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.
suggested that the failure probabilities of special class I and special class II slopes are $10^{-5}$ and $5 \times 10^{-5}$, 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.
The safety factor attained through the reliability analysis is β, and the corresponding acceptable margin of safety factor is βa; however, it is inappropriate to express the relative safety factor as β/βa, because only the correlation of β with 1–Φ (β) has physical significance. Figure 1 presents the ratio of safety margin method demonstrating the correlation between ηR and ηF.

Based on the safety factor sample listed in Figure 1, the reliability indexes β and βa can be evaluated. As β > βa, the corresponding area of the shadow region a is smaller than 1–Φ (βa). Assuming that, upon subtracting a ΔF from all safety factors in the sample, there will be a new safety factor sample F = F–ΔF, 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–Φ (βa), which is 10–6 for class 1 structure. Then, ΔF can be calculated through derivation. Based on formula (4), the ratio of safety margin ηR (based on the reliability method) can be expressed as follows:

\[
\eta_R = (\beta - \beta_a) \sigma_F + 1,
\]

where σF is standard deviation of safety factor.

In Figure 1, the ratio of DC to BA approximates to ηR0 and the ratio of HG to FE approximates to ηF. Thus, the ratio of the safety margin ηR 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 φ = φ0 − Δφσ (σ0/pa) [32], where φ is the secant effective stress angle of internal friction, φ0 is the value of φ for σ0 equal to one atmosphere, Δφ is the reduction in φ for a 10-fold increase in confining pressure, σ3 is the confining pressure, and pa 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 ηF (based on the deterministic method) and the ratio of the safety margin ηR (based on the reliability method) can be calculated. If ηF approximates or equals to ηR, the safety factor of class 1 slope is suitable to be set at 1.3. Next, we evaluated the safety factor and reliability

| 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 | 308        | 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 | 10–6, for people who live closely to the project |
| Slope being built | 10–6, for people who live far away from the project |

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

\[
Py = \frac{P \cdot Nd}{T},
\]

where T is the service life of slope and Nd 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 = Nd, then, formula (1) can be approximately expressed as follows:

\[
Py = \frac{P}{Nd}.
\]
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 | $\beta_a$ |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|-----------|
| 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 $1 \times 10^9$ 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 $1 \times 10^9$ m$^3$. | $5 \times 10^{-8}$          | 4.45      |

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
classes 1 and 2 dams are $10^{-8}$ and $5 \times 10^{-8}$ 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 $5 \times 10^{-7}$, 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 5: List of parameters used for the model calculation.

| Parameters     | φ₀ (°) | Δφ (°) |
|----------------|--------|--------|
| Simple slope   | 2.0    | 1.0    |
| Material 1     | 2.0    | 1.0    |
| Material 2     | 1.8    | 1.0    |
| Material 3     | 1.6    | 1.0    |

Table 6: Calculated results of the slope model.

| Model         | Deterministic method | Reliability method | Comparison |
|---------------|----------------------|--------------------|------------|
|               | F        | η_F | β     | η_R | η_F/η_R=0.91 |
| Model a       | 0.999   | 0.768 | 1.035 | 0.733 | 1.05        |
| Model b       | 1.404   | 1.08  | 5.522 | 1.182 | 0.91        |

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

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.
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 $\rho$ (kg/m$^3$) | Nonlinear strength parameters |
|--------------|----------------|-------------------------------|----------------------------|-------------------------------|
|              |                |                               | $\varphi_0$ (°)            | $\Delta \varphi$ (°)         |
| 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                         | 6.7                          |
|              |                | (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.
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.

### 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 | $5 \times 10^{-8}$            | 4.45              |
|                     | Class 1       | $10^{-7}$                     | 4.20              |
| Slope               | Special class I | $10^{-7}$                     | 4.20              |
|                     | Special class II | $5 \times 10^{-7}$           | 3.95              |
|                     | Class I       | $10^{-6}$                     | 3.70              |

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

**Figure 8:** The correlation of $\eta_F - \eta_R$ of the slope of the Shangzhai hydropower station for different safety standards (special class I dam slopes).
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).
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 $5 \times 10^{-7}$, 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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