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Landslide Reliability Analysis Based on Transfer Coefficient Method: A Case Study from Three Gorges Reservoir

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ABSTRACT: To evaluate the reliability of a landslide in a reservoir, the universal transfer coefficient method, which is popularized by the Chinese standard, is adopted as performance function in this study for: (1) common deterministic method stability evaluation; (2) reliability evaluation based on a Monte Carlo method; (3) comparison of landslide reliability under different water levels and under different correlation coefficients between soil shear strength parameters (*c*, *Φ*), respectively with mean, standard deviation, reliability coefficient and failure probability. This article uses the Bazimen (八字门) landslide, which is located at the outlet of Xiangxi (香溪) River in the Three Gorges Reservoir, as an example to evaluate its stability and reliability under different water levels with two-dimensional deterministic and probabilistic methods. With the assumption that constant mean and normal distributed shear strength parameters (*c*, *Φ*), correlation coefficient $\rho_{c,\Phi}$=-1 based reliability analysis, compared with $\rho_{c,\Phi}$=0 and 1, indicates obviously more increase of reliability index and lower standard deviation as water levels rise. To the case of a certain water level, $\rho_{c,\Phi}$=-1 does not have constantly positive or negative effects on landslide reliability compared with $\rho_{c,\Phi}$=0 or 1, but is associated with water level. Whereas the safety factor F_s by deterministic method, which is almost the same value as corresponding mean of safety factor from probabilistic analysis, will increase slightly as water level increases.

KEY WORDS: transfer coefficient method,

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Monte Carlo method, water level fluctuation, landslide stability reliability, Three Gorges Reservoir.

INTRODUCTION

Availability and capacity of powerful hard- and software for slope stability analysis have substantially increased in the past decades. Nowadays numerical modeling of landslides is widely used for back analyses and for predictions of future behavior under different conditions. Conventionally, deterministic approaches such as Spencer's method (Spencer, 1967), Janbu's method (Janbu, 1973, 1954), and Bishop's method (Bishop, 1955) are used for these tasks. However, different probabilistic approaches such as the first-order second-moment method (FOSM) (Wu and Kraft, 1970), the Monte Carlo simulation method (Cho, 2007; Tobutt, 1982), and the JC method (Vrouwenvelder, 1997) are often used to perform reliability analysis of artificial and natural slopes (Cho, 2007; Low, 2007; Malkawi et al., 2000; Yao and Chen, 1994) as well. In order to improve the simulation and to approach a more realistic situation, Vanmarcke (1980), Auvinet and González (2000), and Malkawi et al. (2000) extended the research on the spatial variability of soil properties to three dimensional soil slopes to discuss the relationship between reliability and horizontal correlation distance. Based on regional landslide analyses, risk assessment of landslides was developed since the 1980s (Chowdhury, 1988; Brabb, 1984) from single to regional and from qualitative to quantitative approaches (Chowdhury and Flentje, 2003, 2000; Flentje and Chowdhury, 1999).

Randomness and uncertainty of soil properties are the most important factors that may affect the reliability of the calculated safety factor F_s (defined as strength divided by load). Christian et al. (1994) reported that uncertainties in soil properties may arise from inherent spatial variability in the properties and/or from random testing errors from the measurements of the soil properties. Also, such uncertainty may come from systematic errors during the sampling process and bias in the measurement process itself. However, some system reliability analyses on the correlation coefficient $\rho_{c,\Phi}$ between cohesion c and friction angle Φ showed that they are uncorrelated or that the correlation coefficient is negligible (Matsuo and Kuroda, 1974; Lumb, 1970). For probability analysis, it is also assumed that $\rho_{c,\Phi}$ is zero in many cases (Christian et al., 1994; Chowdhury and Xu, 1993). There are strong arguments about the reliability evaluation of shallow foundation bearing capacity that, higher reliability indexes are found when the correlations between c and Φ are negative, and when the variability of soil depth has a minimum value (Cherubini, 2000).

For probabilistic methods, a large group of soil variables such as the shear parameters cohesion c and friction angle Φ, unit weight of soil γ, and pore pressure are sampled from their known (or assumed) probability distribution. According to Li and Guan (2002) who studied the contribution of c, Φ, and the unit weight γ to the uncertainty with Janbu's method, the failure probability is very insensitive to γ but extremely sensitive to Φ. In this article uncertainty of slope stability analyses due to the variability of the shear parameters c and Φ is assessed and discussed for different hydrological conditions (fluctuating water levels) in a case study of the Bazimen landslide.

SETTING

Bazimen landslide is located at the west bank of the Xiangxi River about 2 km upstream of its mouth. The Xiangxi River is a northern tributary of the Yangtze River discharging about 40 km upstream of the Three Gorges Dam (Fig. 1). In its lower reach, the Xiangxi River is directly affected by the impoundment of the Three Gorges Reservoir. Since the summer of 2009, water levels in the Three Gorges Reservoir have fluctuated regularly between 145 and 175 m a.s.l. in the course of one year. Impoundment and large scale water level fluctuations and rain are associated with increased landslide activity in the entire Three Gorges Reservoir (Ehret et al., 2010; Kallen et al., 2006). From lab test, field investigation and numerical simulation for landslide, water level is one of the most direct impacts on landslides occurrence (Jiang et al., 2010; Jian et al., 2009).

Bazimen landslide consists of gravelly silt and silty clay with gravels. The bedrock is mainly formed by fine to medium sized clastic sediments (shale, siltstone, and sandstone) from the Upper Triassic

Shazhenxi Formation (T_3s) and the Lower Jurrassic Xiangxi Formation (J_1x). The bedrock is dipping 30º–40º to the west. As Xiangxi River is flowing almost from north to south, the dip direction of the stratum on the west bank is antipodal to the dip direction of the slope. Morphology of the landslide body is concave in the upper part and convex in the lower part (Fig. 2).

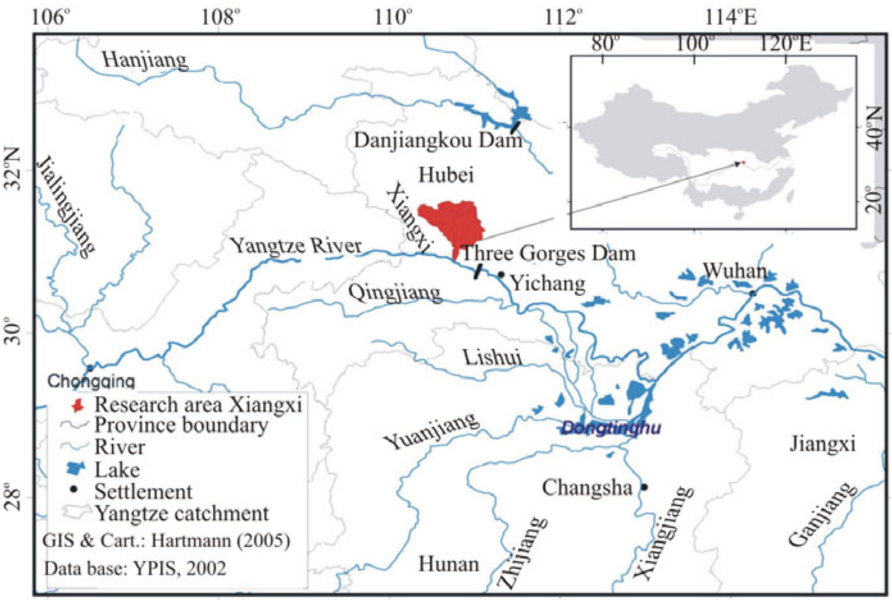

Figure 1. Location of the Xiangxi catchment. Bazimen landslide is located on the right bank of Xiangxi River where is 2 km upstream of the outlet.

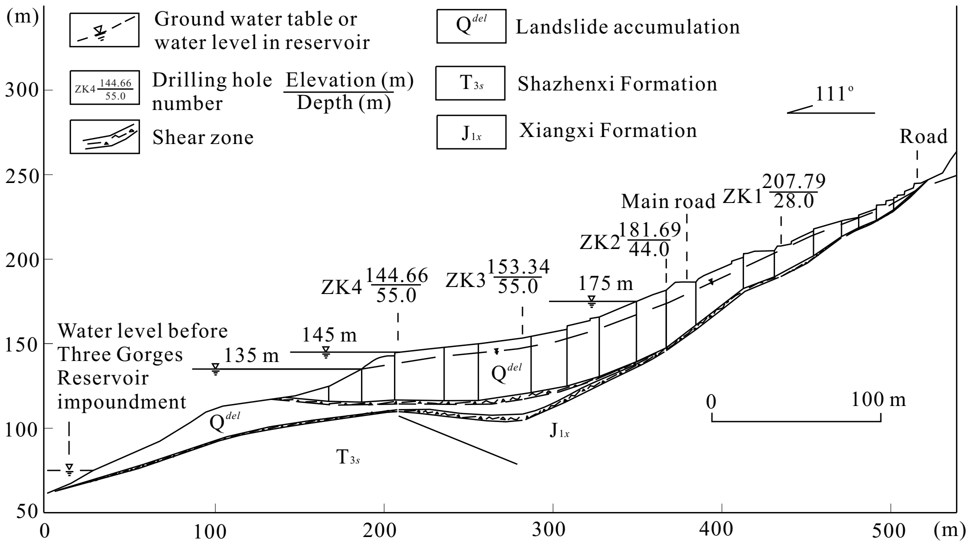

Figure 2. Main profile of Bazimen landslide. The ground water table refers to 135 m water level in the reservoir (simplified from He et al., 2008).

Its main slip direction is roughly 111ºSE. The landslide body is roughly 30 m thick and 550 m long, with a narrow upper part (approximately 80–210 m) and a wide lower part (approximately 400–500 m). The landslide covers an area of 13.5 ha. Its volume was estimated to be 4×10^6 m^3 (Li, 2006).

According to Li (2006), Bazimen landslide is a reactivated landslide which was dormant until 1981. Since then, three different phases of landslide activity can be differentiated.

(1) From 1981 to summer 1998. The first evidence for the reactivation of Bazimen landslide, four

curved cracks between 70 and 120 m a.s.l., were found after the flood peak in 1981 when the impoundment of the Gezhouba Reservoir began and consequently the toe of the landslide was submerged. In the following, the cracks in the landslide body extended and the former primary school at 110 m a.s.l. was deformed too much to be used any longer.

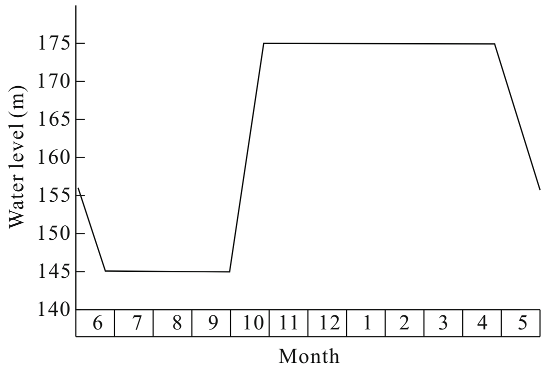

Figure 3. Design water level of the Three Gorges Reservoir in the course of one year during normal operation (HGTTGR, 2005).

(2) Between the summer of 1998 and June 2003 (before the impoundment of the Three Gorges Reservoir). In the summer of 1998, after a period of frequent heavy rain, the outer (i.e., east) flank of the new road at 186 m a.s.l. began to subside accompanied with the formation of many cracks. The houses located between 196 and 225 m a.s.l. were evacuated.

(3) From June 2003, when the impoundment of Three Gorges Reservoir started, until the present, and the regular operation since June 2009 with a cycle of fluctuation between 145 and 175 m a.s.l. per year (Fig. 3). Due to the impoundment, half of the landslide body has been submerged in the water. According to Li (2006), the movement was accelerated between 2003 and 2006.

From the above mentioned, we can obviously notice a response of landslide activity to external factors, which are mainly rainfall and high or fluctuating water levels.

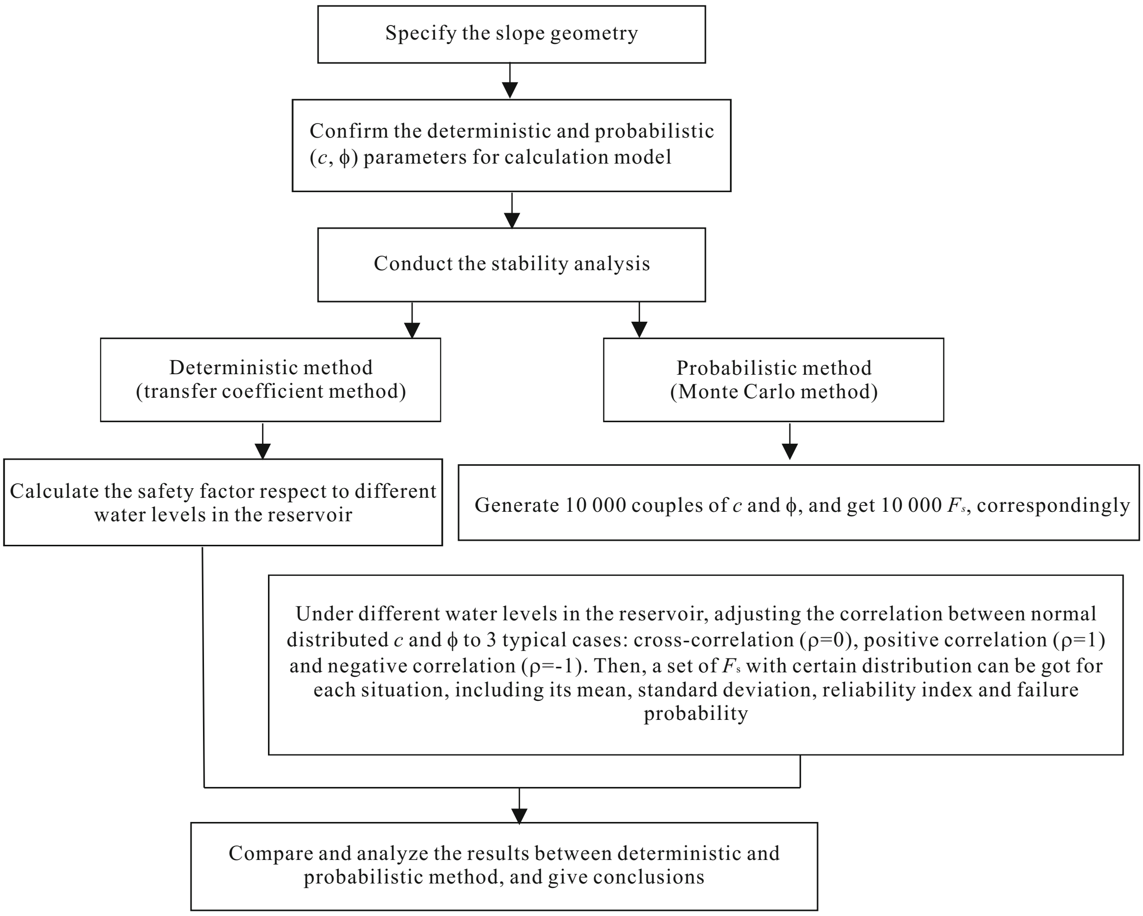

Figure 4. Flow chart describing the applied methodology.

SIMPLIFIED CALCULATION MODEL AND SCHEMATIC REPRESENTATION OF APPROACHES TO SLOPE STABILITY ANALYSIS

For slope stability analyses of landslides, the importance of accurate shear strength parameters can never be too much emphasized. But even for the same kind of soil or rock, cohesion and friction angle fluctuate in a certain range. Currently, most studies about soil uncertainties are focusing on artificial soil slopes with arc shaped failure zones (Cho, 2007). Not much special research is carried out on landslide reliability analysis. But a lot of experiences from geotechnical solutions, such as influence of soil properties on bearing capacity (Cherubini, 2000) or reliability of slopes (El-Ramly et al., 2002) can be consulted at the moment.

Because the real conditions of landslides are very complex, valid assumptions are needed to simplify the calculation model. Because of this simplification, numerical modeling of real world phenomena always is afflicted with uncertainty. Therefore it is important to assess the robustness of the model and the sensitivity to each input parameter by performing sensitivity analyses. In this paper the following assumptions were set.

(1) As can be seen from the profile (Fig. 2), the slip zone is below the water table since the reservoir water level has risen above 135 m a.s.l.. Soil strength parameters (c and Φ) are assumed to be constant to effective shear strength when the ground water table changes by water level fluctuating between 145 and 175 m a.s.l.. Furthermore, physical and chemical effects due to weathering and boundary condition changes over time (Cheung and Tang, 2005) are ignored.

(2) To rule out interference with other boundary conditions (rainfall, seismic or other dynamic load, artificial embankment or slope cut, etc.), we considered only the effect from water level change for our stability reliability analysis.

(3) The permeability of the landslide body is assumed to be high enough to quickly respond to the water level change, which means the hydraulic response lag of the water table to reservoir water level changes is ignored and ground water is considered to be quasi-static (steady flow) for each water level in the calculation.

(4) All assumptions necessary for the limit equilibrium theory are also necessary for the transfer coefficient method.

(5) Only two uncertainty parameters of soil (c and Φ) are considered in this paper. They are considered to be normal distributed (Tobutt, 1982; Matsuo and Kuroda, 1974).

In this article, one typical deterministic method and one typical probabilistic method is adopted for landslide stability and its reliability analysis under different water levels in the reservoir. Figure 4 illustrates schematically the methodology used to evaluate the stability and the reliability of the slope with both deterministic and probabilistic (Monte Carlo) methods. In the first step, the landslide geometry (main profile of the landslide as determined by site investigation) and the calculation parameters (including deterministic and probabilistic parameters) are specified. The second step is different for the two methods which are applied. Firstly, in the case of the deterministic approach the transfer coefficient method is used to calculate F_s. This method is based on the limit equilibrium theory and follows the basic (two-dimensional) method of slices where the sliding mass above the sliding surface or the sliding zone is divided into a number of vertical slices (Bishop, 1955). It takes the force between the neighbor slices into account, and this force is modified by a transfer coefficient which is determined by the dip angle of the slip zone and the friction angle of the slip zone material, see Eq. (1). Secondly for the case of the Monte Carlo method, 10 000 couples of c and Φ are generated for different correlation coefficients $\rho_{c,\Phi}$ ($\rho_{c,\Phi}$=-1, 0, 1) with assigned probability distributions. Then, the safety factor for each couple can be calculated by using the transfer coefficient method as a performance function. So 10 000 F_s values can be obtained correspondingly to each couple of c and Φ. Accordingly, mean, standard deviation, and associated probability distribution of safety factor values are determined. Finally, the reliability index β and the failure probability P_f can be calculated.

DETERMINISTIC METHOD FOR STABILITY ANALYSIS

A conventional deterministic method, the popular transfer coefficient method is applied here, which satisfies force equilibrium but not overall moment and is suitable for any shape of two-dimensional slope or landslide profile.

The formula to calculate the safety factor F_s according to the transfer coefficient method is as follows

$$F_s = \frac{\sum_{i=1}^{n-1}\left(R_i\prod_{j=i}^{n-1}\psi_j\right)+R_n}{\sum_{i=1}^{n-1}\left(T_i\prod_{j=i}^{n-1}\psi_j\right)+T_n} \quad (1)$$

where $\psi_j=\cos(\theta_i-\theta_{i+1})-\sin(\theta_i-\theta_{i+1})\tan\Phi_{i+1}$ is the transfer coefficient for slice $n+1$, $R_i=N_i\cdot\tan\Phi_i+c_i\cdot l_i$ is the resisting force acting on slice i, $T_i=W_i\cdot\sin\theta_i+P_{Wi}\cdot\cos(\alpha_i-\theta_i)$ is the sliding force on slice i, $N_i=W_i\cdot\cos\theta_i+P_{Wi}\cdot\sin(\alpha_i-\theta_i)$ is the normal force acting on slice i, $W_i=V_{iu}\cdot\gamma+V_{id}\cdot\gamma'+F_i$ is the weight of the slice i plus additional load, $P_{Wi}=\gamma_W\cdot i\cdot V_{id}$ is the hydraulic pressure of the ground water acting on slice i, $i=\sin|\alpha_i|$ is the hydraulic gradient of the ground water, and $\gamma'=\gamma_{sat}-\gamma_W$ is the buoyant unit weight of soil/rock.

The transfer coefficient method was introduced as standard for geo-hazard investigation around the Three Gorges Reservoir area (HGTTGR, 2005). It is widely adopted in engineering practice for landslide investigation, treatment and mechanism analysis in China (Xia and Bai, 2008; Hu et al., 2005; Yang et al., 2005). This method is based on the limit equilibrium theory and considers that the moving direction from slice $i-1$ (higher) to slice i (lower) is parallel to slip zone of slice $i-1$ (Fig. 5). So normal stress and shear stress from $i-1$ to i are derived from the decomposition of P_{i-1}. The safety factor of the Bazimen landslide depends on the water level of the reservoir. The safety factor was calculated for 145 (the lowest design water level since 2009), 156 (highest design water level during the second phase mentioned above), and 175 m a.s.l. (the highest design water level since 2009). According to our calculations, the safety factor increases slightly with increasing reservoir water level (Fig. 6).

These results are surprising as one would expect that the higher the reservoir water level, the lower the safety factor. However, our calculations show that the opposite is the case if the following assumptions are made: (1) only the impact from reservoir water level change is considered, (2) the soil strength values of the slip zone remain constant during ground water table fluctuation, (3) the ground water table in the landslide body is considered to be quasi-static (steady flow) for different water levels. So the deterministic method shows that the higher reservoir water level has a positive effect on the slope stability (Fig. 6).

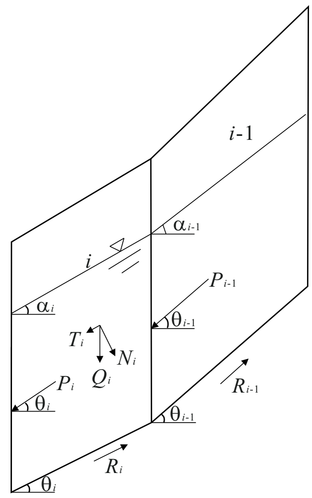

Figure 5. Schematic diagram for the transfer coefficient method.

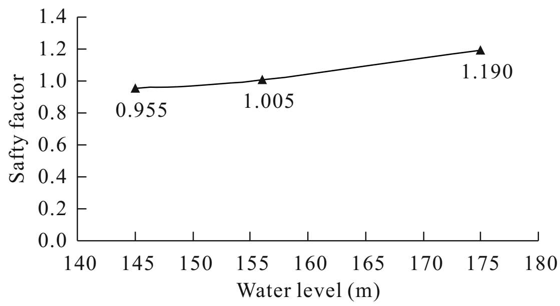

Figure 6. Correlation between water level and safety factor.

PROBABILISTIC METHOD FOR STABILITY ANALYSIS

In landslide mechanism analysis and stability analysis various sources of uncertainties are encountered and well recognized (Malkawi et al., 2000). Several features usually contribute to such uncertainties, like: (1) those associated with inherent randomness of natural processes; (2) model uncertainty reflecting the inability of the simulation model, design technique or empirical formula to represent the system's true physical behavior, such as calculating the safety factor of slopes using limit equilibrium methods of slices; (3) model parameter uncertainties resulting from inability to quantify accurately the method input parameters; (4) data uncertainties including (a) measurement errors, (b) data inconsistency and non-homogeneity, and (c) data handling.

In conventional deterministic analysis, the safety factor F_s is the only parameter to evaluate the stability of the landslide, in which deviations are ignored in the calculation. The slope is considered to be stable only if the safety factor exceeds 1. However, in a probabilistic framework, the safety factor is expressed in terms of its mean value and variance. Reliability analyses are used to assess uncertainties in engineering variables. The reliability index β and failure probability P_f are often used to express the degree of uncertainty in the calculated safety factor.

In this article Monte Carlo simulation is adopted. It can be simply performed in three steps: (1) design of the probabilistic model, (2) sampling from the probability distribution, and (3) performance of the estimation (Zhu, 1986). The first step is described above. The other two are realized as follows.

1) Generation of independent normal distributed c and Φ variables (correlation coefficient between c and Φ, $\rho_{c,\Phi}$=0) with given probability distribution. To generate normal distributed random variables, the Box-Muller simulation method (Box and Muller, 1958) is used as follows: 1. Generation of two independent random variables u_1 and u_2 from the interval [0, 1]; 2. Calculation of two other independent random variables x_1 and x_2

$$\begin{cases} x_1 = \left(-2\ln u_1\right)^{1/2}\cos\left(2\pi u_2\right) \\ x_2 = \left(-2\ln u_1\right)^{1/2}\sin\left(2\pi u_2\right) \end{cases} \quad (2)$$

so that x_1 and x_2 are independent numbers with standard normal distribution; 3. Then two other independent random variables c and Φ with normal distribution $N_c(\mu_c, \sigma_c^2)$, $N_\Phi(\mu_\Phi, \sigma_\Phi^2)$ can be obtained by transformation

$$\begin{cases} c = \mu_c + \sigma_c \cdot x_1 \\ \phi = \mu_\phi + \sigma_\phi \cdot x_2 \end{cases} \quad (3)$$

Frequency histograms of the normal distributed c and Φ are shown as examples in Figs. 7 and 8, respecttively.

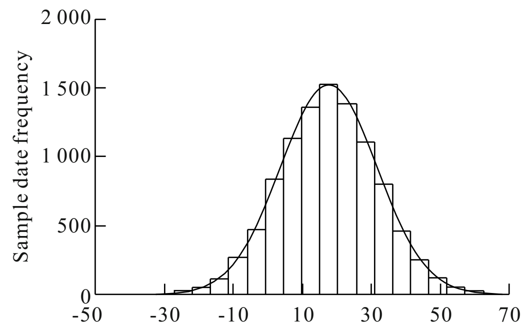

Figure 7. ρ=0, cohesion c classes (kN/m^2) for 175 m water level.

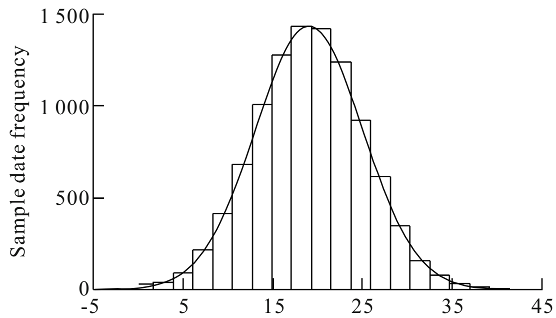

Figure 8. ρ=0, friction angle classes (°) for 175 m water level.

2) Generation of dependent normal distributed c and Φ variables by modifying Eq. (2) as follows

$$x_1=x_2=(-2\ln u_1)^{1/2}\cos(2\pi u_2) \quad (4)$$

to obtain a correlation coefficient $\rho_{c,\Phi}$=1 and by modifying Eq. (2) as follows

$$x_1=-x_2=(-2\ln u_1)^{1/2}\cos(2\pi u_2) \quad (5)$$

to obtain a correlation coefficient $\rho_{c,\Phi}$=-1.

3) By simplifying Eq. (1) we get $F_s=f_s(c,\Phi)$ which is used as performance function to get the two-dimensional joint-distribution of c and Φ, respectively in cases of $\rho_{c,\Phi}$=-1, 0, and 1.

For slope stability problems, direct evaluation of an n-fold integral is virtually impossible. The difficulty is that complete probabilistic information on the soil properties is not available and that the domain of integration is a quite complicated function (Cho, 2007). Therefore, approximate techniques were developed to evaluate this integral distribution.

It is assumed that c and Φ is normal distributed random variables. They are 17.6 kPa and 19°, respectively and the standard deviations are 14 kPa and 6°, respectively. Then, the distribution of the safety factor F_s is determined by the performance function (transfer coefficient method). Monte Carlo simulation offers a practical approach to reliability analysis because the stochastic nature of the system response (output) can be probabilistically duplicated. Ten thousand couples of normally distributed c and Φ values are generated with controlled mean and standard deviation. Then, 10 000 safety factor values can be calculated correspondingly. The frequency histograms for the generated c, Φ (when correlation coefficient $\rho_{c,\ \Phi}$=0) and the associated distribution of safety factor (when $\rho_{c,\ \Phi}$=0, 1, -1, respectively) are given as a example in Figs. 7, 8, 9, 10, and 11.

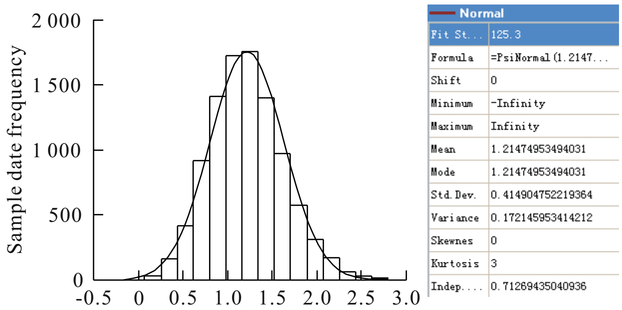

Figure 9. Safety factor classes for 175 m water level.

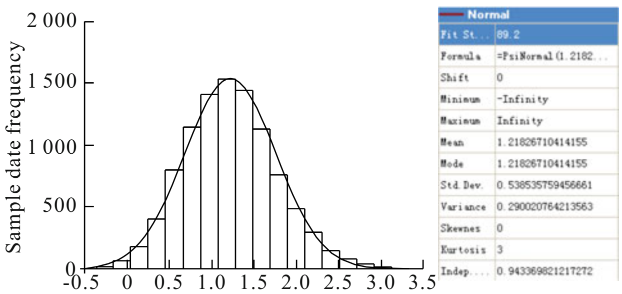

Figure 10. ρ=1, safety factor classes for 175 m water level.

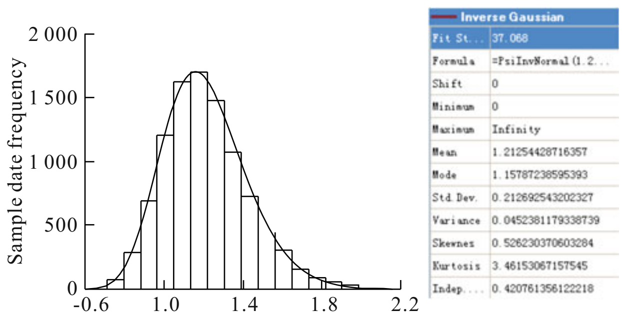

Figure 11. ρ=-1, safety factor classes for 175 m water level.

To perform efficient Monte Carlo simulations, evaluation version 1.0.0.0 of the commercial software Risk Solver Platform is used. It outputs a most approximate distribution function for the input seed samples. To identify the probability distribution of safety factor, 10 000 couples of c and Φ values are generated respectively for each case of calculation. For the distribution of calculated safety factor values, the Chi-square goodness of fit test indicates that the normal distribution adequately fits for the safety factor distribution when the correlation coefficient $\rho_{c,\ \Phi}$=0 and $\rho_{c,\ \Phi}$=1, and Inverse-Gaussian distribution especially steady fit for safety factor distribution when $\rho_{c,\ \Phi}$=-1.

CALCULATION RESULTS AND DISCUSSIONS

The reliability index β and the failure probability P_f are calculated using the safety factor probability distribution in evaluating landslide stability. This approach can be applied to any method of slices, which uses limit equilibrium in the analysis of slopes (Malkawi et al., 2000).

In this article uncertainty in slope stability is quantified by evaluating the reliability index β and failure probability P_f, which are defined as

$$B=[E(F)-1.0]/\sigma(F) \quad (6)$$

where $E(F)$ is the expected value of the safety factor and $\sigma(F)$ is the standard deviation of the safety factor, and $P_f=P\ (F_s<1)$.

As shown in Table 1, under different water level conditions, 145, 156, and 175 m, respectively. Mean μ, standard deviation σ, and failure probability P_f of safety factor distributions were obtained as correlation coefficient $\rho_{c,\ \Phi}$= 0, 1, and -1, respectively.

In Fig. 12, the safety factor obtained from the deterministic method is juxtaposed with the safety factor obtained from the probabilistic method. The deterministic method yields a safety factor that is about 0.02 smaller than the mean of the probabilistic method. Additionally, the mean of the safety factor is not sensitive to the correlation coefficient $\rho_{c,\ \Phi}$ (Fig. 13). The standard deviation of the safety factor increases gently with increasing water level. But the standard deviation of the safety factor for a negative correlation coefficient is always lower than the standard deviation for a correlation coefficient of zero or a positive correlation coefficient (Fig. 14). The lower the correlation coefficient value is, the less deviation of the safety factor occurs. This means, the lowest uncertainty of the safety factor is obtained for $\rho_{c,\Phi}$=-1 (Fig. 15).

Table 1 Results of stability and reliability analysis for Bazimen landslide

Water level (m a.s.l.)	F_s	$\rho_{c,\Phi}$	Mean μ	Std. deviation σ	P_f (%)	β
145	0.955	-1	0.973	0.17	60.19	-0.159
		0	0.973	0.323	55.11	-0.084
		1	0.973	0.426	54.4	-0.063
156	1.005	-1	1.021	0.176	48.76	0.119
		0	1.025	0.351	48.8	0.071
		1	1.028	0.453	49.24	0.062
175	1.190	-1	1.213	0.217	15.54	0.982
		0	1.214	0.415	30.99	0.516
		1	1.218	0.539	36.03	0.404

On the other hand, the effect of rising water level on the reliability index and the failure probability is notable, especially for $\rho_{c,\Phi}$=-1 (see Figs. 16 and 17). A negative correlation coefficient between c and Φ has a positive effect on stability evaluation for rising water levels. It can be noted that the negative correlation between c and Φ will remarkably increase the reliability index for 175 m a.s.l. reservoir water level (Fig. 18). However, it will reduce the reliability index slightly for the 145 m a.s.l. reservoir water level and increase it slightly for the 156 m a.s.l. water level. So negative correlation between c and Φ does not have a constant positive or negative effect on the reliability index but is associated with the boundary conditions.

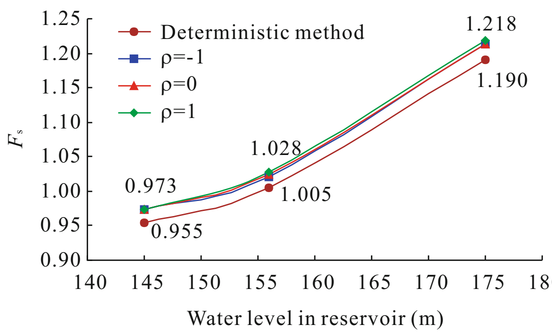

Figure 12. Safety factor from deterministic method and mean of distribution from probabilistic method.

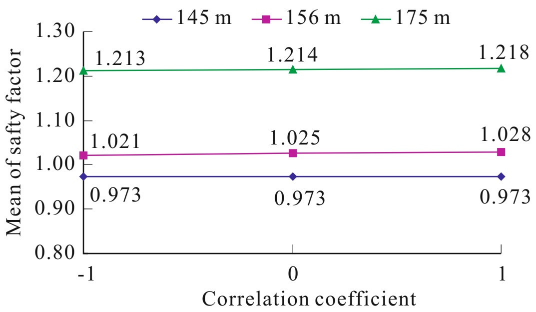

Figure 13. Correlation between mean of safety factor and correlation coefficient.

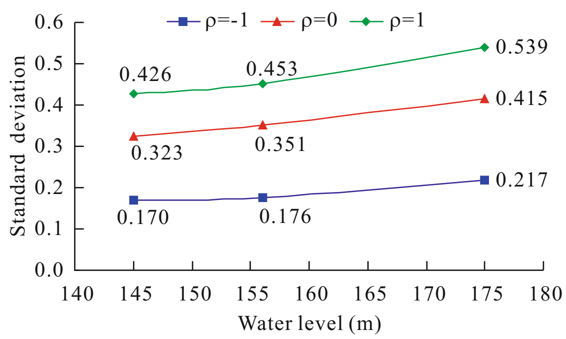

Figure 14. Stand deviation of safety factor change as water level rises.

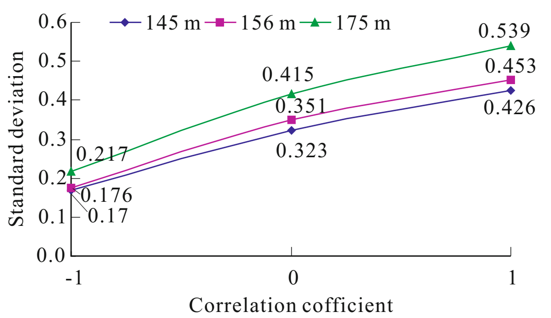

Figure 15. Correlation between standard deviation and correlation coefficient.

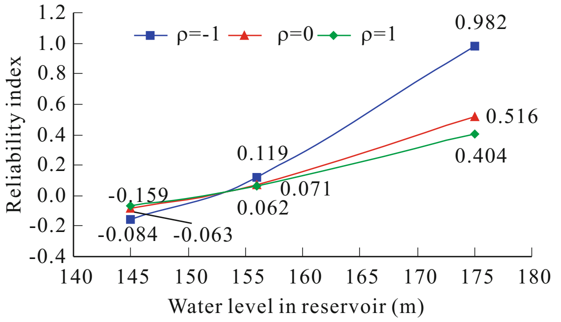

Figure 16. Reliability index change as water level increases.

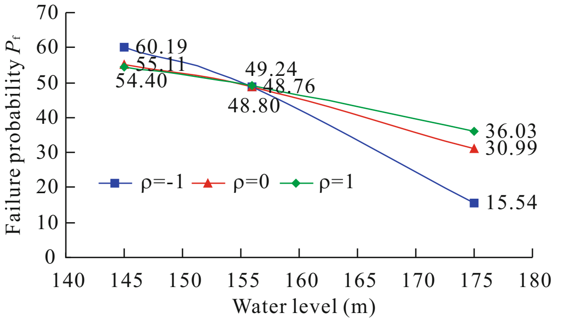

Figure 17. Failure probability change as water level increases.

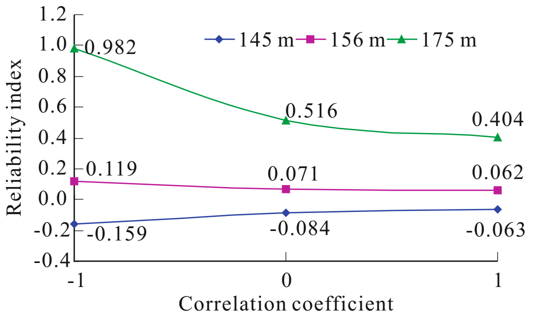

Figure 18. Correlation between reliability index and correlation coefficient.

CONCLUSIONS

This article presents both deterministic and probabilistic methods, in which a typical universal transfer coefficient method and a Monte Carlo method are chosen respectively. With reasonable assumptions for simplifying the calculation model, some results were obtained. Mean and standard deviation of safety factor distribution, reliability index and failure probability are used to illustrate the stability and reliability in the probabilistic method. For comparison, a deterministic method is also carried out. At last, the results are refined in two aspects. The finding of this paper warrants the following conclusions.

1. With the transfer coefficient method which is also popularized as specification, the factor of water level rise brings about positive effects on landslide stability. But what has to be emphasized for these results are that, this result limits to a determinate mechanical model with only change of water, and without considering of soil strength decrease, rainfall, earthquakes etc..

2. Distribution of safety factor values fit to a normal distribution quite well, when the correlation coefficient is assumed to be 0 and 1. But an inverse Gaussian distribution is perfectly suitable to the distribution when assumed to be -1.

3. Based on the previous assumption in this paper, the mean of the safety factor is not sensitive to the correlation between c and Φ, but will be improved together with the reliability index as water level increases. However, for uncertainty evaluation, standard deviation values will also become notably larger as the assumption that positive correlation between c and Φ, and the rise of water level.

4. As water level rises, if correlation between c and Φ are considered to be negative, higher mean and lower standard deviation of safety factor distribution will be obtained, relative to cross-correlation and positive correlation. On this occasion, $\rho_{c,\Phi}<0$ plays a positive role in landslide stability. But correlation $\rho_{c,\Phi}<0$ between c and Φ does not offer constant positive or negative effects on reliability index but is associated with boundary conditions.

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APPENDIX

(1) Characters for Transfer Coefficient Method

α_i. Average angle of ground water table in slice *i*;

γ_W. Unit weight of water;

γ. Unit weight of natural soil/rock;

γ'. Buoyant unit weight of soil/rock;

γ_{sat}. Saturated unit weight of soil/rock;

θ_i. Dip angle of failure surface;

Φ_i. Friction angle of the failure surface of slice *i*;

Ψ_i. Transfer coefficient from slice *i* to slice *i*+1;

c_i. Cohesion of the failure surface of slice *i*;

i. Hydraulic gradient of ground water;

F_s. Safety factor;

F_i. External load from ground on slice *i*;

N_i. Normal force acting on the failure surface of slice *i*;

P_{Wi}. Hydraulic pressure of ground water for unit width of slice *i*;

R_i. Resisting force acting on slice *i*;

T_i. Sliding force acting on slice *i*;

V_{iu}. Volume above the ground water for unit width slice *i*;

V_{id}. Volume below the ground water for unit width slice *i*;

W_i. Weight of slice *i* plus additional load.

(2) Others

β. Reliability index;

μ. Mean;

$\rho_{c,\Phi}$. Correlation coefficient between *c* and Φ;

σ. Standard deviation;

Φ. Friction angle of soil;

P_f. Failure probability.