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Research Article

Safety Standard for Special Class Damslopes Based on Reliability Analysis

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The risk of slope failure is determined by the degree of damage caused by the slope slide. For the special-high slope of some high-risk water conservancy and hydropower projects, the standard should be appropriately raised. Thus, the safety standard for these slopes is explored on the basis of reliability analysis. The slopes with high risk of failure are divided into special class I and special class II slopes depending on the risk levels and acceptable risk standards. The concept of reliability theory-based relative ratio of the safety margin is utilized to establish the relationship between annual failure probability and safety factor, thereby obtaining the reasonable safety factors for different slopes. Results show that the values of safety factors for special class I and special class II are 1.40 and 1.35, respectively. These results can provide a reference for exploring the safety standards of dams with a height of more than 200 m.

1. Introduction

Geological disasters in the reservoir area are mainly manifested as natural disasters such as landslides and debris flows, which can directly lead to the instability of the bank slope of the reservoir, causing damage to water conservancy projects and eventually cause huge economic losses [1, 2]. The class of the slope of the water conservancy and hydropower project shall be divided according to the location of the slope, importance of the slope, and degree of damage. In recent years, many earth and rockfill dams with a height of more than 200 m have been constructed in the world for hydropower generation, such as the Rogun Dam (335 m, Tajikistan), Rumei Dam (315 m, China), Nurek Dam (300 m, Tajikistan), Lianghekou Dam (295 m, China), Boruca Dam (267 m, Republic of Costa Rica), Chicoasen Dam (261 m, Mexico), and Tehri Dam (260 m, India) [3]. The construction of these reservoirs will form a series of hub engineering slopes, reservoir slopes, and river slopes. The stability of these slopes plays a pivotal role in engineering safety; therefore, it is necessary to appropriately improve the safety standards for these important slopes [4, 5].

The traditional safety factor method is commonly referred to as the safety factor *F*, which is expressed by the ratio of resistance to the action effect. For instance, the Chinese design specification for slopes of hydropower and water conservancy project uses a single safety factor to evaluate the slope stability and suggests that the minimum safety factor *F* is 1.3 [6]. The Canadian Foundation Manual specifies an allowable safety factor of 1.35 to 1.50 for earth works including slopes [7]. The Hong Kong Slope Engineering Manual specifies a safety factor of 1.35 [8]. In this definition method, both resistance and force are expressed by a fixed value, and uncertainties such as calculation model and calculation parameters cannot be considered [9]. The allowable value of the safety factor is also determined by engineering experience, so the traditional safety factor method cannot fully reflect the design difference and sensitivity.

Lately, the reliability method and probability-based limit state design method that consider uncertainties have garnered attention [10, 11]. The main approach typically involves the calculation of the reliability index using a numerical method, such as the Monte Carlo method [12], Taylor series method

(FORM) [13], or point estimate method (PEM) [14, 15]. Based on the response surface methodology and first-order reliability method, Babu and Srivastava [16] performed reliability analyses for four selected rehabilitated earth dams. Delgado-Hernández et al. [17] and Peyras et al. [18] explored risk assessment of earth dams based on a continuous Bayesian network; Chen et al. [19]optimized the point estimation method, solved the problem that a large amount of storage space is needed in the calculation process, and applied the point estimation method to embankment slope stability reliability analysis. Recently, several studies have introduced reliability theory into the assessment of ultrahigh dam slope stability. Chen [5] evaluated the values of reliability index of skewback antisliding stability and partial factor and proposed a computing method of structural reliability based on the traditional safety factor. Yi et al. [20] and Dekay and McClelland [21] developed a program combining slope stability and reliability analyses to evaluate safety factors of the critical slip surface. Li et al. [22] and Zhou et al. [23] investigated dams' risk acceptance criteria and risk classification. The authors of this paper have used the theory of relative ratio of safety margin to study the safety standard for slopes of ultrahigh earth and rockfill dams in China [24]. Huang and Xiong [25] studied the seismic sequence performance of earth dams under earthquake loading and proposed a new methodology for evaluating the seismic response of earth dams based on the performance-based approach and a stoichiometric vibration method. This new method of dynamic performance analysis of earth dams demonstrates that performance-based criteria and reliability evaluation can provide more objective indices for decision-making rather than using deterministic seismic acceleration time series as it is the current normal practice. To investigate the seismic liquefaction performance of earth dams under earthquake loading, we present a new methodology for evaluating the seismic response of earth dams based on a performance-based approach and a stochastic vibration method. This new method of dynamic performance analysis of earth dams demonstrates that performance-based criteria and reliability evaluation can provide more objective indices for decision-making rather than using deterministic seismic acceleration time series as it is the current normal practice. Xu et al. [26] demonstrated dynamic time-history analysis of random vibration based on failure probability theory. The failure probabilities of high concrete-faced rockfill dams with different failure grades based on three universal evaluation indices are determined by constructing a virtual generalized probability density evolution method process. At present, most of the research is to analyze the slope stability of the dam, but it does not involve these special class slopes that affect the safe operation of the reservoir and dam. It is necessary to study the stability safety standards of the special class slopes corresponding to these ultrahigh dams.

This paper proposes the acceptable safety standard of traditional deterministic analysis for the special class slopes based on risk analysis. We investigated the correlation between annual failure probability and safety factor based on the concept of reliability theory-based relative ratio of the safety margin and collected a portion of the specification's control criteria for slope failure risk. On this basis, we suggested that the failure probabilities of special class I and special class II slopes are 10^{-5} and 5×10^{-5}, respectively. Based on these acceptable risk standards, this paper studies the safety standard of the high slope in water conservancy and hydropower project and verifies the rationality of the proposed standard. This paper attempts to carry out a study on the values of reliability index and safety factor which are significant in the analysis on the stability of high slope.

2. Risk Control Standard of Slope

The safety and stability of the high slope should be emphasized in the construction of high dams with large reservoirs. In the design code for engineered slopes in water resources and hydropower projects [27], the slope is graded per the grade of hydraulic structure, and no upper limits exist to the technical standard of first-class projects. Therefore, the safety standard of slopes that affect the safe operation of dams should be raised. Besides, in the design codes for slope and earth-rockfill dams, no safety standards of slope have been approved. Thus, this section discusses the risk standard of slope failure from statistics and engineering safety.

In risk analysis and risk management, acceptable risk typically refers to the probability that a single life might be destroyed in 1 year and is used to explain the risk standard of a disaster. Owing to the absence of unified slope risk map and slope risk standard in China, this study aims to summarize the risk control standard of China based on relevant studies that started early and are relatively mature. Based on the 2004–2013 national geological disaster report released by the Ministry of Land and Resources of China [28], casualties of landslide hazard each year are obtained through the total casualties of geological disaster and the proportion of landslide hazard in geological disaster. Table 1 lists the casualties of landslide hazard from 2004–2013.

As shown in Table 1, approximately 400–1000 casualties of landslide hazard were reported each year. According to the risk map, the slope risk ranged from 10^{-5} to 10^{-6}. After assessing the risks of various industries, Fell [29] proposed that the tolerable risk for a passive risk-taker (1 year) should range from 10^{-6} to 10^{-5}. Based on the theory and practice of slope risk, Fell [29] proposed a risk control standard of slope (see Table 2). In addition, a correlation was established between the risk standard of slope and the regional economic development level. Typically, the disaster-related mortality in a country or a region fluctuates around 10^{-6} (see Table 3).

Based on the summarization and analysis of the slope risks of the regions and countries mentioned above and considering the risk standards adopted in other countries and China's economic development level, this study proposes that the acceptable risk of China's natural and engineering slopes in water conservancy and hydropower project, that is, yearly failure probability, should be set at 10^{-5}–10^{-6}. For class 1 slope (dam height, >200 m), which exerts a marked impact on the hydraulic structure after breaking, a failure probability of 10^{-6} is accepted, considering the progress of the dam design level, construction technology, and management capabilities.

Table 1: Statistics of the casualties of landslide hazard in China each year [28].

Year	Casualties	Landslide risk (10^{-5})
2004	735	0.2
2005	486	0.6
2006	970	1.0
2007	635	0.3
2008	757	0.2
2009	394	0.6
2010	647	0.6
2011	302	0.8
2012	380	0.8
2013	476	0.6

Table 2: The risk control standard of slope proposed by Fell [29].

Project	Acceptable yearly failure probability
Slope built	10^{-4}, for people who live closely to the project 10^{-6}, for people who live far away from the project
Slope being built	10^{-5}, for people who live closely to the project 10^{-6}, for people who live far away from the project

Zhou et al. [31] combined the calculated yearly risk P_y with the risk P using the following formula:

$$P_y = \frac{P}{T} \times \frac{N_d}{T}, \tag{1}$$

where T is the service life of slope and N_d is the design base year.

As determining the service life of slope is challenging while calculating using formula (1), a conservative approach is to make $T = N_d$; then, formula (1) can be approximately expressed as follows:

$$P_y = \frac{P}{N_d}. \tag{2}$$

Typically, in water conservancy and hydropower project, the design base year of class 1 structure is 100 years. The failure probability of China's class 1 slope evaluated through formula (2) is 10^{-4}. The comparison table of failure probability and reliability index revealed that the reliability index of class 1 slope is 3.7. Table 4 shows the annual failure probability and allowable reliability index (β_a) for each special class structure.

3. Slope Stability Analyses Based on a Safety Margin Criterion

3.1. Ratio of Safety Margin Method. For the association mapping analysis of the safety standard, safety factor, and a reliability index of the slope, Chen et al. [11] proposed a ratio of safety margin method through which the risk control levels could be compared. The ratio of safety margin η_F implies the ratio of the safety factor (F) of slope antisliding stability to the acceptable margin of safety factor (F_a). The ratio of safety margin can be expressed as follows:

$$\eta_F = \frac{F}{F_a}. \tag{3}$$

The safety factor attained through the reliability analysis is β, and the corresponding acceptable margin of safety factor is β_a; however, it is inappropriate to express the relative safety factor as β/β_a because only the correlation of β with $1-\Phi(\beta)$ has physical significance. Figure 1 presents the ratio of safety margin method demonstrating the correlation between η_R and η_F.

Based on the safety factor sample listed in Figure 1, the reliability indexes β and β_a can be evaluated. As $\beta > \beta_a$, the corresponding area of the shadow region a is smaller than $1-\Phi(\beta_a)$. Assuming that, upon subtracting a ΔF from all safety factors in the sample, there will be a new safety factor sample $F' = F - \Delta F$, suggesting that the y-axis has moved a ΔF toward the right side (see Y' in Figure 1). In this new coordinate system, the area of the shadow region $a + b$ on the left side of Y' is equal to $1-\Phi(\beta_a)$, which is 10^{-6} for class 1 structure. Then, ΔF can be evaluated through derivation. Based on formula (4), the ratio of safety margin η_R (based on the reliability method) can be expressed as follows:

$$\eta_R = (\beta - \beta_a)\sigma_F + 1, \tag{4}$$

where σ_F is standard deviation of safety factor.

In Figure 1, the ratio of DC to BA approximates to η_R, and the ratio of HG to FE approximates to η_F. Thus, the ratio of the safety margin η_R defined through formula (4) could be compared with the ratio of the safety margin obtained through the traditional method in one coordinate system. Thus, a conclusion could be drawn that the values of F and β adopted above are at the same risk control level and could provide a theoretical basis for the establishment of relevant codes.

3.2. Slope Model Verification. We evaluated the safety factor and reliability index through two simple slope models (see Figure 2), which are often used to validate the slope stability. In addition, the safety factors and reliability indexes were evaluated by the simplified Bishop method and Rosenblueth method in the 2D software STAB. Table 5 presents the calculation parameters. In this study, F and β are calculated using a nonlinear strength index (angle of internal friction (φ)) under normal and seismic conditions. The value of φ can be calculated using the nonlinear equation $\varphi = \varphi_0 - \Delta\varphi \lg(\sigma_3/p_a)$ [32], where φ is the secant effective stress angle of internal friction, φ_0 is the value of φ for σ_3 equal to one atmosphere, $\Delta\varphi$ is the reduction in φ for a 10-fold increase in confining pressure, σ_3 is the confining pressure, and p_a is atmospheric pressure.

When the safety factor of class 1 slope is 1.3 (as is stipulated in the code) and the reliability index of class 1 slope is 3.7 (as mentioned above), the ratio of the safety margin η_F (based on the deterministic method) and the ratio of the safety margin η_R (based on the reliability method) can be calculated. If η_F approximates or equals to η_R, the safety factor of class 1 slope is suitable to be set at 1.3. Next, we evaluated the safety factor and reliability

Table 3: Average casualties and annual probability of different countries in recent years [30].

Country or region	Average casualties	Population (million people)	Probability of death
Japan	150	150	$1/1 \times 10^{-6}$
Korea	56	70	$1/1 \times 10^{-6}$
USA	25–50	250	$1-2 \times 10^{-6}$
Australia	<1	17	$1/17 \times 10^{-6}$
Canada	5	30	$1/6 \times 10^{-6}$
Hong Kong	1	5.8	$1/6 \times 10^{-6}$

Table 4: Definition of special class structures.

Classes	Definition	Annual failure probability	β_a
Special class 1	The flood caused by the dam failure will cause a class 1 dam downstream to collapse, even with an effective early warning Dams with a height exceeding 250 m and a capacity exceeding $1 \times 10^9\,\mathrm{m}^3$	10^{-8}	4.70
Special class 2	The flood caused by the dam failure will not cause a class 1 dam downstream to collapse with an effective early warning but will cause it to collapse with an ineffective early warning The flood caused by the dam failure will cause a class 2 dam downstream to collapse even with an effective early warning Dams with heights in the range of 200–250 m and a capacity exceeding $1 \times 10^9\,\mathrm{m}^3$	5×10^{-8}	4.45

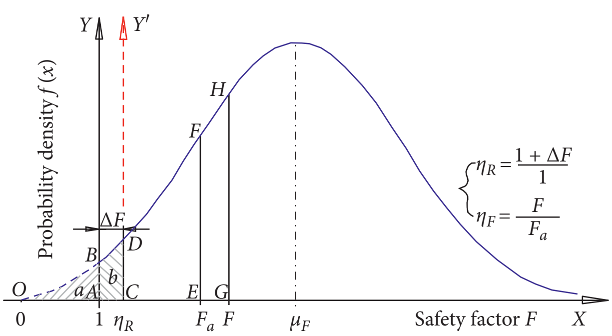

Figure 1: Diagram of $\eta_R - \eta_F$ based on the probability density function.

index of slope model through Figure 2. Table 6 lists the calculated ratio of safety margin s η_F and η_R; the ratios of η_F to η_R of the two slope models approximate to 1. Considering the impact of other factors, the results are acceptable, suggesting that the slope model has the same safety margin when the safety factor is 1.3, and the reliability index is 3.7. Thus, safety factor 1.3 and reliability index 3.7 are at the same risk control level.

3.3. Engineering Verification. We conducted the example verification through the high slopes of dam abutment and spillway in the three hydropower stations—Nuozhadu, Shangzhai, and Lianghekou. The relative safety factors η_F and η_R of different fracture surfaces in different failure modes were evaluated under the safety factor 1.3 and the reliability index 3.7, respectively [33]. The numbers of calculated critical surfaces were 15, 7, and 5, respectively [5, 24, 34]. The relative safety factors η_F and η_R of different fracture surfaces in different failure modes were evaluated under the safety factor 1.3 and the reliability index 3.7, respectively. In addition, we analyzed the stability of each dam slope based on the profile diagram (Figure 3) and statistical parameters (Table 7); the results of the two relative safety factors were linearly regressed. Furthermore, the safety factor 1.3 and the reliability index 3.7 were at the same risk control level if the fitted slope approximates to 1.

Based on the ratio of safety margin theory and considering the impact of parameter variation, the relative safety factors, η_F and η_R, were evaluated through the slope model of antisliding stability. The evaluated relative safety factors were linearly regressed (Figures 4–6).

The linear regression results revealed that the fitted slope of the calculated results of the three projects approximated to 1, and the correlation coefficients were >0.8, suggesting that class 1 slope exhibits the same safety margin when the safety factor is 1.3 and the reliability index is 3.7. In addition, the risk control standards are at the same level when the reliability index of class 1 slope is set at 3.7, and the safety factor of class 1 slope is set at 1.3 (as stipulated in the code for slope).

4. The Value of the Safety Factor of Special Class Dam Slope Stability

We divided the special class slopes into special class I and special class II slopes based on the risk levels and acceptable risk standards. It is inappropriate for special class I and special class II slopes to adopt the same standard for failure probability and acceptable reliability index. The safety standard of the critical high slope in water conservancy and hydropower projects should be set per the relevant codes for high earth-rockfill dam. The authors of this paper have divided the dams with a height over 200 m into special classes 1 and 2 depending on the risk levels and acceptable risk standards; the annual failure probability for special

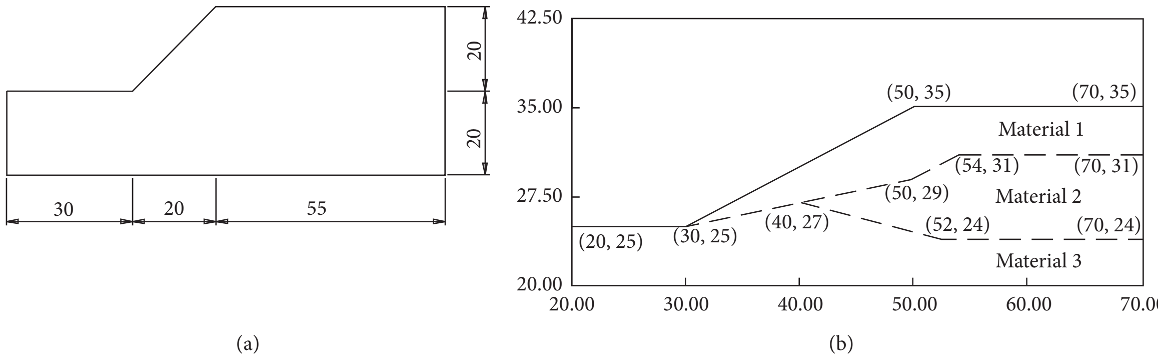

FIGURE 2: Two models for slope stability analyses: (a) simple slope, (b) layered soil slope.

TABLE 5: List of parameters used for the model calculation.

Parameters	φ_0 (°)		$\Delta\varphi$ (°)	
	Standard deviation	Mean of minimum values	Standard deviation	Mean of minimum values
Simple slope	2.0	51.0	1.0	11.0
Material 1	2.0	51.0	1.0	11.0
Material 2	1.8	53.0	1.0	13.0
Material 3	1.6	54.0	1.0	15.0

TABLE 6: Calculated results of the slope model.

Model	Deterministic method		Reliability method		Comparison
	F	η_F	β	η_R	
Model a	0.999	0.768	1.035	0.733	$\eta_F/\eta_R = 1.05$
Model b	1.404	1.08	5.522	1.182	$\eta_F/\eta_R = 0.91$

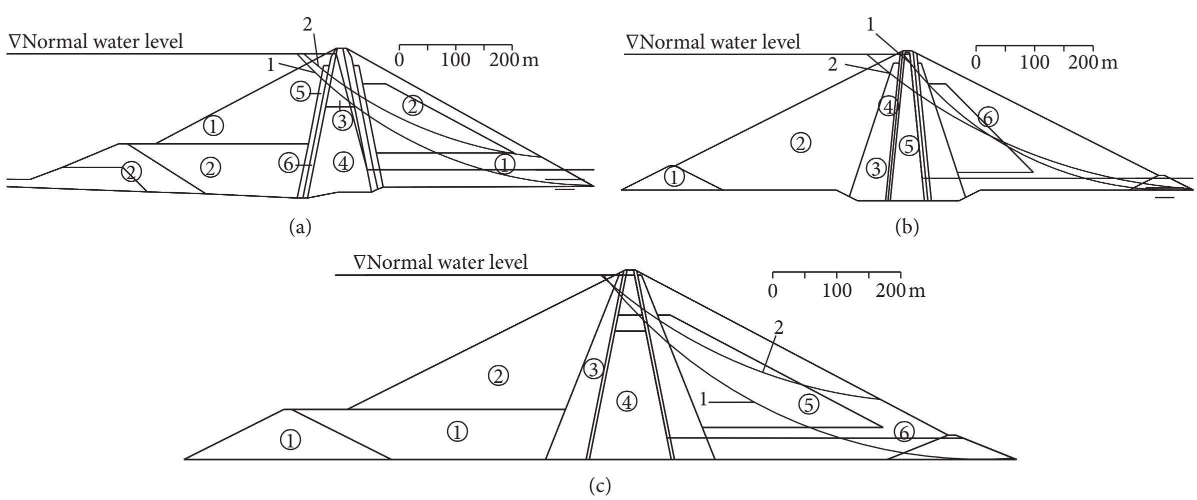

FIGURE 3: The profile diagram for the stabilities of the selected three ultrahigh dams in China with heights of more than 200 m: (1) critical slip surface under normal conditions; (2) critical slip surface under seismic conditions. (a) Nuozhadu. (b) Shangzhai. (c) Lianghekou.

classes 1 and 2 dams are 10^{-8} and 5×10^{-8} respectively, and the corresponding reliability index is 4.7 and 4.45 [24]. As the grade of slope should be lower than that of the structure [35], the yearly failure probability of the acceptable risk level of special class I slope in special class 1 earth-rockfill dam is 10^{-7}, and the corresponding reliability index is 4.2. The yearly failure probability of the acceptable risk level of special class II slope in special class 2 earth-rockfill dam is 5×10^{-7}, and the corresponding reliability index is 3.95. Hence, this section discusses the value of the safety factor through the ratio of safety margin method. Table 8 shows the risk control standards for stability of special dam and slope.

Table 7: Statistical parameters of the three ultrahigh dams in China with heights of more than 200 m.

Dam name	Dam height (m)	Material	Density ρ (kg/m^3)	Nonlinear strength parameters	
				φ_0 (°)	$\Delta\varphi$ (°)
Nuozhadu	261.5	(1) and (2): upstream rockfill	2150	52.0	8.5
		(3): transition material	2100	51.0	8.4
		(4): filter material	2080	50.0	8.3
		(6): downstream rockfill	2030	51.0	8.4
Shangzhai	254	(1): coverage material	2100	46.0	9.0
		(2): main rockfill material	2320	52.0	8.2
		(3): secondary rockfill material	2230	49.0	10.2
		(4): downstream rockfill	2120	46.0	9.0
Lianghekou	295	(1): fine rockfill	2000	51.5	8.4
		(2): rockfill material II	2110	49.1	9.1
		(5): transition material	2040	49.1	6.7
		(6): filter material	1940	49.9	10.1

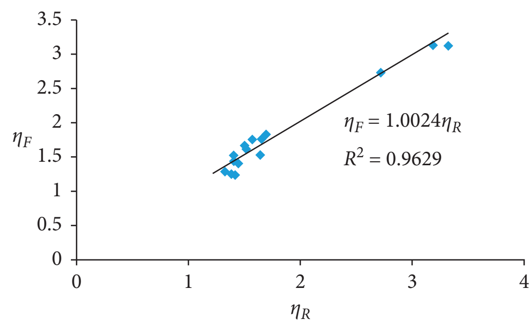

Figure 4: The correlation diagram of $\eta_R - \eta_F$ of the slope of the Nuozhadu hydropower station.

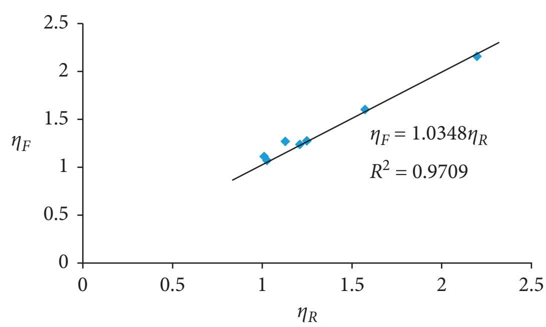

Figure 5: The correlation diagram of $\eta_R - \eta_F$ of the slope of the Shangzhai hydropower station.

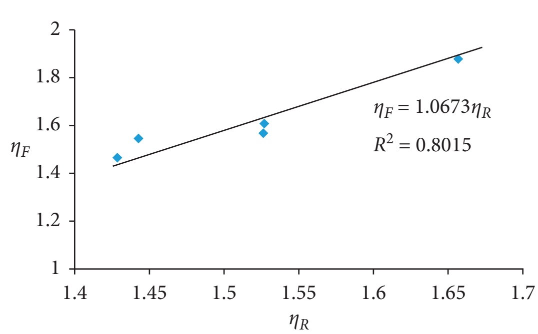

Figure 6: The correlation diagram of $\eta_R - \eta_F$ of the slope of the Lianghekou hydropower station.

Table 8: Proposed value of risk control standards for stability of special dam and slope.

Building type	Class	Yearly failure probability P	Reliability index
Earth-rockfill dam	Special class 1	10^{-8}	4.70
	Special class 2	5×10^{-8}	4.45
	Class 1	10^{-7}	4.20
Slope	Special class I	10^{-7}	4.20
	Special class II	5×10^{-7}	3.95
	Class I	10^{-6}	3.70

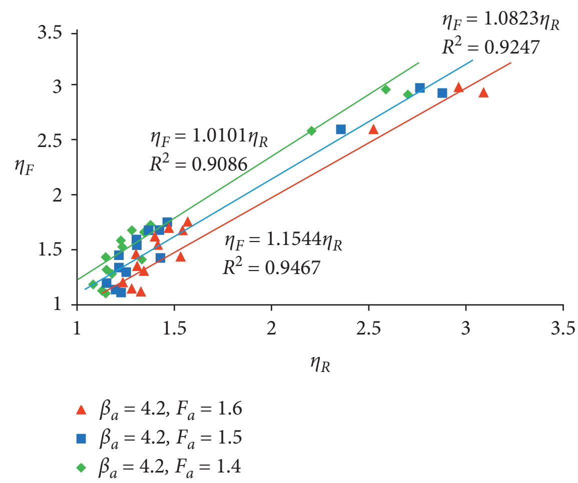

Figure 7: The correlation of $\eta_R - \eta_F$ of the slope of the Nuozhadu hydropower station for different safety standards (special class I dam slopes).

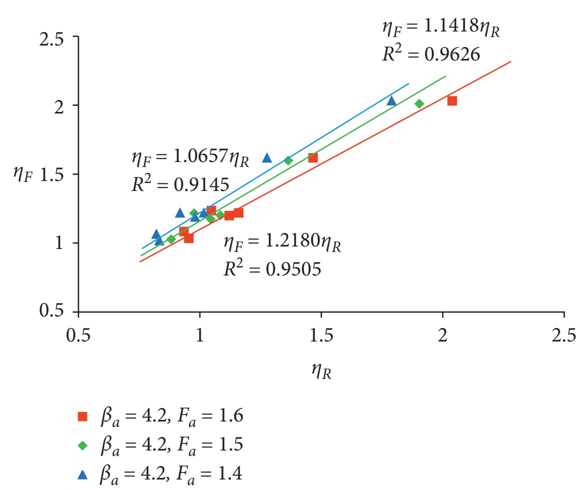

Figure 8: The correlation of $\eta_R - \eta_F$ of the slope of the Shangzhai hydropower station for different safety standards (special class I dam slopes).

4.1. Special Class I Dam Slope. Likewise, we selected the three projects mentioned in Section 3.3 as case studies to discuss the safety factor value of special class I dam slopes. We evaluated the safety factor ratios of the slopes of the three projects through the ratio of safety margin method. In addition, the ratio of safety margin (based on the reliability method) was calculated when the acceptable reliability index was 4.2. The ratio of safety margin (based on the deterministic method) was evaluated when the safety factors were 1.4, 1.5, and 1.6, respectively. Furthermore, the results of the ratio of safety margin were linearly regressed (Figure 7–9). The results of the linear regression revealed that the fitted slopes of safety factor 1.4 and reliability 4.2 were the closest to 1, and the correlation coefficients were the highest. Moreover, the slopes in the projects have the same safety margin when the safety factor is 1.4, and the reliability index is 4.2. Hence, it could be inferred that the safety factor 1.4 and the reliability index 4.2 are at the same risk control level.

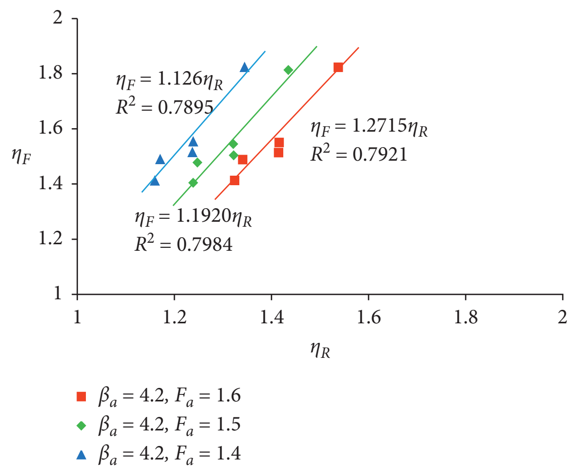

FIGURE 9: The correlation of $\eta_R - \eta_F$ of the slope of the Lianghekou hydropower station for different safety standards (special class I dam slopes).

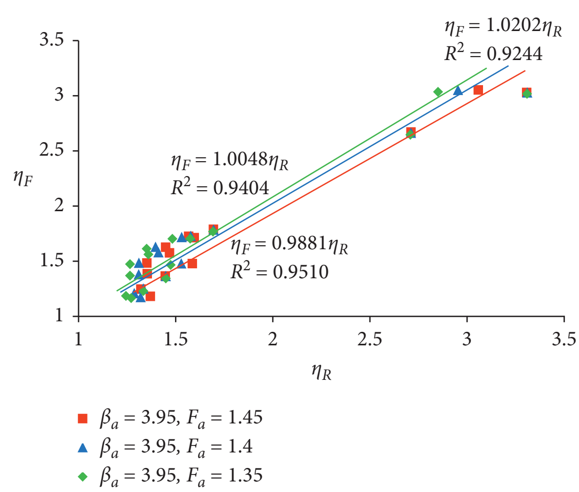

FIGURE 10: The correlation of $\eta_R - \eta_F$ of the slope of the Nuozhadu hydropower station for different safety standards (special class II dam slopes).

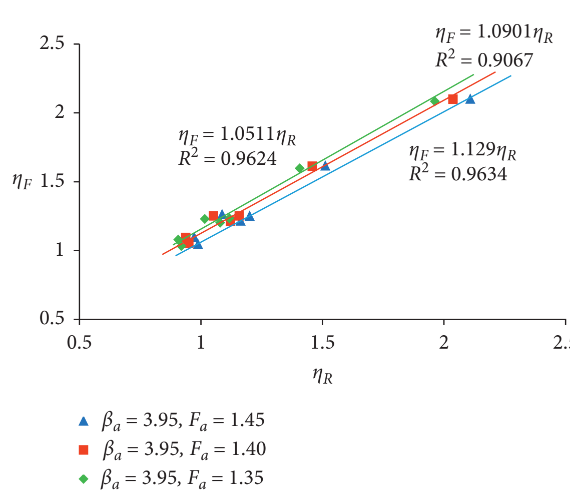

FIGURE 11: The correlation of $\eta_R - \eta_F$ of the slope of the Shangzhai hydropower station for different safety standards (special class II dam slopes).

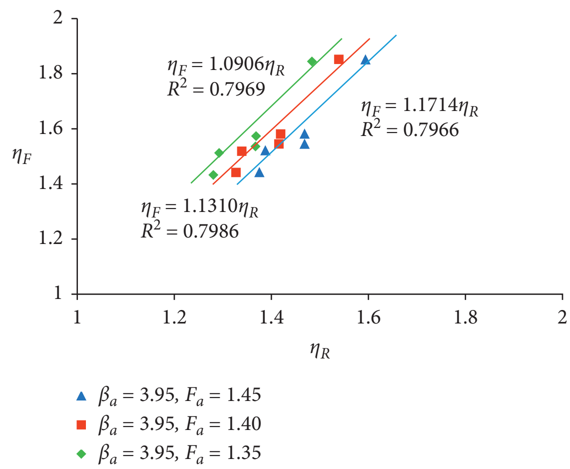

Figure 12: The correlation of $\eta_R - \eta_F$ of the slope of the Lianghekou hydropower station for different safety standards (special class II dam slopes).

4.2. Special Class II Dam Slope. We selected the three projects mentioned in Section 3.3 as case studies to discuss the safety factor value of special class II dam slopes. The safety factor ratios of the slopes of the three projects were evaluated using the ratio of safety margin method. In addition, we evaluated the ratio of safety margin (based on the reliability method) when the acceptable reliability index was 3.95. The ratio of safety margin (based on the deterministic method) was evaluated when the safety factors were 1.35, 1.4, and 1.45, respectively. Furthermore, the results of the ratio of safety margin were linearly regressed (Figure 10–12).

The results of the linear regression revealed that the fitted slopes of safety factor 1.35 and reliability 3.95 were closest to 1, and the correlation coefficients were the highest. The slopes in the projects have the same safety margin when the safety factor is 1.35, and the reliability index is 3.95. Hence, it can be inferred that the safety factor 1.35 and the reliability index 3.95 are at the same risk control level.

5. Conclusions

Based on risk levels and acceptable risk standards for ultrahigh dams, as well as the concept of the relative ratio of safety margin, this study evaluates the safety factor of the stability of special dam class slopes. From this study, the following inferences could be drawn.

For the natural and engineered slopes, the yearly failure probability of the acceptable slope risk level should be set at 10^{-6}, and the corresponding reliability index and safety factor are 3.7 and 1.3, respectively. For the critical high slope in special class I, the yearly failure probability of the acceptable slope risk level is 10^{-7}, and the acceptable reliability index is 4.2. For the critical high slope in special class II, the yearly failure probability of the acceptable slope risk level is 5×10^{-7}, and the acceptable reliability index is 3.95. The minimum safety factors of high slopes of special class I and special class II are suggested as 1.4 and 1.35, respectively.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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