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Reliability assessment of excavation-induced ground surface settlement with groundwater drawdown considering spatial variability

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Abstract: For braced excavations in deep deposits of soft clays or residual soils, the ground surface settlement behind the excavation is correlated with the extent of basal heave as well as the wall deflections and is also affected by the magnitude of the groundwater drawdown behind the retaining system. Reliability analysis based on a recently developed simplified logarithm regression model for estimation of the maximum ground surface settlement is presented. The first-order reliability method implemented with a variance reduction technique while considering soil spatial variability is employed to investigate the probability that certain ground surface settlement threshold is exceeded. This paper presents the effects of spatial averaging and the influence of several key design parameters including the stiffness of the wall system, the magnitude of the threshold ground surface settlement, the coefficient of variation of the soil properties, and the magnitude of the groundwater drawdown on the ground surface settlement. It is concluded that soil spatial variability results in a higher probability of failure (i. e. , a lower reliability index), without considering it would result in an unreliable design. A larger characteristic length results in a lower probability of failure and a higher reliability index. When the spatial variability of both the c_u/σ'_v and E_{50}/c_u are considered, the influence on β is more significant.

Keywords: ground surface settlement; braced excavation; groundwater drawdown; spatial reliability; variance reduction

考虑空间变异性的基坑降水支护开挖引起地面沉降的可靠度评估

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摘　要:对于软黏土或残积土中的深基坑支护开挖,开挖后的地面沉降与基底隆起和挡墙变形密切

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相关，且受墙后地下水变化的影响显著。提出一种基于最新开发的简化对数回归模型的可靠性分析方法预测地面最大沉降，采用考虑土体空间变异性的方差缩减技术实现一阶可靠性方法(FORM)，探讨了地面沉降超过既定阈值的概率，验证了方差缩减技术的高效性。通过分析关于空间平均及关键设计参数的影响发现，土体空间变异性会导致较高的破坏概率，挡墙的系统刚度、地面沉降阈值的大小、土体特性的变化系数以及地下水下降深度也对可靠性指标β有不同程度的影响，忽略其影响会导致不可靠的设计，较大的特征长度会导致较低的破坏概率和较高的β，同时考虑c_u/σ'_v和E_{50}/c_u的空间变异性会比单独考虑其中一项对β影响更大。

关键词：地面沉降；基坑支护开挖；降水；空间变异性；方差缩减

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1 Introduction

Rapid urbanization and continuous development of infrastructure construction have led to an increased demand for deep braced excavations in urban built environments. One major concern with the construction of deep excavation support systems is the potential damage to nearby buildings and tunnels caused by excavation-induced ground movement. The ground movement behind the excavation is correlated with the extent of basal heaves and the magnitude of the wall deflections. Ground settlement is an important hydro-geological factor influencing the groundwater drawdown behind the excavation, due to possible leakage through the wall, flow along the wall interface, or poor connections between wall panels as a result of poor quality control. Therefore, assessing the distribution and magnitude of the ground surface settlement adjacent to a braced excavation is the most important consideration in the design phase. Numerical modeling is widely used, but it's time-consuming and requires considerable computational effort, especially three-dimensional computation. The use of empirical/semi-empirical methods to predict excavation-induced ground movement is more convenient[1-10].

Reliability-based analysis via the first-order reliability method (FORM) is increasingly employed in various geotechnical applications[11-13] to calculate the reliability index as well as the probability of failure. This method adopts the mean average and the standard deviation or the equivalent value to present uncertain parameters. The safety factor or safety margin is determined by measuring the shortest distance from the safety average to the directional standard deviation of the most likely failure combination of parameters on the limit state surface. However, natural soil properties vary spatially due to the complicated geological, environmental, and physical-chemical processes to which the soil has been subjected during its formation[14-15]. Several researchers have highlighted the effects of the spatial variation of soil properties on various geotechnical problems[16-21]. Reliability analysis considering spatial variability has been carried out by many researchers. Luo et al.[22] presented a simplified approach for the reliability analysis of basal heave in a braced excavation considering the spatial variability of the soil parameters using the first-order reliability method (FORM). Wang et al.[23] modeled the inherent spatial variability of the soil properties of drilled shafts by developing a reliability-based design (RBD) approach that integrated a Monte Carlo simulation (MCS)-based RBD with the random field theory. Cheon et al.[24] described the spatial variability of geotechnical properties for foundation design in deep water in the Gulf of Mexico, via a random field model that depicted spatial variations in the design of undrained shear strength. Li et al.[25] investigated the reliability of strip footing in the presence of spatially variable undrained shear strength with a non-stationary random field. Gong et al.[26] proposed a new framework considering the spatial variability of soil properties to analyze the probabilistic ability of a braced excavation in clay, which was modeled with the random field theory. Liu et al.[27] analyzed the reliability of slopes considering the spatial variability of the soil using a simplified framework that applied a strategy of variance reduction to enable more than one shear strength value to be considered in slope reliability problems based on Monte Carlo simulation and the multiple response surface method (MRSM). However, studies on the probabilistic assessment of ground surface settlement induced by the braced excavation that consider the uncertainties arising from the soil stiffness and strength parameters are limited. In addition, the influence of the spatial variability of soil properties, as well as the influence of groundwater drawdown, are scarcely investigated.

This paper adopts a framework combining a recently developed simplified LR model[28] to estimate the maximum ground surface settlement using the FORM EXCEL spreadsheet method to analyze the reliability. The variance reduction technique for considering soil spatial variability is employed to investigate the probability that a certain threshold ground surface settlement is exceeded. Some useful conclusions regarding the effects of spatial averaging, and the influence of several key design parameters such as the stiffness of the wall system, the magnitude of the threshold ground surface settlement, the coefficient of variation of the soil properties, as well as the magnitude of the groundwater drawdown are presented.

2 Review of the developed logarithm regression (LR) model

The developed logarithm regression (LR) model is a semi-empirical model proposed by Zhang et al.[28] for estimating the maximum ground surface settlement induced by the braced excavation considering groundwater drawdown in residual soils. It is based on the results of 746 plane strain finite element (FE) simulations using Plaxis 2D[29]. To reveal the increased stiffness of soils at small strain levels, the hardening small strain (HSS) model was adopted in the analysis. Many studies have utilized the HSS constitutive model in the modeling of excavation in soft/medium clay[30-32]. For the 746 FE model, the range of the excavation width (B) is 30～40 m, the excavation depth (H_e) is 14～20 m, the thickness of the soft clay (T) is 25～30 m, the system stiffness ($\ln S$) is 7.3～8.8, the relative shear strength ratio of the soil ($c_u/\sigma_v{}'$) is 0.25～0.35, the relative stiffness ratio of the soil is (E_{50}/c_u), and the groundwater drawdown (d_w) is 0.3～12 m.

For simplicity, the physical and geometrical model is not shown in this paper. The diaphragm wall was inserted 5 m into the stiff clay layer, which was found to be adequate against basal heave failure. More model details can be found in Zhang et al.[28].

Plaxis can not directly model the consolidation settlement when it is based on undrained parameters. Therefore, method A in Plaxis with c' and φ is used in the analysis, simulating the long-term settlement incurred by groundwater drawdown, without considering the time effects. For an assumed c_u/σ'_v ratio, the effective friction angle φ is computed using the correlation proposed by Wroth et al.[33]

$$\frac{c_u}{\sigma'_v} = 0.5743 = \frac{3\sin\varphi}{3-\sin\varphi} \tag{1}$$

The groundwater drawdown simulation in this paper is implemented by changing the horizontal/vertical permeability ratio of the soil, k_x/k_y. The numerical analysis performed via Plaxis considers fully coupled flow-deformation, in which the groundwater drawdown of 12.0 m, 6.0 m 0.3 m can be realized. The use of the relative shear strength ratio and the stiffness ratios is based on Kung et al.[3], Zhang et al.[32], Xuan[34]).

A simple logarithm regression (LR) model based on the numerical results from 746 hypothetical cases[28], was developed to predict the maximum ground settlement δ_{vm}. It is validated by a total of 19 well-documented actual case histories from various sites. The equation for δ_{vm}(mm) with the coefficient of determination $R^2 = 0.9245$ takes the following form:

$$\delta_{\mathrm{vm}} = 24.26 B^{0.3747} T^{0.7251} (H_e)^{1.2032} (c_{\mathrm{u}}/\sigma'_{\mathrm{v}})^{-1.4687} \cdot (E_{50}/c_{\mathrm{u}})^{-0.5479} S^{-2.2223} (d_{\mathrm{w}})^{0.1013} \quad (2)$$

The index for the drawdown in the LR analysis was only 0.1013, which is relatively small compared to the excavation depth, the relative shear strength ratio, and the system stiffness value. Based on Eq. (2), when other parameters are kept constant, an increase of d_{w} from 0.3 m to 6.0 m will almost double the maximum ground surface settlement, which is consistent with the findings by Wen et al.[35].

3 Reliability analysis considering spatial variability

Since the FE analysis and the proposed LR estimation model are unable to take into account the inherent spatial variability of soil properties, this section introduces a reliability-based method to estimate the braced excavation induced ground surface settlement considering groundwater drawdown by adopting the FORM spreadsheet method and implementing the spatial factors.

3.1 Brief introduction to spatial variability

Spatial variability refers to the nonuniform distribution of basic soil properties such as permeability or the deformation modulus. The change in the spatial average of soil properties in a certain area is smaller than at a certain point, to some extent, and as the size of the area increases, the change in the soil properties decreases. A dimensionless variance reduction function Γ^2 calculated by the scale of fluctuation θ and the characteristic length L, as proposed by Vanmarcke[36], was used to quantify the reduction in the point variance under local averaging. It is subsequently adopted by Vanmarcke to reveal spatial averaging for reliability analysis[37], by means of which the soil parameter variances can be reduced by multiplying a factor less than the unity, i. e. the variance reduction factor. This variance reduction technique has been successfully applied using different constant, triangular, and exponential models[37-38], among which the latter is more commonly assumed for geotechnical random field modeling, expressed as:

$$\Gamma^2 = \frac{1}{2}\left(\frac{\theta}{L}\right)^2\left[\frac{2L}{\theta} - 1 + \exp\left(-\frac{2L}{\theta}\right)\right] \quad (3)$$

The reduced variance σ_Γ^2 can be obtained through:

$$\sigma_\Gamma^2 = \Gamma^2 \cdot \sigma^2 \quad (4)$$

in which σ is the standard deviation of $c_{\mathrm{u}}/\sigma'_{\mathrm{v}}$ or E_{50}/c_{u}. In this study, Γ is the standard deviation reduction factor.

For reliability analysis using the variance reduction technique, the characteristic length is of most importance. Schweiger et al.[39] found that for the analysis of supported excavations, the characteristic length is correlated to the length of the sliding surface. Luo et al.[22] investigated the value of L that should be used and examined the influence of different L on the probability of excavation-induced basal-heave failure. For simplicity, the commonly adopted scale of fluctuation values θ of 2, 5, 20, 50, 100 m[40-41], and the characteristic lengths L=19, 26, 72 m are considered, which are closely associated with the excavation depth, the diaphragm wall depth, and the final strut depth.

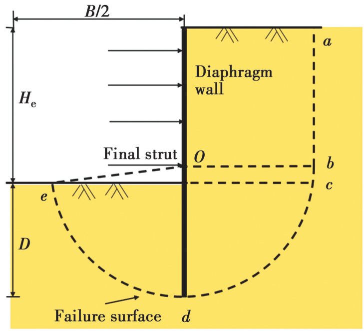


Fig. 1 Schematic diagram of the slip surface for braced excavation stability analysis

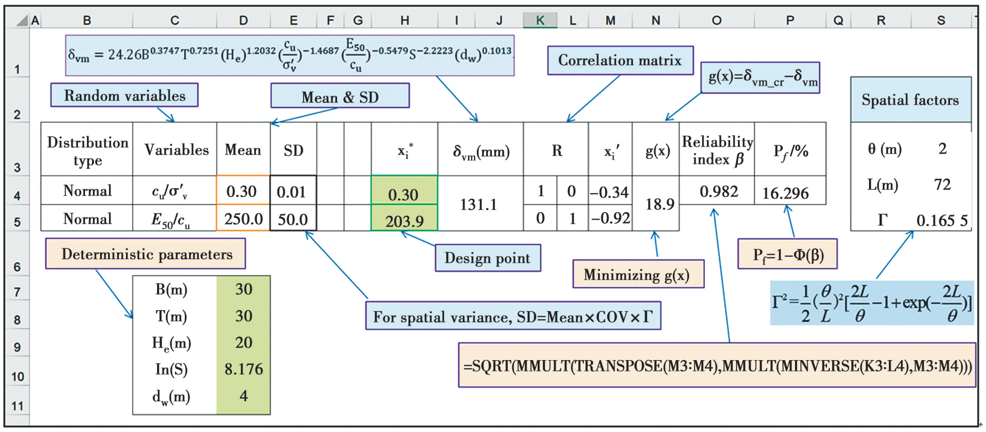
As shown in Fig. 1, the 1st L=19 m is the length of *od* (the distance of the final strut to the bottom of the diaphragm wall), the 2nd $L=26$ m equals the length of the arc cd, and the 3rd $L=72$ m is the length of the sliding surface (arc $abcde$). This method has been similarly adopted by Wu et al.[16] and Luo et al.[22].

3.2 Developed Excel spreadsheet

Fig. 2 plots the FORM EXCEL Spreadsheet setup that implements the spatial variability for the calculation of the reliability index β and the probability of failure P_f based on the proposed estimation model of ground surface settlement. The spatial factors are inserted via Cells R3:S5. The two variables of c_u/σ_v' and E_{50}/c_u are assumed to be normally distributed. Other parameters including B, T, H_e, ln S, and d_w are assumed to be deterministic. In the example shown in Fig. 2, $B=30$ m, $T=30$ m, and $H_e=20$ m are adopted in the spatial variability analysis for the detailed use of the developed spreadsheet[13]. The reliability index β is calculated in Cell O4, numerically expressed as Eq. (5)

$$\beta=\min_{x\in F}\sqrt{\left[\frac{\boldsymbol{x}-\boldsymbol{m}}{\boldsymbol{\sigma}}\right]^{\mathrm{T}}[\boldsymbol{R}]^{-1}\left[\frac{\boldsymbol{x}-\boldsymbol{m}}{\boldsymbol{\sigma}}\right]} \tag{5}$$

where $\boldsymbol{x}$ is the vector of random variables; $\boldsymbol{m}$ is the vector of mean values; $\boldsymbol{\sigma}$ is the vector of standard deviation; $\boldsymbol{R}$ is the correlation matrix; and $\boldsymbol{F}$ is the failure region. Cell $g(x)$ contains the expression of $\delta_{\mathrm{vm}}-\delta_{\mathrm{vm\_cr}}$, which indicates that if the induced maximum ground surface settlement is greater than the threshold value $\delta_{\mathrm{vm\_cr}}$, it would be regarded as a failure or unsatisfactory performance. The column labeled x_i contains the design point. For spatial variance, $SD=\mathrm{Mean}\times\mathrm{COV}\times\Gamma$, in which SD is the standard deviation, Mean is the mean value, COV is the coefficient of variation, Γ is the standard deviation reduction factor. For random variables, the off-diagonal terms are zero. For Gaussian-distributed random variables, a direct relationship exists between β and P_f, i.e., $P_f=1-\Phi(\beta)$, in which Φ is the cumulative normal density function.



$\delta_{vm}=24.26B^{0.3747}T^{0.7251}(H_e)^{1.2032}(\frac{c_u}{\sigma_v'})^{-1.4687}(\frac{E_{50}}{c_u})^{-0.5479}S^{-2.2223}(d_w)^{0.1013}$

$g(x)=\delta_{vm\_cr}-\delta_{vm}$

Distribution type	Variables	Mean	SD			x_i^*	δ_{vm}(mm)	R		x_i'	g(x)	Reliability index β	P_f/%
Normal	c_u/σ'_v	0.30	0.01			0.30	131.1	1	0	−0.34	18.9	0.982	16.296
Normal	E_{50}/c_u	250.0	50.0			203.9		0	1	−0.92			

Spatial factors	
θ (m)	2
L(m)	72
Γ	0.165 5

B(m)	30
T(m)	30
H_e(m)	20
In(S)	8.176
d_w(m)	4

$P_f=1-\Phi(\beta)$

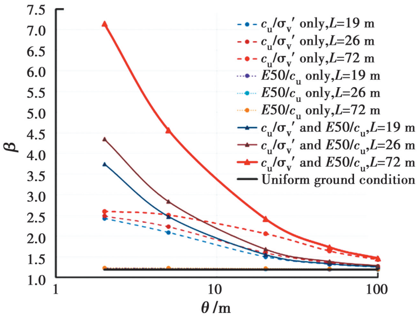
$\Gamma^2=\frac{1}{2}(\frac{\theta}{L})^2[\frac{2L}{\theta}-1+\exp(-\frac{2L}{\theta})]$

=SQRT(MMULT(TRANSPOSE(M3:M4),MMULT(MINVERSE(K3:L4),M3:M4)))

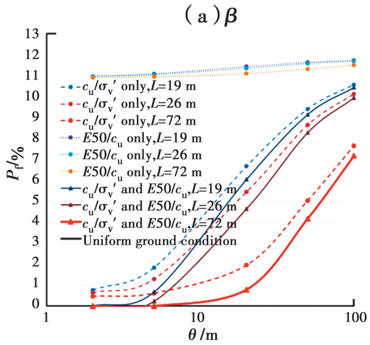
Fig. 2 FORM EXCEL setup for evaluating the β and P_f

3.3 Influence of the c_u/σ_v' and E_{50}/c_u of the soil

Fig. 3 presents β and P_f, which were calculated from several combinations of the spatial variability of c_u/σ'_v and E_{50}/c_u for $L=19$, 26 and 72 m, i.e., consideration of c_u/σ'_v variability only, consideration of E_{50}/c_u variability only, and consideration of the variability of both c_u/σ'_v and E_{50}/c_u. The case without considering any kind of spatial variability, which represents uniform ground conditions, is shown as a comparison. The increases of θ denote a more uniform ground, β converges to the value of 1.183 while P_f converges to the value of 11.845%. β is moderately higher than the case without considering spatial variability only when the spatial variability of c_u/σ'_v is considered. However, β is marginally influenced by the spatial variability of E_{50}/c_u. When the spatial variability of both c_u/σ'_v and E_{50}/c_u are considered, the influence on β is more significant, implying that neglecting the influence of soil spatial variability results in an unreliable design. A larger L results in a lower probability of failure and a higher reliability index.



(a) β



(b) P_f

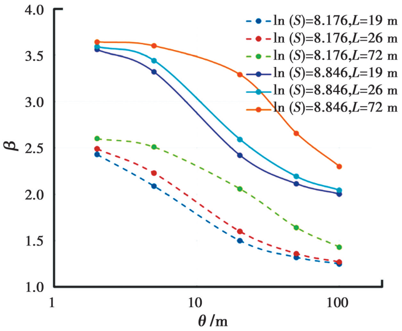
Fig. 3 β and P_f results from different spatial variability

3.4 Influence of ln(S)

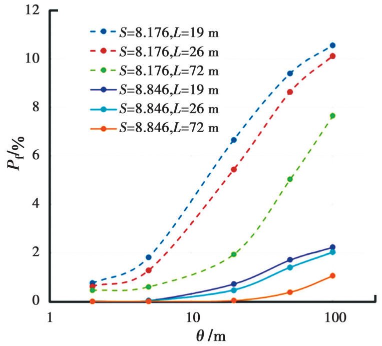
Fig. 4 shows the effects of ln(S) on β and P_f for the case of $B=30$ m, $H_e=20$ m, $\ln(S)=8.176$, and $d_w=4$ m. β increases as the system stiffness ln(S) becomes larger. It is reasonable that β increases with a stiffer excavation supporting system. The system stiffness shows a significant influence on β and P_f; a larger ln(S) will result in a greater β and a smaller P_f.

3.5 Influence of δ_{vm_cr}

In this section, the choice of the threshold (critical) maximum ground settlement δ_{vm_cr} for service ability considerations is considered. Typically, the threshold δ_{vm_cr} is chosen as 0.75%-1.0% of H_e. Fig. 5 plots the effects of θ and δ_{vm_cr} on β and P_f for $B=30$ m, $H_e=20$ m, $\ln(S)=8.176$ and $L=19$, 26, 72 m, respectively. It indicates that both θ and δ_{vm_cr} significantly influence the value of β and P_f. However, the effects of θ on β and P_f are not as remarkable as that of δ_{vm_cr}, especially when θ is greater than 20. β tends to increase with δ_{vm_cr}, while the probability of failure is much lower when a greater threshold is exceeded. In addition, β decreases with the increase of θ. Furthermore, β slightly increases with L, as indicated in Fig. 5(a) and (b).



(a) β



(b) P_f

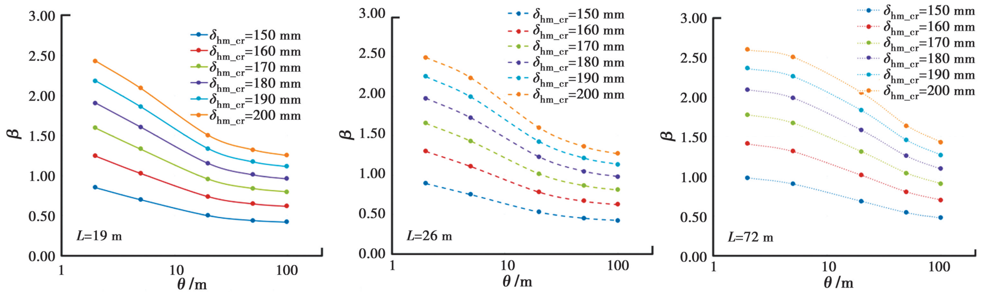
Fig. 4 Influence of the logarithmic system stiffness ln(S) on β and P_f for the case of $B=30$ m, $H_e=20$ m, $\ln(S)=8.176$, and $d_w=4$ m

3.6 Influence of d_w

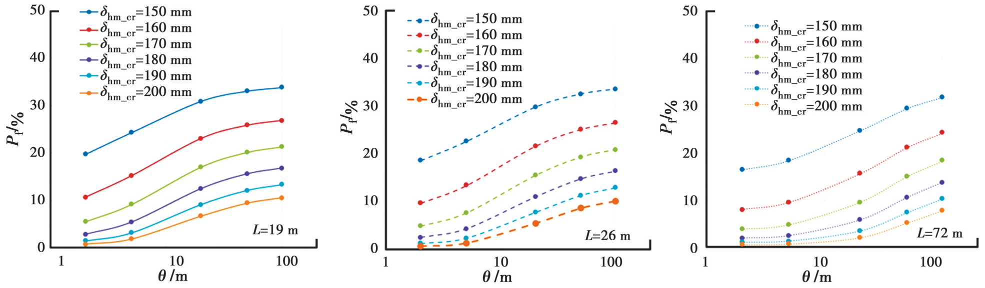
Fig. 6 compares the influence of different groundwater drawdown d_w on β and P_f for the case of $B=30$ m, $H_e=20$ m, $\ln(S)=8.176$, and $\delta_{vm\_cr}=200$ mm. Greater d_w results in a smaller β, indicating that the greater the groundwater drawdown, the greater the probability that δ_{vm} exceeds the threshold δ_{vm_cr}. The magnitude of the groundwater drawdown d_w shows a significant influence on β and P_f.

3.7 Influence of the COV of E_{50}/c_u

Fig. 7 shows the influence of the coefficient of

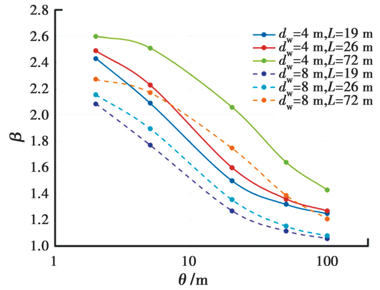


(a) β

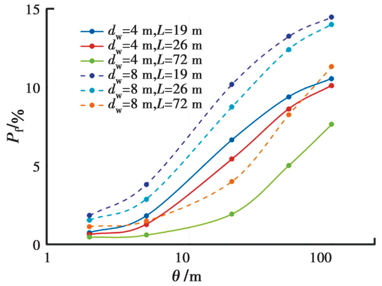


(b) P_{f}

Fig. 5 Influence of θ, $\delta_{\mathrm{vm\text{-}cr}}$ and L on (a) reliability index β and (b) P_{f}

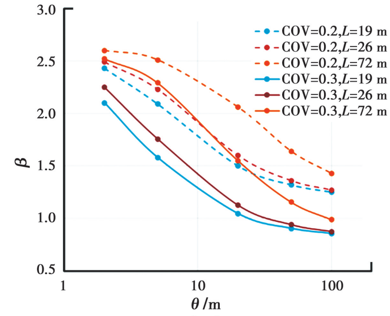


(a) β

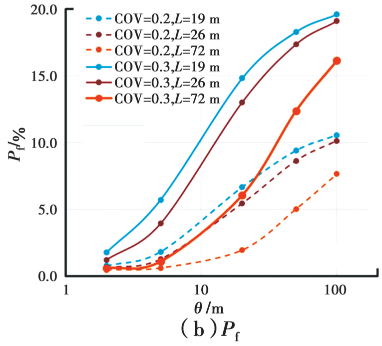


(b) P_{f}

Fig. 6 Effects of d_{w} on (a) β and (b) P_{f}



(a) β



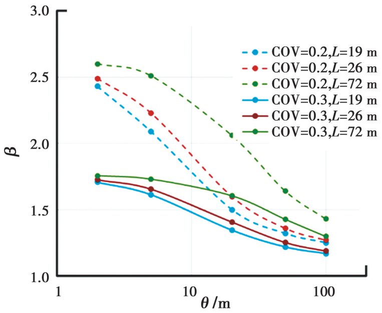
(b) P_{f}

Fig. 7 Effects of the COV of E_{50}/c_{u} on (a) β and (b) P_{f}

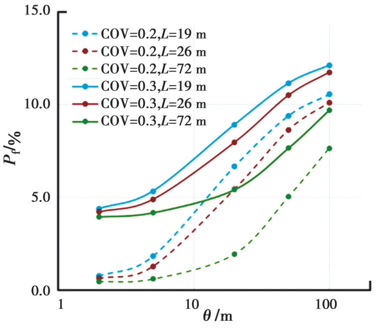
variation, the COV of E_{50}/c_{u} on β and P_{f} for the case of $B=30$ m, $H_{\mathrm{e}}=20$ m, $d_{\mathrm{w}}=4.0$ m, $\ln(S)=8.176$, and $\delta_{\mathrm{vm\_cr}}=200$ mm. Both the COV of E_{50}/c_{u} and L have a significant influence on β and P_{f}. However, when θ is greater than 50, the influence of the COV of E_{50}/c_{u} on β and P_{f} is not as significant as that of L. β decreases with the increase of the COV of E_{50}/c_{u}.

3.8 Influence of the COV of $c_{\mathrm{u}}/\sigma_{\mathrm{v}}'$

Fig. 8 shows the influence of the COV of $c_{\mathrm{u}}/\sigma'_{\mathrm{v}}$ on β and P_{f} for the case of $B=30$ m, $H_{\mathrm{e}}=20$ m, $\ln(S)=8.176$, $d_{\mathrm{w}}=4.0$ m, $\delta_{\mathrm{vm\_cr}}=200$ mm. Both the COV of $c_{\mathrm{u}}/\sigma'_{\mathrm{v}}$ and L significantly influence β and P_{f}. However, the influence of the COV of $c_{\mathrm{u}}/\sigma'_{\mathrm{v}}$ on β and P_{f} is not as significant as that of L, especially when θ is greater than 20. β decreases with the increase of the COV of $c_{\mathrm{u}}/\sigma'_{\mathrm{v}}$.



(a) β



(b) P_f

Fig. 8 Effects of the COV of c_u/σ'_v on (a)β and (b)P_f

5 Summary and conclusions

A reliability-based framework that considers the spatial averaging effect of soil properties is proposed to assess the probability that threshold maximum ground surface settlement is exceeded by combining the FORM spreadsheet and the LR model proposed previously by Zhang et al.[28]. It is concluded that soil spatial variability results in a higher probability of failure (i. e., a lower reliability index).

The parametric analysis shows that the spatial variability of soil, the threshold ground settlement, the stiffness of the system, the level of groundwater drawdown, as well as the COV of c_u/s_v' and E_{50}/c_u have a significant influence on the reliability index. When the spatial variability of both c_u/σ'_v and E_{50}/c_u are considered, the influence on β is more significant. A larger characteristic length results in a lower probability of failure and a higher reliability index. The proposed approach requires much less computational effort in dealing with the spatial variability of soil properties. It is expected that these conclusions will provide useful references and insights for the design of future excavation projects involving spatial variability.

For further study, a detailed characterization of geotechnical model uncertainties, especially from the perspective of the spatial variability of in situ soil properties, is indispensable. The authors are working on this by collecting borehole and bore log information regarding field instrumentation and tests.

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