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"Gheorghe Asachi" Technical University of Iasi, Romania

RESEARCH ON DESIGNING FOR FLOOD RISK BASED ON ADVANCED CHECKING-POINT (JC) METHOD

Lingzhi Huang*, Shouyi Li, Zheng Si

Xi'an University of Technology, Xi'an, Shaanxi, 710048, China

Abstract

Designing for flood risk is an important reference for hydroelectric project planning and design. In this paper, advanced checking-point method (JC method), which is usually used to calculate structure reliability is introduced and used to analyze the downstream design for flood risk, considering upper reservoirs' influence; besides, the design for flood hydrograph is deduced from the typical flood hydrograph. So, JC method not only can consider the influence of upper reservoirs, but also can calculate the design for flood risk on that impact. This is a new attempt to study flood and water project design.

Key words: design flood risk, design flood region composition, JC method

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1. Introduction

For the regulation function of upstream reservoirs or some other flood detention and diversion projects, which all can actually affect the nature characters of flood (Afshar and Marino, 1990), the flow of downstream will be directly changed. So it is important for the downstream design section to analyze the affected flood volume and its homologizing regulation. Design flood region composition refers to the calculation of corresponding peak discharge of each control section and interval when downstream control region has a certain design frequency flood. During the real calculation, several different calculation schemes (Professional Standard of China, 2006) are needed to select the result that may satisfy the design requirements.

Currently, common ways used to calculate the flood region composition are typical year method, homogenous frequency method, frequency combination method and stochastic simulation method. Typical year method refers to selecting those flood which are representative and adverse to flood control from the measured data as typical flood, and regarding flood volumes of design section as a control to calculate the corresponding flood volume of each section according to the proportion of each region flood volumes accounted for flood volumes of design section in typical years. The homogenous frequency region composition method means designating a partition which has the homogenous frequency flood volumes with the downstream design section, and the corresponding flood volumes of the rest partition distributed according to the actual typical year composition.

Therefore, typical year method allocates flood according to the flow parts proportion of the typical year, and homogenous frequency method do this allocation by deciding which part is of same-frequency. These two methods are easy to calculate and are the common methods applied in engineering design as well as the required methods used to calculate the assigned frequency flood composition complying with Regulation for Calculating design flood of water resources and hydropower projects

* Author to whom all correspondence should be addressed: e-mail: hlzsz@126.com; Phone: 0086-15829472610

(SL44-2006). However, both of these two methods may ignore the most dangerous case (Ang and Tang, 2007). Based on reservoir inflow and interval natural flood frequency curve, frequency combination method studies all possible combinations of the flood of each partition and calculates reservoir flood regulating effects on flood of design section under various combinations of situations, thus derive the flood frequency curve and the design value of design section influenced by the reservoir flood regulating. Therefore, frequency combination method greatly depends on the accuracy of frequency curve.

The last method generates a long enough flood series randomly, then dispatch flood to calculate downstream series, regardless of the complicated encounter problems. Since manual flood series is of much work and great inaccuracy, it is not often used in practical work. Besides, considering the great randomness of flood, flood region composition should also take into account of risk, which is ignored by the former four methods.

Advanced checking-point method (JC method) is used to calculate structure reliability, with its mature principle and algorithm, which can find the most dangerous point on failure surface (Rackwitz and Fiessler, 1978). This paper studies the theory and model of using JC method to calculate the design flood risk. It is supposed to get the most dangerous flood composition scheme and failure risk of design flood, and then calculate the design flood process based on typical year flood. This method is a supplement to the present flood design methods.

2. Mathematical modeling of advanced checking-point (JC) method on flood region composition

2.1. Introduction of JC method

JC method is recommended by Joint Committee on Structural Safety (JCSS) to analyze structural reliability (CEB, 1978). The structure limit state equation is expanded by Taylor series and linearized, and the reliability can be obtained with the equation's first and second order moment (Rackwitz and Fiessler, 1978). Compared to first-order second-moment method (FOSM) and advanced first-order second-moment method (AFOSM), JC method can do solution even when state function is nonlinear, and all variables distribution need no limit, the most unfavorable combination and failure risk of variables can be obtained on failure surface (JCSS, 2000).

By now, the theory of JC method has been developed perfectly, and is widely used to some other fields, such as hydraulic design of dam (Mays, 1978), safety design of reservoir spillway tunnel (Chen and Wang, 1996) and so on.

2.2. Mathematical modeling

In water resources engineering management, the risk refers to those unexpected events occur under the condition of a certain time and space. The value of risk refers to the probability of those unexpected events, or defined as the probability which surpassed a certain threshold. According to the hydrologic frequency concept, that is the probability interval which exceeds a certain value.

In this paper, design flood risk P_f is defined to be the probability that the sum of upstream reservoir discharge and region inflow is greater than design flood. On the assumption that the actual maximum inflow volume in control time t of upper reservoir X is $W_{t,I}$, actual maximum flood volume of section Y in control time t is $W_{t,Y}$, design flood volume in control time t of section Z, which is the design section, is signed as $W_{t,d}$, as Fig. 1 shows.

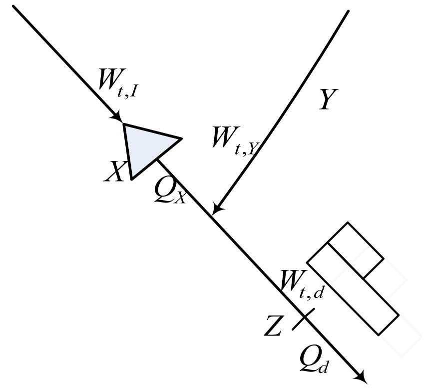

Fig. 1. Protective zone at the single reservoir's downstream

Expression of limit state equation is Eq. (1):

$$g = W_{t,d} - W_{t,I} - W_{t,Y} = 0 \tag{1}$$

Risk is expressed as given by Eq. (2):

$$P_f = 1 - P(W_{t,Y} + W_{t,I} < W_{t,d}) \tag{2}$$

If the downstream protected object is controlled by flood peak, such as dike, then the limit state equation is expressed by Eq. (3):

$$g = Q_d - Q_Y - Q_X = 0 \tag{3}$$

where: Q_d is the flood peak of protected object corresponding to design frequency; Q_X is the discharge runoff of upstream reservoir X, Q_Y is the flood flow of tributary Y.

2.3. Probability distribution of model variables

2.3.1. Probability distribution of flood volume

In China, natural flood process is often regarded as Pearson type-3 distribution (Professional standard of China, 2006), so the probability density function of reservoir X's inflow volume $W_{t,I}$ and section Y's flood volume $W_{t,Y}$ both are expressed as:

$$f(x) = \frac{\beta^{\alpha}}{\Gamma(\alpha)}(x-b)^{\alpha-1} e^{-\beta(x-b)} \qquad (b \le x \le \infty) \tag{4}$$

where α, β and b, which describe the distribution shape, scale and location respectively, can be calculated by hydrological parameters EX (mean value of random variable x, C_v (variation coefficient of random variable x) and C_s (skewness coefficient of random variable x).

$$\alpha = \frac{4}{C_s^{\ 2}} \quad ,\beta = \frac{2}{EXC_vC_s} \quad ,b = EX(1-\frac{2C_v}{C_s}) \qquad (5)$$

2.3.2. Probability distribution of flood peak

Natural flood peak probability distribution obey Pearson type-3 distribution (Professional Standard of China, 2006), but it would be changed greatly after regulation and storage by upper reservoir. Probability distribution of downstream section flood is affected by both natural flood and reservoir operation rules, its real distribution can be solved by probabilistic composite method.

3. Calculation flows of JC method on design flood risk

Using JC method to analyze design flood risk mainly contains: allocating flood volume by JC method, calculating the risk according to former allocating values, and deducing design flood hydrograph based on typical year process.

3.1. Flood volume allocation and risk calculation by JC method

The flow chart as limit state of Eq. (1) or (3) solved by JC method is shown in Fig. 2.

Taking the limit state Eq. (1) as example, the calculation steps (Shiwei, 1990) are given as following:

(1) Given the limit state equation and initial reliability value R_0 and determine all variables distribution type and characteristic parameters of limit state equation.

(2) Assume all initial values of variables, i.e. initial coordinate X_{i1}*.

(3) Normalize the non-normal distribution of variables, i.e. replace non-normal distribution by normal distribution as values of cumulative probability distribution function (CDF) and probability density function (PDF) on design checking point x_i* is consistent with the values of original distribution function (Eqs. 7, 8), that is:

$$F_{X_i}(x_i^*) = \Phi(\frac{x_i^* - M_i^{'}}{\sigma_i^{'}}) \qquad (7)$$

$$f_{X_i}(x_i^*) = \phi(\frac{x_i^* - M_i^{'}}{\sigma_i^{'}}) \cdot \frac{1}{\sigma_i^{'}} \qquad (8)$$

Then, the mean value M_{Xi} and the variance σ_{Xi} of equivalent normal distribution can be calculated using Eqs. (9, 10):

$$\sigma_{X_i} = \phi[\Phi^{-1}(F_{X_i}(x_i^*))] \big/ f_{X_i}(x_i^*) \qquad (9)$$

$$M_{X_i} = x_i^* - \sigma_{X_i}\Phi[F_{X_i}(x_i^*)] \qquad (10)$$

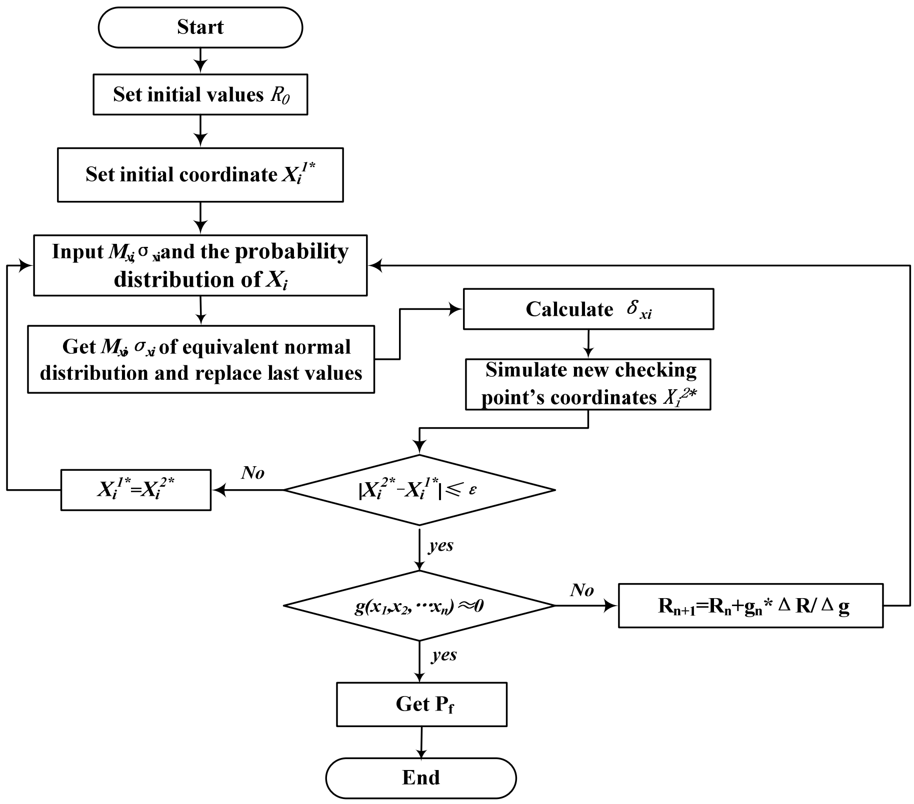

Fig. 2. Flowchart of JC method

where $F_{X_i}(\cdot)$, $f_{X_i}(\cdot)$ is CDF, PDF of variable X_i's original distribution function respectively; $\varphi(\cdot)$, $\Phi(\cdot)$ is CDF, PDF of standard normal distribution; and $M_i^{'}$, $\sigma_i^{'}$.is mean values and variances of original distribution function.

(4) Calculate sensitivity coefficient δ_{X_i}, which expresses the relative influence of random variable X_i to whole standard deviation (Eq. 11):

$$\delta_{X_i} = \frac{\sigma_{X_i} \cdot \frac{\partial g}{\partial X_i}|_{X_i^{1*}}}{\sqrt{\sum_{i=1}^{n}(\sigma_{X_i}\frac{\partial g}{\partial X_i}|_{X_i^{1*}})^2}} \tag{11}$$

For the limit state, equation (1), M_1, M_2, σ_1, σ_2 are expressed as mean values and variances of $W_{t,I}$, $W_{t,Y}$ respectively, then sensitivity coefficients of $W_{t,I}$ and $W_{t,Y}$ are given by Eq. (12):

$$\begin{cases} \delta_1 = \dfrac{\sigma_1}{\sqrt{\sigma_1^2 + \sigma_2^2}} \\ \delta_2 = \dfrac{\sigma_2}{\sqrt{\sigma_1^2 + \sigma_2^2}} \end{cases} \tag{12}$$

(5) Calculate new checking point's coordinates and reliability value through iterative computation until the results difference of two successive iterative computations less than ε (Eq. 13).

$$\begin{cases} W_{t,I}^{2*} = M_1 - \delta_1 R_0 \sigma_1 \\ W_{t,Y}^{2*} = M_2 - \delta_2 R_0 \sigma_2 \end{cases} \tag{13}$$

(6) When the iteration is stable, final checking point's coordinates, which are the most dangerous flood allocation composition on failure surface, and final reliability value R can be obtained, then $1-\Phi(R)$ is the flood risk.

3.2. Calculation of design flood hydrograph

Choosing the most unfavorable flood year from the actual series as typical year, then amplifier each parts' flood hydrograph based on flood volume allocation results. The outflow process of upper reservoir can be calculated according to its flood regulation rules, and then combined with the flood process of section *Y*, thereby the flood process and flood peak of design section *Z* can be obtained. Lastly, analyze the rationality of above results, do few modification and adjustment if necessary.

4. Case studies

Flood protection standard is a 100-year flood recurrence of design section (section *Z* in Fig. 1). Considering the influence of upper reservoir (*X* in Fig. 1), try to calculate the flood process at section *Z* on design frequency 1%.

4.1. Fundamental data

The flood section Z consists in the outflow of upper reservoir *X* and regional flood *Y*, its statistical parameters can be calculated based on historical flood data, assuming control time 15 days. The results are shown in Table 1.

Flood dispatching rules of upper reservoir *X*: when reservoir runoff flood is less than 4250m^3/s, the discharge equals to the inflow; when runoff is more than 4250m^3/s, and less than 1% frequency flood flow, the discharge is controlled to be 4250m^3/s; when runoff is more than 1% frequency flood flow, release without control.

4.2. Analysis flood composition by JC Method

4.2.1. Selection of typical year flood composition

According to history data, deluges occurred at design section Z in 1963, 1964, 1967, 1968, and 1981. Except the flood in 1964, which happened on July, with a thin flood curve, others all happened on September, with a large flood curve. Analyzing the 15-day-flood volume composition of upper reservoir *X* and region *Y* as section *Z* accruing maximum 15-day-flood volume, it can be found that flood of section *Z* is mainly formed by upper inflow, region flood account for a little share.

The foregoing deluge years, except 1981, are of a large region inflow, especially 1963, 1964, which even are of super-frequency floods. So, upon all above analysis, select flood on July, 1964 as typical year composition.

4.2.2. Possibility of discharge peak meeting with regional flood peak

Based on the dispatching rules, the upper reservoir *X* water level is supposed to be on limited water level to prepare for the next flood after this flood peak, that is, reservoir *X* will control discharge flow on 4250m^3/s for a long time.

As 1% frequency flood happened at section *Z*, reservoir *X* will discharge on 4250m^3/s for 24 days, region *Y*, with a steep rising and dropping flood type, flood process commonly persists for 7~8 days, this greatly increases the probability that region peak will be simultaneous with the maximum discharge of reservoir *X*. So, it is suggested to consider the two peaks will superpose when designed.

4.3. Model Solution

(1) Flood allocation and risk calculation

The limit state equation of JC method model is given by the relation (14):

$$57.3 - W_{15,I} - W_Y = 0 \tag{14}$$

where: $W_{15,I}$ and W_Y obey the Pearson type-3 distribution. The calculation results are shown in Table 2. The calculation results show that: when design section Z happens 1% frequency flood, flood allocation volume on upper reservoir and regional river are $55.323\times10^8 m^3$ and $1.977\times10^8 m^3$ respectively, and the design risk can be expressed as $1-\Phi(3.41)=0.3325\%$.

(2) Amplification of typical flood

Amplification factors of each composition part are given in Table 3.

(3) Calculation of design flood process

Amplify the typical flood process of 1964 by using amplification factors in Table 3, calculate the outflow process based on dispatching rules of reservoir X, then deduce the outflow process to design section Z superposing with regional flood process at the same period. The maximum average flow within the prescribed time on section Z is 4450 m^3/s, with a 200 m^3/s from region.

Considering that the discharge of reservoir *X* is no more than $4250m^3/s$, so only the regional flood average flow within time 13 should be transformed to instantaneous flow by multiply a coefficient 1.32, so the maximum instantaneous flow on section Z is 4520 m^3/s.

4.4. The rationality analysis of the results

Based on the frequency curve of flood peak, the natural flood inflow of frequency 1% is 5670 m^3/s on section Z; however, reservoir X's regulation and storage capacity reduces the inflow to 4520 m^3/s. The design data of reservoir X shows its crest-cut of 1% frequency flood is about 1150 m^3/s, so the result is convincible.

Besides, this flood design risk is 0.3325%, which is far less than its hydrological risk 1%, so this design is considered to be safe.

Table 1. Statistical parameters of each section

Item	*parameters*	*mean value*	*variance*	*Cv*	*Cs*	*P=1%*
W_{15} (10^8m^3)	Upstream flood (*X*)	26.5	9.01	0.34	1.36	/
	Regional flood (*Y*)	1.9	0.99	0.52	1.82	/
	Design section flood (*Z*)	/	/	/	/	57.3

Note: All data in table 1 are hydrological parameters of natural water.

Table 2. Results of JC method

cycle number	*risk*	$W_{15,I}$ (10^8m^3)	W_Y (10^8m^3)
1	$1-\Phi(5)$	69.739	2.154
2	$1-\Phi(4)$	60.674	2.043
3	$1-\Phi(3.41)$	55.323	1.977
4	$1-\Phi(3.41)$	55.323	1.977

Note: Data in line 1 refers to initial value, after four rounds trial calculation according to "3.1. Flood Volume allocation and Risk calculation By JC Method", flood allocation results and the corresponding risk values are obtained.

Table 3. Amplification factors of flood hydrograph and each subfield's flood volume

Item	*Upper reservoir section*		*Region*	
	W_{15} (10^8m^3)	*amplification factor*	W_{15} (10^8m^3)	*amplification factor*
Typical flood of 1964	31.9		1.8	
Design flood	55.323	55.323/31.9=1.734	1.977	1.977/1.8=1.098

Note: Data in line 1 is hydrological parameters in typical years

Table 4. Calculation of flood hydrograph unit: m^3/s

Period of time	*Typical flood hydrograph of 1964*			*Designed flood hydrograph*			
	Section Z	*Upper-reservoir inflow*	*Regional flow*	*Upper-reservoir inflow*	*Regional flow*	*Upper-reservoir outflow*	*Section Z flow*
	(1)	(2)	(3)	(4)=(2)×1.734	(5)=(3) ×1.098	(6)	(7)=(5)+(6)
…	…	…	…	…	…	…	…
10	2580	2510	170	4350	190	4250	4440
11	2590	2400	210	4160	230	4160	4390
12	2620	2560	160	4440	180	4250	4430
13	2530	2450	180	4250	200	4250	4450
…	…	…	…	…	…	…	…
				Q_{max}=4250+200×1.32≈4520			

Note:① Amplification coefficients 1.734 and 1.098 come from the calculation results in Table 3.② Because of the big volume of flood, flow values round to ten level.③ Data column (6) refers to outflow flood process ④ Calculation of Table 4 does not considered the regulation and storage capacity of river.

5. Conclusions

It is a new attempt to apply JC method to analyze flood region composition. JC method get rid of dependence on frequency curve, and find the worst flood region composition on failure surface based on the probability distribution of all composition factors. It can be used even when the natural flood frequency curve is inaccurate. Besides, JC method can gain the design flood risk of the composition results, if the permitted risk is provided, safety of the design section can be decided, and sometimes the discharge grade would be adjusted if necessary.

In this paper, only one single reservoir on upper stream is discussed, the uses of JC method on group reservoirs still need deeper research. In addition, flood process is random, but the combination of flood volume of trunk stream exists a certain rule. Therefore, how to express the complex hydrological rule as the boundary conditions of JC method will also be one of the directions of the further research.

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