Mid-term Diversion Risk Prediction from the Correlation between the Flood Peak and Volume during High Rockfill Dam Construction

LIU Lian, LUO Shu, ZHAO Chunju, and ZHOU Yihong

Abstract*—The flood peak and flood volume are generally considered to be independent random variables in early-term dam construction diversion risk simulation, while the cofferdam elevation is a definite value. Due to the continual construction of high dams at the 200 m-level in southwest China, the effect of flooding on dams lasts longer than before due to greater filling volumes and longer construction periods. The correlation between the flood peak and the volume has been shown to affect the accuracy of mid-term diversion risk analysis. Aiming at determining the mid-term diversion risk of high rockfill dams, this paper presents a joint distribution for the construction flood peak and volume using the copula function. Then, a simulation model for the monthly filling height during the flood season is given considering the filling intensity and effective construction days, in which the daily rainfall and the stoppage standards for rain, which affect the effective construction days, were analysed. Additionally, stochastic factors such as the hydrology, hydraulics, stop days, and filling intensity were considered to resolve the diversion risk rate by using the Monte Carlo method. Finally, an example of a high rockfill dam in southwest China was provided to verify the correlation between the flood peaks and volumes and to calculate the mid-term diversion risk during its construction by incorporating historical flood data, rainfall days, and diversion standards. The results reflect the probability distribution of a construction flood more accurately, avoiding the overestimation of a low-probability flood event, with a high peak but a small volume, that leads to a lower risk rate and lower designed reliability for diversion structures. In addition, the monthly diversion risk and its corresponding maximum water level in the equivalent reappearance period can provide design references for coordination between flood prevention measures and construction schedules.

***Index Terms*—high rockfill dam construction, mid-term diversion, copula function, risk stochastic simulation**

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Liu Lian, College of Hydraulic and Environmental Engineering, Three Gorges University, Yichang, Hubei, China (Tel: 008613986742217; Email: liulian1986@hotmail.com).

Luo Shu, College of Hydraulic and Environmental Engineering, Three Gorges University, Yichang, Hubei, China (Email: ls360356312@qq.com).

Zhao Chunju, State Key Laboratory of Hydropower Project Construction and Management of Hubei Province, Three Gorges University, Yichang, Hubei, China (Email: chunju.zhao@qq.com).

Zhou Yihong, State Key Laboratory of Hydropower Project Construction and Management of Hubei Province, Three Gorges University, Yichang, Hubei, China (Email: yhzhou_ctgu@qq.com).

I. INTRODUCTION

HIGH rockfill dams have become a major dam type utilized in southwest China due to the advantages of using local materials, simple construction techniques, and high adaptability to geological conditions. Most high rockfill dams are located in high mountains and gorge areas where floods may suddenly occur, water levels vary due to flooding and dry weather, and long construction periods are common. These factors challenge flood risk prediction, flood prevention and control, particularly in the mid-term diversion stage when the dam filling height exceeds the cofferdam height and reaches the water retaining level [1]. In this situation, the distinct interactions between the diversion risk and the construction schedules be disregarded because decision-making errors in flood prevention are likely to cause significant casualties and economic losses. Therefore, an accurate risk prediction method for mid-term diversion risk is vital for achieving safe and economical high dam construction during the flood season.

The maximum water level in front of a dam, which exceeds the filling height that can retain water, has been extensively accepted as a failure of a diversion system during the flood season [2]-[4]. The probability of this failure can be described by the diversion risk. Previous studies have focused on the short-term diversion risk without considering the construction schedule because many small-scale dams have a short flood period—one or two flood seasons. Hu [3]-[5] performed short-term diversion risk analysis and simulated flood processes considering a single variable, such as the flood peak or volume, or assumed independent variables that can satisfy the short-term diversion standard requirement. Regarding a high dam, some related characteristics of floods should be concentrated in the mid-term risk analysis. Normally, the mid-term diversion standard of high rockfill dams was substantially increased compared with the early-term diversion standard [6] because the differences in the hydrological features between simulations using a single flood variable and multiple variables are magnified during a long construction period. If the real flood distribution cannot be represented, the design or construction performance for the water retaining level will be affected. The filling height uncertainty was rarely considered in previous studies. The early-term diversion risk models generally defined the cofferdam elevation as a constant [7],[8], and mid- or late-term diversion risk models compared diversion risks among typical elevation nodes of a dam [9]. Fan [10], Chu[11], and

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Luo[12] introduced schedule risk to an integrated diversion risk model based on the principle of independent events and conditional probabilities. Zhong[13] established a risk preference- schedule-completion probability distribution curve based on the uncertainty of the construction progress for a rockfill dam. The filling height of a dam deviates from the original plan in practical dam construction. Therefore, the mid-term diversion stage should focus more on the uncertainty of the filling height, which is one of the control variables in the risk model. Li [14] and Zhang[15] provided the filling height distribution for high rockfill dams in the construction progress, considering the uncertainties of the working duration and the average filling speed per day to further improve the risk model.

The abovementioned study suggests that the early-term diversion risk analysis has attracted the most attention before high dams emerge, and only a single flood variable (peak or volume) or two independent variables (peak and volume) were considered in the flood simulation. In addition, seeing the water retaining height as a constant had limited application in the mid- and late-term diversion risk prediction. This paper presents a joint distribution for the construction flood peak and flood volume based on the copula function, considering the correlation between the flood peak and volume, and the discharge capacity of diversion structures to simulate the stochastic flood level in front of the dam. Additionally, a monthly filling height simulation model is provided for the flood season, considering the filling intensity and effective construction days; in this model, the daily rainfall distribution, and the stoppage standards of the dam for rainfall are analysed to determine the effective construction days. A mid-term diversion risk prediction method for a high rockfill dam is provided based on Monte Carlo (MC) simulations. Finally, a case study of a high rockfill dam in southwest China is provided to verify this method. The calculation results reveal the distribution characteristics of some uncertainties in mid-term diversion and the spatiotemporal diversion risk variations, which provide references for flood prevention decision-making and accurate control for dam construction schedules during the flood season.

II. Flood and Water Level Simulation

Flood events are usually represented by several correlation characteristic variables, such as the flood peak, flood volume and flood duration, which are described by multivariate analysis [16]. The copula function is an effective tool for capturing the nonlinear, asymmetric, and tail-dependent relationship [17] among hydrologic random variables; thus, it can divide the joint distribution into two parts: the edge distribution and the correlation structure [18],[19]. The joint distribution of the flood peak and volume is generally constructed by the Clayton copula function [20],[21] and employed to simulate the flood process in return periods due to their significant positive correlation. Assuming that the flood peak x and flood volume y are continuous random variables, a P-III distribution has been proposed to fit their marginal distribution functions, $F_X(x)$ and $F_Y(y)$, according to many years of hydrologic frequency calculations for rivers in China. The joint distribution of the flood peak and volume $F(x,y)$ can be described by the copula function C in (1) as follows:

$$F(x,y)=C(u_1,u_2)=(u_1^{-\theta}+u_2^{-\theta}-1)^{-1/\theta},\theta\in(0,\infty) \tag{1}$$

where $u_1=F_X(x)$, $u_2=F_Y(y)$, θ is a parameter of C, and the parameters of the marginal distribution function can be estimated by the linear-moment method. θ and the Kendall rank correlation coefficient τ satisfy $\tau=\theta/(\theta+2)$.

The joint empirical frequency $H(x_i, y_i)$ of the flood peak and flood volume has been calculated by the Gringorten formula with (2) [22], and (x_1, y_1), (x_2, y_2),…(x_L, y_L) are the combined observations of the peak and volume:

$$F(x_i,y_i)=P(X\le x_i,Y\le y_i)=\frac{m_i-0.44}{L+0.12} \tag{2}$$

where L is the number of observation samples and m_i is the number of observation samples that satisfy both $X\le x_i$ and $Y\le y_i$ (i=1,2,…L).

In the Clayton copula function [23], u_1, u_2, and the conditional distribution $S(u_2|u_1)=\frac{\partial C(u_1,u_2)}{\partial u_1}$ obey a uniform distribution on [0,1]. k_1 and k_2 are random numbers sampled on the MC method. If $u_1=k_1$, $S(u_2|u_1)=k_2$, u_1 can be obtained. The flood peak x with a frequency of 1-u_1 and the 7-day maximum flood volume with a frequency of 1-u_2 are calculated according to the P-III distribution. A typical flood process line was selected from the observed flood data, and a polyploidy amplification method can be used to address and simulate the flood process during the dam construction progress.

The water level in front of a temporary dam section is related to the flood and discharge capacity of the diversion structures. The roughness coefficient of the diversion structures is assumed to obey an approximately triangular distribution [24] considering the randomness of the hydraulic parameters [25]. Therefore, the water level distribution sequence in front of the temporary dam section $G=\{g_1,g_2,\ldots,g_n\}$ is calculated by flood routing after the simulated discharge capacity is determined.

III. Filling Height Simulation

The mid-term diversion risk per month can be simulated with when having different water retaining heights according to the construction schedule. However, the filling heights are influenced by random factors such as rainfall, process connection and mechanical efficiency, which render the planned elevations uncertain. The filling height uncertainty should be considered in risk simulation modelling. The following three assumptions are made before modelling the filling height.

1) The adjacent sections of a dam are filled by parallel ascending, and the transportation intensity and filling intensity meet the construction constraints.

2) The filling height uncertainty is determined only by the uncertainty of the rainfall and the filling intensity.

3) The high rockfill dam is divided into m filling areas per g metres in elevation. The construction technology and step

distances are approximately regarded as equal in each working face.

The simulation model of the filling height G_n in the n-th month is expressed as follows in (3):

$$\begin{cases} G_n = G_0 + g\sum_{i=0}^{n}\frac{(d_i - D_i)}{\sum_{j=1}^{m} T_j} \\ T_j = \frac{hw}{Q_j} \end{cases} \tag{3}$$

where G_0 is the initial height, d_i is the number of days in the i-th month, D_i is the number of stop days in the i-th month, T_j is the number of working hours in the j-th filling area, h is the thickness of the clay spread in the filling areas, w is the filling area (m^2), and Q_j is the filling intensity in the j-th filling areas (m^3/day).

During the construction of high rockfill dams, the suspension of work at the dam surface due to rainfall causes a decrease in the effective construction days per month, which directly affects the filling schedule. In this paper, the stop days per month D_i is regarded as a stochastic variable, and the occurrence time and daily rain capacity per month were assumed to be mutually independent for many years, according to the observations of the rain capacity and rain days at the dam site [26]. Therefore, the effective construction days are indirectly determined by the stoppage standards for rain [27], provided that the distribution of the monthly stop days has been obtained. The stop days are assumed to be normally distributed due to the normal distribution of the rain capacity, and hypothesis tests can verify this finding.

The complexity of the dam construction technology and, the diversity of the mechanical configurations as well as the time constraints on key nodes, produce a disequilibrium of the dam filling intensity. Therefore, this paper considers the filling intensity per day Q_j as a stochastic variable, which was simulated based on the current appearance of the dam, the mechanical configuration scheme and the planned filling intensity by stage. The filling intensity distribution was deduced via a simulated data fitting test.

IV. Diversion Risk Simulation

A. Diversion Risk Model

Mid-term diversion schemes for high rockfill dams generally include 1) retaining water by whole or temporary dam filling sections and 2) allowing for a breach on the dam surface to accommodate flow. When the retaining water scheme is selected, a possibility that the flood level exceeds the water retaining level exists due to filling schedule deviation or flood prediction error. Once this possibility occurs, it will cause enormous losses.

To describe these events, this paper defines the mid-term diversion risk as the probability that the flood level exceeds the filling height for water retaining without flow protection, when the dam filling height exceeds the cofferdam height. The risk model is shown in (4):

$$R(n) = prob[\max(H_n) \geq G_{n-1} \mid D_n, G_{n-1} \geq G_*] \tag{4}$$

where $R(n)$ is the diversion risk in the n-th month during the flood season, D_n is the simulated flood process in the n-th month, H_n is the simulated highest water level in front of the dam, G_{n-1} is the simulated filling height in the n-1-th month, and G^* is the upstream cofferdam height.

B. Simulation Process

Stochastic factors such as the hydrology, hydraulics, and filling intensity were considered to simulate the water level and filling height by the MC method to obtain the probability statistics of the water level beyond the standard. The simulation process for the mid-term diversion risk of a high rockfill dam is described as follows:

1) A typical flood hydrograph was selected according to historical flood data to verify the flood volume and peak distribution.

2) A joint distribution function of the flood peak and flood volume was established based on the copula function.

3) Random numbers of peaks and volumes were generated. The peaks and volumes for corresponding return periods were obtained according to the joint probability density function, and then the flood process was described by the polyploidy amplification method.

4) Random numbers for the hydraulic parameters of the discharge were generated to fit the discharge capacity curve, and the highest water level in front of the dam was attained after storage routing.

5) According to the statistics of daily rainfall at the dam site, coupled with the stoppage standards for rain, the distribution functions of stop days, and effective construction days per month were derived.

6) The distribution of the filling intensity was derived according to the statistics of the filling volume per day in detailed construction records.

7) The simulation times N and months were determined before simulating the flood process and discharge capacity, and the highest water level in front of dam H_n was calculated.

8) The filling height G_{n-1} was obtained according to (3) according to the simulated stop days and filling intensity.

9) The number of times M that the flood level exceeded the water retaining level was counted; thus, M/N was the mid-term diversion risk for the high rockfill dam.

V. Case Study

A. Case Background

A high core wall rockfill dam located in southwest China with a maximum dam height of 261.5 m was selected for the case study. A one-time river closure and earth rock cofferdam that retains water were adopted in the short-term diversion plan with a standard of a 50-year return period flood. Mid-and late-term diversion (from June in the third year to October in the fifth year) adopted a temporary dam section to retain water with an upper limit standard of a 200-year return period flood; the corresponding designed discharge and water level were 22,000 m^3/s and 672.69 m, respectively. The flood and dry seasons at the dam site were noticeable in this river valley, and floods were primarily caused by torrential rain from June to October. Due to the lower water retaining height in the first flood period of the mid-term diversion, the possibility of over-level flooding is high; thus, requirements for the filling speed and schedule were needed during this period. Therefore, the diversion risk calculation in this paper primarily focused on the first flood season in the mid-term diversion between June in the third year and October in the fifth year of the dam construction period.

B. Uncertainty Analysis

The hydrologic uncertainty and hydraulic uncertainty as well as the filling height uncertainty, were regarded as the stochastic factors in this risk simulation, in which the filling height was mainly influenced by the uncertainties of the filling intensity and stop days.

1) Hydrologic and hydraulic uncertainties: According to the 28-year historical flood data provided by a hydrological station near the dam site, a typical flood process hydrograph was selected to determine the mean values of the flood peak discharge μ_x and 7-day flood volume μ_y. The coefficient of deviation *Cv*, the coefficient of skewness *Cs*, and the Clayton copula function parameters are shown in Table 1.

Table 1 shows the Kendall rank correlation coefficient τ =0.51 and the copula function parameter θ=2.11, which revealed a higher nonlinear correlation between the flood peak and flood volume in this river basin. The joint distribution passed the Kolmogorov-Smirnov (K-S) test with a 5% confidence level. Their correlation, particularly the higher tail dependence correlation, was distinctly described by the distribution and density of the copula function, as shown in Fig. 1 and Fig. 2, which indicates that the larger the flood was, the higher the correlation. In addition, the discharge capacity of diversion structures was modelled as a random variable with a triangular distribution, whose upper limit *a*, mode *b* and lower limit *c* were 0.97, 1.00, and 1.05, respectively.

2) Stop day uncertainty: Generally, a short time stoppage has minimal influence on the total construction schedule if protective measures are taken on rainy days for the clay and filter material of rockfill dams. Therefore, the stoppage of a dam with a large filling volume that distinctly influenced the total schedule is considered in this paper, namely, when the work is stopped for 1 day as the rainfall exceeds 30 mm per day and its duration exceeds 8 h. Using the observed data of daily rainfall from June to October over the last two decades measured at the hydrologic station nearby combined with the stoppage standards for rain, the stop days per month (as shown in Table 2) and their frequency ranges and distribution functions were calculated. Therefore, the stop day distributions are determined, as shown in Table 3, if the number of days in each month was assumed to be consistent. The effective construction days can be indirectly obtained.

3) Filling intensity uncertainty: The parallel ascending filling technology was adopted to fill the adjacent section of the dam. The dam body was assumed to be divided into 3 areas per 5 m in elevation; the thickness of the clay *h* was 0.5 m. As the filling elevation increased, the length of the working face varied from 60 m to 100 m. Therefore, the simulation data for the filling intensity per day can be obtained based on the average monthly filling intensity from the stage plans, the mechanical configuration, and the production efficiency. The ogarithmic distribution, exponential distribution, uniform distribution, and normal distribution were compared by distribution fitting; the exponential distribution described the characteristics of the filling intensity well, as shown in (5).

$$f(Q)=\begin{cases} 9.75e^{-9.75Q}, Q>0 \\ 0, Q\le 0 \end{cases} \tag{5}$$

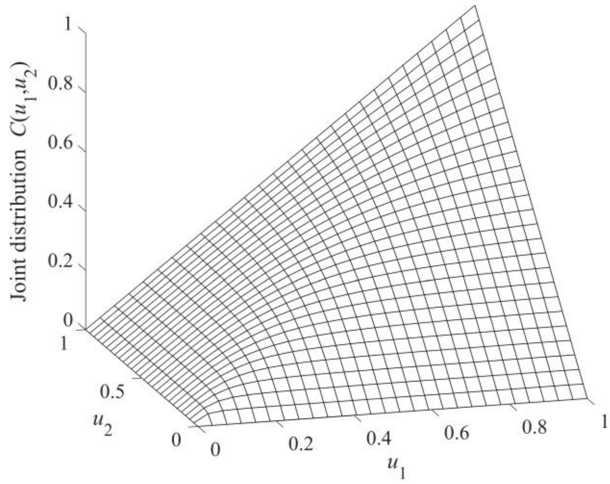

Fig. 1 Joint distribution function of peak and volume

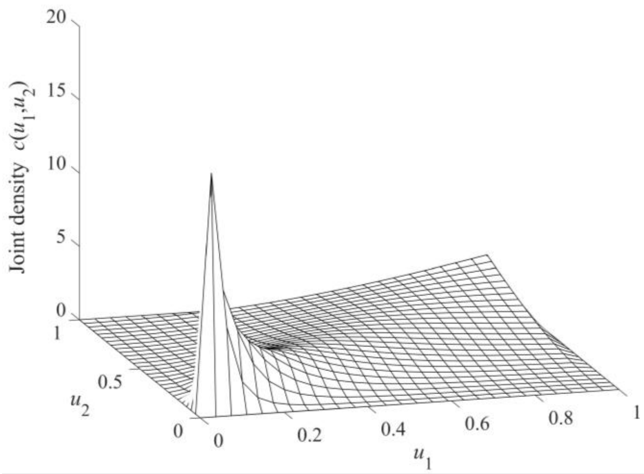

Fig. 2 Joint density function of peak and volume

TABLE I
STATISTICAL PARAMETERS OF THE CONSTRUCTION FLOODS

Flood peak flow			7-day flood volume			Parameters for correlation	
μ_x/(m$^3\cdot$s^{-1})	*Cv*	*Cv*/*Cs*	μ_y/ (10^8 m^3)	*Cv*	*Cv*/*Cs*	τ	θ
7700	0.28	3.89	136.99	0.25	2.76	0.51	2.11

TABLE II
RAINFALL DAYS PER MONTH DURING THE FLOOD SEASON FROM 1990 TO 2010

Daily rainfall	Jun.	Jul.	Aug.	Sept.	Oct.
>5 mm	212 d	290 d	257 d	183 d	112 d
>10 mm	132 d	182 d	149 d	113 d	68 d
>20 mm	44 d	90 d	62 d	34 d	21 d
>30 mm	16 d	39 d	26 d	15 d	11 d

TABLE III
DISTRIBUTION OF STOP DAYS

Month	Distribution of stop days
Jun.	$N(0.76,1.18)$
Jul.	$N(1.86,1.28)$
Aug.	$N(1.24,0.83)$
Sept.	$N(0.71,0.78)$
Oct.	$N(0.52,0.81)$

C. Risk Simulation Results

Random sampling was conducted for the flood process, discharge capacity, stop days, and filling intensity. The mid-term construction diversion risk rates in the first flood season were calculated based on the diversion risk model and filling height model. The risk rates considering whether the correlation between the flood peak and volume were considered were simulated 5000 times for two discharge schemes. Consequently, the probabilities that the flood level in front of the dam will exceed the filling height, namely, the monthly risk rates from June to September, are shown in Table 4. The time of the maximum flood peak emergence in this basin was in mid-October, and as the typical flood hydrograph was amplified by the multiple ratio amplification method, the risk in October sharply increases.

To reflect the influence of the correlation structure on the random number of peaks and volume, the joint distributions from the copula and the independent distributions for two variables from the P-III distributions, were separately used to simulate the flood peaks and volumes 500 times. Two comparisons of the simulated peak flow and 7-day flood volume, and their frequencies, are shown in Fig. 3 and Fig. 4.

Considering July from scheme 1 as an example, the simulated risks of mid-term diversion from 300 to 10000 times are shown in Fig. 5, considering both the correlation and independence of these two variables. As shown in Fig. 5, the correlated and uncorrelated mid-term diversion risk rates in July tend to be stable after 2000 simulations, and their difference is consistently 2%.

The equivalent return periods each month were obtained by simulating the risk rates from scheme 2 (Table 4), which can determine the water retaining height for filling reference in the stage plan. A comparison between the planned filling height and water retaining height in equivalent return periods is shown in Table 5. As previously described, the risk increased in October, thus, the equivalent return period for this month decreased accordingly.

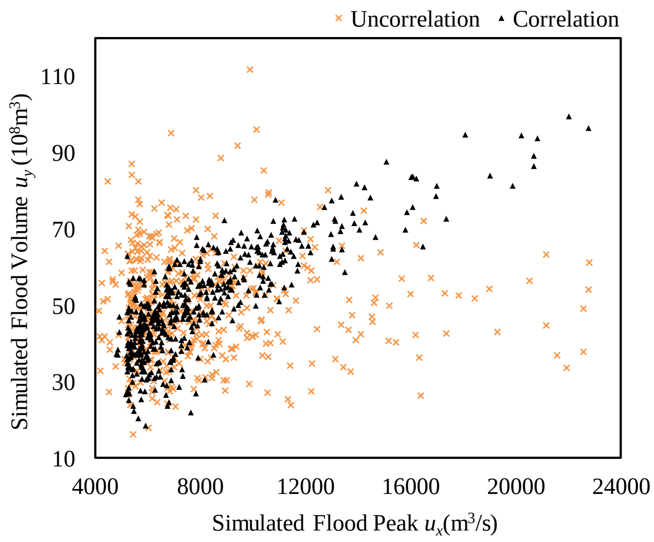

Fig. 3 Comparison between simulated peak and 7-day volume

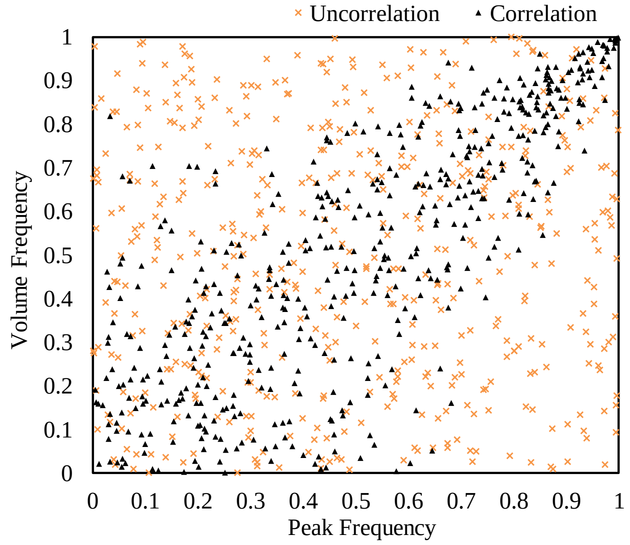

Fig. 4 Comparison between the frequency of the peak and 7-day volume

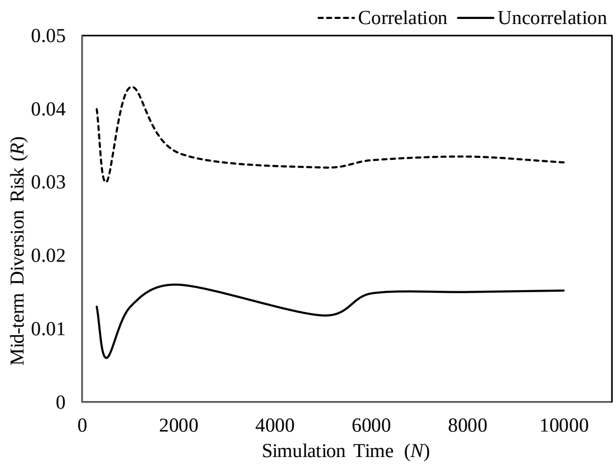

Fig. 5 The effect of the simulation time on the results

TABLE IV
MID-TERM DIVERSION RISKS FROM THE TWO SCHEMES

Month	Scheme 1 (Joint discharge by the #1 and #2 diversion tunnels)		Scheme 2 (Joint discharge by the #1, #2 and #3 diversion tunnels)	
	Correlated	Uncorrelated	Correlated	Uncorrelated
Jun.	0.0656	0.0172	0.0320	0.0118
Jul.	0.0482	0.0080	0.0240	0.0044
Aug.	0.0460	0.0035	0.0200	0.0024
Sept.	0.0120	0.0102	0.0100	0.0074
Oct.	0.0512	0.0480	0.0340	0.0294

TABLE V
COMPARISON BETWEEN PLANNED FILLING HEIGHTS AND WATER RETAINING HEIGHTS

Month	Designed water retaining stander/m	Planned filling height/m	Equivalent return period/y	Water retaining height in equivalent return period/m
Jun.		656	31.25	668
Jul.		668	47.62	670
Aug.	672.69	680	50.00	670.29
Sept.		692	100.00	671.36
Oct.		704	29.41	667.85

A sensitivity analysis for risk was conducted by changing the mean value μ and the variation coefficient δ of three stochastic but controllable artificial variables: the discharge capacity, effective construction days, and filling intensity of the high rockfill dam. The change in these variables, which range from -0.4 to 0.4, was regarded as Φ.

Considering July as an example, the initial statistical values for the distribution functions of three variables are shown in Table 6, and the sensitivities of the variables regarding the mid-term diversion risks in June and July during the first flood season are shown in Fig. 6 and Fig. 7.

TABLE VI
PARAMETERS FOR SENSITIVITY ANALYSIS

Variables		μ	δ	Φ
Discharge capacity		0.97	1.03	
Effective construction days	Jun.	0.76	1.18	(-0.4, +0.4)
	Jul.	1.86	1.28	
Filling intensity		0.11	9.75	

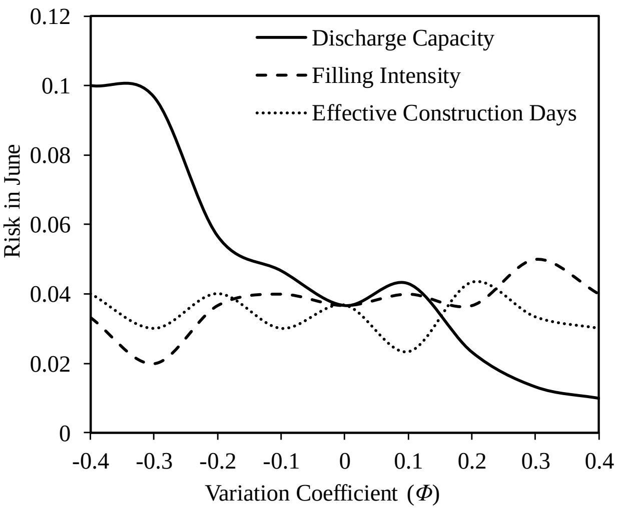

Fig. 6 Sensitivity analysis for mid-term diversion risk in June

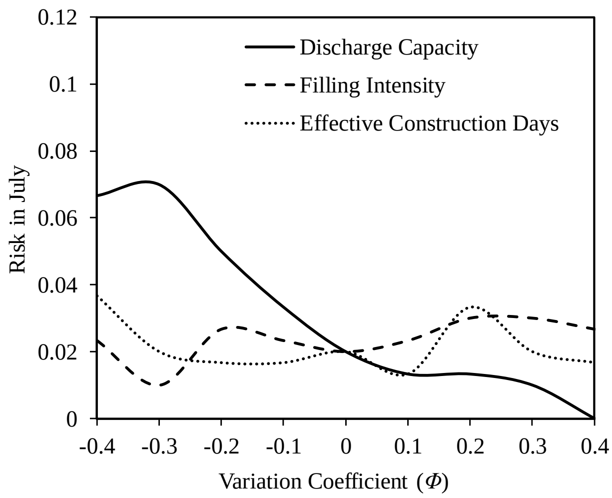

Fig. 7 Sensitivity analysis for mid-term diversion risk in July

D. Analysis of the Results

1) Table 4 shows that the risk per month in scheme 2 is generally less than that in scheme 1, which is consistent with current engineering practice, as the increasing trend in the discharge capacity reduces the average water level in front of the dam, which causes a lower over-topping probability. Additionally, low-probability flood events with a high peak but a small volume will appear among the simulated samples if their correlation is not considered, while these extreme events are regarded as regular probabilistic events in conventional calculation (as in Fig. 4, the scattered points are distributed uniformly), which induced risks lower than those in real situations. The verification of the historical data proves that the flood process has a higher tail dependence between the peak and the volume, which can reflect the real distribution of extreme flood events with high peaks but small volumes and effectively avoid a low designed reliability for diversion structures.

2) In Table 5, the original standard of the mid-term diversion was designed to resist a 200-year return period flood, and its corresponding highest water retaining height for the dam was 672.69 m during the flood season. The

equivalent return periods (maximum of 100 years in Table 5) and simulated highest water retaining heights (maximum of 671.36 m in Table 5) from June to October in the third years are below the designed standard of mid-term diversion, which demonstrates that the original standard is sufficiently safe and reliable for appropriately reducing the water retaining height during the construction process. The filling heights of 656 m for June and 668 m for July in the original construction plan are lower than the heights of 668 m and 670 m in the equivalent return periods. Thus, considering these heights as references, decision makers can adjust the dam filling schedule according to the acceptable risks.

3) The discharge capacity, filling intensity, and effective construction days are three controllable artificial variables in the risk simulation. Fig. 6 and Fig. 7 show that the risk is most sensitive to the discharge capacity in this case. When the discharge capacity is increased by 30%, the risk decrease becomes less distinct. This trend indicates, at this point, that the discharge capacity of the diversion structures is approximately equal to that of the upstream river channel, which causes a decrease in the variation amplitude of the water level in front of the dam. Although means such as enhancing the filling intensity and increasing the effective construction days have limited control over the risk, they remain feasible as alternatives for flood prevention during the dam construction period if temporary diversion structures are not operational.

VI. CONCLUSION

The mid-term diversion risk of high dams is a key reference for diversion standard selection, diversion scheme optimization and construction schedule regulation during the flood season. Based on random sampling simulation for diversion risk, this paper focused on the correlation between flood peak and flood volume, and its influence on mid-term diversion risk calculation for high rockfill dams. First, the Clayton copula function was adopted to establish a joint distribution for the construction flood peak and volume to avoid the overestimation of low-probability flood events with high peaks but small volumes with the assumption of mutual independence among variables, which improves the accuracy and reliability of the risk calculation. Second, a simulation model for the monthly filling height was regarded as a stochastic variable during the flood season, considering the filling intensity and effective construction days determined by the daily rainfall and the stoppage standards of rockfill dams for rain. This model described the dynamic characteristic of the mid-term diversion risk along with the ascending filling height. Finally, a high rockfill dam in southwest China was considered as an example to verify the correlation between the flood peak and the flood volume, to simulate the mid-term monthly diversion risks, and to estimate the corresponding maximum water levels in equivalent return periods. After comparing the designed levels and planned filling heights, the simulated water levels in front of the dam can be employed to determine the necessary flood control requirements and construction schedule adjustments according to the various acceptable risks suggested by different decision makers. However, the filling height model sometimes simplified the stoppage standards for rain during dam construction and assumed that stoppage and rain-proofing actions would directly delay the construction period in the critical path. In addition, closing the diversion tunnel gates and plugging tunnels to satisfy the dam storage requirement during late-term diversion should be further discussed, as the sudden changes in the discharge capacity of diversion tunnels will have an distinct influence on the diversion risk.

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Liu Lian: Graduated from the College of Water Resources and Hydropower, Wuhan University in Wuhan City, China, in 2014 with a Ph.D. in the field of hydropower engineering construction; from the College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang, China, in 2011 with a Master's degree in the field of management science and engineering; and from the College of Economics and Management, China Three Gorges University in 2008 with a Bachelor's degree in the field of information management and information systems.

She is an associate professor of hydropower engineering management at China Three Gorges University. Her research interests include dam construction risk analysis and decision making, quantitative risk assessment, and stochastic simulation.