The earth dam overtopping risk model and computational method for tow reservoirs in series

LIJUAN ZHANG [1,2] ZHONG LI [2] ZHAOHE CHEN [1] SUPING PENG [2]
Department of foundation education……
1 Beijing University of Technology, Beijing 100083, China
2 China University of Mining and Technology, Beijing 100044, China
zhlijun@tom.com

Abstract: In this paper, the earth dam overtopping risk theory for cascade reservoirs is developed considering all uncertainties of inflow flood, wind wave, reservoir storage, discharge capacity and interactions between two consecutive reservoirs. The theory for cascade reservoirs is generalized from the overtopping risk theory for single reservoir developed by previous researchers [9~12]. A computational method for risk, called AFOSM-JC method for cascade reservoirs, is developed according to the risk computation method such as Direct integration, Monte Carlo, MFOSM, AFOSM, Rackwitz—Fiessler(JC), WU method, and so on. A case study for two existing reservoirs in series is given by applying the method and corresponding computational procedure presented herein. In the application the overtopping risk is calculated for a series of cascade reservoirs including Xiao Nanhai and Zhang Wu reservoirs; and the possibility of driving up the limiting level before flood (LLBF) is discussed.

Key-Words: Overtopping risk , reservoirs in series , AFOSM-JC method ,safety reliability , earth dam

1 introduction

Flood risk analysis research has made prodigious development, but only one or tow risk factors be considered in most of these literatures [1-7] .Only in literatures [8-12] authors consider all possible uncertainties such as uncertainties resulted from inflow flood, wind wave, reservoir storage, discharge capacity in analyzing the overtopping risk for single reservoir. The overtopping risk theory for single reservoir has been developed and successfully applied to four existing reservoirs[8~12]. Basing on it, the overtopping risk model and computation method for two reservoirs in series are developed in this paper. The overtopping risk model and computation method for upper reservoir will be described first, then for lower reservoir, finally for the system of two reservoirs. An application to two existing reservoirs in series is presented here by using the method and computation procedure in this paper. Furthermore, the overtopping risk model and computation method for multiple reservoirs in series have also been developed by the authors, but they will not be discussed in this paper due to the limited space .

2 Uncertainties

For a single reservoir the uncertainties are listed as follows:

a. Inflow flood

An inflow flood is either a designed, or a forecasted, or a measured one, it is always considered in the traditional reservoir design as a random process. For the design flood, its randomness is initiated from the stochastic characteristics of the statistics of historical hydrological data(storm rainfall ,peak flow of flood, etc), of typical flood hydrograph ,of loss of rainfall, and of unit hydrograph. And the design flood is considered P−Ⅲ distribution usually.

b. Discharge capacity

The discharge capacity is a random quantity whose randomness is resulted from many sources, such as the schematization of 3D flow to1D flow, the value of roughness coefficient, the Scale effect of model test and various tolerances in geometrical sizes during construction.

c. Reservoir area and storage volume

Although the reservoir area and storage volume are traditionally considered as deterministic quantities, they are actually random variables. The contour lines plotted by different surveyors for a given reservoir topography may be different. with the same contours, the calculated reservoir area and storage volume at a given level may be different due to variety of computation philosophy and instrument used. Moreover, the underwater topography may change due to the sediment transportation during and after a flood.

d. Wind

The wind of any magnitude from any direction is a random event. As for the overtopping risk of an earth dam, the wind toward the dam during flood period is major concern and is define as "effective wind for overtopping" by us. Due to lack of data we take the series of maximum wind toward the dam during flood period when we analyzed the overtopping risk, which will bring the results of risk analysis conservatively.

For reservoir in series the uncertainties are as follows. Besides inflow flood, wind wave, reservoir storage volume, and discharge capacity, the uncertainties also include intervening flood between upper and lower reservoir, the design flood composition for reservoir in series, the overtopping risk of upper reservoir transferred to the lower reservoir, which will be deduced later.

3 overtopping risk theory for two reservoirs in series

Overtopping refers to the situation that reservoir water level Z rises above the top elevation of the dam Z_C. Overtopping risk $\overline{R}$ is the probability of reservoir water level over the top elevation of the dam during a specified period T for analysis, and may be expressed as

$$\overline{R}(T) = P(Z(t) \geq Z_c) \quad 0 \leq t \leq T \qquad (1)$$

If Z(t) is a periodic random process with a period of C (such as annual hydrological cycle), the risk within time interval T may be derived from that during only one period C as follows:

$$\overline{R}(T) = 1-(1-P_0)^{T/C} \qquad (2)$$

Where T/C is a positive integer and P_0 is the risk during only period C. The relationship between $\overline{R}$ and safety reliability R is

$$\overline{R} + R = 1 \qquad (3)$$

Z(t) is a periodic random process with a period of one year and the risk within time interval T may be derived from that during one year and therefore the study of annual overtopping risk becomes the basic of research on overtopping.

The truth for only serious loads can cause an overtopping event is used to simplify the load series L(t) as a series of annual maximum random events $L_{\max}$ and When it is multiple loads take it as the sum of individual series of each maximum random load. The above simplification brings obviously some approximation, but it is simple and practical while the approximations make the results of risk analysis both with satisfactory accuracy and on the safe side.

So, if we consider the main four factors of uncertainty, i.e. flood, wind, discharge capacity and reservoir storage volume, we can built the overtopping risk against simultaneous action of annual maximum flood and wind wave during flood period as follows.

$$R = P(Z(t) \geq Z_c) = P(Z_0 + H_{\max} + e + Rp \geq Z_C) \quad (4)$$

The equation is the overtopping risk against the series of flood and the series of wind. where Z_0 is water level before flood, $h_{\max}$ is maximum water level rise due to load, Z_C is a critical elevation control level (such as dam crest elev. or top elev. of parapet), e is setup due to wind, Rp is run up.

When the flood event $[Q_{i-1}, Q_i]$ and wind event $[W_{i-1}, W_i]$ occur simultaneously, the overtopping risk P_{ij} is :

$$P_{ij} = P(Z_0 + H_{\max i} + e_{ij} + Rp_{ij} \geq Z_C) \quad (5)$$

And the total overtopping risk is as following.

$$\overline{R} = \sum_{i=1}^{\infty} f_Q(Q_i) dQ_i [\sum_{j=1}^{\infty} f_W(W_j) dW_j P_{ij}] \quad (6)$$

2.1 The risk computation method

The risk computation methods include direct integration method, Monte Carlo method, MFOSM method, AFOSM method, Rackwitz—Fiessler(JC) method, WU method and so on. At the present time, AFOSM and JC methods are more popular flood risk computation method in literatures compared to the methods such as straight integral method, MC method and MFOSM method.

In this paper we use AFOSM - JC method. Because of difficulties such as the probability distribution and inhesion relation of various random variables usually are not available, we cannot use direct integration method. In MFOSM method, Taylor linear expansion is used to simplify the computational problem, and mean and variance are calculated to model the probability distribution. AFOSM method is the method which uses extreme point (risk point) in Taylor linear expansion according to abnormal distributions. We adopt the main idea of the AFOSM method in our method. We also use JC method to replace abnormal distribution with normal distribution.

2.2 Overtopping risk model and computation method for upper reservoir of two reservoirs in series

In the system of two reservoirs in series, whether the lower reservoir overtopping occurs or not, the lower reservoir doesn't affect the upper one, and other factors such as water level or discharge volume between the two reservoirs have been considered in the regulation scheme. While there is no backwater effect, it is unnecessary to consider the lower reservoir during the computation of overtopping risk for the upper reservoir. Thus, the overtopping risk model and computation for upper reservoir are the same as that for a single reservoir. The main sources of uncertainty are resulted from four factors, i.e. flood, wind, discharge capacity and reservoir storage volume. This overtopping risk against simultaneous action of annual maximum flood and wind wave during flood period is as follows.

For the upper reservoir, assume Q_u is in flood peak series $[Q_{u(i-1)}, Q_{ui}]$ and its probability of occurring is $f_{Qu}(Q_{ui})dQ_{ui}$, whereas W_u is in wind series $[W_{u(j-1)}, W_{uj}]$, its probability of occurring is $f_{Wu}(W_{uj})dW_{uj}$. Under these two factors, the overtopping risk $\overline{P}_{ij}$ is :

$$\overline{P}_{ij} = P(Z_{0u} + H_{fu\max i} + e_{uij} + Rp_{uij} \geq Z_{Cu}) \quad (7)$$

where Z_{0u} is the water level before flood, and is fixed as a constant for a given regulation scheme, $h_{fu\max}$ is the maximum water level rise due to load and normally distributed, Z_{Cu} is a critical elevation control level (such as dam crest elev. or top elev. of parapet), e_{uij} is setup due to wind, Rp_{uij} is run up, f_{Qu} is the probability density function for flood peak. f_{Wu} is the probability density function for wind velocity during flood period. The probability distribution of maximum wind velocity during a time interval is extreme type I distribution. The subscript u refers to the upper reservoir. The risk can be computed with AFOSM-JC method. So the overtopping risk $\overline{R}_{uij}$ with the flood peak in $[Q_{u(i-1)}, Q_{ui}]$ and wind in $[W_{u(i-1)}, W_{ui}]$ is:

$$\overline{R}_{uij} = f_{Q_u}(Q_{ui})dQ_{ui}\, f_{Wu}(W_{uj})dW_{uj}\, \overline{P}_{uij} \qquad (8)$$

and the total overtopping risk may be written as:

$$\overline{R_u} = \sum_{i=1}^{\infty} f_{Q_u}(Q_{ui})dQ_{ui}[\sum_{j=1}^{\infty} f_{Wu}(W_{uj})dW_{uj}\, \overline{P}_{uij}] = \int_b^{Q_{Pu}} \int_0^{W_{Pu}} f_{Qu}(Q_{ui}) f_{Wu}(W_{uj}) \overline{P}_{uij}\, dQ_{ui}\, dW_{uj} \qquad (9)$$

2.3 Overtopping risk for lower reservoir in two reservoirs in series

2.3.1 The factors influencing overtopping risk for the lower reservoir

The factors influencing overtopping risk for the lower reservoir are:

1）the uncertainty of inflow flood (including discharge flood from upper reservoir and intervening flood between upper and lower reservoir), wind wave, reservoir storage volume, discharge capacity, and the overtopping risk of upper reservoir transferred to the lower reservoir.

The transferring of risk from upper reservoir may occur in one of the following two cases.

①The upper reservoir doesn't overtop. In this case, the overtopping risk of upper reservoir can be regarded as a factor of overtopping risk for lower reservoir.

②The upper reservoir overtops. In this case, two conditions A and B should be considered:

A. The upper reservoir overtops, and then the lower reservoir overtops successively such that the overtopping risk for lower reservoir is equal to that for the upper one.

B. The upper reservoir overtops, but the lower reservoir doesn’t overtop. Obviously, case A is more serious than case B. Therefore, for the safety evaluation and overtopping analysis of two reservoirs in series, we should consider the case A only.

2） the sequence of discharge for both the upper and lower reservoirs which can be considered in a specified regulation scheme .

3） the sequence of flood occurring in the upper or lower reservoir which can be reflected by flood regional synthesis for the lower reservoir .

2.3.2 Overtopping risk for lower reservoir against the simultaneous action of annual maximum flood series and wind wave during flood period.

Considering the simultaneous action of annual maximum flood series and wind wave, the overtopping risk for lower reservoir can be expressed as follows.

$$\overline{P}_{dij} = P(Z_{0d} + H_{fd\max} + e_{dij} + Rp_{dij} \geq Z_{Cd}) \qquad (10)$$

where the subscripts “d” refer to the lower reservoir. The overtopping risk for lower reservoir can be solved with integration-AFOSM method for two reservoirs and the procedure of computation is as follows.

1）divide the annual maximum flood series at the dam site of lower reservoir into a large number of small intervals, for any small interval $[Q_{Pt}(i-1), Q_{Pt}(i)]$, its occurrence probability is $P_i = f_{Q_{Pt}}(Q_{Pt}(i))dQ_{Pt}(i)$, where $Q_{Pt}(i)$ within the interval can be regarded as a fixed value,

$Q_{Pt}(i)$,instead of flood peak, may be either flood volume or net rainfall), and $Q_{Pt}(i)$ is the corresponding hydrograph of the annual maximum flood.

2) The corresponding upper reservoir flood $Q_u(i)$ and intervening flood $Q_b(i)$ with flood hydrograph $Q_{ui}(t)$ and $Q_{bi}(t)$, respectively can be computed from the regional composition of lower reservoir flood .

3)Let $Q_{ui}(t)$ be the inflow flood of upper reservoir. With the assumption that $Q_{ui}(t)$ and $[W_{u(j-1)}, W_{uj}]$ occur simultaneously, the upper reservoir risk $\overline{P}_{uij} = P(Z_{0u} + H_{fu\max} + e_{uij} + Rp_{uij} \geq Z_{Cu})$ can be computed with AFOSM—JC method, while the upper reliability is $1-\overline{P}_{uij}$.
As mentioned above, two cases should be dealt with separately to compute overtopping risk of the lower reservoir considering the transfer of the upper reservoir risk.

The first case: the upper reservoir doesn't overtop and does operate normally. The computation can be proceeded as follows.
4) divide the lower reservoir wind series into a great number of small intervals $[W_{d(m-1)}, W_{dm}]$ with corresponding occurrence probability $P_{Wd} = f_{Wd}(W_d(m))dW_d(m)$. within any interval $[W_{d(m-1)}, W_{dm}]$, the setup due to wind can be computed and the runup follows Rayleigh distribution. So the overtopping risk for lower reservoir is

$$\overline{R}_{1dm} = P(Z_{0d} + H_{fd\max} + e_{dij} + Rp_{dij} \geq Z_{Cd}) \quad (11)$$

5) Then, the total overtopping risk of lower reservoir is

$$\overline{R}_{2dm} = \sum_{i=1}^{\infty} f_{Q_{Pt}}(Q_{Pt}(i))dQ_{Pt}(i) \sum_{j=1}^{\infty} f_{W_u}(W_u(j)dW_u(j)(1-\overline{P}_{uij}) \sum_{m=1}^{\infty} f_{W_d}(W_d(m)dW_d(m)\overline{R}_{1dm} \quad (12)$$

The second case: the upper reservoir overtops and the lower reservoir overtops successively.
6) In such a case, the overtopping risk for the lower reservoir is equal to that for the upper reservoir therefore ,

$$\overline{R}_{3dm} = \sum_{i=1}^{\infty} f_{Q_{pt}}(Q_{pt}(i))dQ_{pt}(i) \left(\sum_{m=1}^{\infty} f_{Wu}(W_u(j)dW_u(j)\overline{P}_{uij}\right) \quad (13)$$

7) The overtopping risk for the lower reservoir is summed up as

$$\overline{R}_d = \overline{R}_{2dm} + \overline{R}_{3dm}$$

$$= \sum_{i=1}^{\infty} f_{Q_{Pt}}(Q_{Pt}(i))dQ_{Pt}(i) \sum_{j=1}^{\infty} f_{W_u}(W_u(j)dW_u(j)(1-\overline{P}_{uij}) \sum_{m=1}^{\infty} f_{W_d}(W_d(m)dW_d(m)\overline{R}_{1dm} \square$$

$$+ \sum_{i=1}^{\infty} f_{Q_{pt}}(Q_{pt}(i))dQ_{pt}(i) \left(\sum_{m=1}^{\infty} f_{Wu}(W_u(j)dW_u(j)\overline{P}_{uij}\right) \quad (15)$$

2.4 Overtopping risk model and computation method for the system of two reservoirs in series

If the two reservoirs in series are considered as a system, the failure due to overtopping of any one reservoir will cause the system failure. Therefore the failure probability of the reservoir system is due to both upper and lower reservoir failure probability A and B. So, the failure probability of the reservoir system is:

$$\overline{R}_f = P(A \cup B) \quad (16)$$

Following the theory of probability, we have

$$\overline{R}_f = P(A) + P(B) - P(AB) = P(A) + P(B) - P(A)P(B/A) \quad (17)$$

where P(B/A) is the conditional probability that the lower reservoir overtops given the upper reservoir overtops. Because only one case that the lower reservoir overtops successively after the upper reservoir overtops to be considered in this paper, then P(B/A)=1 and

$$\overline{R}_f = P(A \cup B) = P(B) \qquad (18)$$

The equation (18) means that the overtopping risk for the reservoir system is equal to that for the lower reservoir and may be computed by equation (15).

3 The overtopping risk criteria

Regarding the flood prevention duty reservoirs, particularly the earth stone dam reservoirs, choosing the overtopping risk standard is very important. According to the statistics of dam overtopping or dam breaking in the US, Japan, Spain and some other countries, the earth dam overtopping risk standard is 10^{-5} Magnitude. In China, the statistic data of dam overtopping or dam breaking indicate the probability for Chinese reservoirs earth dam breaking due to dam overtopping is 10^{-5} Magnitude per year per dam also. For the reservoirs that when their dams break they could cause serious consequences, the limit restrictions must be raised. For earth dam the overtopping is strictly forbade unless it is previously permitted during designing. Once overtopping of earth dam occurs, the dam should be considered as beginning of dam break which may result in a catastrophe. So in literature[1~6], the order of magnitude of 10^{-6} was taken as acceptable risk and the corresponding reliability is more than 99.999%. This criterion will be used for the two reservoirs in series before the publishing of national standard.

4 Engineering application

The overtopping risk theory for two reservoirs in series is applied to Xiao Nanhai and Zhang Wu reservoirs in series to investigate the overtopping risk for them and the possibility of increasing flood limiting water level. Xiao Nanhai reservoir lies on Nanyanghe river, a tributary of of Weihe river of Haihe river system. The two reservoirs are utilized jointly to achieve diversified economic benefits such as flood prevention, irrigation, pisculture and so on. Xiao Nanhai's reservoir storage volume is $1.0745 \times 10^8 m^3$. Zhang Wu reservoir locates 10 km downstream from Xiao Nanhai, with a total reservoir volume of $0.7829 \times 10^8 m^3$. The dam crest elevation, top elevation of parapet, design flood frequency with corresponding peak, extreme flood frequency with corresponding peak, as well as the original designed limiting water level before flood for Xiao Nanhai reservoirs are 188.10 m, 189.20 m, 1/100 with 4300 m^3/s , 1/2000 with 8440 m^3/s , and 160.0 m respectively, And the counterparts for Zhang Wu reservoir are 137.6 m, 138.8 m, 1/50 with 1994 m^3/s (intervening flood) and 3115 m^3/s (correspondence with Xiao Nanhai), 1/1000 with 3410 m^3/s (intervening flood) and 6245 m^3/s (correspondence with Xiao Nanhai) and 123.6 m respectively .

The frequency of design flood of Xiao Nanhai is 1%, The frequency of extreme flood of Xiao Nanhai is 0.5%, and the frequency of design flood of Zhang Wu is 2%, the frequency of extreme flood of Zhang Wu is 0.1% respectively. The two reservoir design flood series are deduced by rainstorm material indirectly. According to the clear distinction of zone topography, geological conditions in upper Henshui and zone of Henshui ~ Xiao Nanhai, as well as the characteristics of the area composition of the reservoir flood, it can be divided into four units: (1) zone of Henshui ~Xiao Nanhai (2) upper Xiao Nanhai, (3)zone of to Xiao Nanhai ~Zhang Wu, (4) upper Zhang Wu. Through produces of mingle and runoff generations and calculates of the design flood composition the design flood of Xiao Nanhai reservoir and Zhang Wu reservoir is obtained. Because we use the flood series frequency distribution when we calculate risk, therefore we do not apply directly the given flood process line, but apply primitive rainstorm series.

The flood load process used in the risk computational process, is produced by computation of mingle and runoff generations. Thus using project characteristic of the upper and lower reservoir, the aerial drainage relations, the reservoir characteristic curve, the character and wind material and so on, we obtain the risk value.

On the basis of data presented by the reservoir administration the results of risk computation with the method mentioned above are show in tables 1 and 2.

When the design flood was taken as the upper limit of flood series, the overtopping risks computed for upper reservoir, lower reservoir and the reservoir system are all 0.000000000, which means high safety reliability for overtopping.

When the extreme flood was taken as the upper limited of flood series, table 1 and 2 show that for the upper reservoir-Xiao Nanhai, even though the limiting level before flood is raised from the original designed level 160 m to normal light water 173 m , it still holds a risk less than 10^{-6} and keeps overtopping safety, while for the lower reservoir –Zhang Wu, even though the limiting level flood is lowered from the original designed level 123.6 m to dead water level 118.0 m, it still holds a risk higher than the acceptable one, 10^{-6} and keeps not overtopping safety. As for the two reservoirs considered as a system, Table 1 and 2 show also that the system does not keep overtopping safety.

A thorough analysis for the highest water level in both reservoirs was carried out and the results show that both discharge capacities in the beginning period are not enough, which causes the results mentioned in the above paragraph. In order to improve flood control and ensure safety, we suggest that either increase the dam height or increase the discharge capacity, which should be decided by technical and economic analyses and comparison.

5 Conclusion

The results show that if the order of magnitude of 10^{-6} was taken as overtopping risk criterion, or the corresponding safety reliability against overtopping was taken as 99.999%, When the design flood was taken as the upper limit of flood series, the overtopping risks computed for upper reservoir, lower reservoir and the reservoir system are all 0.000000000, which means high safety reliability for overtopping. When the extreme flood was taken as the upper limited of flood series the overtopping risks of both Zhang Wu and Xiao Nanhai reservoir as well as the two reservoirs system against simultaneous actions of flood series and wind wave during flood period under the respective original regulation scheme are over the criterion. Whereas the LLBF should be lowered, instead of increasing .Thus an analysis for the highest water level in both reservoirs was carried out ,and the results show that both discharge capacities in the beginning period are not enough .In order to improve flood control and ensure safety ,we suggest that either increase the dam height or increase the discharge capacity ,which should be decided by technical and economical analyses and comparison . So Overtopping risk analyses model and computation method for reservoirs in series can be used to compute the risk of existing reservoirs in series, it also can be used in design of reservoirs in series. The authors have also developed the overtopping risk model and computation method for multiple reservoirs in series which will not be discussed here due to the limited space.

(1) In this paper the overtopping risk model and computation method for the two reservoirs in series is developed considering all possible uncertainties such as flood, wind, storage volume and discharge capacity as well as the interaction of the overtopping risks between the two reservoirs in series. The computation of overtopping risk for the upper reservoir adopts the computation method for

single reservoir risk. The computation of overtopping risk for lower reservoir has to consider the influence of upper overtopping risk transferred to the lower reservoir.

(2) Engineering application for two reservoirs in series show that through the risk computation for each reservoir and the reservoir system, we can find the relationship between the overtopping risk and the original designed limiting water level before coming flood, and then the limiting water level before coming flood may be optimized with safety reliability of 99.999% to increase the economic benefits of the reservoir system.

(3) The risk computation method for cascade reservoirs AFOSM-JC method was chosen by studying the risk computation method such as direct integration method, Monte Carlo method, MFOSM method, AFOSM method, Rackwitz—Fiessler(JC) method, WU method and so on.

(4) Overtopping risk anlyzes model and computation method for reservoirs in series can be used to compute the risk of existing reservoirs in series, it also can be used in design of reservoirs in series.

(5) The order of magnitude of 10^{-6} was taken as acceptable risk and the corresponding reliability is more than 99.999% for the two reservoirs in series in accordings with the criterion for the single reservoir. This criterion is in favor of security aspect, so the criterion needs to be tested.

(6) The theory of overtopping risk analysis for reservoir in series has been extended to the system of multiple reservoirs, either in series or in parallel, or mixed, which cannot be discussed herein due to the limited space.

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Table 1 The overtopping risk value when each reservoir takes the extreme flood as upper limit of flood series under different limiting water levels of the upper reservoir.

Upper reservoir itself				Lower reservoir itself (H=123.6)			The two reservoirs in series as a system	
H_0	$\overline{H}_{max}$	$\overline{R}_1$	$\overline{R}_2$	$\overline{H}_{max}$	$\overline{R}_1$	$\overline{R}_2$	$\overline{R}_1$	$\overline{R}_2$
160.		1.9334×10^{-7}	3.6913×10^{-8}		1.0134×10^{-5}	1.8835×10^{-5}	1.0327×10^{-5}	1.8872×10^{-5}
160.5	187.5873	1.9379×10^{-7}	3.1251×10^{-7}	137.2609	1.0155×10^{-5}	1.9081×10^{-5}	1.0349×10^{-5}	1.9394×10^{-5}
162.0	187.5873	1.9402×10^{-7}	3.1711×10^{-7}	137.2607	1.0160×10^{-5}	1.9369×10^{-5}	1.0354×10^{-5}	1.9686×10^{-5}
162.3	187.5873	1.9407×10^{-7}	3.1812×10^{-7}	137.2609	1.0171×10^{-5}	1.9518×10^{-5}	1.0365×10^{-5}	1.9836×10^{-5}
163.0	187.5874	1.9412×10^{-7}	3.1985×10^{-7}	137.2614	1.0212×10^{-5}	1.9870×10^{-5}	1.0406×10^{-5}	2.0190×10^{-5}
163.6	187.5878	1.9515×10^{-7}	3.2449×10^{-7}	137.2806	1.1146×10^{-5}	2.8562×10^{-5}	1.1341×10^{-5}	2.8887×10^{-5}
164.0	187.5901	1.9790×10^{-7}	3.5013×10^{-7}	137.2984	1.2088×10^{-5}	3.9213×10^{-5}	1.2286×10^{-5}	3.9563×10^{-5}
166.0	187.6000	2.1252×10^{-7}	4.8721×10^{-7}	137.3630	1.6107×10^{-5}	1.2742×10^{-4}	1.6319×10^{-5}	1.2790×10^{-4}
168.0	187.6049	2.2056×10^{-7}	5.7934×10^{-7}	137.4047	1.9641×10^{-5}	2.3074×10^{-4}	1.9862×10^{-5}	2.3131×10^{-4}
170.0	187.6084	2.4466×10^{-7}	6.4866×10^{-7}	137.4391	2.2693×10^{-5}	3.3488×10^{-4}	2.2937×10^{-5}	3.3553×10^{-4}
172.0	187.6268	2.5438×10^{-7}	1.0568×10^{-6}	137.5594	3.9617×10^{-5}	9.3970×10^{-4}	3.9871×10^{-5}	9.4076×10^{-4}
173.0	189.6380	2.7322×10^{-7}	1.4571×10^{-6}	137.6332	5.7602×10^{-5}	1.3909×10^{-3}	5.7876×10^{-5}	1.3924×10^{-3}

Table 2 The overtopping risk value when each reservoir takes the extreme flood as upper limit of flood series under different limiting water levels of the lower reservoir.

Upper reservoir itself(H=160.0)			Lower reservoir itself				The two reservoirs in series as a system	
$\overline{H}_{max}$	$\overline{R}_1$	$\overline{R}_2$	H_0	$\overline{H}_{max}$	$\overline{R}_1$	$\overline{R}_2$	$\overline{R}_1$	$\overline{R}_2$
187.5872	1.9334×10^{-7}	3.6913×10^{-8}	124.7	137.2650	1.0280×10^{-5}	1.9029×10^{-5}	1.0473×10^{-5}	1.9066×10^{-5}
187.5872	1.9334×10^{-7}	3.6913×10^{-8}	124.0	137.2605	1.0135×10^{-5}	1.8862×10^{-5}	1.0328×10^{-5}	1.8899×10^{-5}
	1.9334×10^{-7}	3.6913×10^{-8}	123.6		1.0134×10^{-5}	1.8835×10^{-5}	1.0327×10^{-5}	1.8871×10^{-5}
187.5872	1.9334×10^{-7}	3.6913×10^{-8}	122.6	137.2605	1.0131×10^{-5}	1.8742×10^{-5}	1.0324×10^{-5}	1.8779×10^{-5}
187.5872	1.9334×10^{-7}	3.6913×10^{-8}	121.6	137.2605	1.0128×10^{-5}	1.8666×10^{-5}	1.0321×10^{-5}	1.8703×10^{-5}
187.5872	1.9334×10^{-7}	3.6913×10^{-8}	120.6	137.2605	1.0126×10^{-5}	1.8613×10^{-5}	1.0319×10^{-5}	1.8650×10^{-5}
187.5872	1.9334×10^{-7}	3.6913×10^{-8}	120.0	137.2605	1.0125×10^{-5}	1.8586×10^{-5}	1.0319×10^{-5}	1.8623×10^{-5}
187.5872	1.9334×10^{-7}	3.6913×10^{-8}	119.0	137.2605	1.0123×10^{-5}	1.8538×10^{-5}	1.0317×10^{-5}	1.8575×10^{-5}
187.5872	1.9334×10^{-7}	3.6913×10^{-8}	118.0	137.2605	1.0121×10^{-5}	1.8485×10^{-5}	1.0315×10^{-5}	1.8521×10^{-5}

Remark：In table1and 2, H_0 is the limiting water level before flood, m；$\overline{H}_{max}$ is the mean value of the highest water level m；$\overline{R}_1$ 、$\overline{R}_2$ are the overtopping risks under the first and second critical mode respectively .The top elevation of parapet is taken as the first critical mode, it resists the action of flood, wind setup and runup. Whereas the dam crest elevation is taken as the second critical mode, it resists the action of flood and wind setup only.