

Monte Carlo-Based Reliability Assessment of Multiple Failure Modes in Truss Soil Retaining System Considering Soil Parameter Uncertainty

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Abstract:

Rapid urbanization has increased the demand for deep excavations, emphasizing the need for reliable and economical retaining systems. This study presents a probabilistic reliability assessment of truss soil retaining systems using Monte Carlo simulation coupled with the limit equilibrium method. The probabilities of sliding, pile failure, footing failure, and shotcrete failure are evaluated by considering excavation depth, truss spacing, and surcharge load as deterministic variables, while soil cohesion and internal friction angle are modeled as correlated random variables. The results indicate that 10,000 Monte Carlo simulations provide satisfactory convergence. Surcharge significantly increases the probabilities of sliding, pile, and footing failures but has a negligible effect on shotcrete failure. Truss spacing mainly influences sliding reliability, whereas its effect on the other failure modes is limited. Compared with the normal distribution, the log-normal distribution generally predicts lower probabilities of sliding, pile, and footing failures. In addition, the correlation between cohesion and friction angle has a noticeable influence under low lateral loading conditions, while its effect becomes insignificant for deep excavations or high surcharge loads. Overall, the results demonstrate that conventional deterministic safety factors may produce overly conservative designs. The proposed framework provides an efficient and practical tool for the reliability-based design of truss retaining systems under geotechnical uncertainty.

Key words: Excavation; Soil truss retaining structure; Reliability; Monte Carlo simulation; Geotechnical uncertainty

1.Introduction

The need for excavation is increasingly felt today due to population growth on the one hand and limited space and rising land prices on the other. Ignoring the spatial variability of soil properties can significantly overestimate the slope failure probability [1]. Different environmental conditions have led to the emergence of various excavation methods among which, the Soil Truss Retaining Structure (STRS) can be mentioned. This retaining structure consists of triangular elements that, due to their shape and arrangement, can effectively withstand various loads.[2] As **Fig. 1** (a) shows, the components of a STRS include horizontal and vertical members, trusses, supports, and connections.[3] The key parameters in designing a STRS include the excavation depth (H), surcharge loading (q), and the distance between trusses (S). Additionally, the soil's mechanical properties, specifically cohesion (c) and internal friction angle (ϕ), are crucial factors in the design process. In **Fig. 1** (b) the angle θ is assumed to be 30° . The parameter B_1 can be easily calculated based on the known angle and excavation depth.

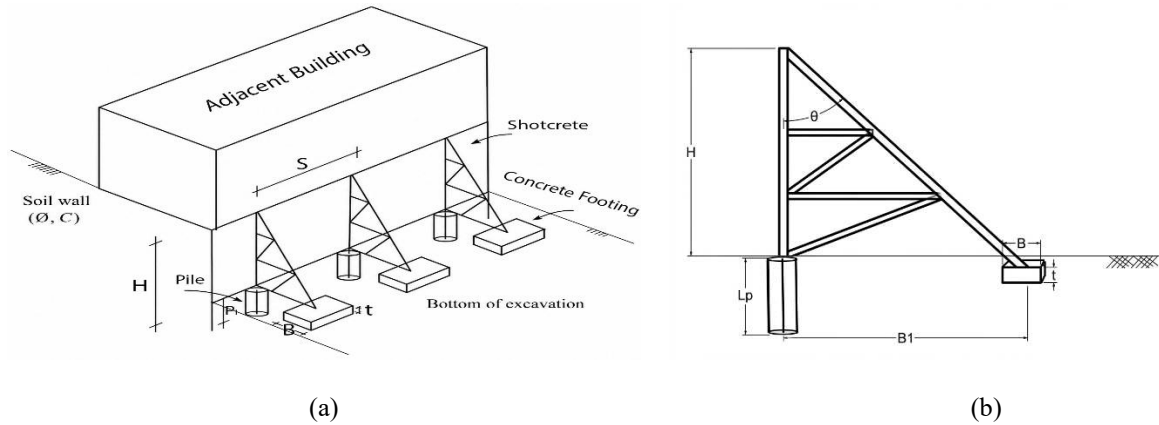


Fig. 1 Soil truss retaining structure: (a) three-dimensional view and (b) schematic cross-section

STRS is widely used in urban excavations because of their relatively low construction cost, adaptability to restricted construction sites, and simple installation procedure. However, the system requires considerable working space and generally has a slower construction rate than modern retaining systems[4].

These uncertainties arise from inherent spatial variability of soil properties, measurement errors, statistical uncertainty associated with limited site investigation data, transformation uncertainty, and constitutive model uncertainty.[5] Thus, it becomes necessary to utilize probabilistic methods. In probabilistic analyses, parameters are no longer considered deterministic but are instead represented probabilistically.[6] However, consideration of

the spatial variability of soil properties can significantly increase the computational burden.[7] Consequently, advanced sampling strategies and computationally efficient reliability methods are often required to make probabilistic analyses feasible for complex geotechnical systems.[8]

Various probabilistic methods have been developed for reliability analysis in geotechnical engineering, including the First-Order Reliability Method (FORM), Second-Order Reliability Method (SORM), Monte Carlo Simulation, Response Surface Method (RSM), Importance Sampling (IS), and Subset Simulation (SS) [9-11]. Among these methods One of the common probabilistic analysis methods is the Monte Carlo method (MCS). which is a computational technique that uses random sampling to estimate numerical results. It is widely used for simulating complex systems, calculating probabilities, and approximating integrals that are difficult to solve analytically.[12] The MCS offers several advantages, including high flexibility, accurate uncertainty analysis, and broad applicability. However, its disadvantages include high computational demand and only approximate accuracy.[13]

To enhance the efficiency of reliability-based analyses in geotechnical soils, researchers have generally relied on two main approaches. The first involves the development of simplified or surrogate performance functions to avoid the high computational cost associated with nonlinear and implicit soil behavior.[14-17] The second approach focuses on improving MCS efficiency by employing variance-reduction techniques, including Importance Sampling and Subset Simulation,[8, 18, 19] thereby enabling accurate probabilistic evaluation with fewer simulations.

Duncan[20] considers uncertainty in geotechnical engineering to be inevitable. Duncan has provided typical ranges for the coefficient of variation of various geotechnical parameters. According to Duncan studies, the coefficient of variation for the internal friction angle generally ranges between 2% and 13%. Phoon and Kulhawy[21] investigated the variability of soil parameters considering different soil types, noting that the degree of variability depends on the soil classification and the testing method used. They reported coefficients of variation for geotechnical parameters and showed that the coefficient of variation for the internal friction angle ranges from 7% to 20% when determined using direct shear tests, and from 10% to 15% when obtained from cone penetration tests (CPT). These ranges are generally consistent with the values reported by Duncan.[20]

Miar Naeimi et al[22] compared the FORM and MCS for analyzing dam failure. They[22] concluded that both methods yield close results, with the MCS providing more accurate results in some cases. Additionally, the study found that when the MCS results were not precise, increasing the number of samples in the MCS led to more accurate outcomes. Sekhvatian and Janalizadeh [23] compared the MCS and RS methods in deep excavation analysis. Sekhvatian and Janalizadeh concluded that probabilistic analysis significantly reduces costs in deep excavation projects. Additionally, Sekhvatian and Janalizadeh found that both methods yield close results, but the MCS generally produces less error. Arabani Nejad and Fakher [24] compared various probabilistic methods with software modeling methods. the results of the MCS are very close to those of the software modeling method, while the RS probabilistic method yields significantly different results. Overall, Arabani Nejad and Fakher[24] concluded that the MCS is a superior approach for evaluation, which aligns with the findings of Sekhvatian and Janalizadeh [23]. Sharma[25] compared the probabilistic MCS with the results of software analysis using PLAXIS and GeoStudio for an excavation. The findings indicate that for different sections of the excavation, there is a very good agreement between the MCS and the software methods. However, the results of the MCS are closer to those of PLAXIS, while in some cases, there is a slight difference compared to the results obtained from GeoStudio.

Ghaffarpour et al.[26] investigated the reliability of a soil nailing system for excavation stabilization using the MCS. Ghaffarpour et al results indicated that as the excavation depth increases, the reliability index decreases, implying an increase in failure probability. In addition, it was found that increasing the reinforcing bar diameter improves system performance and leads to a higher reliability index.

Wang et al.[27] performed a three-dimensional numerical modeling study combined with MCS simulation to evaluate the reliability of a nailed slope. they conducted a sensitivity analysis on internal friction angle and cohesion, by considering different coefficients of variation for each parameter. Their results showed that increasing the coefficient of variation of the internal friction angle leads to a reduction in the safety factor and an increase in failure probability. Similarly, an increase in the variability of cohesion also results in a lower safety factor and a higher probability of failure. In addition, they reported that the influence of cohesion variability on failure probability is more significant than that of the internal friction angle, indicating that cohesion is the more dominant parameter in controlling the reliability of the system.[28] Zevgolisi and Dafas [29] investigated the effect of the

correlation between the internal friction angle and cohesion on the probability of failure. They concluded that the correlation between cohesion and the internal friction angle does not significantly affect internal stability. However, it directly influences the external stability of the excavation, sliding stability, and static stability. Shabakhty et al.[30] investigated the reliability of the internal and external stability of reinforced soil retaining walls under static loading conditions. They examined the effects of various uncertain parameters, including soil internal friction angle, unit weight of soil, reinforcement strength, wall base friction angle, and applied surcharge, as well as the correlation between these variables on both internal and external stability. A sensitivity analysis of the influential random variables was also performed. For this purpose, the FORM was employed, and its results were validated using MCS simulation. In addition, the effect of correlation coefficients on the reliability index was investigated, and it was observed that correlation has a negligible influence in this study, as the reliability index for different failure modes, including bearing capacity and overturning, remained approximately constant with increasing correlation.

Babu and Singh[31] evaluated the reliability of soil nailing systems using the FORM. They investigated the effect of variations in the internal friction angle on the reliability index. Their results showed that increasing the variability of the internal friction angle leads to a reduction in the reliability index across all failure modes, and consequently an increase in failure probability. This finding is consistent with the results reported by Shabakhty et al.[30]. Another important observation is that variations in the internal friction angle have the most significant impact on sliding stability compared to other failure modes, indicating that sliding is the most sensitive mechanism to changes in this parameter.

Despite significant advancements in reliability-based geotechnical design, most existing studies have focused on conventional retaining systems such as diaphragm walls, anchored systems, and soil nailing, while relatively limited attention has been given to STRS within a probabilistic framework. In particular, reliability-based analyses of truss-supported excavation systems remain scarce in the literature compared to other well-established support methods. [21, 32]

A number of studies in geotechnical engineering have traditionally employed deterministic approaches, while others have adopted simplified probabilistic frameworks with limited consideration of failure mechanisms and random variables[21] In many cases, the interaction between key design parameters such as excavation depth,

surcharge load, and truss spacing, together with the inherent uncertainty in soil properties, has been investigated only in a partial or case-specific manner rather than within a fully integrated reliability-based framework. In addition, the effects of probability distribution type and the correlation between soil parameters on system reliability have not been sufficiently addressed in previous research [33, 34].

The increasing demand for underground space in rapidly urbanized areas has made excavation works more critical than ever. The use of high safety factors in deterministic design often leads to overly conservative and uneconomical solutions. In contrast, probabilistic approaches that explicitly consider geotechnical uncertainties can provide more rational and cost-effective designs[32]. Moreover, neglecting the inherent variability of soil parameters may result in unsafe conditions and potential failures, while construction and design uncertainties can further affect the overall performance and reliability of geotechnical systems. Therefore, a more rigorous reliability-based framework is required to properly quantify these uncertainties and enhance both safety and efficiency.[4]

2. Probabilistic Framework and Methodology

2.1 Probabilistic Analysis

Probabilistic analysis methods are widely used for evaluating and managing uncertainties and risks associated with the design and implementation of geotechnical projects. After defining the problem and determining the desired probability distribution, the required number of samples must be considered. The number of samples should be sufficient for the solution to converge. Convergence means reaching a stable solution such that increasing the number of samples does not change the result. The required number of samples to achieve convergence is usually determined through trial and error. However, as an initial approximation (where the required number of samples may be lower or higher), the coefficient of dispersion or coefficient of variation can be used. This coefficient is a statistical measure of the spread of data points around the mean and, for the probability of failure, is defined in Equation (1).

$$COV = \frac{\sigma_{pf}}{\mu_{pf}} = \sqrt{\frac{1 - p_f}{N \cdot p_f}} \quad \text{Equation (1)}$$

where COV is the coefficient of variation of the estimated probability of failure, σ_{pf} is the standard deviation of the estimated failure probability, μ_{pf} is its mean value, P_{pf} is the probability of failure, and N is the total number

of MCS samples. Equation (1) can be used to estimate the number of samples based on the required accuracy of the failure probability and the coefficient of variation. It is evident that the required number of samples may be greater or smaller than the value obtained from this equation [32]. In the MCS, the probability of failure for each parameter is calculated using the following equation:

$$p_f = \frac{1}{N} \sum_{i=1}^N R_i \quad \text{Equation (2)}$$

In this equation R_i can take two values: for the failure condition occurs R_i equals 1; otherwise, it equals 0.

2.2 Design Procedure of STRS

The geotechnical parameters adopted in this study were selected to represent typical sandy soil conditions commonly encountered in urban excavations. The values of the unit weight, internal friction angle, cohesion, and other soil properties were chosen within the ranges reported in the geotechnical literature for sandy soils and are considered representative of practical engineering conditions. Therefore, the selected parameters provide a realistic basis for evaluating the reliability of STRS under typical field conditions [20, 21, 29]. The values of geotechnical parameters are among the key factors in determining the forces applied to the truss. Table 1 presents the parameter values used in the present study.

Table 1. Values of variables in the present study

Parameter Title	Symbol	Unit	Value
Soil unit weight	γ_{soil}	$\frac{kN}{m^3}$	20
Excavation depth	h	m	3,20
Surcharge load	Q	$\frac{kN}{m^2}$	10 – 20 – 40 – 80
Cohesion	c	$\frac{kN}{m^2}$	0 , 50
Internal friction angle	ϕ	degree	25 , 45
Concrete unit weight	$\gamma_{concrete}$	$\frac{kN}{m^3}$	24
Concrete compressive strength	f_c	MPa	35
Yield stress of steel	f_y	MPa	400
Pile diameter	D_p	m	0.8
Footing thickness	b_f	m	0.5
Distance between trusses	S	m	3 – 4 – 5

By reviewing previous studies, the coefficient of variation is obtained and the mean values are considered according to Table 2 it is noteworthy that in this study the normal distribution function has been used to generate random numbers; however, the effect of using the log-normal distribution function has also been investigated.

Table 2. Random Variables

Random Variable	Unit	Mean, μ	Coefficient of Variation, COV (%)
$\emptyset$	degree	35	15
C	kPa	25	25

The loads applied to the truss include the surcharge on top of the excavation and the lateral force resulting from soil pressure. For calculating soil stress in the design of the retaining structure, the active state is considered critical. Therefore, the active stress is calculated using Rankine formula. [35]

The use of a retaining structure is not necessarily always required, and the excavation may be stable without using a retaining structure. To investigate this issue, the concept of tensile crack must first be introduced. If the soil cohesion is high, the upper part of the excavation is subjected to tension. The depth at which the stress becomes zero is called the tensile crack depth (h_t), which is calculated using Equation (3).

$$h_t = \frac{2c}{\gamma\sqrt{k_a}} \quad \text{Equation (3)}$$

where h_t is the depth of tensile crack, c is the soil cohesion, γ is the unit weight of soil, and k_a is the active earth pressure coefficient. If the excavation depth is less than the stable depth of the excavation, there is no need for a retaining structure. The stable excavation depth is twice the tensile crack depth. Therefore, considering a safety factor of ($FS=2$), the stable excavation depth is calculated as Equation (4).

$$H_s = \frac{2h_t}{FS} = \frac{2c}{\gamma\sqrt{k_a}} - \frac{Q}{\gamma} \quad \text{Equation (4)}$$

where H_s is the stability height, h_t is the depth of tensile crack, and FS is the factor of safety, while the remaining parameters are defined previously. The stress acting on the retaining structure can take one of the two forms shown in **Fig. 2**. It is noteworthy that in this study, when the stress distribution is trapezoidal, the trapezoidal stress distribution is considered in its entirety as shown in **Fig. 2 (a)** In contrast when the stress distribution on the retaining structure is triangular, the tensile stress zone is neglected, as shown in **Fig. 2 (b)** , because of the negligible tensile strength of soil, and only the compressive stress zone is taken into account. The STRS is designed to prevent sliding, pile failure, footing failure, and shotcrete failure. The first type of failure examined in the present study is pile failure. To calculate the pile length, it is first necessary to determine the force applied to the pile which show in **Fig. 2**. In this figure, (σ_x) represents the distributed load acting on the truss due to the

active earth pressure at depth (H) and the spacing between trusses. To calculate the force acting on the pile, it is sufficient to apply the laws of statics.

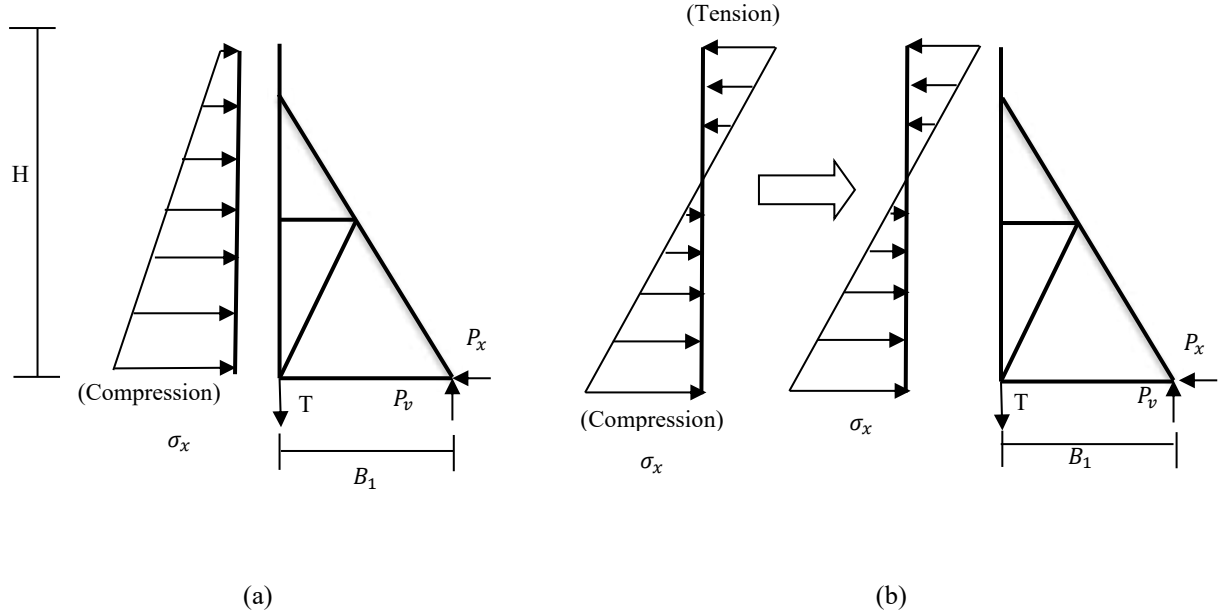


Fig. 2 Schematic representation of the loading conditions and tensile force components considered in the design of STRS: (a) trapezoidal stress distribution and (b) triangular stress distribution.

The pile located at the lower end of the vertical truss member is designed based on tensile control. The tensile capacity of the pile is calculated using Equation (5):

$$T_u = W + Q_f \quad \text{Equation (5)}$$

where T_u is the ultimate tensile force, W is the self-weight of the pile, and Q_f represents the shaft resistance of the pile. To calculate the pile length, the weight of the pile must first be determined. For this purpose, Equation (6) is used.

$$W = \frac{\pi d^2 L_p}{4} \times \gamma_c \quad \text{Equation (6)}$$

where (γ_c) is the unit weight of concrete, (L_p) is the pile length, and (d) is the pile diameter. The shaft resistance of the pile is calculated using Equation (7).

$$Q_f = \sum_{i=1}^n \beta_i \sigma'_i \times (perimeter \times length)_i \quad \text{Equation (7)}$$

$$\beta = 2 - 0.15z^{0.75}; \quad 1.8 \geq z \geq 0.25 \quad \text{Equation (8)}$$

where Q_f is the shaft resistance of the pile, n is the number of soil layers, β_i is the shaft friction coefficient in layer i , σ'_i is the effective vertical stress in layer i , and $(perimeter \times length)_i$ represents the contact surface area of the pile within layer i . Finally, after determining all the parameters in Equation (5) and considering the known force applied to the truss, the required pile length is obtained.[35] To determine the footing width, the bearing capacity equations proposed by Das [36] have been used which show in Equation (9):

$$q_u = \gamma D_f (N_q - 1) i_q S_q + 0.5 \gamma B N_\gamma i_\gamma S_\gamma \quad \text{Equation (9)}$$

where q_u is the ultimate bearing capacity of the soil, γ is the unit weight of soil, D_f is the foundation depth, B is the foundation width, N_q and N_γ are the bearing capacity factors, and i_q , i_γ and S_q , S_γ are the load inclination and shape factors, respectively. Another form of failure in the retaining structure is sliding under the effect of active earth pressure. In this case, the resisting factor is the shear strength of the soil at the footing base.

To check sliding in an excavation, it is first necessary to calculate the driving and resisting forces. For this purpose, the driving force is initially calculated for the two loading conditions. Driving force under triangular loading:

$$F_a = [(\gamma h + Q)k_a - 2c\sqrt{k_a}] \frac{SH}{2} \quad \text{Equation (10)}$$

$$H = h - h_t \quad \text{Equation (11)}$$

where F_a is the resultant active earth force, In the case of trapezoidal loading, the driving force is obtained from the following formulation:

$$F_a = [[(\gamma h + Q)k_a - 2c\sqrt{k_a}] + slope \times h_t] \frac{SH}{2} \quad \text{Equation (12)}$$

where the additional term $slope$ represents the inclination of the stress field. Once the driving force is determined, the next step is to calculate the resisting force. For this purpose, Equation (13) which is based on the Rankine theory, is used. It should be noted that in Equation (13), (t) represents the footing thickness, and the

217 factor $(\frac{2}{3})$ in the last term of the equation is included to account for the contact area between the soil and the
 218 structure. [36]

$$F_p = k_p \gamma \frac{d}{2} L_p^2 + 2c \sqrt{k_p} (dL_p + Bt) + \left[c \times \left(\frac{\pi d^2}{4} + B^2 \right) \right] + k_p \left(t^2 \frac{B}{2} \right) \gamma$$

$$+ \left[\gamma \times \left(\frac{\pi d^2}{4} L_p + \gamma B^2 t \right) \right] \tan\left(\frac{2}{3} \phi\right)$$

Equation (13)

219 where F_p is the passive force, d is the pile diameter. Finally, the factor of safety against sliding is calculated using
 220 Equation (14). In this equation, the design factor of safety is considered to be 1.5 due to the temporary nature of
 221 the retaining structure. If the calculated factor of safety is less than this value, sliding will occur; otherwise, sliding
 222 will not occur.

$$N_s = \frac{F_p}{F_a} \geq 1.5$$

Equation (14)

223 where N_s is the stability factor. For designing the cover between the trusses, shotcrete is used. To design the
 224 shotcrete, it is first necessary to convert the load applied to the retaining structure into an equivalent load, so that
 225 a uniform distributed load acts on the shotcrete layer.

226 To equivalently represent a triangular load, the simplifying assumption shown in **Fig. 3** (a) is used to convert the
 227 triangular load into an equivalent uniform load. In this assumption, the total force exerted by the triangular load
 228 is equal to that of the equivalent uniform load.

229 Another loading condition is trapezoidal loading. In this case, the equivalent uniform load is also equal to the
 230 total force exerted by the trapezoidal load. **Fig. 3** (b) illustrates the method of converting a trapezoidal load into
 231 an equivalent uniform load.

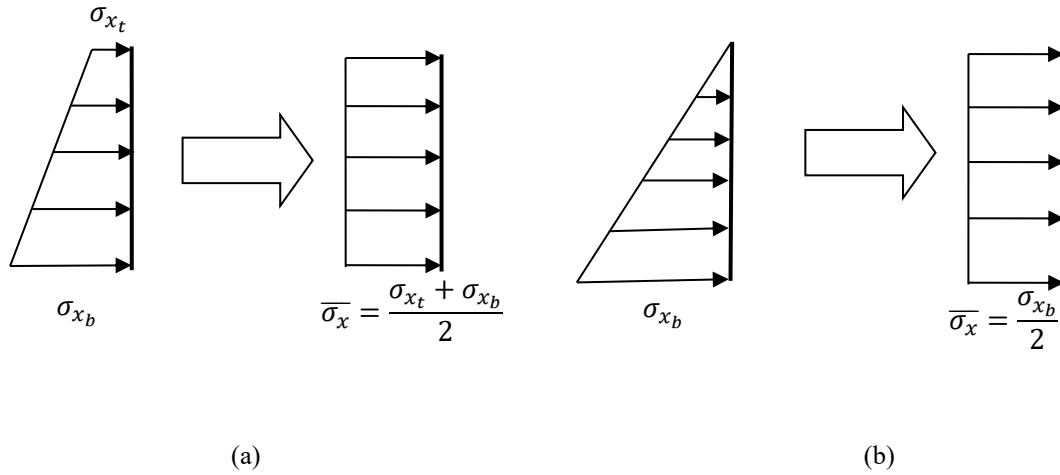


Fig. 3 Conversion of stress distribution: (a) from trapezoidal to rectangular, (b) from triangular to rectangular

To determine the shotcrete thickness, it is first necessary to calculate the shear force and bending moment acting on the shotcrete. For this purpose, using the results shown in **Fig. 4**, obtained from structural analysis, the maximum shear force and bending moment on the structure can be easily determined.

To calculate the shear force, the relevant coefficients are multiplied by the surcharge load. Similarly, to calculate the bending moment, the coefficients related to bending moment between the trusses are multiplied by the surcharge load.[37]

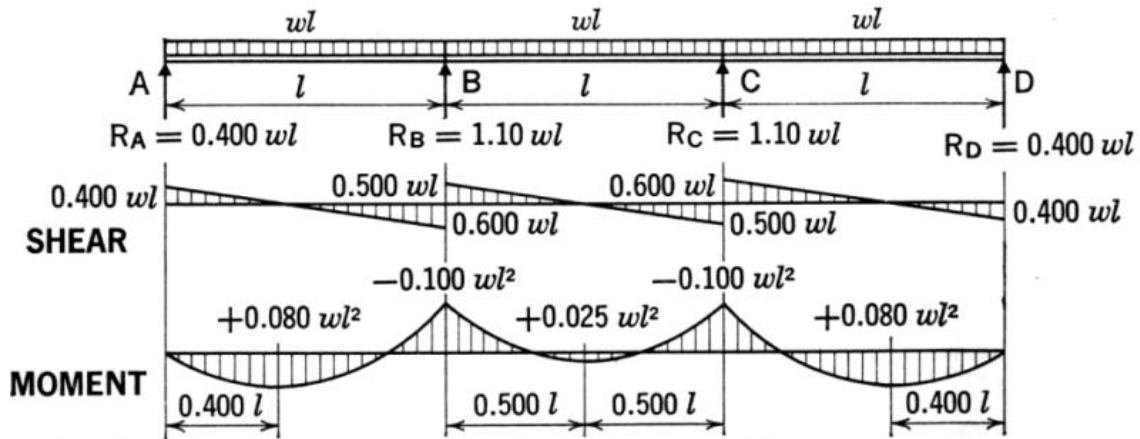


Fig. 4 Structural Analysis [37]

ACI 318-14 [37] expresses the shear capacity of shotcrete according to Equation (15). Assuming the use of an IPE220 section at the specified spacing between trusses so shear force can be calculated simply.

$$V_c = \frac{1}{6} \sqrt{f_c} b d \quad \text{Equation (15)}$$

where V_c is the shear capacity, f_c is the compressive strength of concrete, b is the width of the section and d is the effective depth.

After calculating the shear force, the bending check of the shotcrete is also performed. The equations provided in ACI 318-14 are used to determine the flexural moment capacity. For bending verification, this code is based on the assumptions of classical bending theory.[37] Equation (16) determines the value of the bending moment. Then, using the calculated moment, the required steel reinforcement area is obtained from Equation (17).

$$M_a = 0.08 w'_x \times \text{Spacing}^2 \quad \text{Equation (16)}$$

$$\rho = \frac{1}{m} \left(1 - \sqrt{1 - \frac{2mR_n}{f}} \right) \quad \text{Equation (17)}$$

where M_a is the design bending moment, w'_x is the design lateral load per unit length, and Spacing is the spacing between adjacent trusses. ρ is the reinforcement ratio, m is the modular parameter, R_n is the nominal moment coefficient, and f is the yield strength of reinforcing steel.

The calculations were performed according to the MCS. Using the truss spacing and the surcharge magnitude, the probabilities of sliding, pile failure, footing failure, and shotcrete failure were evaluated and presented graphically.

2.3 Determination of the Required Number of MCS Samples

checking convergence in the MCS is the first step in solving the problem. For this purpose, a surcharge equivalent to a two-story building (20 kPa) and a truss spacing of 4 m were selected. Next, the required number of data samples to achieve convergence must be evaluated for the probability of sliding, pile failure, footing failure, and shotcrete failure.

In this study, the convergence criterion is defined as a difference of less than 2% between successive results. Table 3 presents the number of data samples required to achieve convergence for each of the aforementioned cases.

Table 3. Number of samples required for convergence

Failure mode	Required sample size
Sliding	2000
Pile	10000
Footing	10000
shotcrete	10000

3.Results and Discussion

3.1 Effect of Surcharge Load

One of the parameters that directly affects the design of the retaining structure and, consequently its stability, is the surcharge adjacent to the excavation. This value may be subject to errors or may change between the design stage and the construction stage of the retaining structure.

in this study the surcharge adjacent to the excavation was considered variable, with values of 10 kPa, 20 kPa, 40 kPa, and 80 kPa, and its effect on the probability of sliding was evaluated.

A noteworthy aspect of this study is that sliding and structural failure are evaluated under two different scenarios: design inadequacy and probability of failure. In the design inadequacy analysis, the same factor of safety is adopted for all cases to ensure a consistent basis for comparison. In contrast, for the probabilistic analyses of sliding and failure, a factor of safety equal to unity is assumed for designs based on laboratory-determined soil parameters. For the remaining probabilistic analyses, the required factor of safety is selected in accordance with relevant design codes. Finally, the design parameters obtained using the code-prescribed safety factors are compared with those corresponding to a factor of safety of unity to evaluate the influence of safety factor selection on the probability of failure and the reliability of the retaining system.

3.1.1 Sliding Reliability Assessment

Surcharge has a direct influence on both design inadequacy and the probability of sliding. As shown in **Fig. 5**, increasing the surcharge increases the design inadequacy of sliding, and this effect becomes more pronounced as the spacing between trusses increases. In addition, sliding inadequacy becomes unavoidable at greater excavation depths, indicating that sliding should be considered a critical design criterion for truss retaining systems. Although truss spacing directly affects sliding inadequacy, the difference between various truss spacings decreases with increasing surcharge. **Fig. 5** also presents the probability of sliding. The results indicate that the overall trend is consistent with that observed for design inadequacy. In both analyses, increasing the surcharge and truss spacing

leads to a higher likelihood of sliding, highlighting the necessity of carefully addressing sliding stability in the design of STRS.

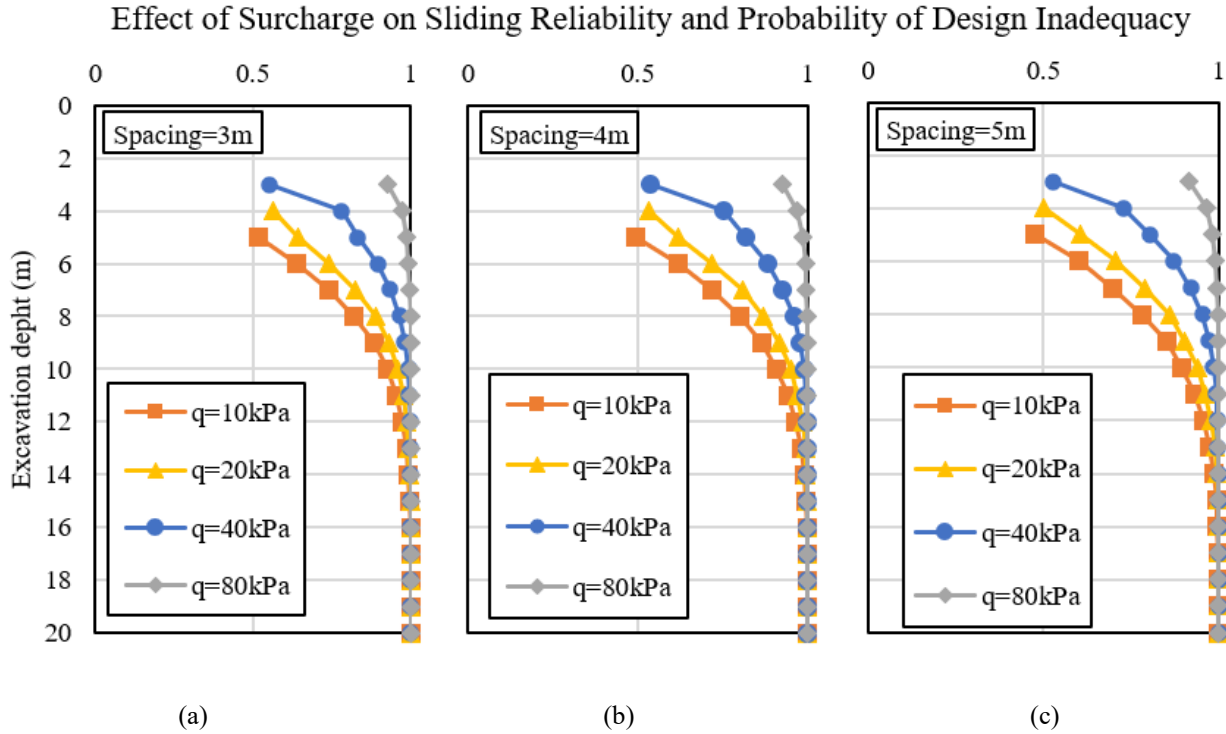


Fig. 5 Effect of surcharge on the probability of design inadequacy and reliability of sliding for different truss spacings: (a) truss spacing = 3 m, (b) truss spacing = 4 m, and (c) truss spacing = 5 m.

3.1.2 Pile Reliability Assessment

Surcharge load is a key parameter governing pile length design and, consequently, the design inadequacy and failure probability of the pile system. As illustrated in **Fig. 6** (a), an increase in surcharge leads to a corresponding rise in pile design inadequacy. For excavation depths greater than 8 m, the design inadequacy converges to approximately 50% for all considered surcharge levels, indicating a stable probabilistic response at larger depths. The influence of truss spacing is also reflected in this analysis; however, its effect is only introduced through a proportional scaling in the design procedure, resulting in a uniform adjustment of the pile length without altering the overall failure trend. As a result, it induces a proportional change in the designed pile length for both laboratory-based and probabilistic parameter sets, and therefore does not significantly affect pile design inadequacy.

Fig. 6 (b) presents the probability of pile failure. The results indicate that at shallow excavation depths, the probability of failure is relatively high, suggesting that a conventional safety factor is necessary under such conditions. However, with increasing depth, this deterministic safety factor becomes less efficient and may lead to non-conservative or uneconomical designs. In addition, an increase in surcharge results in a reduction in the probability of pile failure, implying that the use of a fixed safety factor under high surcharge conditions may lead to overly conservative and uneconomical designs. Finally, truss spacing has no significant influence on the probability of pile failure, consistent with the behavior observed in the design inadequacy analysis.

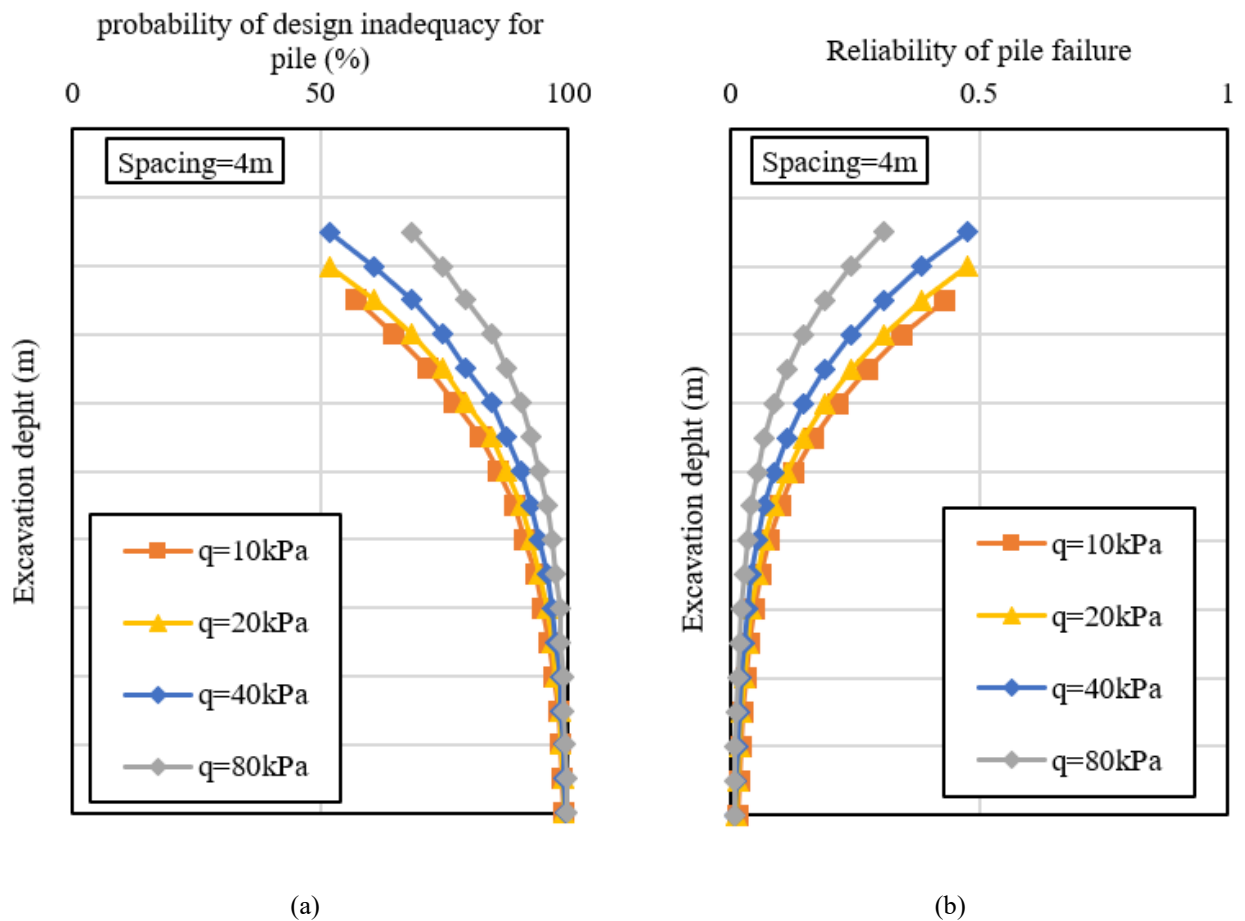


Fig. 6 Effect of surcharge for pile truss spacing = 4 m: (a) probability of design inadequacy (b) reliability of pile failure

3.1.3 Footing Reliability Assessment

Based on equilibrium considerations, the load acting on the footing—and consequently its required dimensions—is directly dependent on the surcharge load. As shown in Fig. 7 (a), an increase in surcharge results in a higher

footing design inadequacy. For excavation depths greater than 10 m, the design inadequacy converges to approximately 50% for all considered surcharge levels, indicating a stable probabilistic response at larger depths. The effect of truss spacing on footing design inadequacy can also be examined through equilibrium relations. Since the load transferred to the footing is identical to that of the pile, a similar design rationale is adopted, leading to a proportional variation in footing dimensions for both deterministic (laboratory-based) and probabilistic designs. Consequently, footing design inadequacy is independent of truss spacing. Probability of footing failure presents in **Fig. 7 (b)**. In general, an increase in lateral loading (due to higher surcharge or greater excavation depth) leads to a reduction in the probability of failure, indicating that the use of conventional safety factors may become uneconomical under low lateral load conditions. Moreover, truss spacing has no significant influence on the reliability of the footing system.

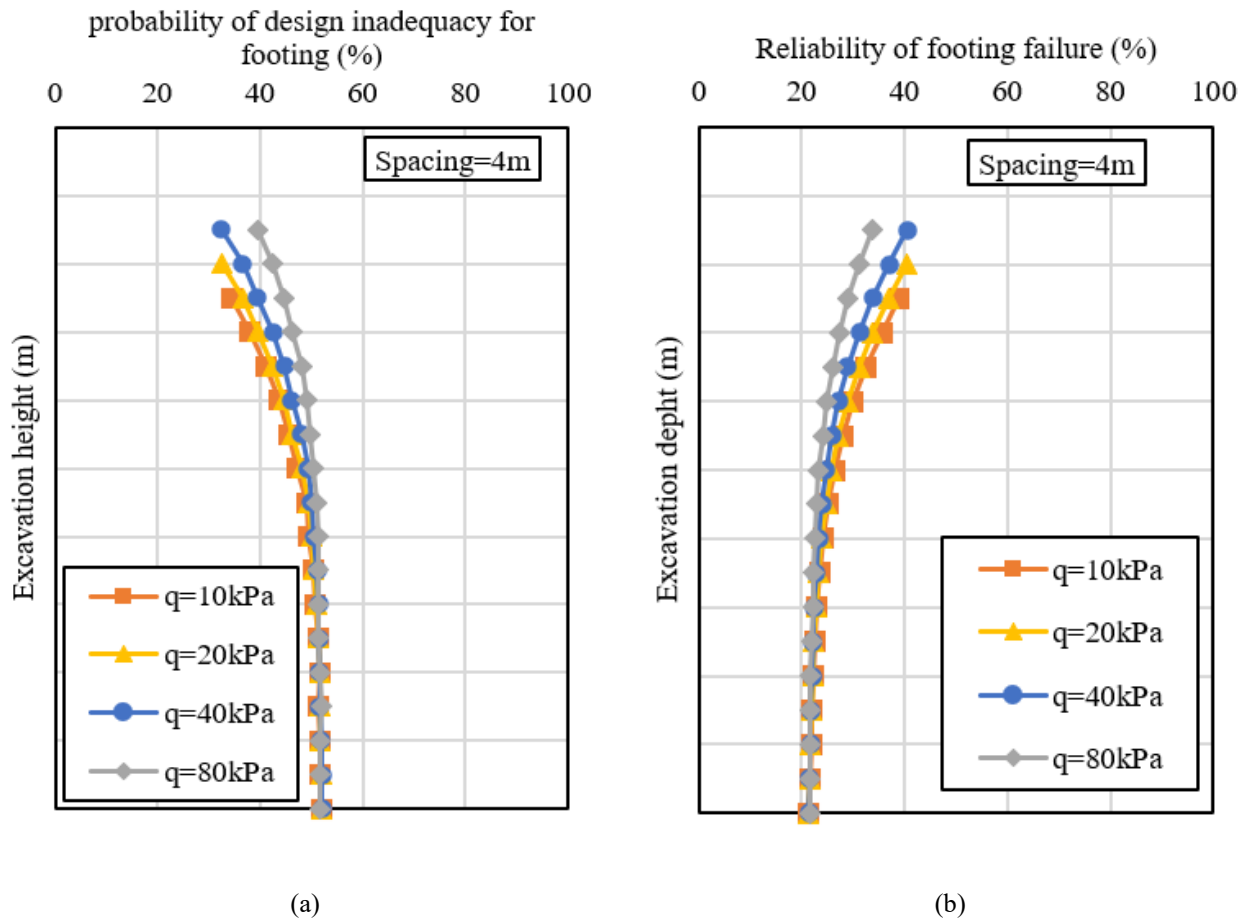


Fig. 7 Effect of surcharge for footing truss spacing = 4 m: (a) probability of design inadequacy (b) Reliability of footing failure

3.1.4 Shotcrete Reliability Assessment

The lateral earth pressure acting on the shotcrete lining is dependent on the surcharge load. Accordingly, the design thickness of shotcrete is directly governed by the magnitude of the lateral load, increasing under higher loading conditions and decreasing when the load is reduced. Assuming a normal distribution of the governing load, approximately half of the realizations exceed the design value, while the remaining half are lower, resulting in a design inadequacy level of about 50%. As shown in Fig. 8 (a), this behavior is correctly captured, where the shotcrete design inadequacy remains approximately constant at 50% and is not affected by changes in surcharge. This outcome is consistent with the adopted design framework.

Although truss spacing influences the magnitude of the lateral load, it does not affect the probabilistic design outcome; therefore, the shotcrete design inadequacy remains approximately 50% regardless of truss spacing. Fig. 8 (b) presents the probability of shotcrete failure. The results indicate that an increase in lateral loading (due to higher surcharge or greater excavation depth) leads to a reduction in failure probability, suggesting that the use of conventional safety factors under low loading conditions may be uneconomical. Finally, truss spacing has no significant influence on the reliability of the shotcrete system.

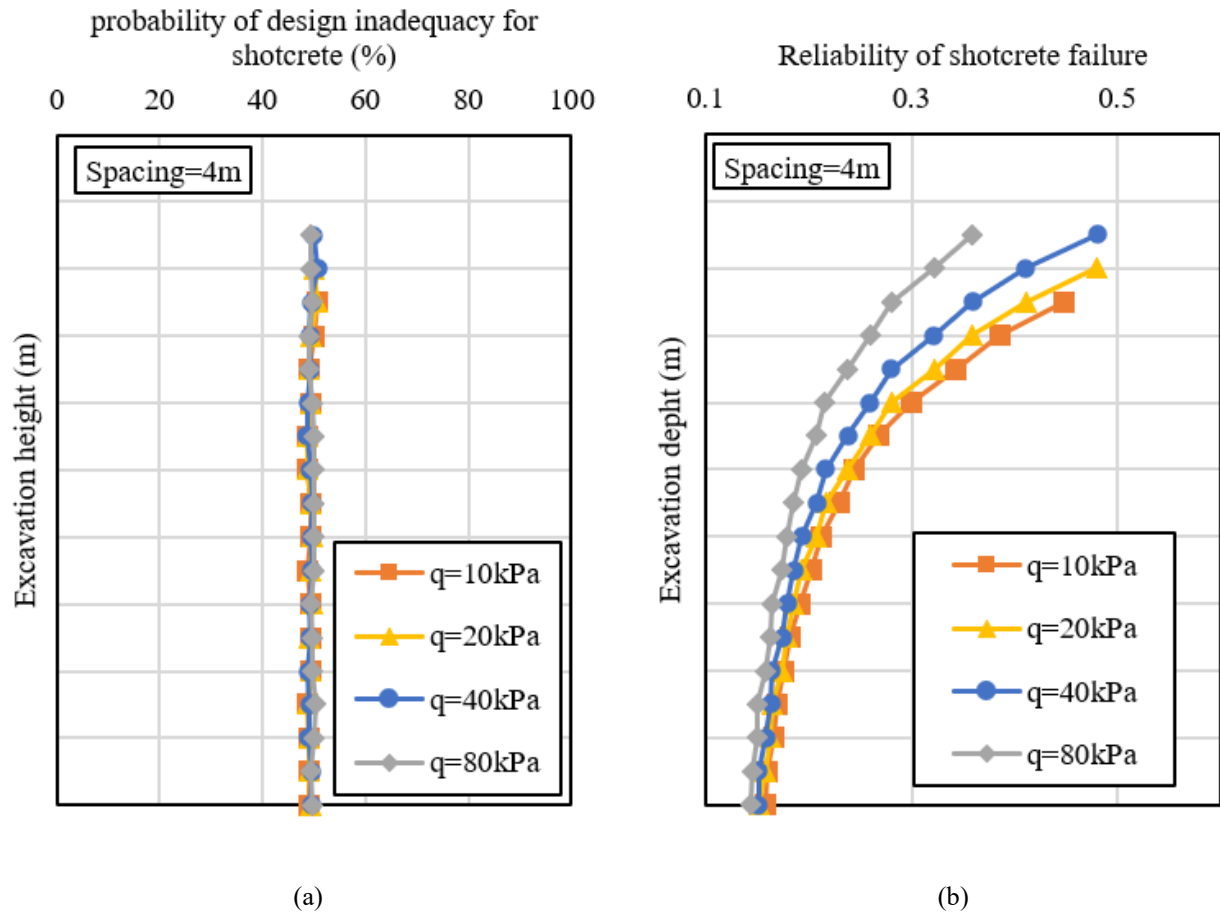


Fig. 8 Effect of surcharge for truss spacing = 4 m: (a) probability of design inadequacy for shotcrete (b) Reliability of shotcrete failure

3.2 Effect of Probability Distribution Function

Another parameter examined in this study is the effect of the probability distribution function on failure probability. The following sections investigate the impact of changing the distribution function from normal to log-normal on various failure scenarios.

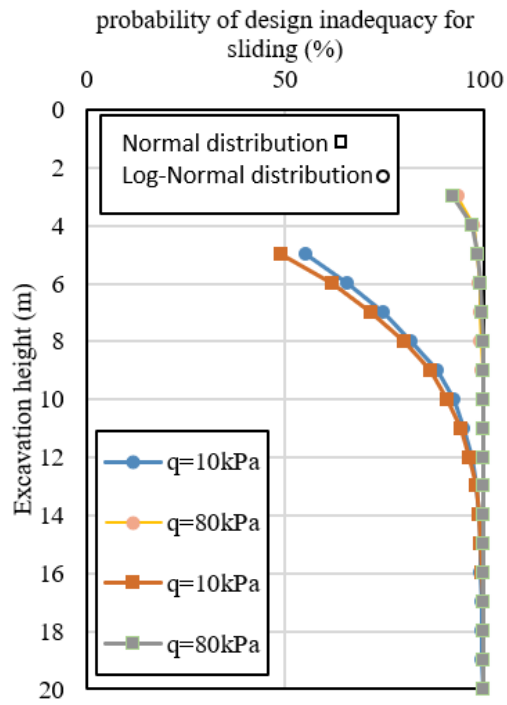
The effect of the distribution function on the probability of sliding for a truss spacing of 4 m is illustrated in **Fig. 9** (a). As can be observed, the influence of the distribution function decreases as the lateral force increases, which may result from either an increase in excavation depth or surcharge load. Consequently, at sufficiently high lateral forces, the probability of failure becomes nearly independent of the assumed distribution function, such that the probabilities obtained from normal and log-normal distributions converge and remain essentially unchanged

despite variations in the distribution model. However, under low lateral forces, the probability of sliding is lower for the log-normal distribution compared to the normal distribution.

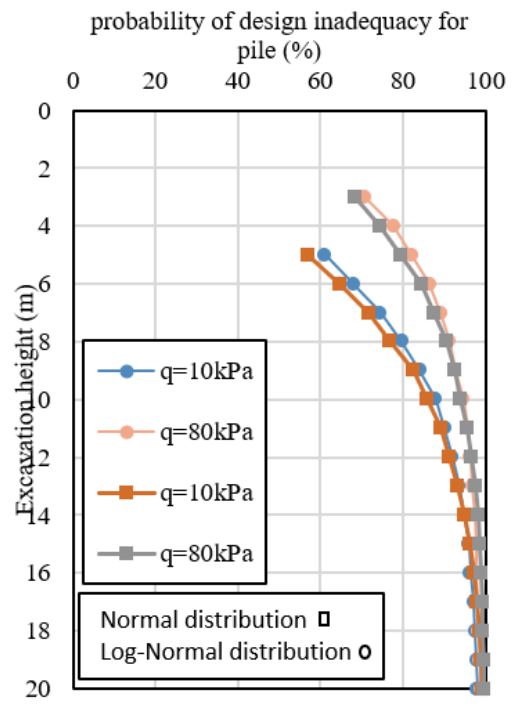
The effect of the distribution function on the probability of pile failure for a truss spacing of 4 m shows in **Fig. 9** (b). The results indicate that the choice of distribution function plays a significant role in evaluating pile failure probability. As observed, for a surcharge of 80 kPa, the probability of failure predicted by the normal distribution is consistently higher than that predicted by the log-normal distribution at all excavation depths. The influence of the distribution function is more pronounced at lower surcharge levels; for instance, under a surcharge of 10 kPa, the normal distribution yields a higher probability of failure than the log-normal distribution. Moreover, an important observation is that, when the log-normal distribution is adopted, convergence of the failure probability is reached more rapidly than when the normal distribution is used.

The distribution function also affects the probability of footing failure. **Fig. 9** (c) illustrates this effect for a truss spacing of 4 m. A noteworthy observation is that the impact of changing the distribution function on footing failure probability is similar to its effect on pile failure probability. In other words, when using the normal distribution, the probability of footing failure is higher at all depths and for all surcharges compared to the case using the log-normal distribution. Another point to note is that the choice of distribution function affects convergence in failure probability. Overall, using a log-normal distribution results in a lower probability of failure than using a normal distribution.

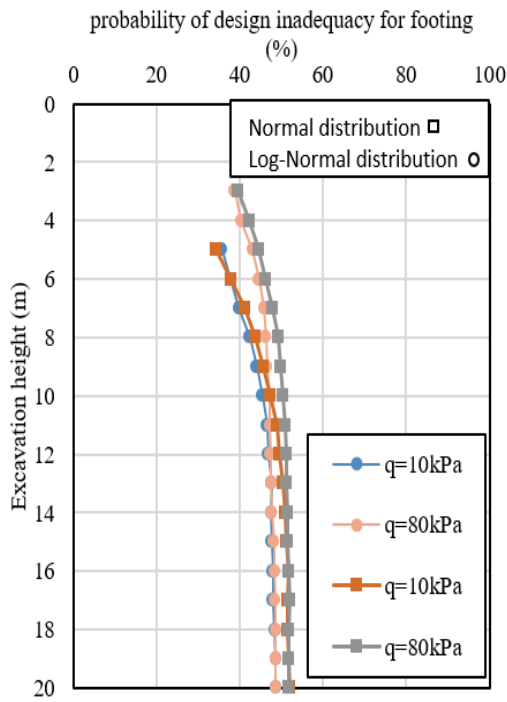
The distribution function also influences the probability of shotcrete failure. However, no significant change in the overall failure behavior is expected. **Fig. 9** (d) illustrates the effect of the distribution function on shotcrete failure probability. A noteworthy observation in this figure is that the probability of failure is higher when using the log-normal distribution, which is opposite to the trend observed for pile and footing failure probabilities.



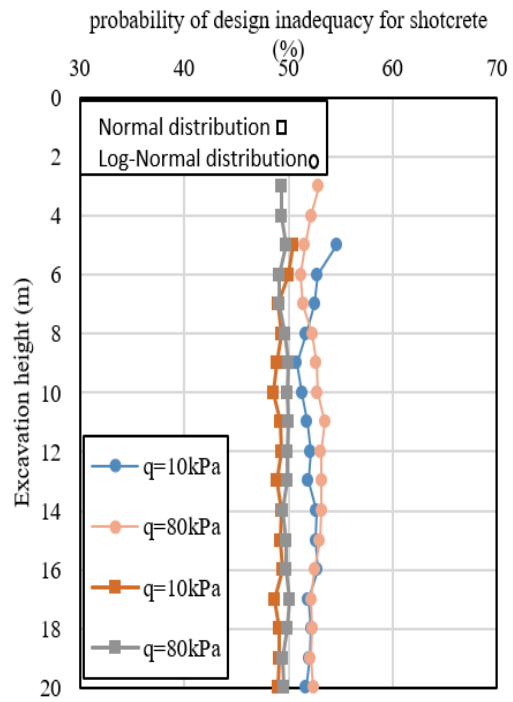
(a)



(b)



(c)



(d)

Fig. 9 Effect of probability distribution type on the probability of design inadequacy for different failure modes at a truss spacing of 4 m and surcharge loads of 10 and 80 kPa: (a) sliding, (b) pile failure, (c) footing failure, and (d) shotcrete failure.

3.3 Effect of Correlation between Soil Parameters

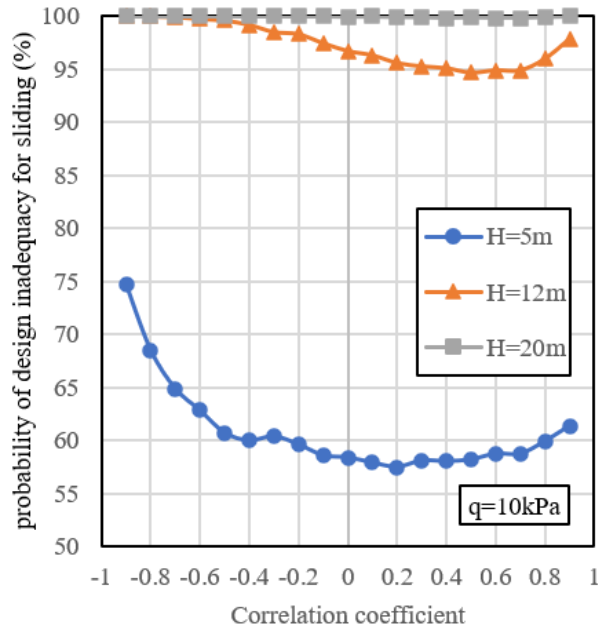
The correlation coefficient between the soil internal friction angle and cohesion is an important indicator that can provide substantial information about the combined behavior of these two parameters. The existence of correlation between soil shear strength parameters can be considered reasonable to some extent, because the internal friction angle and cohesion are, in most cases, introduced jointly into governing equations. In the following, the effect of correlation on probability of sliding, probability of pile failure, probability of shotcrete failure, and probability of footing failure is examined. In all cases, the spacing between trusses is assumed to be 4 m.

The effect of correlation between internal friction angle and cohesion on sliding probability is shown in **Fig. 10** (a, b). From this figure, it can be concluded that when the surcharge magnitude is not significant, the effect of correlation becomes apparent. As this coefficient moves away from zero and increases the dependency between internal friction angle and cohesion (either directly or inversely), its influence becomes more pronounced. Another conclusion drawn from this figure is that when the lateral force increases (due to surcharge or increased excavation depth), the effect of correlation diminishes, and the overall trend of sliding probability does not change despite the presence of correlation.

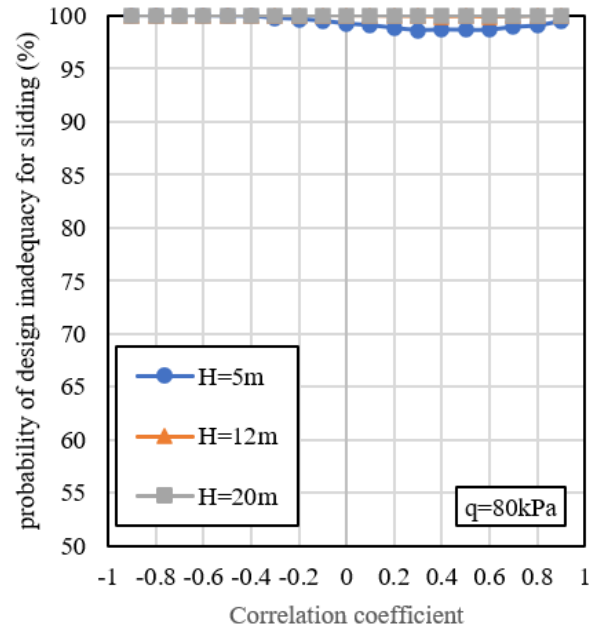
The effect of the correlation between the internal friction angle and soil cohesion on the probability of pile failure is illustrated in **Fig. 10** (c, d). The influence of correlation on pile failure probability is such that, with increasing excavation depth or surcharge load, the effect of correlation diminishes and the overall trend of pile failure probability remains unchanged. However, when the surcharge is small or the considered depth is shallow, moving the correlation coefficient away from zero—and thus increasing the dependency between internal friction angle and cohesion, whether directly or inversely—leads to an increase in the probability of pile failure.

The effect of the correlation between the internal friction angle and soil cohesion on footing failure probability is shown in **Fig. 10** (e, f). The influence of correlation on footing failure probability is similar to its effect on sliding probability. In other words, when the lateral force becomes large, the effect of the correlation coefficient

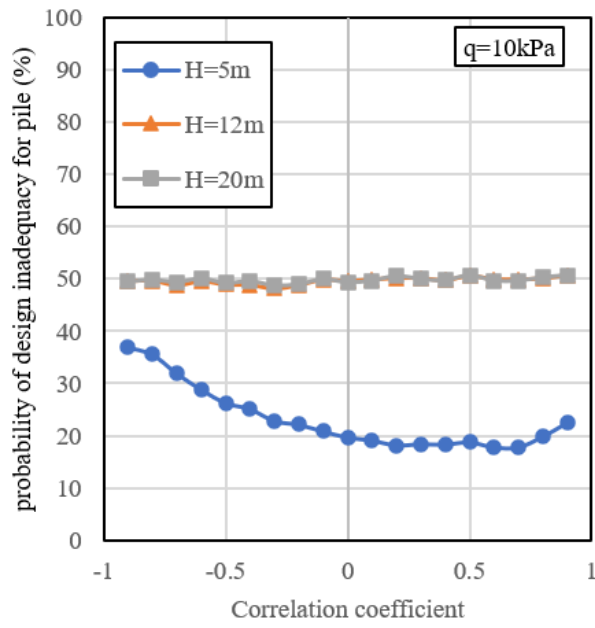
diminishes. However, when the lateral force decreases, the greater the dependency between the internal friction angle and cohesion, the higher the probability of failure. **Fig. 10** (g, h) illustrates the effect of the correlation between the internal friction angle and soil cohesion on the probability of shotcrete failure. As the correlation coefficient changes under different surcharge loads and excavation depths, the probability of shotcrete failure does not change.



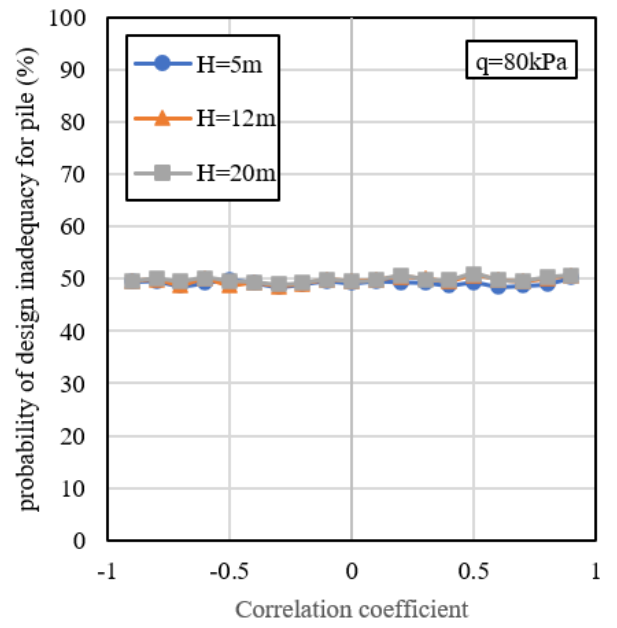
(a)



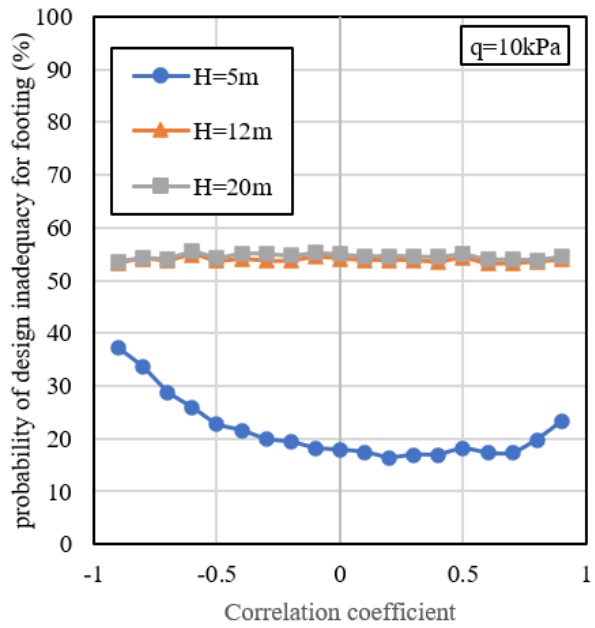
(b)



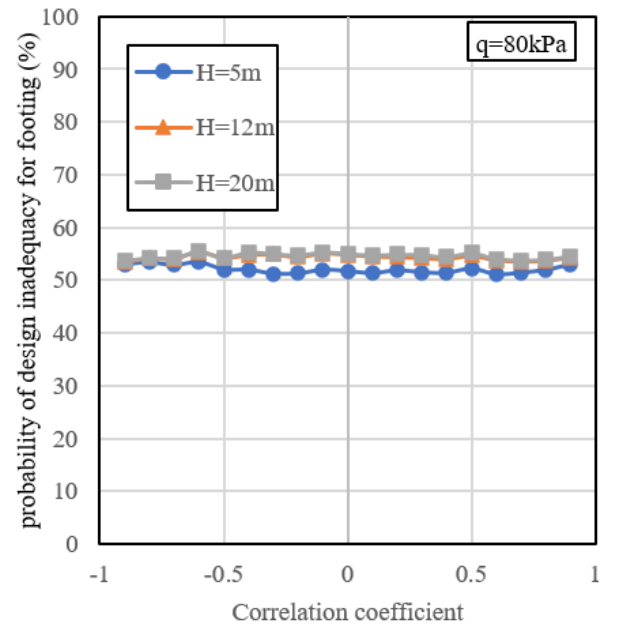
(c)



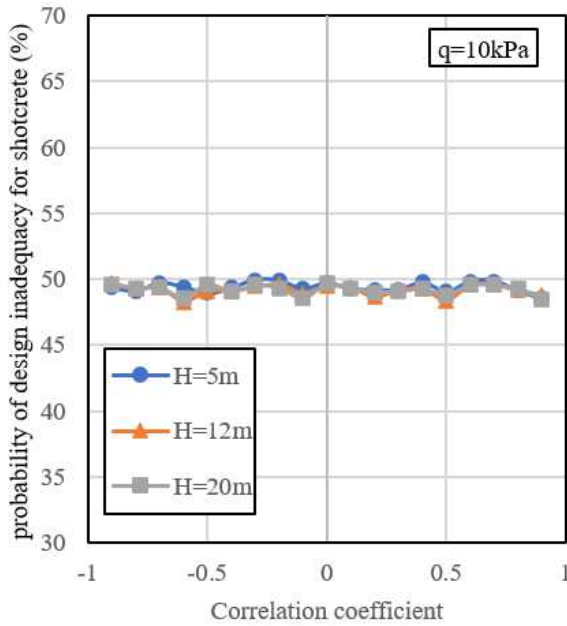
(d)



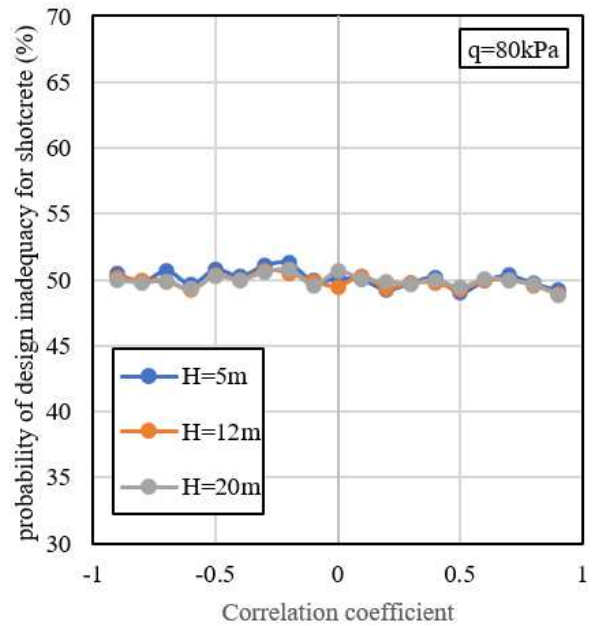
(e)



(f)



(g)



(h)

Fig. 10 Effect of the correlation between internal friction angle and cohesion on the probability of design inadequacy under different surcharge loads: (a, b) sliding, (c, d) pile failure, (e, f) footing failure, and (g, h) shotcrete failure; (a, c, e, g) surcharge = 10 kPa and (b, d, f, h) surcharge = 80 kPa.

4. Summary and Conclusions

The reliability of the trussed retaining structure was evaluated using MCS simulation implemented in MATLAB. The study systematically investigated the effects of key parameters, including excavation depth, surcharge load, truss spacing, soil shear strength parameters, and statistical uncertainty, on multiple failure modes such as sliding, pile failure, footing failure, and shotcrete failure.

A total of 10,000 MCS samples was found to be sufficient to achieve stable convergence of the estimated reliability indices for all analyzed failure modes, while maintaining an appropriate balance between computational efficiency and simulation accuracy.

The results demonstrate that surcharge load plays a dominant role in sliding behavior. Specifically, increasing surcharge significantly raises sliding probability, with its influence becoming more pronounced at greater excavation depths. In contrast, for pile and footing failure modes, surcharge has a strong effect in shallow

excavations; however, as depth increases, the failure probabilities tend to converge toward approximately 50%, indicating that lateral earth pressures become the governing factor.

For shotcrete behavior, failure probability is largely independent of surcharge variations due to the fixed-load-based design assumption, resulting in an approximately constant reliability level across different loading scenarios.

Truss spacing significantly influences sliding probability, where larger spacing reduces system stability against sliding. However, its effect on pile, footing, and shotcrete failure modes is negligible, since its influence is uniformly distributed in the load transfer mechanism.

The choice of probability distribution function has a noticeable impact on reliability results. In general, lognormal distributions lead to lower failure probabilities compared to normal distributions for most failure modes, while shotcrete exhibits the opposite trend due to its formulation.

Soil parameter correlation shows limited influence under high lateral loading conditions; however, under lower loading levels, increased correlation leads to higher failure probabilities across all examined modes, particularly for sliding and bearing-related failures.

This study contributes to a more comprehensive reliability-based assessment of trussed retaining systems by integrating multiple failure mechanisms within a unified probabilistic framework and by evaluating the combined effects of key geotechnical and structural parameters.

Several limitations of the present study should be acknowledged. Spatial variability of soil properties was not modeled using random field theory, and progressive or system-level failure mechanisms were not explicitly considered. In addition, the analysis was based on MCS, which may become computationally demanding for more complex three-dimensional configurations. Furthermore, field validation was not performed, and only normal and lognormal distributions were considered. Future work should address these limitations by incorporating spatial variability, advanced sampling.

Statements and Declarations

The authors have no relevant financial or non-financial interests to disclose. In addition, on behalf of all authors, the corresponding author states that there is no conflict of interest.

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