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Talus Slope Stability Analysis in a Chemical Industrial Park Based on Dual Factor System

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Due to the high risk in the production process and the toxicity of the products, the location of chemical Industry is required to be far away from urban areas and other densely populated areas. Therefore, more and more chemical companies are removed from urban areas and moved to industrial parks. The establishment of Chemical Industrial Park is conducive to the safety control of the production process. Meanwhile, the site far away from densely populated areas also improves the controllability of the hazards after the accident. However, in the mountainous areas, there is an inevitable existence of large-scale accumulation slopes in the siting area of the chemical industrial park. The stability of this kind of slope is a direct threat to the chemical plant production and building safety. This paper aims to develop an ideal tool for evaluating talus slope stability. To this end, a realistic dual index system was put forward in light of the existing approaches. Specifically, the type of distribution of the material indices was determined by the Kolmogorov-Smirnov (K-S) test method, and the slope reliability was discussed by the Monte-Carlo (MC) method. The proposed system was applied to the stability analysis of a talus slope in a chemical industrial park. According to survey data, four cases of the slope were selected for deliberation. The results prove the feasibility of our dual index system. Suffice it to say that this research provides a meaningful reference to studies in similar fields.

1. Introduction

The safety factor, a key evaluation index of slope stability, has been extensively applied in slope engineering. However, it is impossible to measure slope stability solely by this factor, because slope is a system with uncertain, illegible and time-varying features. In other words, a slope fulfilling the designed safety factor may still suffer from landslide (Abbaszadeh et al., 2011).

In view of this, the reliability theory has been introduced to slope stability evaluation to tackle the uncertainties and correlations in the slope system (Zhu, 1993). The new evaluation approach demands lots of reliability indices (e.g. material parameters and external factors), leading to a soaring computing load. For better application, the safety factor and the reliability indices must be employed simultaneously to get the whole picture of slope stability (Li et al., 2016). This calls for a slope stability evaluation system that fully integrates the safety factor with reliability indices.

In such an attempt, the dual index analysis combines the mean safety factor (MSF) and the reliability into the coupled safety factor (CSF) for slope stability evaluation (Gui et al., 2014). In this method, the distribution of rock and soil parameters is expressed as a pure mathematical probability distribution model (Luo et al., 2005), and the scope of geotechnical parameters is not clearly defined. Hence, the results are too conservative to meet the requirements of actual engineering. The dual index analysis inspires several dual evaluation systems. Unfortunately, these systems still face numerous problems in two aspects. On the one hand, most of them only highlight the statistical values of physical-mechanical indices of rock and soil, failing to consider the distribution range of these indices; on the other hand, the physical-mechanical indices are assumed to obey the normal distribution, resulting in errors in reliability analysis and low evaluation accuracy.

Being one of the most unstable slopes, the talus slope is formed by various materials under complex conditions, and featured by highly uncertain physical-mechanical indices (Kornejady et al., 2014). To evaluate the stability of such a slope, it is necessary to determine the distribution of physical-mechanical indices by the Kolmogorov–Smirnov (K-S) test method. Meanwhile, the pure mathematical model should be modified, such

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that the safety factor will remain below the critical value. Following this train of thoughts, the author proposed a realistic dual index system to evaluate the stability of talus slope.

2. Theoretical analysis

2.1 Principle of Monte-Carlo method

The Monte-Carlo method (M-C method), also known as the random sampling method or statistic testing method, is a statistics-driven probability estimation approach that relies on repeated random sampling to obtain the chance of risk generation. In this method, random sampling is employed to select a set of values that satisfy the probability distribution of the input variables, and then the set of values are substituted to the state function to acquire the evaluation indices corresponding to the sampling values of different indices. The statistical probability of the object is obtained according to the evaluation index of the probability distribution (Lim et al., 2017).

In light of the actual problems in slope stability evaluation, the relationship between the safety factor and the slope stability indices can be established by combining the structure, failure mechanism and stress state of the rock-soil mass:

$$F(X) = f(x_1, x_2, \cdots, x_n) = \frac{R(x_1, x_2, ..., x_n)}{S(x_1, x_2, ..., x_n)} \tag{1}$$

where F(X) is the safety factor function of the slope; $x_1, x_2, \ldots, x_n$ are the random variables representing the influencing factors of slope stability, namely bulk density, friction angle, cohesion, external load and seismic acceleration; $R(x_1, x_2, \ldots, x_n)$ is the function of the anti-sliding force; $S(x_1, x_2, \ldots, x_n)$ is the function of the sliding force.

According to the statistical values, the variables either obey the normal distribution or follow the lognormal distribution. To ensure the relative independence among sampled safety factors (F_1, F_2, ..., F_N,), variables x_i were randomly extracted from those of the same type of distribution, and substituted into the state function (1) for N times to get the results. The safety factor in the limit equilibrium state (F(X)=1) was adopted as the criterion of slope stability. Let the number of samples with smaller-than-one safety factor, the slope failure probability can be determined as:

$$P_F = p\left\{f(x_1, x_2, \cdots, x_n) < 1\right\} = \frac{M}{N} \tag{2}$$

The influencing factors of slope stability are random variables. Depending on the specific geological environment, different factors have different impacts on slope stability. Here, the uncertain influencing factors of the stability of an example slope was analysed in an all-round way, with the most prominent factors (i.e. friction angle, cohesion and bulk density) being random variables and the other factors as constants.

2.2 Principle of the K-S test

Named after Kolmogorov and Smirnov, the K-S test is an easy-to-use method to verify hypotheses without grouping the data or sacrificing information integrity. It works well in solving the limited amount of sample data caused by sampling difficulty and high testing cost. The basic idea of the K-S test is to determine the type of probability distribution for cumulative frequency by comparing the observed cumulative frequency with the probability distributions under different assumptions.

For the empirical distribution function with the sample content n, the sectionalized cumulative frequency can be determined as:

$$F_n(x) = \begin{cases} 0, x \le x_i \\ \dfrac{i}{n}, x_i \le x \le x_{i+1} \\ 1, x \ge x_{i+1} \end{cases} \tag{3}$$

where x_1, x_2, …, x_n are the sorted sample data, $F_n(x)$ is a ladder shape curve.

In the range of random variable X, the maximum difference between $F_n(x)$ and $F_X(x)$ can be expressed as:

$$D_n = \max_{-\infty \prec x \prec \infty} \left|F_X(x) - F_n(x)\right| < D_n^{\alpha} \tag{4}$$

where α is the significance level; D_n is a random variable depending on n; D_n^{α} is the critical value of α. Assuming that the $F_n(x)$ reaches the significance level α, it can be expressed with the theoretical distribution $F_X(x)$, and vice versa.

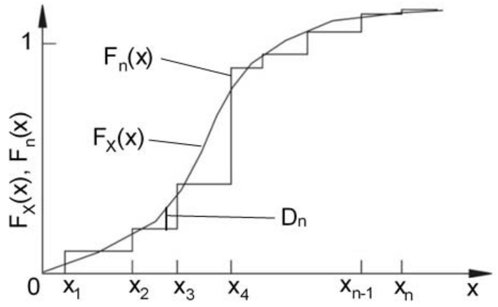

Figure 1: Function curves $F_n(x)$ and $F_X(x)$

2.3 Dural index system for slope stability evaluation

Let F_{cr} be the critical value of the safety factor. Then, the limit equilibrium state equation of the slope can be expressed below according to Equation (2):

$$Z = F(X) - F_{cr} = f(x_1, x_2, \cdots, x_n) - F_{cr} = 0 \quad (5)$$

The corresponding probability of slope failure can be expressed as:

$$P_F = P(F < F_{cr}) = \int_{-\infty}^{Fcr} f_F(f_s) df_s \quad (6)$$

where, $f_F(f_S)$ is the probability density function of the safety factor.
To the left of F_{cr} and the x-axis lies the unstable area of the slope (P_F), i.e. the area enclosed by the function $f_F(f_S)$; the rest of the slope to the right of F_{cr} is the stable area of the slope, and its reliability index can be expressed as $P=1-P_F$. The slope is in the critical state when $F=F_{cr}$.

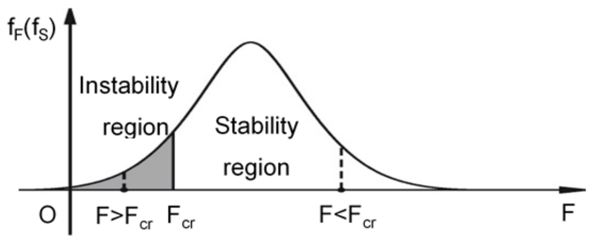

Figure 2: Probability density distribution of safety factor

According to actual conditions, the physical-mechanical indices of slope materials cannot be negative or infinite, and the safety factor F must be greater than 0. In view of this, the pure mathematical model was modified. First, the K-S test was performed to define the type of distribution and the range of the physical-mechanical indices. The range of the distribution function curve is limited by the geotechnical test results. Then, M-C sampling and calculation was conducted N times to obtain N relatively independent samples of the safety factors (F_1, F_2, ..., F_N) within this range, as well as the intervals of these safety factors [F_{min}, F_{max}]. The probability of slope failure can be expressed as a piecewise function within the range:

$$P_F = \begin{cases} 1, F_{cr} \geq F_{max} \\ P\left(F < F_{cr}\right) = \int_{F_{min}}^{F_{cr}} f_F\left(f_S\right) df_S, F_{max} > F_{cr} > F_{min} \\ 0, F_{cr} \leq F_{min} \end{cases} \quad (7)$$

During the K-S test, the type of distribution of the safety factor samples was defined as follows: denote the value of the majority of the samples as the most probable safety factor (F_0); multiply F_0 by the slope reliability to reduce the safety factor, forming the reliable safety factor F_1. The F_1 can be expressed as follow:

$$F_1 = F_0 \left(1 - P_F\right) \tag{8}$$

If the $F_1>1$, the slope is stable; if the $F_1<1$, the slope is unstable; if the $F_1=1$, the slope is in the limit equilibrium state. Thus, the critical failure probability of the slope can be obtained under the limit equilibrium state by the equation below:

$$P_{Fcr} = \begin{cases} 1 - \frac{1}{F_0}, & F_0 > 1 \\ 0, & 0 < F_0 < 1 \end{cases} \tag{9}$$

According to the equation above, the author obtained the relationship curve of the critical failure probability and the most probable safety factor (Figure 3). Then, the slope stability was evaluated against the relationship curve, considering the dual index subarea, the safety factor, and the failure probability. The stability was determined by comparing the reliability results with the subarea of the dual index system.

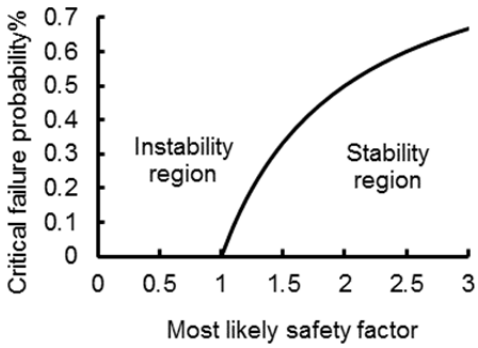

Figure 3: Dual index system subarea

3. Case study

3.1 Overview of the talus slope

The research object is a talus slope in a chemical industrial park. The slope is located on the north of the park and formed via repeated collapses of the original slope. The 850~1,115m-long, 370~630-wide and 23.4m-thick slope tilts towards the SE by an angle of 30°. It encompasses 8.53×10^6 m^3 of rock and soil masses. The survey data shows that the groundwater level rises markedly during rains. In rainy weather, the pore water pressure increases and the internal structure changes, lowering the effective stress of the slope. Meanwhile, the physical-mechanical indices are reduced under the softening effect of water (Dou et al., 2015), posing an imminent threat to slope stability.

3.2 Establishment of calculation model

In light of survey data, the author selected a representative section along the main sliding direction of the slope. The talus slope was divided into 4 layers: the original slope layer (C_1b) mainly consists of Baizuo formation limestones; the deposit layer (Q_{4-1}^{del}) is formed with limestones collapsed from the original slope; the discontinuous sandwich layer (Q_{4-2}^{del}) between C_1b and Q_{4-1}^{del} is composed of the gravel soil deposited during landslides; the alluvial-pluvial layer (Q_4^{apl}) contains the fluvial transported cobbles and gravels.

3.3 Index selection based on K-S test

The physical-mechanical indices of the four layers are listed in Table 1. The bulk density, friction angle and cohesion of each layer are all independent, random variables.
According to the demand on calculation accuracy, the critical value $D_n^{0.05}$ at the significance level α=0.05 was selected as the measure, and compared with the D_n obtained by the K-S test. In this way, the type of distribution was determined for the selected indices. Six types of distribution were employed for the hypothesis testing, namely normal distribution (Nor.), lognormal distribution (Log nor.), uniform distribution (Uni.), Poisson distribution (Poi.), exponential distribution (Exp.) and Rayleigh distribution (Ray.). The testing results are given in Table 2.

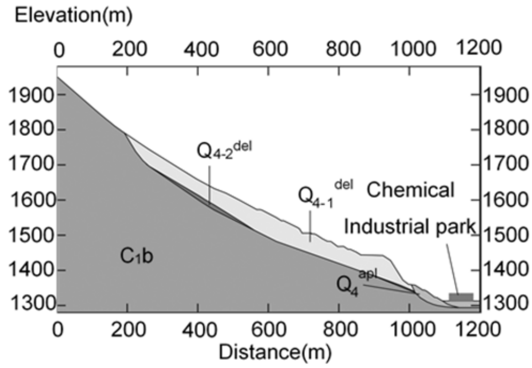

Figure 4: Cross-section of the talus slope

3.4 Reliability calculation results and analysis

Considering the geological environment of the slope, the climate of the chemical industrial park, and the impacts of rains and earthquakes, the following four cases were analysed in details: the slope is in the natural state without any rain (Case 1), the slope is under the rain (Case 2), the slope is hit by the earthquake without any rain (Case 3), and the slope is under the earthquake and under the rain (Case 4). According to survey data, the seismic fortification intensity of the chemical industrial park is VII and the seismic acceleration is 0.1g. The type of distribution was ascertained by the traditional distribution hypothesis method and the K-S test method, respectively. Then, the M-C method was adopted to analyse the slope reliability under different working conditions. According to the results in Table 3, the talus slopes in Cases 1 and 2 are generally stable without being affected by earthquakes; when the slope is hit by the earthquake without any rain (Case 3), the safety factor is greater than 1 and the failure probability is lower than 1.51%, indicating that the slope is also stable as a whole; In Case 4, under the effect of earthquake, the safety factor decreases significantly but still stays above 1, and the failure probability grows to 17.31%.

Table 1: Test parameters of the avalanche deposit slope

Layer	Unit weight ρ / KN/m^3				Friction angle φ /°				Cohesion c /Kpa			
	Mean	Std dev	Max	Min	Mean	Std dev	Max	Min	Mean	Std dev	Max	Min
Q_{4-1}^{del}	26.3	0.68	28	25	28.8	1.46	32	27	200	7.68	213	185
Q_{4-2}^{del}	20.5	1.28	23.2	18.2	25	1.03	27	22.5	20	1.99	25	15
Q_4^{apl}	21.2	1.8	25.2	18.2	26.5	1.37	29.1	25	30	1.7	33	27
C_1b	27.4	1.32	30	25	43.8	4.32	50	37	1250	24.4	1300	1210

Table 2: Results of K-S test

Layer		n	$D_n^{0.05}$	D_n						Distribution type
				Nor.	Log Nor.	Uni.	Poi.	Exp.	Ray.	
Q_{4-1}^{del}	ρ	20	0.29	0.19	0.20	0.28	0.45	0.61	0.60	Normal
	φ	20	0.29	0.18	0.17	0.31	0.42	0.61	0.58	Log Normal
	c	20	0.29	0.15	0.14	0.19	0.18	0.60	0.57	Log Normal
Q_{4-2}^{del}	ρ	20	0.29	0.13	0.14	0.24	0.34	0.59	0.54	Normal
	φ	20	0.29	0.09	0.08	0.23	0.34	0.59	0.56	Log Normal
	c	20	0.29	0.13	0.14	0.25	0.27	0.53	0.48	Normal
Q_4^{apl}	ρ	15	0.34	0.21	0.20	0.30	0.30	0.58	0.52	Log Normal
	φ	15	0.34	0.23	0.24	0.35	0.44	0.61	0.59	Normal
	c	15	0.34	0.11	0.11	0.10	0.33	0.59	0.55	Uniform
C_1b	ρ	10	0.41	0.22	0.23	0.26	0.37	0.60	0.56	Normal
	φ	10	0.41	0.14	0.16	0.16	0.17	0.57	0.51	Normal
	c	10	0.41	0.20	0.23	0.26	0.21	0.62	0.61	Normal

Table 3: Reliability calculation results and slope stability analysis results based on dual index system

Condition	Rainfall effect	Earthquake effect	N	k	p_f / %	β	F_1	PF_{cr}/%
Case 1	N	N	30000	1.258	0.00	6.96	1.26	20.51
Case 2	Y	N	30000	1.236	0.00	6.55	1.24	19.09
Case 3	N	Y	30000	1.062	1.51	1.99	1.05	5.84
Case 4	Y	Y	30000	1.030	17.31	0.98	0.85	2.91

3.5 Slope stability analysis based on dual index system

Based on the results of the reliability analysis, the slope stability was analysed by the dual index system. Specifically, the reliable safety factor (F_1) and the critical failure probability (P_{Fcr}) of each step were calculated with Equations (8) and (9), respectively, and the most probable safety factor (F_0) and failure probability (p_f) were obtained in reference to the results of slope reliability analysis (Table 3).

The calculation results reveal that the most probable safety factor of Cases 1, 2 and 3 are all greater than 1.0, and the reliability safety factor is below 1.0 in Case 4. The results of most probable safety factor show that the slope is unstable in Case 4, and the results of critical failure probability exhibits a high possibility of sliding under the limit equilibrium condition in Cases 1 and 2.

4. Conclusions

Based on the safety factor and the failure probability, this paper integrates the dual index system of talus slopes with the type of distribution for the physical-mechanical indices of slope materials. The integrated method prevents the errors caused by the normal distribution assumption in the traditional hypothesis method, and modifies the pure mathematical theory model, making it possible to rationalize the analysis and evaluation of talus slope stability.

Specifically, the K-S test method was used to verify the physical-mechanical indices of a talus slope, and determine the type of distribution for the influencing factors on slope stability. Then, the range of indices was determined through the slope reliability analysis by the M-C method. The reliability analysis is made more accurate with these moves.

According to the results of stability analysis, the talus slope not hit by the earthquake is stable, but still prone to sliding if it is under the limit equilibrium condition; when the slope is under the earthquake and the rain, the safety factor remains below 1, indicating that the slope is threatened by landslide.

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