Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 6191933, 13 pages
https://doi.org/10.1155/2022/6191933

Research Article

Probabilistic Risk Assessment of Slope Failure in 3-D Spatially Variable Soils by Finite Element Method

Ya-Nan Ding,[1,2] Zu-Fang Qi,[1,2] Miao Hu,[3] Jin-Zhu Mao,[1,2] and Xiao-Cheng Huang[4]

[1] *Changjiang Survey Planning Design and Research Co.,Ltd., No. 1863 Jiefang Avenue, Wuhan, Hubei, China*
[2] *National Dam Safety Research Center, No. 1863 Jiefang Avenue, Wuhan, Hubei, China*
[3] *State Key Laboratory of Water Resources and Hydropower Engineering Science,*
Institute of Engineering Risk and Disaster Prevention, Wuhan University, 299 Bayi Road, Wuhan 430072, China
[4] *School of Civil Engineering, Hunan University of Science and Technology, Xiangtan, China*

Correspondence should be addressed to Xiao-Cheng Huang; hxc@hnust.edu.cn

Received 7 September 2021; Accepted 14 December 2021; Published 2 March 2022

Academic Editor: Jie Liu

Quantitative risk assessment of landslides induced by slope failure is an important precondition for formulating effective disaster prevention, mitigation measures, and establishing a landslide risk warning system. In general, the location of the critical slip surface and the failure mode is unlikely to be predicted due to the spatial variability in soil. It remains a challenging task to effectively identify the critical slip surface and conduct the efficient risk assessment based on a three-dimensional (3-D) slope with spatial variability. Based on Monte Carlo simulation and the random field method, a quantitative risk evaluation method for slope failure considering the spatial variability of soil parameters is proposed in the study. Compared with a uniform soil slope, the landslide volume, the critical slip surface, and the factor of safety considering the spatial variability of soil are all uncertain; thus, the soil spatial variability has a significant effect on the failure mode and stability of the slope. By using the random finite element method, the critical slip surface of the slope is accurately identified, the corresponding landslide volume and slide distance are calculated, and the modified risk index for a landslide is further enriched, which can provide the reference basis for predicting the landslide deformation, quantitatively evaluating the landslide risk, and mitigating the landslide disaster.

1. Introduction

In mountain regions, landslides are one of the most dangerous natural hazards, which can result in devastating and fatal disasters to human society and urban agglomeration [1–4]. One of the most destructive landslide events is the 2020 Pettimudi landslide in India, which resulted in more than 66 fatalities and destroyed and buried severe village infrastructures. The occurrence dangers are affected or dominated by the concealment and irregularity of the critical slip surface of the slope, the spatial variability of geotechnical parameters, and the temporal and spatial variation of various boundary conditions [5, 6]; Qi and Li 2018 [7], where the spatial variability of geotechnical parameters is one of the most vital uncertainties affecting the slope stability [8]. Griffiths et al. [9] demonstrated that soils inherently exhibiting spatial variability can impact slope stability significantly on account of the complicated geological processes during their formation. Jiang et al. [10] illuminated the great necessity for quantitatively assessing the risk of landslide hazards induced by slope instability considering the soil spatial variability. Cheng et al. [11] expounded that many geotechnical designers should not only take into account the slope stability but also the failure consequence caused by slope instability from an engineering perspective.

Quantitative risk assessment of slope instability plays a significant role in slope design and risk mitigation, and most of the previous studies have paid close attention to quantitative risk assessment methods in geotechnical engineering (e.g., [12–14]. Huang et al. [15] developed an efficient framework for quantitative risk assessment of slope instability where the failure consequence for each failure mode of the slope is assessed respectively; however, the influence of the correlation between slip surfaces has not been considered effective by the method. Li and Chu [16] proposed a quantitative risk assessment approach for two-dimensional (2-D) slope lope failure that can identify a series of representative slip surfaces by limit equilibrium method, where this method only considers the slope failure risk with the horizontal spatial variability of soil parameters. The typical investigations on risk assessment of landslide hazards due to slope failure are summarized in Table 1.

Table 1 illustrates that the landslide hazard risk assessment mainly includes two elements. One is the possibility of slope instability, namely failure probability. The other is the impact of landslides on people, property, society, and the environment, which can be summarized as failure consequences. Obviously, the failure probability and the failure consequences are directly related to the failure mode of the slope. The effective identification of the failure mode of the slope is a key step in the quantitative assessment of landslide risk. Due to the spatial variability of soil parameters, multiple failure modes may exist in the slope and the effective identification of the critical slip surface is a complicated problem. Overall, how to quantify the risk assessment of landslide hazards induced by slope failure considering the soil spatial variability remains an intricate challenge.

Previous researches on slope stability analysis and risk assessment considering soil spatial variability were dominated by 2-D analysis (e.g., [24]; Li et al. 2016; [25]. However, the 2-D model cannot reflect the failure mode of slope more realistically in terms of the shape, location, and length of the critical slip surface. Liu et al. [26] illuminated that slope failure will occur in areas with low soil shear strength due to the spatial variability of soil parameters, which directly affects the shape and position of the slip surfaces of the slope. Meanwhile, how to effectively identify the potential and critical failure slip surface of a 3-D slope and quantitatively calculate the landslide volume is still a complicated problem. Thus, it is necessary to investigate the stability analysis and risk assessment of 3-D slope with the spatial variability of soil properties.

Several studies (e.g., [22, 27, 28] have made great efforts to estimate 3-D slope reliability. Xiao et al. [5] proposed an auxiliary random finite element method to quantify the risk of 3-D slope considering spatial variability of soil properties. Vanmarcke et al. [29] pioneered the quantitative risk assessment of 3-D slope that is regarded as an extension of 2-D slope reliability analysis based on the first-order second-moment method. However, previous studies on the quantitative risk assessment of slope failure require a presumed critical failure surface of the slope, which becomes impractical when the soil spatial variability is taken into account.

In this study, the problem that effectively identifies the exact location of slip surface and estimate the probability of failure in a 3-D slope consisting of spatially random soils can be solved by the finite element analysis (denoted by FEA), where the irregular slip surface caused by the spatial variation can be captured automatically in a 3-D slope without a prescribed slip surface and the volume of slide mass can therefore be calculated exactly. Based on Monte Carlo simulation and the random field method, a quantitative risk evaluation method for slope failure considering the spatial variability of soil parameters is proposed. By calculating the corresponding landslide volume and travel distance, a modified risk index is proposed to evaluate the landslide hazard, where the risk index can be used for a regional landslide hazard assessment. This research aims to provide a practical method for quantitative risk assessment of slope failure, formulate the risk prevention, and control plan of landslide disasters.

2. Finite Element Model

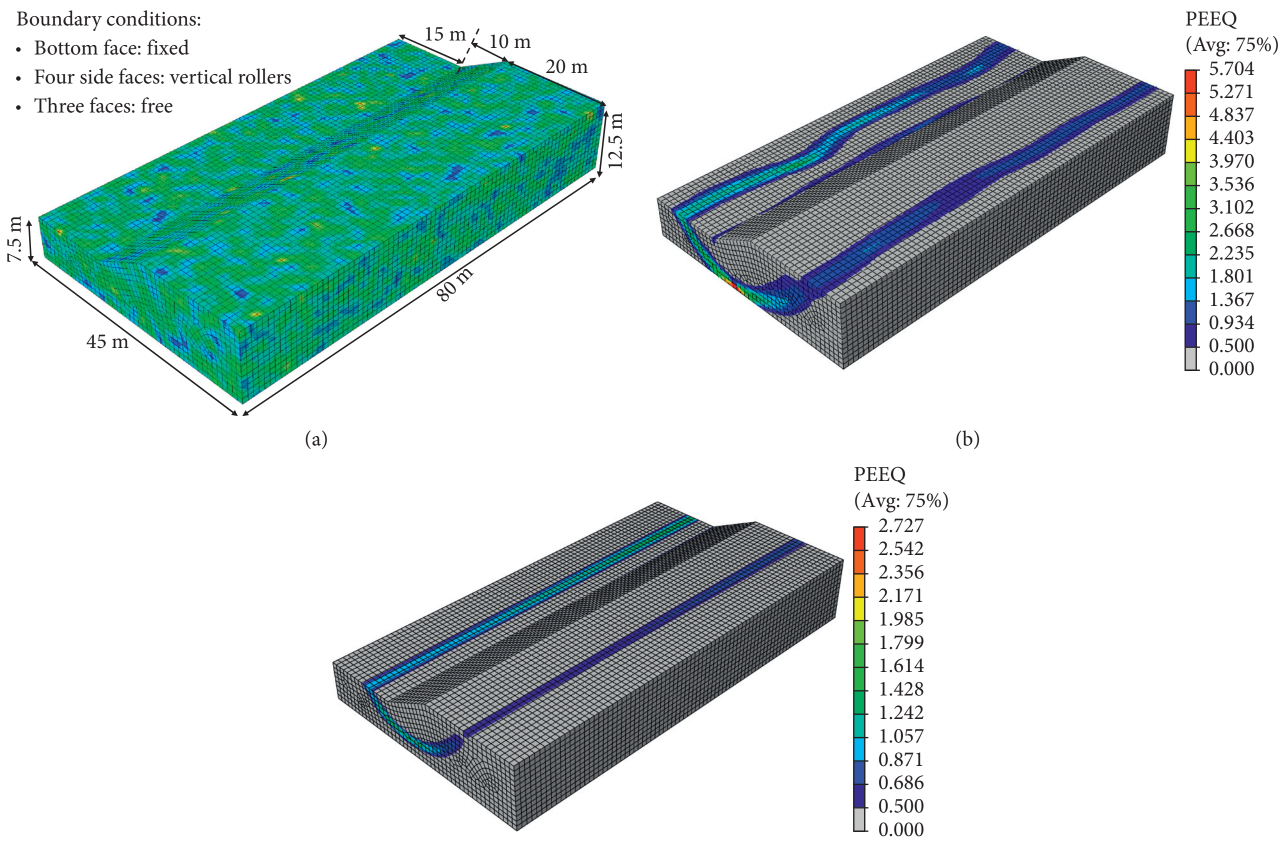
The quantitative risk assessment of the 3-D slope in spatial variability soil is conducted by the finite element method. Figure 1(a) illustrates the 3-D slope model that consists of 43,200 eight-node brick elements and the soil undrained shear strength (denoted by c_u) is characterized by a random field. The corresponding 2-D plane strain model is shown in Figure 2(a), where the plane strain boundary conditions are also in accord with the 3-D finite element model. Since the properties of materials are strictly positive, a lognormal random field is applied to embody the random variables so, that guarantees all soil properties are nonnegative. Therefore, a 3-D lognormal random field is adopted to characterize the undrained shear strength, where the lognormal random field is obtained from a Gaussian random field that is generated by the modified linear estimation method (see [30]).

Figure 1(b) illustrates the contour of the maximum principal plastic strain of a typical sample. A small element size is used to capture the potential slip surface by the finite-element program in each simulation, where the sensitivity of results to mesh refinement in a 3-D slope is verified by Griffiths and Marquez [2]. The spatial correlation length along the vertical directions (denoted by Θ_y) and the spatial correlation length along the horizontal direction (denoted as Θ_x) refer to the values in Li et al. [31]. Xiao et al. [8] demonstrated that the failure mode and stability of 3-D slopes can be significantly influenced by the horizontal spatial variability. Thus, the Θ_x is considered to explore its effect on the overall performance of landslides. The soil is regarded as an elastic-perfectly-plastic material based on the Mohr-Coulomb yield criterion. The parameters displayed in Table 2 are assumed to be deterministic except for the undrained shear strength, which is referred to as those reported by Liu and Shields [32].

Due to the spatial randomness of the soil, the potential slip surfaces and the failure modes varied from one simulation (or realization) to another. For this reason, 600 realizations of the lognormal random field for the 3-D full-model were generated in this study; that is, Monte-Carlo simulations were conducted to examine the performance of those models [33]. For each simulation, the factor of safety (FS) is calculated by the strength reduction method, and the volume of the slide mass is calculated by summing the volume of elements whose displacement is greater than a specific value that is set at 0.2 m in this study. The

Table 1: Summary of typical studies on risk assessment.

References	Mode	Remarks
Lee and ching [14]	3-D	Developing a methodology for calculating landslide volume of infinite slope considering spatial variability of soil parameters.
Li et al. [15]	2-D	Presenting a risk assessment and analysis method considering multiple failure modes of slope based on area failure probability.
Liu et al. [16]	2-D	Investigating the effects of the stratigraphic boundary uncertainty on the slope reliability analysis and risk assessment considering the spatial variability of soil properties.
Xiao et al. [5]	3-D	Developing a collaborative risk assessment framework for 3-D slope reliability analysis and risk assessment in spatially variable soils.
Zhang and Huang [11]	2-D	Proposing a new method to evaluate risk assessment of slope taking into account the multiple failure surfaces.
Li et al. [17]	2-D	Enhancing the efficiency of the random finite element method in slope reliability analysis and risk assessment based on subset simulation.
Ali et al. [18]	2-D	Proposing an analytical framework for quantitative risk assessment of landslides caused by rainfall considering the spatial variability of permeability coefficient.
Hicks et al. [19]	3-D	Investigating the influence of the spatial variability of soil parameters on the probability of failure and the failure consequence of a 3-D slope.
Li et al. [20]	2-D	Proposing an approach for quantitative risk assessment of slope instability considering multiple failure modes based on Monte Carlo simulation.



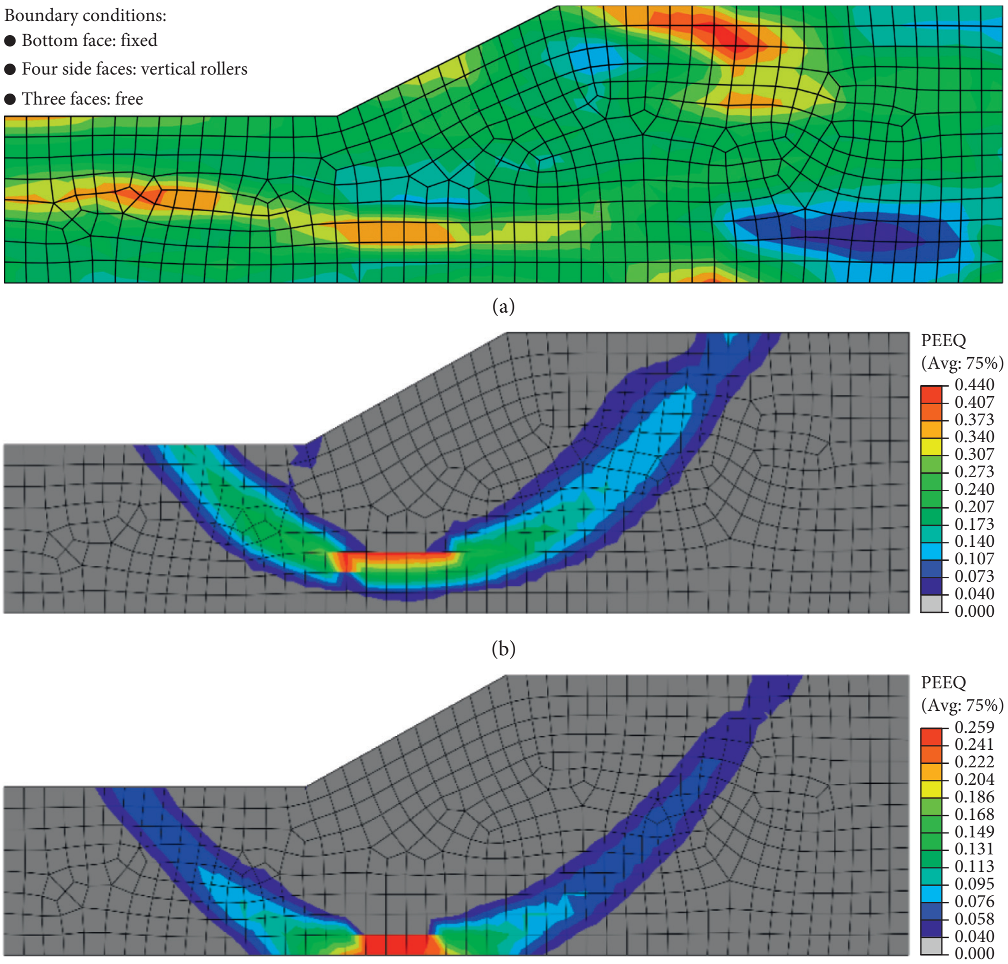
(a)

(b)

(c)

Figure 1: Typical realizations of undrained shear strength $((c)_u)$ field together with the geometric size and boundary conditions shown in (a). The spatial correlation length Θ_x is 2 m in (a), where red regions signify higher strength values; (b) contour of the maximum principal plastic strain of 3-D slope with spatially random strength. (c) Contour of the maximum principal plastic strain of 3-D slope with uniform strength.

displacement of element and volume of slide mass can be calculated by equations (1)–(3). Thus, 600 FSs and the corresponding volume of the slide mass can be obtained for each scenario (i.e., each implementation of random field), where the volume of the slide mass can be considered as an "equivalent quantity" to characterize the failure consequence



(a)

(b)

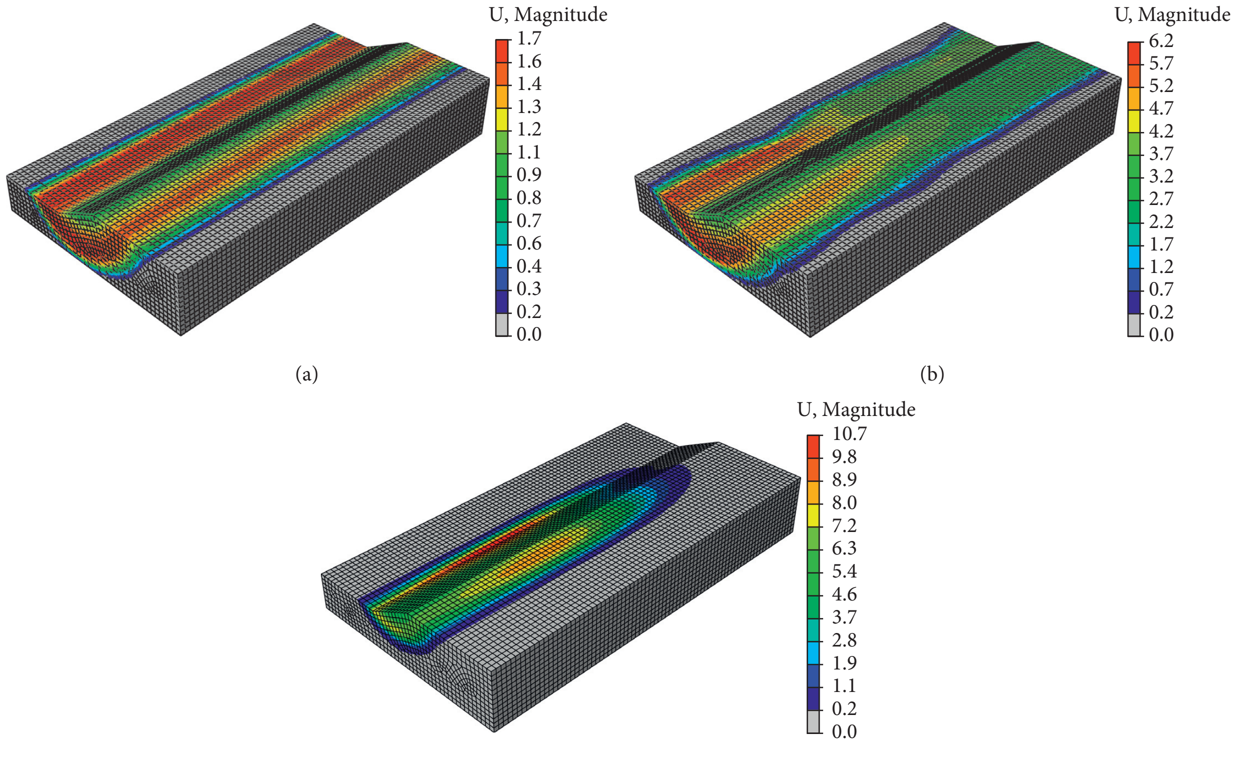
(c)

Figure 2: Illustrations of "2-D full-model" consisting of 597 four-node quadrilateral elements: (a) boundary conditions and contour of undrained shear strength $(c)_u$, where red regions signify higher strength values; (b) contour of the maximum principal plastic strain of 2-D slope with spatially random strength. (c) Contour of the maximum principal plastic strain of 2-D slope with uniform strength.

Table 2: Parameters for soil properties and finite element model.

Parameter	Unit	Value
(a) Deterministic parameters		
Friction angle	Degree	0
Undrained shear strength, c_u	kPa	Spatially random (see part *b* of this table
Dilation angle	Degree	0
Young's modulus	kPa	10^4
Poisson's ratio	–	0.49
(b) Statistical parameters of the lognormal random field for cu		
Mean	kPa	25
Coefficient of variation	–	0.4
Spatial correlation length (horizontal)	m	2; 10; 80; 1,000
Spatial correlation length (vertical)	m	2

of slope in landslide risk assessment [18]. For the models shown in Figure 3, the elements with nongrey color formed the slide region of the landslide, which suggests the failure mode of the slope is dominated by the spatial variability of soil parameters. The calculation procedure of the quantitative risk assessment of a 3-D slope instability considering the spatially variable soils parameters is schematically shown in Figure 4.



(a)

(b)

(c)

Figure 3: Schematic diagram of influence of spatial variability of soil parameters on 3-D slope slide region. Contours of slide region for slopes (a) with uniform strength and (b, c) with spatially random strength.

$$u_k = \frac{\sum_{i=1}^{8} u_{ki}}{8}, \tag{1}$$

$$u_i = \sqrt{\left(x_{ki}^2 + y_{ki}^2 + z_{ki}^2\right)}, \tag{2}$$

$$V = \sum_{k=1}^{n} V_k, \tag{3}$$

where u_k denotes the deformation displacement of the kth element greater than a specific value of displacement; u_{ki} is the displacement of the ith node of the kth element; x_{ki},y_{ki}, and z_{ki} are the coordinate of ith node of the kth element, respectively; ΔV_k is the volume of the kth element; V is the volume of slide mass.

3. Results

The irregular slip surface caused by the spatial variation of soil parameters may fail at any location of the slope, which can lead to additional difficulty in identifying the exact location of the critical slip surface and calculating the volume of slide mass. However, the critical slip surface can be automatically identified by the finite element method in each simulation prior to a prescribed slip surface. Thus, it is reasonable to accurately evaluate the failure probability of the slope and the corresponding failure consequence that depends on the area (2-D model) or volume (3-D model) of the slide mass. To evaluate the risk of landslide hazard induced by slope failure with the spatial variables in soil, 600 realizations of different random strength fields are generated so that can obtain 600 values of the FSs and the corresponding consequence of slope failure. In the study, the landslide volume and the corresponding travel distance are regarded as the evaluation indicators of the failure consequences of slope instability, and probabilistic parametric studies on landslide hazard risk are conducted for the cases where the Θ_x value is presented in Table 2.

3.1. Comparison between 2-D and 3-D Slope Stability Analyses. To preferably assess the landslide hazard induced by the slope failure with the spatial variability of soil, we herein introduce a concept of the standardized landslide volume, which is defined as the ratio of slide volume of a slope with spatially random strength over the slide volume of a slope with uniform strength. Thus, the standardized landslide volume can be treated as a simple indicator to characterize the consequence of the landslide hazard. Figure 5 displays the histogram of the 600 values of the standardized landslide volume on the basis of 2-D and 3-D analyses with various Θ_x values. The histograms suggest that the spatial variability of soil has a prominent influence on the perspective of the standardized landslide volume compared to the deterministic model (a blue arrow) whether it is a 3-D or a 2-D analysis. The reason is that the material parameter characteristic values of nonuniform slopes are different in different regions, the region with stronger or weaker soil strength is

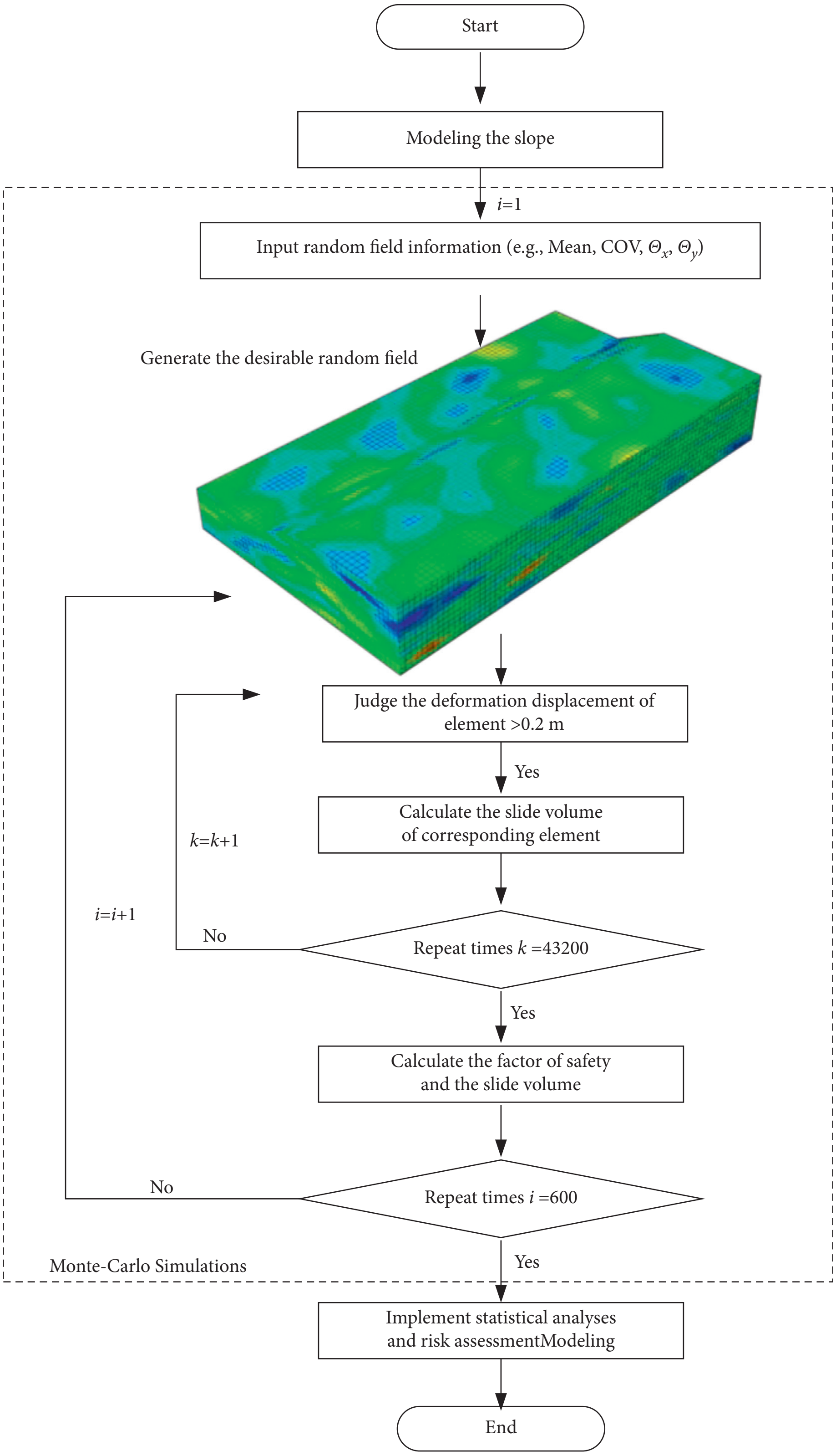
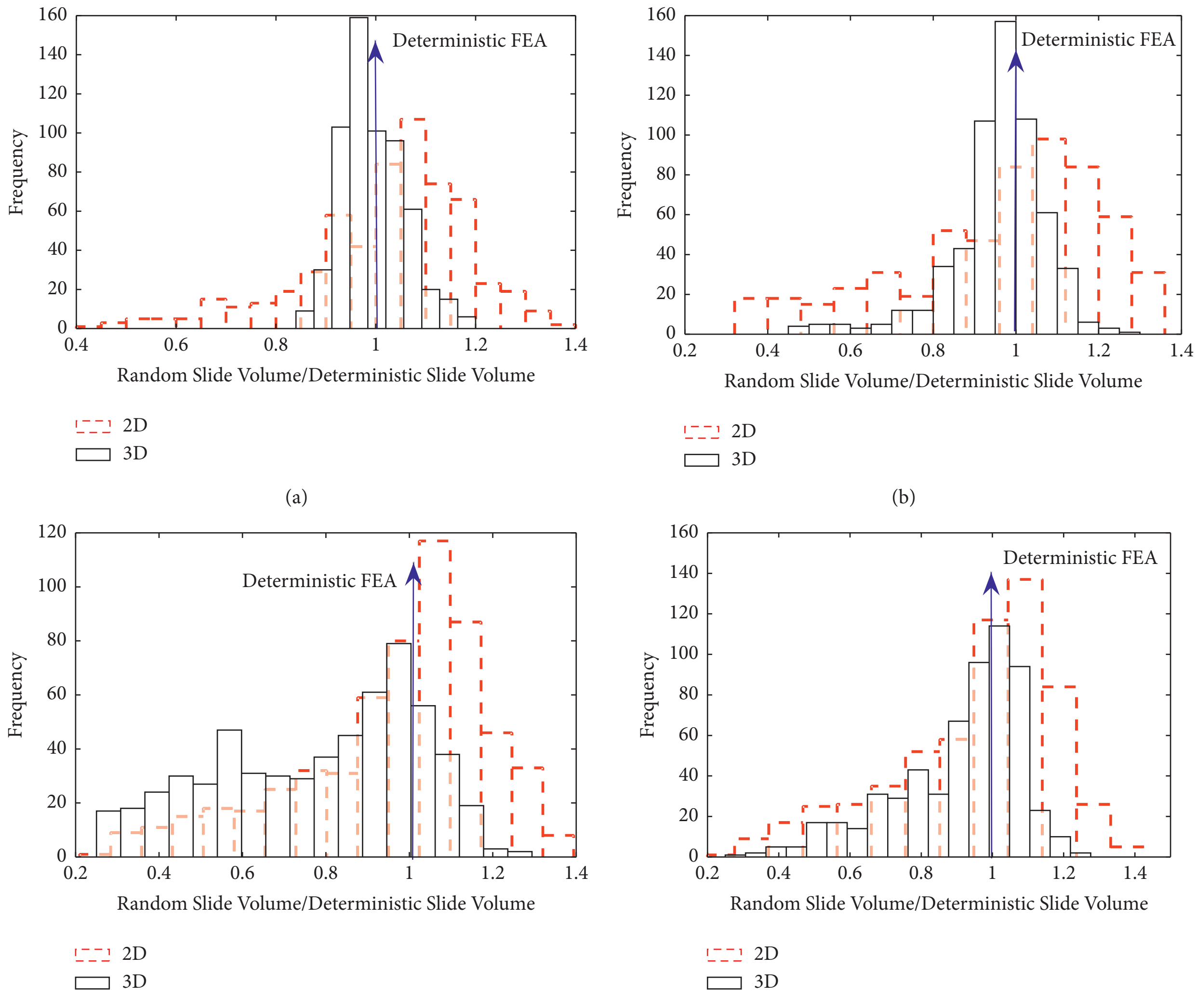


Figure 4: Calculation procedure for 3-D slope risk assessment with Monte-Carlo simulations.

uncertain from one simulation to the next, however, slope failure will occur in the region with a low shear strength of soil, which can directly affect the location and shape of the critical slip surface and result in the irregular failure modes of slope and these uncertainties will inevitably affect the volume of the slide mass (see Figure 3). This result also emphasizes the necessity of considering the spatial variation in soils in slope stability analysis.



(a)

(b)

(c)

(d)

Figure 5: Histograms of standardized landslide volume with various Θ_x values based on 2-D and 3-D models. (a) $\Theta_x = 2$ m, (b) $\Theta_x = 10$ m, (c) $\Theta_x = 80$ m, and (d) $\Theta_x = 1000$ m.

For cases presented in Table 2, the standardized landslide volume range of the 2-D model is larger, and the range of standardized landslide volume of 3-D is more concentrated. The findings can be explained that the 3-D model can more realistically reflect the location and shape of the critical slip surface and failure consequences of the slope compared to the 2-D model. The range of the standardized landslide volume in Figure 5 is overtly wider when Θ_x is 1000 m compared with those of the models that Θ_x is 2 m for both 2-D and 3-D models. These findings indicate that the location of the critical slip surface of the slope with a larger value of Θ_x will be tough to be identified which results in the difficulty of quantitative assessment of the landslide volume. This phenomenon can be reflected by the COV of the calculated results summarized in Table 3. For instance, when Θ_x is 1000 m in the 3-D model, the COV of the standardized landslide volume is as high as 0.19. Such a high COV value indicates that the volume of the slide mass is uneasy to be evaluated, which can make the landslide risk assessment sophisticated in reality. The reason is that a larger value of Θ_x indicates a stronger correlation between neighboring zones and the possibility of a local failure becomes greater on account of the inherent existence of randomness in soil (Li et al. 2021).

The difference between the 2-D model and the 3-D model (e.g., the standardized landslide volume) is inversely proportional to the Θ_x. The failure mechanism of landslides can be factually reflected by the 3-D slope in terms of the shape, position, and length of the critical slip surface compared to the 2-D model. For a conservative estimation, the infinitely large horizontal spatial correlation length is recommended to quantitatively evaluate the landslide hazard taking into account the inherent spatial variability in soils. The tail of the histograms in Figure 5 lies on the left-hand side of the distribution; that is, the data are left-skewed, which can be verified by the skewness of all cases with random soils. The skewness of the calculated results summarized in Table 3 is generally negative. This finding

Table 3: Statistics of random finite element analyses of 3-D slope model.

		The slide volume of a nonuniform slope/the slide volume of a uniform slope									
Case no.	Θ_x m	2-D					3-D				
		Mean	Mode	COV	Skewness	Kurtosis	Mean	Mode	COV	Skewness	Kurtosis
1	2	1.02	1.03	0.17	−1.06	4.70	0.99	0.94	0.07	0.56	3.11
2	10	0.96	1.04	0.25	−0.85	2.99	0.95	0.96	0.12	−1.27	6.14
3	80	0.96	1.04	0.24	−0.95	3.42	0.95	0.98	0.17	−0.41	2.05
4	1000	0.95	1.05	0.24	−0.86	3.16	0.91	0.99	0.19	−0.97	3.36
#	—	1	—	—			1	—	—		

represents the deterministic result.

suggests that some smaller portion of the slide (i.e., local failure) may come up in reality. From the perspective of standardized landslide volume, the study reveals that the spatial variability of soil parameters has played a significant role in the quantitative assessment of landslide risk.

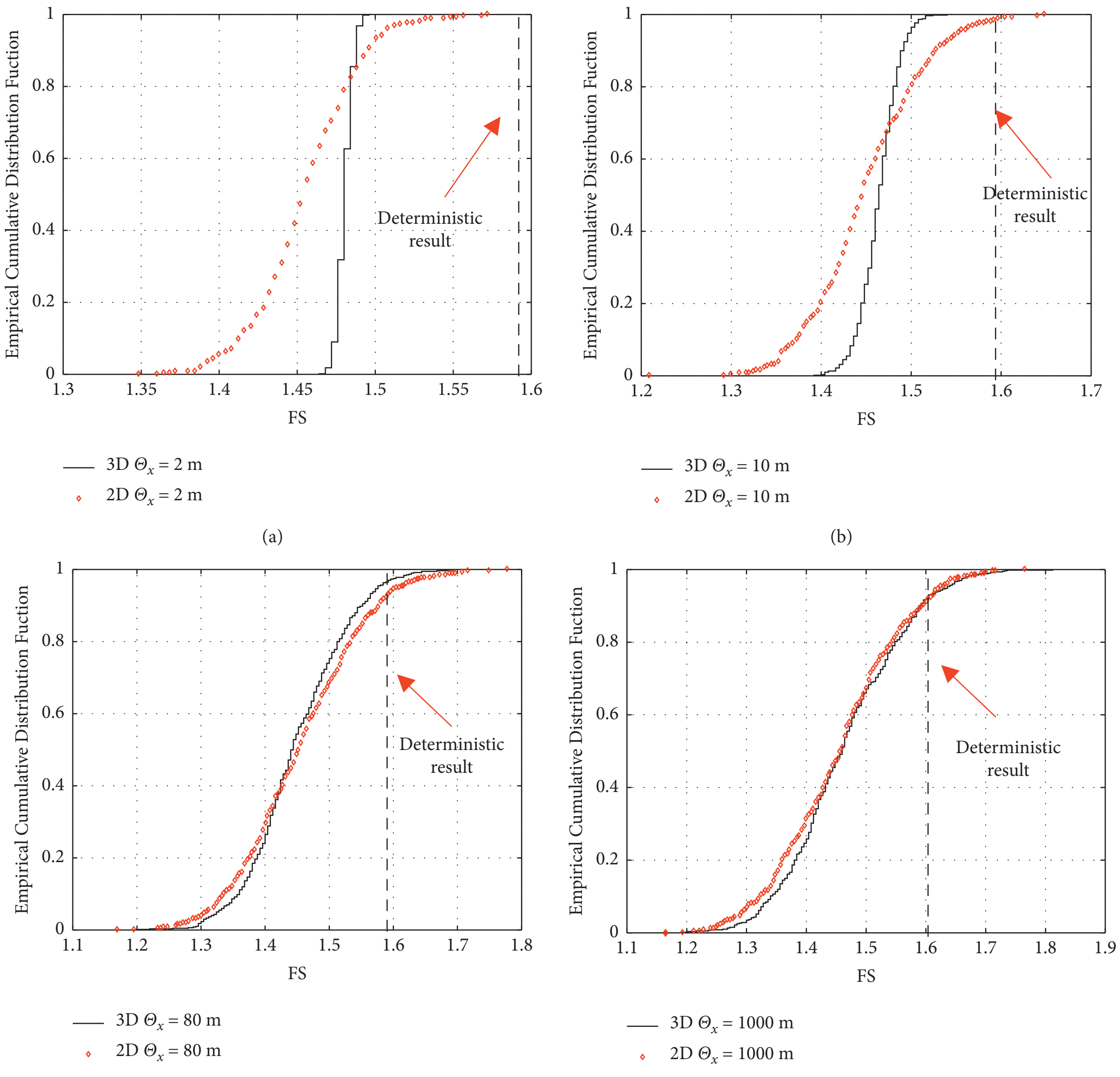
The empirical cumulative distributions of FS of all the cases are plotted in Figure 6. Figure 6 illustrates that the stability of the slope can be dominated by the spatial variability of soil parameters when compared to the deterministic model (black dashed line). However, the traditional slope stability analysis method demands a presumed critical failure surface of the slope, which becomes impractical when the soil spatial variability is taken into account. The spatial variability of soil parameters can result in the critical failure surface being irregular and unknown, which makes the probability of a slope local failure become greater. The slip surface of local failure is small, and the energy required for failure is low, which can result in a small FS for slope. Moreover, Figure 6 clearly illuminates the conservativeness of the 2-D analysis from the perspective of FS, which is in accord with the results of previous researchers [2, 23].

3.2. Stability Analyse and Failure Consequence for 3-D Slope. For a 3-D slope with spatially random strength, the slide volume varies from one simulation (or realization) to another. The variables plotted in Figure 7 can examine the relationship between the slide volume fraction (defined as slide volume over the total volume) and the stability (FS) of the 3-D model. As Figure 7 shows that the deterministic result is located near the most likely occurrence point in terms of the slide volume fraction, however, the FS calculated by the deterministic FEA is significantly greater than the results of random analysis, which can be verified by the mode of the calculated results in Table 3. Especially, for the case shown in Figure 7(a), where the spatial correlation length in both directions is set at 2 m, the FS obtained by random FEA are all lower than the deterministic result. The FS obtained from random FEA increases to a certain extent with the increases of Θ_x but still less than the deterministic result in general, which can manifest the assumption that a uniform soil is likely to overestimate the stability of a slope in terms of FS.

The spatial variability of soil properties has a remarkable effect on the slide volume fraction, especially as shown in Figure 7(d). The COV of the slide volume fraction can reach up to 0.19 and the slide volume fraction change from 15.2% to 75.8% when Θ_x is 1000 m. The larger COV indicates that the evaluation of slide volume of the slope is of complexity, which increases the difficulty of quantitative assessment of the risk of landslide hazard. The slide volume fraction of random finite element analysis is still different from the deterministic result with the decrease of Θ_x. Overall, the spatial variability of soil parameters can impact observably the slope stability and failure mode. Figure 7 indicates that the slide volume fraction can be treated as being independent of the FS, which can make the landslide hazard assessment be complicated and changeable. In addition, when the horizontal spatial correlation length is greater than the model size, the results of cases show display similar characteristics, which can be demonstrated by the histogram in Figures 5 and 6.

4. Risk Assessment

Quantitative risk assessment of slope instability is an important basis for landslide disaster risk management and the formulation of various disaster prevention and mitigation measures. The main purpose of carrying out a special landslide disaster risk assessment is to conduct risk management and control, mitigate or eliminate landslide risks, and avoid the hazards caused by the landslide disasters to the safety of personnel and property in complex geological conditions. The effect of spatial variability of soil properties on slope risk may be profound on account of the failure consequences associated with different slope failure modes generally differ. Li et al. (2021) illustrate that the traditional equation may not be directly applicable to a 3-D slope risk assessment with a large number of potential slip surfaces due to the spatial variability of soil properties [11]. When the spatial variability exists in the undrained shear strength, the potential slip surface is unknown and makes the consequence of slope failure also uncertain. However, the failure probability and the failure consequences are directly connected with the failure mode of the slope; thus, the effective identification of the critical slip surface is a crucial step in the quantitative risk assessment of landslide hazard. The potential and irregular slip surface can be automatically captured by the finite element software so that the quantitative risk assessment of slope failure with the spatially variable soils can be implemented [3]. Since the 2-D model cannot reflect the location and shape of the critical slip surface, the failure mode of the slope is a large-scale 3-D problem. Thus, a quantitative risk assessment method for 3-D slope failure



(a) (b) (c) (d)

Figure 6: Empirical cumulative distribution functions of the FS with various cases. (a) $\Theta_x = 2\,\text{m}$, (b) $\Theta_x = 10\,\text{m}$, (c) $\Theta_x = 80\,\text{m}$, and (d) $\Theta_x = 1000\,\text{m}$.

considering the spatially variable soils is proposed based on Monte Carlo simulation and the random field method, which can provide valuable risk assessment information for project designers.

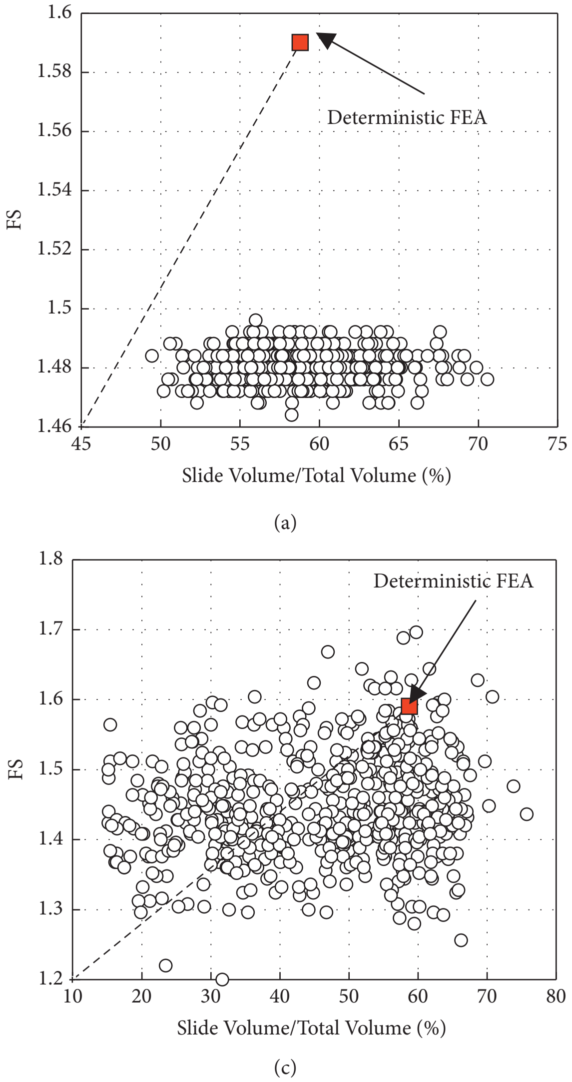
Huang et al. [15] elaborated that the failure consequence of slope depends on the landslide volume. Meanwhile, Scheidegger [34] demonstrated that the landslide volume is one of the predominant factors on landslide travel distance. The prediction of landslide travel distance is a significant prerequisite for formulating rational strategies to improve disaster prevention and relocation of residents and infrastructures facilities nearby. Thus, the travel distance can be regarded as the landslide hazard intensity factor, and the modified risk index R for landslide hazard is proposed in this study, where R combines the probability of slope instability and the corresponding failure consequence.

The empirical formula for predicting the value of travel distance is as follows:

$$\lg\left(\frac{H}{L}\right) = -0.15666\lg V + 0.62419, \tag{4}$$

where H is the maximum fall elevation of the slope; L denotes the travel distance; V is the slide volume.

$$\begin{aligned} C_i &= L_i / L_t, \\ R_i &= C_i \times \frac{FS_{\min}}{FS_i}, \end{aligned} \tag{5}$$



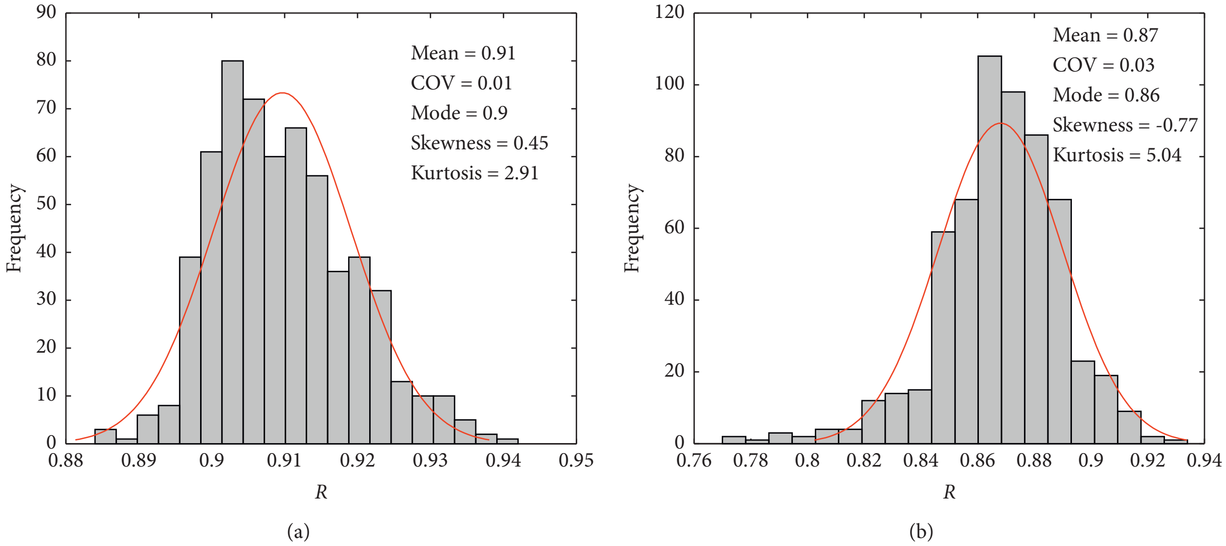
(a)

(b)

(c)

(d)

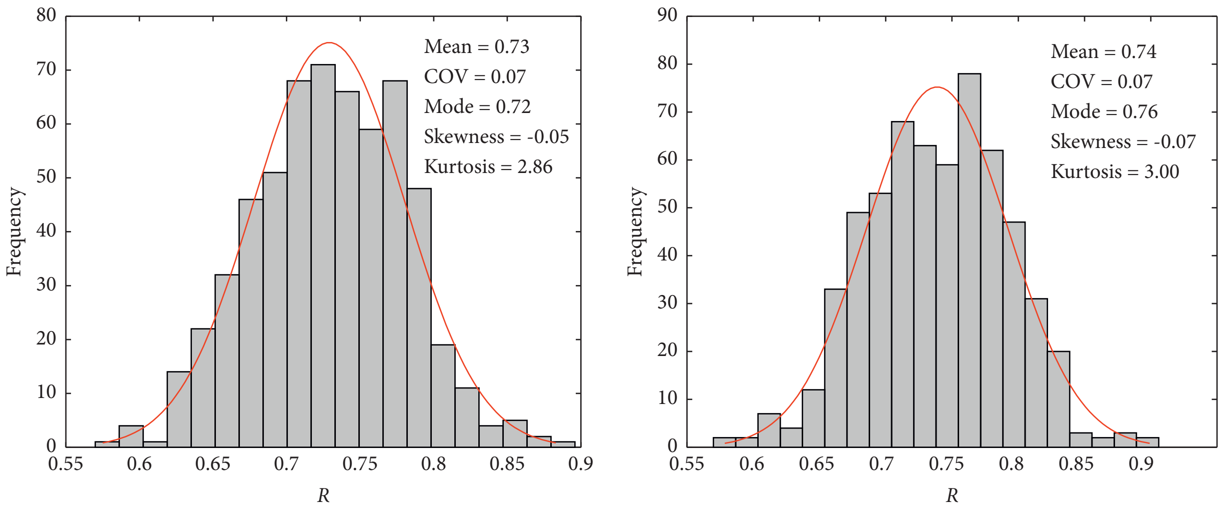
Figure 7: Relationship of slide volume fraction and FS of 3-D slope model with various Θ_x values. (a) $\Theta_x = 2$ m, (b) $\Theta_x = 10$ m, (c) $\Theta_x = 80$ m, and (d) $\Theta_x = 1000$ m.



(a)

(b)

Figure 8: Continued.



(c)

(d)

Figure 8: Histograms of risk index (R) of 3-D slope model under various Θ_x values. (a) $\Theta_x = 2$ m, (b) $\Theta_x = 10$ m, (c) $\Theta_x = 80$ m, and (d) $\Theta_x = 1000$ m.

Table 4: Quantitative risk assessment on landslide considering spatially variable soils.

Case ID	Θ_x m	Risk assessment		
		$R > 0.8$ (%)	$R > 0.85$ (%)	$R > 0.9$ (%)
Case 1	2	100	100.0	86
Case 2	10	98.3	83.5	5.3
Case 3	50	6.7	1.0	0
Case 4	1000	12.0	1.3	0.3

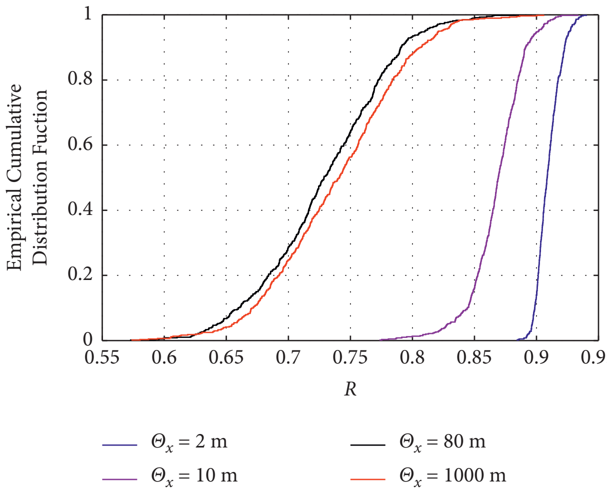


Figure 9: Empirical cumulative distribution functions of risk index (R) of 3-D slope model.

where C_i denotes the consequences of landslide hazard; L_i denotes the travel distance of ith; L_t is the travel distance induced by the total failure of the slope; R_i and FS_i are the risk index and the ith simulation of FS, respectively; $FS_{\min}$ is the minimum FS calculated out of the Monte-Carlo simulations. In this manner, we can readily evaluate the average risk and maximum risk out of Monte-Carlo simulations, which can be employed to categorize the landslide hazard. Thus, it is viable to effectively evaluate the risk induced by slope failure, which can result in the landslide risk assessment is not complicated. By doing so, the risk index can make the serious consequences of landslide hazards be easy-to-understand, which enhances the risk perception and communication for geotechnical practitioners.

Figure 8 demonstrates the histogram of R of the cases listed in Table 4, where the risk index R is generally less than 0.95. The acceptable value of R should be determined by the practitioner based on the specific site in a particular geological environment. The results in the histograms can provide powerful evidence that the horizontal spatial variability of soil parameters has a vital role in determining the slope risk, which can be proved by the COV of the calculated results summarized in Figure 8. Figure 9 shows the empirical cumulative distribution functions of the 3-D slope model under various Θ_x values and can obtain a risk assessment table (see Table 4). According to the table, different risk levels can be categorized. By this means, more quantitative information for risk assessment can be provided rather than merely giving an FS or the consequence of slope failure.

5. Conclusions

This study proposed a simple but effective approach for quantitative risk assessment of slope instability considering the spatial variability of soil properties based on Monte Carlo simulation and the random field method. The critical slip surface of the slope is accurately identified the corresponding landslide volume and travel distance are calculated by the random finite element method. By comparing the 2-D model and 3-D model, the effect of horizontal spatial variability on slope stability and risk assessment of landslides is explored. Three main findings can be summarized:

(1) Compared to a uniform soil slope, the landslide volume, the critical slip surface, and FS of slope considering the spatial variability of soil are all uncertain, which cast lights the role that the soil with inherently spatial variability has a vital effect on the stability of the slope and landslide hazard assessment

(2) A longer horizontal spatial length can lead to a larger range of slope failure consequences. For a conservative estimation, it is suggested that the infinite horizontal spatial correlation length should be considered in the quantitative risk assessment of landslide hazards

(3) A modified risk index proposed in this study combines the probability of slope instability and corresponding failure consequence, which can be adapted to the risk assessment of landslide hazard under various working conditions, and provide a reference for the emergency plan of landslide hazard and formulating the risk prevention and control plan of landslide disaster

However, the current study merely focuses on the effect of the spatial variability of soil properties on the landslide risk assessment, and the landslide hazard induced by rainfall or earthquakes is not conducted. These issues are equally important for the quantitative assessment of landslide disaster risk and are worthy of further study. In addition, a more complete and specific assessment of the damage consequences of landslide disasters is a future research objective.

Data Availability

The data are available on request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the National Key Research and Development Program of China (Grant No. 2018YFC1505005) and the Natural Science Foundation of Hunan Province, China (Grant No. 2021JJ40201), and Science and Technology Progress and Innovation Project of Transport Department of Hunan Province (202009).

References

[1] G. Formetta and G. Capparelli, "Quantifying the three-dimensional effects of anisotropic soil horizons on hillslope hydrology and stability," *Journal of Hydrology*, vol. 570, pp. 329–342, 2019.

[2] X. C. Huang and X. P. Zhou, "Probabilistic assessment for slope using the generalized chebyshev inequalities," *International Journal of Geomechanics*, vol. 20, no. 4, pp. 506–513, 2020.

[3] X. P. Zhou, X. C. Huang, and X. F. Zhao, "Optimization of the critical slip surface of three-dimensional slope by using an improved genetic algorithm," *International Journal of Geomechanics*, vol. 20, no. 8, 2020.

[4] X. P. Zhou, Y. X. Xie, X. C. Huang, and B. Z. Zhu, "Probabilistic analysis of step-shaped slopes using random field models," *International Journal of Geomechanics*, vol. 20, no. 1, pp. 4019145.1–4019145.15, 2020.

[5] D. V. Griffiths and R. M. Marquez, "Three-dimensional slope stability analysis by elasto-plastic finite elements," *Géotechnique*, vol. 57, no. 6, pp. 537–546, 2007.

[6] D. Q. Li, X. H. Qi, K. K. Phoon, L. M. Zhang, and C. B. Zhou, "Effect of spatially variable shear strength parameters with linearly increasing mean trend on reliability of infinite slopes," *Structural Safety*, vol. 49, pp. 45–55, 2014.

[7] X. J. Chen, D. Q. Li, X. S. Tang, and Y. Liu, "A three-dimensional large-deformation random finite-element study of landslide runout considering spatially varying soil," *Landslides*, vol. 18, pp. 1–14, 2021.

[8] T. Xiao, D. Q. Li, Z. J. Cao, S. K. Au, and K. K. Phoon, "Three-dimensional slope reliability and risk assessment using auxiliary random finite element method," *Computers and Geotechnics*, vol. 79, pp. 146–158, 2016.

[9] D. V. Griffiths, J. Paiboon, J. Huang, and G. A. Fenton, "Homogenization of geomaterials containing voids by random fields and finite elements," *International Journal of Solids and Structures*, vol. 49, pp. 2006–2014, 2012.

[10] S. H. Jiang, J. S. Huang, C. Yao, and J. H. Yang, "Quantitative risk assessment of slope failure in 2-D spatially variable soils by limit equilibrium method," *Applied Mathematical Modelling*, vol. 47, pp. 710–725, 2017.

[11] H. Z. Cheng, J. Chen, R. P. Chen, G. L. Chen, and Y. Zhong, "Risk assessment of slope failure considering the variability in soil properties," *Computers and Geotechnics*, vol. 103, pp. 61–72, 2018.

[12] E. E. Alonso, "Risk analysis of slopes and its application to slopes in Canadian sensitive clays," *Géotechnique*, vol. 26, pp. 453–472, 1976.

[13] L. Vranken, G. Vantilt, M. Van Den Eeckhaut, L. Vandekerckhove, and J. Poesen, "Landslide risk assessment in a densely populated hilly area," *Landslides*, vol. 12, no. 4, pp. 787–798, 2014.

[14] J. Zhang and H. W. Huang, "Risk assessment of slope failure considering multiple slip surfaces," *Computers and Geotechnics*, vol. 74, pp. 188–195, 2016.

[15] J. Huang, A. V. Lyamin, D. V. Griffiths, K. Krabbenhoft, and S. W. Sloan, "Quantitative risk assessment of landslide by limit analysis and random fields," *Computers and Geotechnics*, vol. 53, pp. 60–67, 2013.

[16] L. Li and X. Chu, "Risk assessment of slope failure by representative slip surfaces and response surface function," *Ksce Journal of Civil Engineering*, vol. 20, no. 5, pp. 1783–1792, 2016.

[17] S. W. Lee and J. Ching, "Simplified risk assessment for a spatially variable undrained long slope," *Computers and Geotechnics*, vol. 117, pp. 103–228, 2020.

[18] D. Q. Li, Z. Y. Yang, Z. J. Cao, and L. M. Zhang, "Area failure probability method for slope system failure risk assessment," *Computers and Geotechnics*, vol. 107, pp. 36–44, 2019.

[19] L. L. Liu, Y. M. Cheng, X. M. Wang, S. H. Zhang, and Z. H. Wu, "System reliability analysis and risk assessment of a layered slope in spatially variable soils considering stratigraphic boundary uncertainty," *Computers and Geotechnics*, vol. 89, pp. 213–225, 2017.

[20] D. Q. Li, S. H. Jiang, Z. J. Cao, W. Zhou, C. B. Zhou, and L. M. Zhang, "A multiple response-surface method for slope reliability analysis considering spatial variability of soil properties," *Engineering Geology*, vol. 187, pp. 60–72, 2015.

[21] A. Ali, J. Huang, A. V. Lyamin, S. W. Sloan, D. V. Griffiths, and M. J. Cassidy, "Simplified quantitative risk assessment of rainfall-induced landslides modelled by infinite slopes," *Engineering Geology*, vol. 179, pp. 102–116, 2014.

[22] M. A. Hicks, J. D. Nuttall, and J. Chen, "Influence of heterogeneity on 3-D slope reliability and failure consequence," *Computers and Geotechnics*, vol. 61, pp. 198–208, 2014.

[23] L. Li, Y. Wang, Z. J. Cao, and X. Chu, "Risk de-aggregation and system reliability analysis of slope stability using representative slip surfaces," *Computers and Geotechnics*, vol. 53, pp. 95–105, 2013.

[24] D. V. Griffith, J. Huang, and G. A. Fenton, "On the reliability of earth slopes in three dimensions. Proceedings of the Royal Society A: Mathematical," *Physical and Engineering Sciences*, vol. 465, no. 2110, pp. 3145–3164, 2009.

[25] H. Zhu, L. M. Zhang, L. L. Zhang, and C. B. Zhou, "Two-dimensional probabilistic infiltration analysis with a spatially varying permeability function," *Computers and Geotechnics*, vol. 48, pp. 249–259, 2013.

[26] Y. Liu, W. Zhang, L. Zhang, Z. R. Zhu, J. Hu, and H. Wei, "Probabilistic stability analyses of undrained slopes by 3-D random fields and finite element methods," *Geoscience Frontiers*, vol. 9, no. 6, pp. 1657–1664, 2018.

[27] J. Ji and C. L. Chan, "Long embankment failure accounting for longitudinal spatial variation – a probabilistic study," *Computers and Geotechnics*, vol. 61, pp. 50–56, 2014.

[28] K. Q. Li, D. Q. Li, and Y. Liu, "Meso-scale investigations on the effective thermal conductivity of multi-phase materials using the finite element method," *International Journal of Heat and Mass Transfer*, vol. 151, no. 2020, Article ID 119383, 2020.

[29] E. H. Vanmarcke, "Risk of limit-equilibrium failure of long earth slopes: how it depends on length," *Geotechnical risk assessment and management*, vol. 26-28pp. 1–24, Atlanta, GA, USA, 2011.

[30] Y. Liu, F. H. Lee, S. T. Quek, and M. Beer, "Modified linear estimation method for generating multi-dimensional multi-variate Gaussian field in modelling material properties," *Probabilistic Engineering Mechanics*, vol. 38, pp. 42–53, 2014.

[31] D. Q. Li, Y. N. Ding, X. S. Tang, and Y. Liu, "Probabilistic risk assessment of landslide-induced surges considering the spatial variability of soils," *Engineering Geology*, vol. 283, no. 1, Article ID 105976, 2020.

[32] Y. Liu and M. D. Shields, "A direct simulation method and lower-bound estimation for a class of gamma random fields with applications in modelling material properties," *Probabilistic Engineering Mechanics*, vol. 47, pp. 16–25, 2017.

[33] Y. N. Ding, D. Q. Li, C. Zarei, B. L. Yi, and Y. Liu, "Probabilistically quantifying the effect of geotechnical anisotropy on landslide susceptibility," *Bulletin of Engineering Geology and the Environment*, vol. 80, pp. 1–13, 2021.

[34] A. E. Scheidegger, "On the prediction of the reach and velocity of catastrophic landslides," *Rock Mechanics*, vol. 5, pp. 231–236, 1973.