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Reliability of a Soil-Nailed Slope Considering Regional Shear Strength Information

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Abstract: This paper presents a reliability case study of a soil-nailed slope, considering probability distributions of shear strength parameters based on a regional database of triaxial test results for different soil types in Hong Kong. In particular, the distributions of colluvium and saprolitic soil parameters were each derived using data from hundreds of soil specimens retrieved from various projects across the city. The probability of failure for the slope is evaluated by Monte Carlo simulations, which were implemented through the limit equilibrium analysis software, SLOPE/W,together with a tailor-made Microsoft Excel spreadsheet. Probabilistic analyses were performed for the slope with and without the soil nails, and the results offer another perspective to assess the effectiveness of upgrading works in reducing failure probability in the face of significant uncertainty associated with the soil properties. The hazard levels associated with various combinations of $c' - \phi'$ parameters and potential slip surfaces are extracted from the analyses and presented on two-dimensional 'contour' plots of factor of safety, which also change with the installation of soil nails to upgrade the slope.

Keywords: triaxial test database; completely decomposed granite; colluvium; soil-nailed slope; slope reliability.

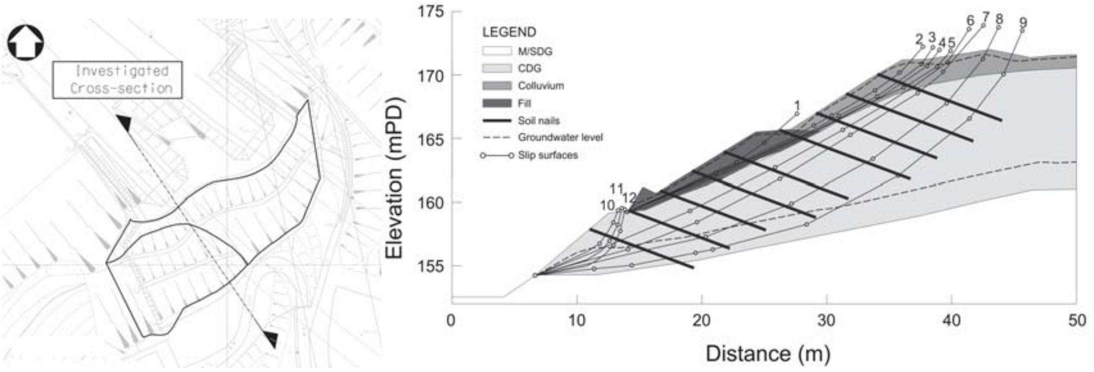
1 Introduction

Recent years have seen significant advances in numerical methods for probabilistic analyses of slopes and other geotechnical engineering systems. Some obstacles to their widespread applications may involve the difficulties in selecting representative probability distributions for the dominant soil parameters pertinent to the site conditions and project characteristics. In a companion paper, Chan et al. (2022) described the establishment of a 'regional' database of shear strength parameters based on triaxial tests on thousands of soil specimens retrieved from various parts of Hong Kong, covering six major types of soils commonly encountered in the city. The rich database represents an important resource for probabilistic analyses of geo-infrastructures such as slopes in particular, since the shear strength parameter of soils is one of the key factors affecting the stability of slopes. This paper presents the probabilistic analyses of a slope in Hong Kong which has been upgraded by soil nailing. The analyses adopt the probability distributions of shear strength parameters of the associated geo-materials based on information from the regional database. The probabilities of failure of the slope before and after the upgrading works are compared, which provides a perspective on the effectiveness of the works in reducing landslide risks.

2 Project Background

The slope case analyzed in this study is located in Kwai Chung, New Territories of Hong Kong.The slope cross-section selected for analyses is indicated in Figure1(a). It has a height of about 20 m and an average slope angle of 38°.Ground investigation works were carried out in 2015, which comprised 3 drillholes (BH1 to BH3) and 4 trial pits (TP1, TP3, TP5 & TP6). Figure 1(b) shows the idealized geological profile of the slope subsequently used in the analysis models. The geological profile comprises of fill, colluvium and saprolitic soils locally referred to as completely decomposed granite (CDG), underlain by granitic bedrock. The design main groundwater level, based on a 1-in-10 year-return period rain storm, was taken to be 2.0 m above the bedrock surface. In addition,a design perched groundwater table was considered within the fill/colluvium layer above the CDG layer due to the higher permeability of the superficial deposit. This design perched water table is taken to be close to the slope surface, i.e., 3.0 m above the interface of CDG and fill or colluvium layer. In subsequent analyses, the pore water pressures were evaluated separately for different soil layers under the effects of perched ground water. The site-specific information on soil types and shear strength parameters were found to be in line with statistical characteristics displayed in the regional database of local soils reported in the companion paper by Chan et al. (2022), as shown in Figure 2. In this paper, the 'regional' probability distributions of the relevant soil types are therefore adopted in the subsequent analyses.

According to the design report, based on deterministic analyses of the slope using the limit equilibrium method and adopting the design shear strength parameters, the factor of safety (FOS) was found to be 0.891, which is below the required safety standards of FOS ≥ 1.4.Therefore, upgrading works were designed for the slope which consisted of 9 rows of soil nails at different levels of the slope. This case study involves probabilistic analyses where soil shear strength distributions from the regional database are combined with the soil nail layout of the actual slope design. Through this study, the application of the probabilistic study tools can be illustrated, demonstrating the value of the database and the slope stability enhancement brought by soil nailing in reliability.



(a) (b)

Figure 1. Site plan and cross section of case study.

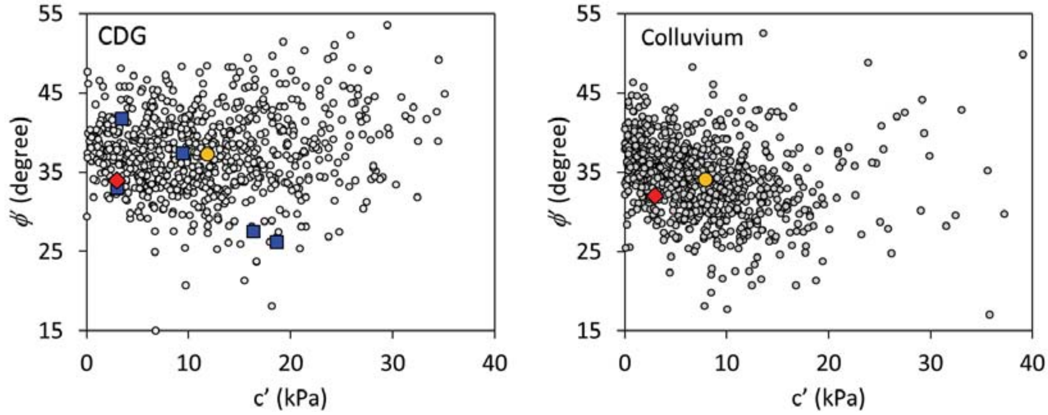


Figure 2. Regional data (grey circles); regional average (yellow circles); site-specific information (blue squares) and design values (red diamond) of soil shear strength parameters.

3 Analysis Methods

The SLOPE/W software (GEO-SLOPE 2021) is popular for limit equilibrium analysis of slopes and is commonly used in the local practice for deterministic analysis and slope designs with or without soil nails. This study also adopts this software for probabilistic assessment of slope reliability, where the probability distributions of shear strength parameters are specified through the 'offset' function, which represents the difference between the random variables and parameter values used in deterministic analysis. As stated in the companion paper (Chan et al. 2022), the probability distributions of shear strength parameters for CDG and colluvium both involve gamma distribution for cohesion and normal distribution for friction angle. For CDG, the mean and standard deviation for c' values are 11.9 kPa nd 7.6 kPa, respectively, while the mean and standard deviation for ϕ' are 37.6° and 5.2°; for colluvium, the mean and standard deviation for c' values are 7.9 kPa nd 6.1 kPa, respectively, while the mean and standard deviation for ϕ' are 34.2° and 4.7°. Whenc' and ϕ' are correlated, the correlation coefficient can also be specified in the software. According to the SLOPE/W manual (GEO-SLOPE 2021), this is achieved through correlation between $F(c')$ and $F(\phi')$, where $F(\cdot)$ is the cumulative probability function of the variable. Fixed shear strength parameters are used for Fill, where c' is 2 kPa and ϕ' is 35°.

The built-in functionality of Monte Carlo simulation in the SLOPE/W software can be utilized, where the potential slip surfaces can either be fully-specified by the user or searched automatically once the ranges of 'entry' and 'exit' points of slip surfaces are specified (the 'entry-exit' method).It should be noted that in SLOPE/W (version 2021.3), reliability is evaluated separately for each slip surface, and the software does not evaluate the system reliability considering all potential slip surfaces. It is therefore necessary to extract and post-process the FOS values from the individually specified surfaces. Extracting the FOS values is possible for SLOPE/W version later than 2018, and values extracted for each slip surface can be combined in an MS Excel spreadsheet, through which the minimum FOS for each combination of random variables (i.e. shear strength parameters)can be determined, together with the corresponding slip surface. After obtaining the minimum FOS for each simulation, the distribution of FOS as well as the system failure probability can be assessed for the slope.The system failure probability is calculated by the ratio of the number of failed cases (FOS <1) to the total number of cases.

3.1 Probabilistic Analysis of Soil Nailed Slope

An additional complication in this slope case arises from the need to incorporate the effect of soil nails. The stabilization forces provided by the soil nails are modelled as point loads on the slope surface in SLOPE/W. To evaluate these stabilization forces, recommendations of local design guidelines (GEO2017) are incorporated, where three types of forces are considered. The first type of stabilization forces is the allowable pullout resistance provided by soil-grout bond length in the passive zone behind the slip surface, which is evaluated as:

$$T_{SG} = \frac{(c'P_c + 2D\sigma_v'\mu^*)L}{F_{SG}} \tag{1}$$

where c' = effective cohesion of soil; P_c = outer perimeter of cement grout sleeve; L = bond length of soil nail in passive zone; D = outer diameter of cement grout sleeve; $\sigma_v{}'$ = vertical effective in soil at mid-depth of soil nail in passive zone, capped at a maximum value of 300kPa; μ^* = coefficient of apparent friction of soil, can be taken astan ϕ' of soil (GEO, 2017) for a ‘drill-and-grout’ nail with irregular surface texture (Cheung and Ho, 2021); F_{SG} = designated factor of safety against pullout failure at soil-grout interface (1.5 for soil nails carrying transient loads and bonded in weathered granite or volcanic rocks).

The second source of stabilization force is the allowable pullout resistance provided by grout-reinforcement bond length in the passive zone, and evaluated as:

$$T_{GR} = \frac{2.25\eta_1\eta_2 f_{ctd}P_r L}{F_{GR}} \tag{2}$$

where η_1 = coefficient related to the quality of the bond condition and the position of the bar according to Clause 8.4.2 of Eurocode (2004) (0.7 in this case); η_2 = coefficient related to the steel bar diameter according to Clause 8.4.2 of Eurocode (2004) (1.0 in this case); f_{ctd} = design value of concrete tensile strength (1.2 MPa); P_r = effective perimeter of soil-nail; L = bond length of the soil-nail reinforcement in the passive zone; F_{GR} = designated factor of safety against pullout failure (taken as 2.0). The third type of stabilization force arises from the allowable tensile capacity of reinforcement steel bar, evaluated as:

$$T_T = \frac{f_y A}{F_T} \tag{3}$$

where f_y = characteristic yield strength of the steel bar (500 MPa); A = effective cross-sectional area of soil-nail; F_T = factor of safety against tensile failure of soil-nail (1.5). All three components of soil nail forces are normalized by the horizontal spacing of soil nails, and the stabilization force provided by a row of soil nail is taken as the minimum of the three normalized forces, and subsequently input into the SLOPE/W model.

Within Eqs. (1) to (3), the component that is considered as random variable is the allowable pullout resistance provided by soil-grout bond length, asit depends on $c' - \phi'$values of the soil. Other parameters such as the yield strength of steel bar or borehole diameter are taken as constants in the following analyses. The soil nail forces that vary in different simulations pose a challenge for reliability analysis in SLOPE/W, since the software does not incorporate alteration of the pullout resistance inside the built-in Monte Carlo simulation module. Therefore, the stabilization force needs to be approximated externally, and then fed into the SLOPE/W models. An Excel spreadsheet is compiled for this purpose to automate the procedure so that soil nail forces can be changed with the Monte Carlo simulation of shear strength parameters, enabling probabilistic analysis of soil nailed slope. The main input parameters include the coordinates of the slope surface, the coordinates of groundwater table, the coordinates of the slip surfaces, the entry coordinates of the soil nail (x_1,y_1), the length of soil nail (l), inclination of soil nail (α), and $c' - \phi'$ of the soil. Based on these geometrical information, an algorithm in the spreadsheet determines the intersection point between soil nail and the slip surface and that between soil nail and the groundwater table. The bond lengths at passive zone above and below the water table (L_1 and L_2) and vertical effective stress at mid-depth of soil nail in passive zone ($\sigma_{v1}{}'$ and$\sigma_{v2}{}'$ for portions above and below the water table) are evaluated. In this case, T_{SG} corresponding to a certain $c' - \phi'$combination is evaluated as:

$$T_{SG} = \frac{(c'P_c + 2D\sigma'_{v1}\tan\phi')L_1 + (c'P_c + 2D\sigma'_{v2}\tan\phi')L_2}{F_{SG}} \tag{4}$$

4 Results and Discussions

4.1 Probabilistic Analysis of Bare Slope Before Upgrading

Reliability analysis is first performed for the slope before upgrading, following the fully specified slip surfaces as shown in Figure 1b. Monte Carlo simulation (with 4000 simulations for each slip surface) is performed adopting the probability density functions of the regional distribution of CDG and colluvium parameters. The resulting mean and standard deviation of FOS are 1.098 and 0.179 respectively, with system failure probability of 0.354 (Figure3a). Table 1 shows the failure probability of individual slip surfaces, and the FOS evaluated based on mean value of regional distribution (mean regional) or design values of shear strength parameters. The slip surface inside colluvium (No. 4) contributes to almost all the failure cases(i.e. being the critical slip) among various combinations of shear strength parameters. There is also a slight possibility for the slope to fail along the shallow slips inside CDG (No. 10 and 11).

By extracting the $c' - \phi'$ values used during the Monte Carlo simulation, a FOS 'contour map' can be plotted (Figures3b and 3c), which facilitates the visualization of the FOS value for each $c' - \phi'$ combination. The points below the 'FOS=1' (i.e. limit state) line correspond to the failure cases, which are accounted for in the evaluation of system failure probability. Moreover, the critical slip surface for each $c' - \phi'$combination of the slope can be clearly identified. For example, the shallower slip (No. 10) is associated with small c' values, while the deeper slip (No. 9) is associated with higher c' levels. Slip surface No. 4 is identified to be dominant for stability of the slope. Strictly speaking, it is not possible to draw such a '2-D' map with four variables (c' and ϕ' for CDG and colluvium).However, in this case the FOS of Slips No. 1-5 depends entirely on colluvium parameters, and the FOS of Slips 6-12 depends almost entirely on CDG parameters. Hence it is possible to present two separate FOS contours to reflect the slope reliability.

Table 1. Probability related to slip surfaces before slope upgrading.

		Deterministic Analysis		Probabilistic Analysis Using Regional Distribution	
Slip Surface No.	Failure mode	FOS based on mean regional $c' - \phi'$ parameters	FOS based on design $c' - \phi'$ parameters	Individual failure probability	Probability of being the critical slip given failure
1	Through Colluvium	1.552	0.925	0.133	0
2		1.267	0.906	0.215	0
3		1.181	0.867	0.313	0
4		1.151	0.857	0.349	0.97
5		1.16	0.881	0.308	0
6	Through CDG	2.019	1.426	0.001	0
7		1.956	1.433	0.002	0
8		2.024	1.552	0.001	0
9		2.088	1.644	0	-
10		2.596	1.299	0.008	0.02
11		2.254	1.251	0.01	0.01
12		2.281	1.336	0.006	0

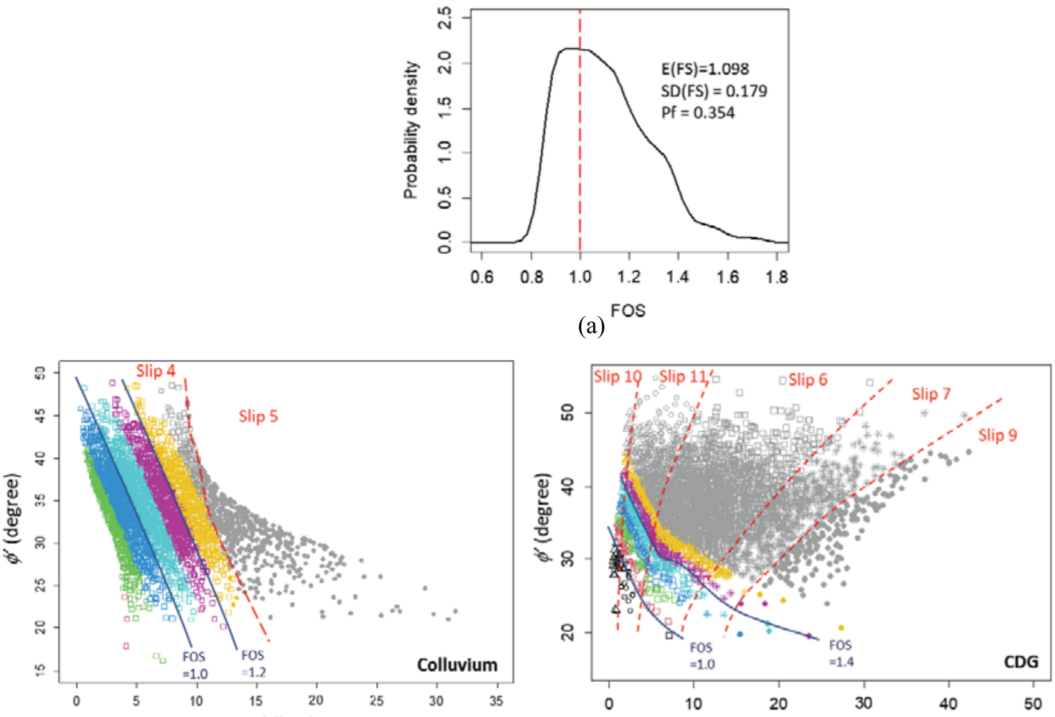
4.2 Probabilistic Analysis of Slope Upgraded by Soil Nailing

Both the deterministic analysis during the design stage and the probabilistic assessment presented in the previous section indicate a substandard level of slope safety. Soil nailing was designed based on the design shear strength parameter to upgrade the slope, and the upgrading works consisted of nine rows of soil nails, with their general layout indicated in Figure 1b. The soil nails are composed of 25-mm diameter high yield steel bars, inserted into drillholes of 150 mm in diameter which are subsequently filled by cement grout. The top six rows of soil nails are 10 m in length, and the bottom three rows are 8 m long. The horizontal spacing between soil nails was 1.5 m and the nails were inclined at an angle 20^{o} from horizontal. The passive zones of the soil nails (portions behind the slip surfaces) were inside the CDG layer for most of the cases. As detailed earlier, the stabilization forces of the soil nails are modelled accordingly, as point loads on the slope surface, and the associated parameters include η_1 = 0.7; η_2 = 1; f_{ctd} = 1.2 MPa; f_y = 500 MPa; F_T = 1.5; F_{GR} = 2.0 and F_{SG} = 1.5. Adopting the design shear strength parameters, the FOS was found to be 1.611, which satisfies the required safety standards of FOS $\geq$ 1.4.

Monte Carlo simulation of soil nailed slope is then performed adopting the same set of regional probability distribution of $c' - \phi'$ as in the previous section. The stabilization point loads provided by the soil nails for each combination of shear strength parameters are evaluated through the abovementioned formulation. The resulting

FOS distribution is also shown in Figure 4a. The mean and standard deviation of FOS are 2.16 and 0.45 respectively. After installing soil nail, the probability of failure decreases from 0.354 to 0.00096.

Table 2 shows the failure probability of individual slip surfaces, together with the FOS evaluated based on mean regional or design values of shear strength parameters. Slips 9 and 11, which are primarily within the CDG stratum, are found to be the most probable critical slip surfaces in the scenario of soil-nailed slope.The FOS contour for Slips 9 and 11 are shown in Figures4b and 4c. Convergence issue was encountered for Slip 11, where the slip surface is shallow and point load is high. For Slip 11, FOS cannot be solved for certain $c' - \phi'$ combinations. Therefore, the FOS contour for Slip 11 is interpolated and smoothened, which produces the smoothed FOS contour map. Combining the FOS maps of Slips 9 and 11 lead to the minimum FOS map. Before installing soil nails, the surficial slip surfaces in colluvium (Slips 4 and 5) are the most critical. After installing soil nails, the slip surfaces inside CDG become most critical instead.



(a)

(b) (c)

Figure3.(a) FOS distribution for the slope before upgrading, (b)(c) MinimumFOS contour for bare slope under various combinations of shear strength parameters (colours of the points correspond to the bands of minimum FOS in 0.1 interval; slip number correspond to the slip where minimum FOS is found).

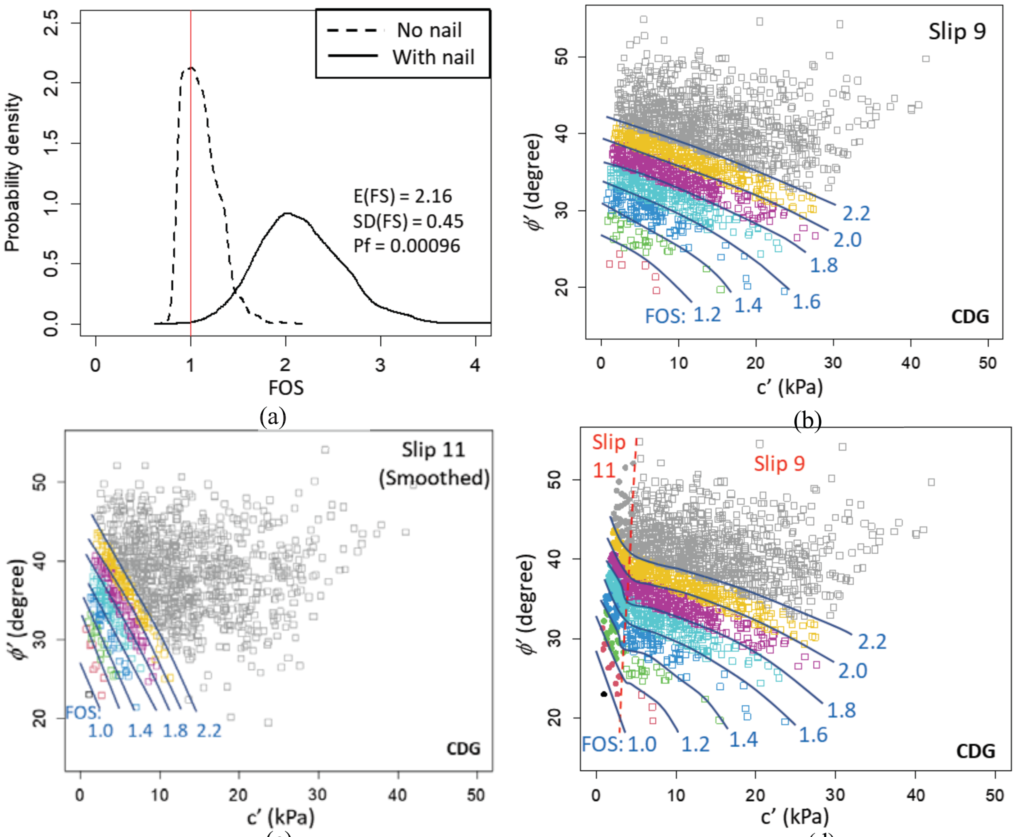
Table 2. Probability related to slip surfaces after slope upgrading.

		Deterministic Analysis		Probabilistic Analysis Using Regional Distribution	
Slip Surface No.	Failure mode	FOS based on mean regional $c' - \phi'$ parameters	FOS based on design $c' - \phi'$ parameters	Individual failure probability	Probability of being the critical slip given failure
1	Through Colluvium	>5	>5	0	-
2		>5	>5	0	-
3		>5	>5	0	-
4		>5	>5	0	-
5		>5	>5	0	-
6	Through CDG	>5	3.810	0	-
7		4.2	2.543	0	-
8		2.621	1.906	0	-
9		2.171	1.695	0	-
10		3.122	1.665	0	-
11		2.845	1.611	0.00096	1
12		2.91	1.656	0	-

5 Conclusions

This paper presents reliability assessment of a slope case in Hong Kong, before and after upgrading works by soil nailing. The use of a common limit equilibrium analysis software, SLOPE/W, is illustrated, and the approaches to assess system failure probability are elaborated. The evaluation of various components of soil nail stabilization forces are implemented using a simple spreadsheet, and such forces are then incorporated into the SLOPE/W models using a macro for probabilistic analyses. These tools are all readily available to most practising engineers. The case study also shows that probabilistic analyses provide another perspective on the effectiveness of slope upgrading works, as the associated reduction in probability of failure can be quantified in face of the uncertainty in properties of geomaterials.

Some ongoing additional works on this case study include the hybridization of site-specific triaxial test data with the regional database, following a concept similar to that in Ching et al. (2021). The hybridized probability distributions would incorporate the site-specific features of material variability displayed by the site data, while the statistical uncertainty (due to limited site data)would be reduced by the knowledge from regional database. The effects of hybridized on slope stability, with and without installation of soil nails, will be explored in this and other slope cases in Hong Kong.



(a) (b)

(c) (d)

Figure4.(a) FOS distribution for the slope after upgrading by soil-nailing, (b)(c)(d) FOS contourfor soil-nailed slopeunder various combinations of shear strength parameters.

Acknowledgments

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