao⁵, Bo Wu^{1,3,4}, Da Gao⁵, Wei Huang¹, Guixiang Liu⁶

¹ College of Civil Engineering and Architecture, Guangxi University, Nanning 530004, China;

² Key Laboratory of Disaster Prevention and Structural Safety of Ministry of Education, Guangxi University, Nanning 530004, China;

³ School of Civil and Architectural Engineering, East China University of Technology, Nanchang 330013, China;

⁴ School of Architectural Engineering, Guangzhou City Construction College, Guangzhou 510925, China;

⁵ Jinan Rail Transit Group Co., Ltd., Jinan 250101, China;

⁶ China Railway Beijing Engineering Group Co., Ltd., Beijing 102308, China;

* Corresponding author: Hongbin Qiu, E-mail: 1039273208@qq.com

Abstract: In order to solve the problem that only considering the deformation of the side wall or the ground settlement of a single factor of the reliability evaluation may lead to insecurity, a deformation reliability evaluation method considering both the deformation of the side wall and the ground settlement is proposed. This evaluation method is used to evaluate the reliability of foundation pit structure deformation of Jinan metro in Shandong Province, China. Through the study of the deformation of the side wall and ground settlement loss on six profiles, the influence of the coefficient (λ , α and β) on the reliability is considered, and the recommended value of the coefficient (λ , α and β) is given. The reliability of six profiles is evaluated and the reliability level is obtained successfully. The reliability evaluation method can solve the problem that considering a single failure mode may lead to insecurity, and can provide an effective solution to the reliability evaluation of foundation pit retaining structure deformation.

Key words: Ground settlement; Reliability evaluation; Foundation pit; Reliability level; Structure deformation

1. Introduction

In the past few decades, the mileage and scale of metro in the world have increased rapidly, and the chain reaction has brought about the continuous growth of the number and scale of deep foundation pits. Due to the high, large, difficult and dangerous characteristics of deep foundation pit engineering, the consequences of foundation pit accidents are often not willing to bear, which will cause economic losses, casualties and negative social impact. In addition, it will also drag down the progress of construction, cause delay in construction period, and fail to deliver the project on schedule. In order to prevent the occurrence of such engineering accidents, soil settlement and structure deformation will be taken as important control items in the design and construction of foundation pit engineering. The failure of deep foundation pit deformation can be explained as the deformation beyond the predefined threshold. The deformation of side wall and ground surface concerned by engineering practice is only the deformation at the monitoring point. The deformation value is affected by various uncertain factors. The influence of uncertain factors has been studied in geotechnical engineering. Considering the uncertainty of geotechnical parameters, the randomness and variability of design parameters are described by probability theory, and the probability estimation of risk can be obtained

¹⁻⁴. In order to solve the uncertainty of support structure design (geotechnical design) and potential risks, Perk recommends using the observation method as an effective tool. Luo et al. ⁵ used bootstrap method to evaluate the maximum wall deflection or ground settlement overrun probability of foundation pit under the uncertainty of design parameters. The randomness and variability of design parameters are affected by the spatial variability of soil. It is important to consider the spatial variability of soil in the design and response analysis of foundation pit support structure ⁶. When the spatial variability is ignored, the variation on design parameters may lead to significantly overestimation or underestimation of failure probability ⁶; ⁷. Reliability assessment in the process of foundation pit construction can reduce the occurrence of accidents in the process of foundation pit construction. In recent years, many scholars had made contributions to this field. Papaioannou et al. used different deformation measurement information in the construction stage to update the reliability of geotechnical site ². Hsiao, Evan C., et al. ⁸ used semi empirical model to calculate the settlement caused by foundation pit excavation, and evaluated the reliability of adjacent buildings. Gholampour, A., and A. Johari. ⁹ proposed a method to analyze the reliability of foundation pit support in unsaturated soil with spatial variation. Spross, J., & Johansson, F. ¹⁰ introduced a reliability constraint on the observation method of geotechnical engineering projects, which may be a valuable tool for daily work and risk management. Straub, D., and Papaioannou, I. ¹¹ interprets the Bayesian updating problem as a structural reliability problem, and illustrates the generality and efficiency of Bayesian updating through three application examples. Xu, Li, et al. ¹² put forward a new method to analyze the deformation reliability of deep foundation pit supporting structure by using the field monitoring data, and illustrated the applicability of the method through an example. Wang, Feiyang, et al. ¹³ studied the time-varying reliability of time-varying deformation of cohesive soil. However, most of the previous reliability studies only consider a single factor: surface settlement or sidewall deformation. In practical engineering, it is not safe from only considering the single factor reliability evaluation. At the same location, the displacement of the side wall may not exceed the safe range, but the ground settlement may have exceeded the safe range. Similarly, sometimes the ground settlement may not exceed the safe range, but the displacement of the side wall may have exceeded the safe range. The evaluation based on system reliability shows that the failure probability of the system is greater than or equal to the probability of each single failure mode, which indicates that the evaluation considering a single failure mode may lead to insecurity ⁷. Therefore, a reliability evaluation method of foundation pit retaining structure deformation considering ground settlement and side wall deformation is proposed.

2. Methods

2.1 Deformation Analysis of Foundation Pit

The construction process of deep foundation pit of subway station is a process of constant mechanical balance. The excavation of deep foundation pit will make the structure develop towards the unbalanced direction, which inevitably leads to the deformation of soil and stressed structure. In the process of foundation pit excavation, after the soil in the excavation area is removed, the soil pressure on both sides of the side wall are out of balance. The side wall will produce the unbalanced soil pressure difference of horizontal transverse deformation to the unloading side ¹⁴. The unbalanced earth pressure difference causes the deformation response of the side wall and the ground surface.

The current research results have achieved a good prediction of ground settlement and side wall deflection. There are two common prediction methods of ground settlement caused by foundation pit

excavation: finite element method and empirical method. Hsieh and Ou¹⁵ proposed an empirical method to predict the spandrel and concave settlement profiles, and the effectiveness of the empirical method was verified by a case study. The finite element method which does not use the accurate expression of small strain nonlinearity in soil model to predict the ground settlement near excavation is not effective. When using an implicit numerical integration algorithm to implement a highly nonlinear elasto-plastic constitutive models in FEM simulations, some difficulties would encounter¹⁶. Therefore, Gordon T., et al.¹⁷ proposed a simplified semi empirical model, the results show that the model can accurately predict the maximum wall deformation and ground settlement caused by foundation pit excavation in soft clay. Hsieh and Ou.¹⁵ put forward the concept of primary settlement influence area and secondary settlement influence area. The settlement of the building is related to whether it is in the primary settlement influence area¹⁸. The settlement of buildings located in the primary settlement influence area will be greater than that in the secondary settlement influence area. References^{19, 20} explained the relationship between the uneven settlement of soil and the inclination, cracking, deformation and collapse of buildings, and proposed setting threshold to prevent unacceptable failure. Therefore, the deformation of side wall, the settlement of surrounding ground and the settlement of buildings is closely related⁸. This may indirectly reflect the failure of surrounding buildings by studying the reliability of surface and side wall deformation.

The deformation modes of side wall of deep foundation pit includes: cantilever mode and expansion mode²¹, as shown in Fig. 1. We can also understand that Fig. 1 are three profiles of the deformation of the side wall and the ground settlement. The cantilever model in Fig. 1(a) is easier to form spandrel settlement profile on the surface. The expansion model in Fig.1 (b)、(c) is easier to form spandrel settlement profile on the surface. The relationship between the area of the deep inward member (A_s) and the area of the cantilever member (A_c) can be obtained by simple estimation¹⁵. In the existing studies, it has been shown that there is a correlation between the maximum settlement and the maximum deformation of the side wall. This solves the problem of estimating the maximum ground settlement. By comparing the calculation results with the field observation results, a method of predicting the concave settlement profile of soft clay and hard clay is proposed¹⁵. The concave settlement profile is shown in Fig. 2. Clough and O'Rourke proposed a method for predicting spandrel settlement profile, which is suitable for sand, hard clay to very hard clay, medium soft clay to medium clay^{17, 21}. The spandrel settlement profile is shown in Fig. 3. The above two prediction methods are applied to the surface settlement profile of subway foundation pit in Jinan, Shandong, China. The prediction process is as follows:

- (1) Estimate the maximum deformation of the side wall (δ_{hm});
- (2) Calculate the cantilever area (A_c) and deep inward area (A_s) of the wall deflection;
- (3) According to Fig. 16 of reference¹⁵, the type of ground settlement profile is determined;
- (4) According to Fig. 17 of reference¹⁵, the maximum ground settlement is estimated δ_{VM} ;
- (5) The allowable ground settlement loss ($V(x)$) behind the side wall is calculated according to the type of surface settlement profile.

Fig 1. Modes of deformation of the side wall. (a) Cantilever movement; (b) Deep inward movement; (c) Cumulative movement.

Fig 2. Concave settlement profile.

Fig 3. Spandrel settlement profile. (a) Sands; (b) Stiff to very hard clays; (c) Soft to medium clays.

2.2 Reliability Analysis Method

2.2.1 Algorithm Introduction

The research based on time-varying reliability of structure has been started a long time ago²²⁻²⁴. Poisson distribution originated from binomial distribution, which is a kind of discrete probability distribution often seen in statistics and probability. Publish by French mathematicians (Siméon-Denis Poisson) in 1838. In the binomial distribution with " n " and " p " as parameters, " n " is the number of tests and " p " is the probability of failure. The failure probability of Eq. (1) $X = k$ can be obtained.

$$P(X = k) = C_n^k p^k (1 - p)^{n-k} \quad k = 0, 1, L \quad (1)$$

Note: When n is very large ($n \geq 100$), p is very small ($p \leq 0.1$), Let $np=\lambda$ be a normal number, there is an approximate Formula (2):

$$P(X = k) = C_n^k p^k (1-p)^{n-k} \sim \frac{\lambda^k}{k!} e^{-\lambda}, k = 0, 1, L \quad (2)$$

The sufficient expiration of model uncertainty is very important for reliability analysis based on unknown credible geotechnical engineering analysis model²⁵. Poisson distribution is applied to describe the number of random events per unit times. The number of foundation pits construction n can be regarded as a large number ($n \geq 100$), and the failure probability p can be regarded as a small amount ($p \leq 0.1$). Then, the reliability probability of foundation pit construction cycles is consistent with Poisson distribution. λ is a probability parameter about construction cycle (c), geological condition (g), side wall type (s) and process parameter (p). Its expression is shown in Eq. (3). Therefore, the probability function of Poisson distribution considering (c, g, s, p) can be expressed as Eq. (4). The reliability probability $P(X \leq r)$ in the construction cycle is shown in Eq. (5). The side wall of foundation pit is divided into diaphragm wall and bored pile wall. Construction processes please refer to technical measures in Section 3.3.3. Generally speaking, the shorter the construction cycle is, the better the geological conditions are, and the process are strictly implemented according to the technical measures, the smaller the λ value is. On the contrary, it may be bigger.

$$\lambda = F(c, g, s, p) \quad (3)$$

$$P(X = k) = \frac{\lambda^k}{k!} e^{-\lambda}, \quad k = 0, 1, L \quad (4)$$

$$P(X \leq r) = \sum_{k=0}^r \frac{\lambda^k}{k!} e^{-\lambda}, \quad k = 0, 1, L \quad (5)$$

Where λ is represents the probability parameter related to (c, g, s, p); where k is represents the construction cycle.

The monitoring data of the side wall is a group of discrete samples of random sequence varying from the depth. Compared with the soil, the stiffness of the side wall is regarded as infinite. Therefore, the maximum lateral displacement measured by the inclinometer is regarded as the maximum deformation of the side wall. The reliability of side wall deflection is expressed by Eq. (6).

$$L(\delta) = \exp\left(\frac{\delta}{-\alpha \delta_{hm}}\right) \quad (6)$$

Where α is represents the coefficient of foundation pit side wall.

The monitoring data of ground settlement are collected by horizontal intermittent distribution. Because the data collected from the actual monitoring of the cumulative maximum ground settlement is a point sequence, the settlement points are connected into fold lines, and the monitoring settlement loss is obtained by piecewise integration of the linear equation. The monitoring settlement loss is shown in formula (7). The greater the monitoring settlement loss, the greater the impact on the surrounding buildings, the greater the risk of uneven settlement, cracking, or even collapse of the surrounding buildings, and the lower the reliability.

$$V_s(x) = \sum_{i=1}^n \int_{x_i}^{x_{i+1}} b_i x dx \quad (7)$$

Where b_i is represents the coefficient of the i fold line, where n is represents the number of fold line segments, $V_s(x)$ is the actual ground settlement loss.

Eq. (8) is used to represent the reliability of the monitored ground settlement loss.

$$W(V_{(x)}) = \exp\left(\frac{V_{s(x)}}{-\beta g V_a}\right) \quad (8)$$

Note: where β is represents the profile coefficient.

Finally, reliability assessment. The indication function is used to control the allowed deformation of the side wall and the allowable settlement loss. Reliability assessment equation is shown in Eq. (9).

$$R(x) = P(X \leq r)gL(\delta)gW(V_{(x)})gI(\delta \geq \delta_{hm})gI(V_s(x) \geq V(x)), \quad k = 0, 1, L \quad (9)$$

Where $I(?)$ is represents an indicative function. If the statement in brackets is false, it returns 1, otherwise it returns 0.65.

The fuzzy uncertainty of geotechnical engineering determines the fuzziness of reliability. The reliability can be directly expressed by quantitative classification. The reliability classification table is shown in Table 1.

Range of R(x)	<65%	65%≤R(x)<75%	75%≤R(x)<85%	85%≤R(x)
Reliability classification	D	C	B	A
Evaluation	poor	medium	good	excellent

Table 1. Reliability classification table.

2.3 Case Study

2.3.1 Engineering Background

Yan Qianhu station is located in Jinan 2, Shandong Province, China, is a transfer station with R2 lines and M1 lines. The total length of the station is 485.2m, the width is 21.3m, and the depth of the foundation pit is 18.2m. Cut and cover method is adopted for construction. The retaining structure of foundation pit adopts bored pile wall + internal support system. a、 The standard section depth of the foundation pit is about 17.9 ~ 18.2m. It uses $\Phi 1,000\text{mm}@1,500$ bored pile wall, the effective pile length is 26.56 ~ 30.56m. Four layers of support are set along the depth direction of the foundation pit, the first layer is reinforced concrete support, and the profile size is 800mm × 900mm. The second and fourth layers are $\Phi 609\text{mm}$ (t = 20mm) steel pipe support. The third layer is $\Phi 800\text{mm}$ (t = 16mm) steel pipe support. b、 The small mileage depth of R2 line end well is about 17.9 ~ 18.2m. It uses $\Phi 1,200\text{mm}@1,500\text{mm}$ bored pile wall, the effective pile length is 28.84m. Four layers of support are set along the depth direction of the foundation pit, the first layer is reinforced concrete support, and the profile size is 800mm × 900mm. The second and fourth layers are $\Phi 609\text{mm}$ (t = 20mm) steel pipe support. The third layer is $\Phi 800\text{mm}$ (t = 16mm) steel pipe support. c、 The large mileage depth of R2 line end well is about 19.75m. It uses $\Phi 1,200\text{mm}@1,500\text{mm}$ bored pile wall, the effective pile length is 27.15m. Four layers of support are set along the depth direction of the foundation pit, the first layer is reinforced concrete support, and the profile size is 800mm × 900mm. The second layer is $\Phi 609\text{mm}$ (t = 20mm) steel pipe support. The third and fourth layers are $\Phi 800\text{mm}$ (t = 16mm) steel pipe support. The plane diagram of foundation pit as shown in Fig.4.

Fig 4. The plane diagram of foundation pit.

2.3.2 Hydrogeological Condition

The typical foundation soil distribution in the construction area from top to bottom is as follows: 1-1 miscellaneous fill, 1-2 plain fill, 7 clay, 7-1 silty clay, 10-1 silty clay, 14-1 silty clay, 19-1 completely weathered diorite, 19-2 strongly weathered diorite and 19-3 moderately weathered diorite. The main aquifers of pore phreatic water in Quaternary loose layer are as follows: 1-1, 1-2 layers of artificial filling bottom, 10-1, 14-1 layer of powder clay. 7-1 Powder clay, rich water and permeability are relatively small. The main aquifers of bedrock fissure phreatic water are as follows: 19-1 completely weathered diorite and 19-2 strongly weathered diorite. Bedrock fissure water has the characteristics of large aquifer thickness and rich water. Main aquifuges: 19-3 moderately weathered diorite. The aquiclude is characterized by relatively complete rock mass, undeveloped fissures and low permeability. The typical geological profile of foundation pit is shown in Fig. 5.

Fig 5. The typical geological profile of foundation pit.

2.3.3 Quality Assurance Measures

The reliability of foundation pit engineering is often related to construction methods and quality control. When the engineer fails to implement the quality control measures, the performance of deep foundation pit retaining structure may fail to achieve the expected function. It will affect the reliability of normal function and increase the potential risk. Therefore, strictly following the quality assurance measures is an important measure to ensure the reliability. Diaphragm wall and other types of technical measures, please refer to the relevant information. Next, the technical measures of bored pile wall are introduced.

2.3.3.1 Retaining Structure

The bored pile adopts the method of jumping holes in batches to avoid the hole collapse caused by too close distance between two adjacent piles and short time interval of continuous hole forming construction. The construction shall be carried out at least 2 holes apart, and the construction sequence is shown in Fig. 6. That is, the pile of the serial number "1" is applied, and then the number "2" is applied, and finally the "3" pile is applied, and so on.

Fig 6. Construction sequence.

2.3.3.2 Foundation Pit Excavation

Reasonable construction sequence is of great significance in controlling the deformation of foundation pit^{18; 26}. In the construction, the potential risks caused by its large scale are minimized. We adopt the excavation method of horizontal segmentation, vertical stratification, rapidly excavation and timely support. This method is helpful to control the deformation of foundation pit²⁶⁻³¹.

2.4 Reliability Assessment

Determine the λ value: the construction cycle of foundation pit project is generally 2 years. It is predicted that the reliability probability within 2 years is $P(X \leq 2)$. The longer the foundation cycle of the foundation pit, the higher the probability of the accident. When the construction cycle is determined, the λ value determines the size of the probability, the correlation between the λ value and the probability is shown in the Fig.7. As the λ value increases, the reliability probability is reduced. This regularity provides a good condition for selecting λ values within a certain range. Take full account of geological conditions, side wall types and process parameters to determine the value, see Eq. (3). Next, the qualitative analysis of Eq. (3) is carried out. In the study of diaphragm wall and bored pile wall by Goh³², the improved apparent pressure diagram is proposed. The apparent pressure of soft clay is higher than that of hard clay. The worse the engineering properties of the soil, the greater the settlement and the surface force acting on the outer surface of the side wall, and the greater the deformation of the side wall. The overall stability of diaphragm wall is higher than that of bored pile wall, which is a loss of economy for diaphragm wall. Therefore, generally speaking, the α value of diaphragm wall is smaller than that of bored pile wall. The effect of different processes on the performance is inestimable. "Horizontal segmentation, vertical stratification, rapid excavation and timely support" can minimize the impact of performance. In this case, $\lambda = 0.6$ is recommended, and the reliability probability is 97.7%.

Determine $L(\delta)$: During sectional excavation, the deflection of the side wall of each section will be monitored, and the deflection at the position where the maximum deformation occurs will be taken δ . In the deformation reliability analysis of the side wall, Xu, L., et al.¹² set the displacement limit to 73.5mm. The setting of δ_{hm} can be multiplied by a coefficient greater than 1.0, or set with reference to the existing experience. Here, take 1.2 times of the maximum deformation of profile 1 for setting.

Determine $V(x)$: According to the typical geological profile in Fig.5, the excavation depth of the foundation pit in the construction site is mostly soft clay. According to the construction technology and soil type, it can be determined as a concave settlement profile, which is checked by the settlement monitoring data and determined as a concave profile again. For $V_s(x)$, the more monitoring data points, the more accurate the monitoring section settlement area is. There are buildings in the primary settlement influence area and secondary settlement influence area, and more monitoring points are arranged. In areas without buildings, the number of monitoring points is less, which can save human resources. The area of settlement profile has a high correlation with the lateral displacement area. In most cases, the area of both is very close.

Reliability calculation: Select profile 1 to determine the parameters. In order to illustrate the applicability of the evaluation method, based on the parameters of profile 1, profile 1 ~ profile 6 are selected for reliability evaluation. The obtained reliability and reliability level are shown in Table 2.

Position Project	Profile 1		Profile 2		Profile 3		Profile 4		Profile 5		Profile 6	
	ZQT01	DBC01	ZQT02	DBC02	ZQT03	DBC03	ZQT04	DBC04	ZQT05	DBC05	ZQT06	DBC06
λ	0.6		0.6		0.6		0.6		0.6		0.6	

δ	46.14		39.38		25.59		15.85		21.85		23.5	
δ_{VM}	55.37		55.37		55.37		55.37		55.37		55.37	
α	6		6		6		6		6		6	
β		5		5		5		5		5		5
Va		1.34		1.34		1.34		1.34		1.34		1.34
$V_s(x)$		0.54		0.53		0.95		1.29		0.56		0.34
R(x)	0.78		0.80		0.79		0.77		0.84		0.87	
Reliability level	B		B		B		B		B		A	

Table 2. Reliability evaluation.

3. Results and Discussion

It can be seen from the reliability evaluation table in Table 1 that there are differences in the reliability of the six profiles. In the same construction site of foundation pit construction project, the same side wall type, the same construction cycle, the same technical measures. Hydrogeological conditions, process parameters and surrounding environment may be the main factors causing the reliability difference. Next, let's discuss about it.

Hydrogeological conditions: during the excavation of foundation pit, the change of groundwater level has a great influence on the surface settlement. In the excavation of foundation pit, the ground settlement of existing buildings is not only affected by the construction task of foundation pit excavation, but also greatly affected by the dewatering soil in the construction of foundation pit³³. Due to the large decrease in the underground water level, the maximum deflection of the wall are relatively small compared to the significant largest ground settlement³⁴. Although groundwater control measures have been taken, it is observed that the groundwater level behind the side wall will gradually decrease with the increase of excavation depth. Due to the decrease of groundwater level, obvious ground settlement was observed³⁵. The increase of ground settlement will increase the soil loss, which will reduce the reliability. In addition, the soil type can also affect the settlement. The better the engineering properties of soil, the smaller the settlement and the higher the reliability. In order to explain the influence of hydrogeological conditions on reliability, the Profile 1 is selected for discussion λ Value. As shown in Fig. 8, the reliability decreases with the increase of λ value. Under the condition that other factors remain unchanged, the reliability evaluation values of each grade can be obtained by taking different λ values. This also shows that λ values is flexible.

Fig 7. λ - P- k.**Fig 8. λ - R.**

Process parameters: diaphragm wall and bored pile wall have different construction techniques, which cause different performance. The diaphragm wall has good integrity and good waterproof effect. Bored pile wall has a good economy, but the integrity and anti-seepage effect is poor. In addition, the stiffness of diaphragm wall is larger than that of bored pile wall. The larger the stiffness is, the stronger the constraint on the surrounding soil is, which can reduce the settlement and is good for the reliability. Next, set up $\lambda = 0.6$, $\beta = 5$, we will expound the influence of coefficient on reliability. The influence curve of α is shown in the Fig.9.

Fig 9. α - R. **Fig 10. β - R.**

Through the study of six profiles, it can be seen that the reliability increases with the increase of the α value, and the growth mode of the reliability of each profile is similar, as shown in Fig. 9. When the α value is between 1 and 8, the reliability increases rapidly with the increase of the α value. When the value is greater than 8, the reliability increases slowly with the increase of the α value, and finally tends to be stable. According to the influence of α value on reliability, it is suggested that α values should be controlled in [3, 10]. For the more mature process, the smaller the deformation response, the higher the reliability, and the higher the value of α . For the process of large deformation response, α is smaller.

Construction technology will affect the type of settlement profile. The influence of settlement profile type of reliability is mainly reflected on the range of settlement influence and the maximum settlement. In the cantilever mode, the lateral displacement of the top of the side wall is not limited, resulting in the maximum deformation of the top of the side wall. This creates favorable conditions for the formation of spandrel profile. The expansion mode is limited by the lateral displacement of the top of the side wall. It is easy to form a concave settlement profile. The influence range of concave settlement profile is larger than that of spandrel settlement profile. This means that it is more likely to affect the surrounding buildings, which is unfavorable for reliability. Next, six profiles are also discussed. The value of λ is 0.6, the value of α is 6, the influence of correlation coefficient β on reliability is studied. As shown in Fig. 10, the influence of correlation coefficient β on reliability has the same trend as that of correlation coefficient α . We suggest that the value range of α should be controlled in [3, 8]. We also suggest that the concave settlement profile should be smaller and the spandrel settlement profile should be larger.

The layout of monitoring points has a general influence on the monitoring settlement loss. The more monitoring points, the more accurate the monitoring settlement loss and the more accurate the reliability. It is also worth noting that the settlement of buildings within the influence area. Due to the

gravity of the building itself, the settlement will be larger than that without the building. This means that there is a sudden change in the amount of settlement monitored at the location of buildings, which may overestimate the amount of soil loss monitored. The spatial variability of soil in the affected area may also affect the accuracy of monitoring. Ignoring the existence of spatial variability, reliability may be underestimated or overestimated^{9; 36; 37}. In this study, the influence of soil spatial variability on the accuracy of settlement monitoring is not considered.

The construction cycle of foundation pit in this case is 2 years, λ value is 0.6, α value is 6, and β value is 5. The obtained reliability and reliability evaluation level are shown in Table 2. The evaluation results may be used to reduce the risks in the construction process.

4. Conclusions

Four reliability evaluation problems are solved through the case: 1. The nature of input uncertainty; 2. Reliability analysis method; 3. Geotechnical analysis model; 4. Interpretation output. The probability function of Poisson distribution is connected with (c, g, s, p) . Combining probability with deformation of side wall and ground settlement, a reliability evaluation method considering probability, deformation of side wall and settlement loss is established. This method makes up for the previous reliability evaluation method which only considers wall deformation or ground settlement. In order to illustrate the applicability of the evaluation method, six profiles are selected for reliability analysis. The feasibility and applicability of the evaluation method is illustrated by a case, and some conclusions are drawn.

(1) Only considering the deformation of the side wall or the ground settlement may not reflect the reliability of the actual project. Considering the deformation of the side wall and the reliability evaluation method of surface settling can be more realistic reflecting the reliability of the actual performance state.

(2) According to the influence law of α on reliability, the recommended values of diaphragm wall and bored pile wall are put forward to distinguishing the influence of side wall structure type on reliability.

(3) Different construction technology will result in different settlement profiles. The influence range of concave profile is larger than that of spandrel profile, and the β value of concave profile is smaller. According to the influence of β value on reliability, the recommended values of different settlement profile types are given.

(4) The evaluation method does not consider the influence of soil spatial variation on reliability, and further work will be carried out in the future.

Competing interests

The authors declare no competing interests.

Acknowledgements

The authors would like to appreciate the funding supports from the National Natural Science Foundation of China [grant number 51678164], the National Natural Science Foundation of China [grant number 51478118], Guangxi Natural Science Foundation Program [2018GXNSFDA138009], Guangxi Science and Technology Plan Projects [AD18126011], the Scientific Research Foundation of Guangxi University [No. XTZ160590] and project supported by GDHVPS [2019].

References

1. TANG, Y. Probability-Based Method Using Rfem for Predicting Wall Deflection Caused by Excavation. *Journal of Zhejiang University. A. Science.* **12**, 737-746 (2011).

2. Papaioannou, I. & Straub, D. Reliability Updating in Geotechnical Engineering Including Spatial Variability of Soil. *Comput. Geotech.* **42**, 44-51 (2012).
3. Tang, X., Li, D., Zhou, C. & Phoon, K. Copula-Based Approaches for Evaluating Slope Reliability Under Incomplete Probability Information. *Struct. Saf.* **52**, 90-99 (2015).
4. Luo, Z., Li, Y., Zhou, S. & Di, H. Effects of Vertical Spatial Variability On Supported Excavations in Sands Considering Multiple Geotechnical and Structural Failure Modes. *Comput. Geotech.* **95**, 16-29 (2018).
5. Luo, Z., Atamturktur, S. & Juang, C. H. Bootstrapping for Characterizing the Effect of Uncertainty in Sample Statistics for Braced Excavations. *J. Geotech. Geoenviron.* **139**, 13-23 (2013).
6. Luo, Z., Di, H., Kamalzare, M. & Li, Y. Effects of Soil Spatial Variability On Structural Reliability Assessment in Excavations. *Underground Space.* **5**, 71-83 (2020).
7. Luo, Z., Hu, B., Wang, Y. & Di, H. Effect of Spatial Variability of Soft Clays On Geotechnical Design of Braced Excavations: A Case Study of Formosa Excavation. *Comput. Geotech.* **103**, 242-253 (2018).
8. Hsiao, E. C., Schuster, M., Juang, C. H. & Kung, G. T. Reliability Analysis and Updating of Excavation-Induced Ground Settlement for Building Serviceability Assessment. *J. Geotech. Geoenviron.* **134**, 1448-1458 (2008).
9. Gholampour, A. & Johari, A. Reliability-Based Analysis of Braced Excavation in Unsaturated Soils Considering Conditional Spatial Variability. *Comput. Geotech.* **115**, 103163 (2019).
10. Spross, J. & Johansson, F. When is the Observational Method in Geotechnical Engineering Favourable? *Struct. Saf.* **66**, 17-26 (2017).
11. Daniel, S. & Iason, P. Bayesian Updating with Structural Reliability Methods. *J. Eng. Mech.* (2014).
12. Xu, L., Xu, Y., Wang, C. & Feng, K. Data-Driven Deformation Reliability of Retaining Structures in Deep Excavations Considering Measurement Error. *Applied Sciences.* **9**, 5466 (2019).
13. Wang, F., Huang, H., Yin, Z. & Huang, Q. Probabilistic Characteristics Analysis for the Time-Dependent Deformation of Clay Soils Due to Spatial Variability. *Eur. J. Environ. Civ. En.* 1-19 (2021).
14. Teruo, N., Lianmin, X. & Hisayoshi, Y. 3D and 2D Model Tests and Numerical Analyses of Settlements and Earth Pressures Due to Tunnel Excavation. *Soils Found.* **37**, 31-42 (1997).
15. Pio-Go, H. & Chang-Yu, O. Shape of Ground Surface Settlement Profiles Caused by Excavation. *NRC Research Press Ottawa, Canada.* **35**, 1004-1017 (1998).
16. Geng, D., Dai, N., Guo, P., Zhou, S. & Di, H. Implicit Numerical Integration of Highly Nonlinear Plasticity Models. *Comput. Geotech.* **132**, 103961 (2021).
17. Kung, G. T., Juang, C. H., Hsiao, E. C. & Hashash, Y. M. Simplified Model for Wall Deflection and Ground-Surface Settlement Caused by Braced Excavation in Clays. *J. Geotech. Geoenviron.* **133**, 731-747 (2007).
18. Yong, T., Xiang, L., Zhijun, K., Junxi, L. & Yanbing, Z. Zoned Excavation of an Oversized Pit Close to an Existing Metro Line in Stiff Clay: Case Study. *J. Perform. Constr. Fac.* **29**, (2014).
19. Skempton, A. W. & MacDonald, D. H. The Allowable Settlements of Buildings. *Proceedings of the Institution of Civil Engineers.* **5**, 727-768 (1956).
20. Tan, Y. & Wei, B. Performance of an Overexcavated Metro Station and Facilities Nearby. *J. Perform. Constr. Fac.* **26**, 241-254 (2012).
21. Clough, G. W. Construction Induced Movements of Insitu Walls. *Journal of Geotechnical Engineering.* **118**, 439-470 (1990).
22. Engelund, S., Rackwitz, R. & Lange, C. Approximations of First-Passage Times for Differentiable Processes Based On Higher-Order Threshold Crossings. *Probabilist. Eng. Mech.* **10**, 53-60 (1995).
23. Schall, G., Faber, M. H. & Rackwitz, R. The Ergodicity Assumption for Sea States in the Reliability Estimation of Offshore Structures. *Journal of Offshore Mechanics and Arctic Engineering.* **113**, 241-246 (1991).

24. Li, C. Q. & Melchers, R. E. Time-Dependent Reliability Analysis of Corrosion-Induced Concrete Cracking. *Acı Struct. J.* **102**, 543-549 (2005).
25. Knut, O. R. & Peter, B. Model Uncertainty Representation in Geotechnical Reliability Analyses. *Journal of Geotechnical Engineering.* **119**, (1993).
26. Li, M., Zhang, Z., Chen, J., Wang, J. & Xu, A. Zoned and Staged Construction of an Underground Complex in Shanghai Soft Clay. *Tunn. Undergr. Sp. Tech.* **67**, 187-200 (2017).
27. Tan, Y. & Wang, D. Characteristics of a Large-Scale Deep Foundation Pit Excavated by the Central-Island Technique in Shanghai Soft Clay. II: Top-Down Construction of the Peripheral Rectangular Pit. *J. Geotech. Geoenviron.* **139**, 1894-1910 (2013).
28. Yong, T. & Dalong, W. Characteristics of a Large-Scale Deep Foundation Pit Excavated by the Central-Island Technique in Shanghai Soft Clay. I: Bottom-Up Construction of the Central Cylindrical Shaft. *J. Geotech. Geoenviron.* **139**, 1-37 (2013).
29. Yong, T., Dalong, W., Ye, L. & Tao, F. Excavation of Middle Huai-Hai Road Station of Shanghai Metro Line 13: Challenges, Risks, Countermeasures, and Performance Assessment. *Practice Periodical on Structural Design and Construction.* **22**, (2017).
30. Yong, T., Bin, W., Xin, Z. & Yanping, D. Lessons Learned From Construction of Shanghai Metro Stations: Importance of Quick Excavation, Prompt Propping, Timely Casting, and Segmented Construction. *J. Perform. Constr. Fac.* **29**, (2014).
31. Xu, G., Zhang, J., Liu, H. & Ren, C. Shanghai Center Project Excavation Induced Ground Surface Movements and Deformations. *Frontiers of Structural and Civil Engineering.* **12**, 26-43 (2018).
32. Goh, A. T. C., Zhang, W. G. & Wong, K. S. Deterministic and Reliability Analysis of Basal Heave Stability for Excavation in Spatial Variable Soils. *Comput. Geotech.* **108**, 152-160 (2019).
33. Zhang, X., Yang, J., Zhang, Y. & Gao, Y. Cause Investigation of Damages in Existing Building Adjacent to Foundation Pit in Construction. *Eng. Fail. Anal.* **83**, 117-124 (2018).
34. Zhang, W. G. et al. Performance of Braced Excavation in Residual Soil with Groundwater Drawdown. *Underground Space.* **3**, 150-165 (2018).
35. Goh, A. T. C. et al. Numerical Study of the Effects of Groundwater Drawdown On Ground Settlement for Excavation in Residual Soils. *Acta Geotech.* **15**, 1259-1272 (2020).
36. Elachachi, S. M., Breyse, D. & Denis, A. The Effects of Soil Spatial Variability On the Reliability of Rigid Buried Pipes. *Comput. Geotech.* **43**, 61-71 (2012).
37. Breyse, D., Niandou, H., Elachachi, S. & Houy, L. A Generic Approach to Soil-Structure Interaction Considering the Effects of Soil Heterogeneity. *Geotechnique.* **55**, 143-150 (2005).