ORIGINAL PAPER

Risk assessment of earth dam overtopping and its application research

Sherong Zhang · Yaosheng Tan

Abstract   The problem of dam safety is one of the most important research topics of water conservancy projects, and many researchers pay much attention to study the risk of earth dam overtopping. This paper synthesizes in the definition of risk the probabilities of dam failure and the corresponding losses, including the probability estimation, losses evaluation and criteria exploring risk approaches. Then, a comprehensive risk assessment system of dam flood overtopping is established, which is widely applicable. Gate failure, randomness of flood, initial water level and time-varying effects are incorporated in the failure probability model. Many complex factors are simplified in losses estimation. In addition, thresholds of various types of losses are proposed and are adapted to the national conditions. The methodology is applied to the Lianghekou hydropower station in China to illustrate the assessment process of flood overtopping risk and to evaluate its safe loophole with a view to the failure of spillway gates. Monte Carlo simulation and JC method programs are adopted to solve the model based on MATLAB tools and DELPHI. The results show that the losses pose significant impact on the risk assessment and should be considered in the assessment of risk. Probability calculation and loss estimation could be well combined with standards, providing a basis for risk management and decision-making.

Keywords   Earth dam · Risk assessment · Flood overtopping · Failure probability · Losses evaluation · Risk thresholds

S. Zhang · Y. Tan (✉)
Department of Hydraulic Engineering, State Key Laboratory of Hydraulic Engineering Simulation and Safety, School of Civil Engineering, Tianjin University, 92 Weijin Road, Nankai District, Tianjin 300072, People's Republic of China
e-mail: tjutantan@126.com

S. Zhang
e-mail: tjuzsr@126.com

1 Introduction

In order to cope with the problem of uneven distribution of water resources and to meet the requirements of rapid industrial and agricultural development, many countries have constructed a large number of water conservancy infrastructures at the watershed scale. There are many advantages for the earth dam, such as it could be constructed with local materials thus to avoid long-distance transportation, with less consumption of steel, cement and other materials and so on. Therefore, it plays a very important role in building water conservancy projects. However, for many reasons, various degrees of risk exist in many constructed dams, which not only limit the use of the reservoir and maximization of economic benefits, but also may cause potential catastrophic consequences like life losses and property damages once wrecked. According to statistics, major crash modes of the earth dam are flood overtopping, seepage piping, slope failure, foundation collapse and so on. Nearly 50 % of earth dam disasters in China and one-third in the world are caused by overtopping (Hege 1997; Jin 2008). In principle, the dam is considered to be destroyed once suffered flood overtopping and might lead to unexpected consequences. Therefore, it is important and urgent to improve the risk analysis and assessment so as to provide a scientific basis and reference for risk management and security decision-making.

The risk, defined by ICOLD on the 20th Congress in 2000, is a measure of the possibility and seriousness of adverse consequences on life, health, property and environment. It is computed as the product of the likelihood of unfavorable incidents and the corresponding consequences in the field of hydropower projects (Kreuzer 2000). Risk-based analysis started in 1976, the concept of risk was initially put forward by US Army Corps of Engineer (USACE) Hagen who used relative risk index to discriminate dam risk (Li et al. 2006), and risk-based analysis was applied to analyze the failure of the Teton dam in the USA for the first time (Chadwick 1976). The Australian National Committee on Large Dams (ANCOLD) setup risk assessment guidelines in 1994 (ANCOLD 1994), then made new guidelines in 2003 (ANCOLD 2003). They determined some key steps for risk classification, risk assessment and risk handling. Canada BC Hydro applied the method of risk analysis to assess dam safety, and argued that dam risk analysis should include design calculation, standards, construction record, dam operation and maintenance etc. (Lou 2000). National weather service (NWS) developed a series of dam-break models, such as DAMBRK model, BREACH model, FLAWAV model and so on (Li et al. 2006). Particularly, International Commission on Large Dams (ICOLD) put forward risk assessment guidelines in 1998 as well (ICOLD 1998), they gave a theoretical basis and technical support for risk-based analysis in dam safety assessment.

In general, most of current researches consider merely either the probability analysis of dam overtopping or the loss estimates of dam failure (Mo and Liu 2010; Li et al. 2006). Zhang et al. (2013) presented a new evaluation model based upon the interval analytic hierarchy process (IAHP) and the extension of technique for order performance. It is similar to ideal solution (TOPSIS) with interval data and helps to make better the confidence level of risk identification on hydropower projects. Béjar (2011) discussed the probability of flood-induced overtopping of barriers in watershed-reservoir-dam systems. They translated a random representation of the storm hourly rain into effective runoff, containing losses due to evaporation, interception and surface retention. Sun and Huang (2005) applied the theory of risk analysis to establish an overtopping risk model of Dongwushi reservoir in China, under the joint action of flood and wind wave. They comprehensively considered the uncertainties of flood, wind, storage capacity of reservoir and the discharge capacity of the project. Hsu et al. (2011) developed a probability-based

methodology to assess overtopping probability in view of uncertainties arised from wind speed and peak flooding. They compared overtopping probabilities based upon monthly maximum series models and those of the annual maximum series models. Kuo et al. (2007) proposed an innovative concept to assess dam overtopping in consideration of spillway gate availability, mainly including evaluation of conditional dam overtopping risk for different numbers of malfunctioning spillway gates, assessment of spillway gate reliability and dam inspection schedule. They also applied their methodology to Feitsui Reservoir in northern Taiwan and to appraise its time-dependent overtopping risk. Mo et al. (2008) discussed a model of overtopping risk under the joint effects of floods and wind waves and took into account the uncertainties of floods, wind waves, reservoir capacity and discharge capacity of the spillway to explore arithmetic by the method of the Integration-JC and its simplified procedure. Li et al. (2012) developed a LHS-MC method to evaluate dam overtopping probability that accounted for the uncertainties arising from wind speed and peak flood. They used Latin hypercube sampling (LHS) to efficiently simulate the random variable samples, instead of Monte Carlo method. Kwon and Moon (2006) applied non-parametric probability density estimation methods for selected variables to evaluate the probability of dam overtopping, using LHS to improve the efficiency of the exhaustive Monte Carlo simulation driven by the multiple random variables and bootstrap resampling to determine the initial water surface level. Zhong et al. (2011) suggested a risk-based analysis method for appraising the risk of hydrological factors, seepage and bank slope failure, respectively, and for evaluating the integrated risk when these factors were coupled. Shi et al. (1998) divided economic losses induced by the dam break into three parts: direct damages, consequential damages and engineering losses, and researched computational methods for all losses. Graham (2001) came up with the nonlinear relationship between life losses and people at risk and obtained experience formulas of life losses. Zhou (2006) estimated life losses by D&M and Graham method and then compared the results with actual damage to setup population mortality tables of dam-break risk. Yang et al. (2013) proposed a systematic approach for the evaluation of inundation risks induced by landslide dam formation and breaches, including the assessment of dam-breach probability, appraisement of upstream inundation hazard, evaluation of downstream inundation hazard and the classification of flood hazards.

According to the above researches, the predecessors focused more on solving the risk model and calculating overtopping probability, risk and uncertainty analysis by mathematical and statistical approaches is often used to evaluate systematic risks and uncertainties, as LHS-MC, Rosenblueth's point estimation method (RPEM), Harr's point estimation method (HPEM) etc., all are relatively new methods. They also researched life losses and economic losses from qualitative analysis and quantitative calculation, but few studies are based on these two aspects at the same time. Some scholars even ignored losses caused by flood overtopping, and instead, assessed the level of risk with failure probability directly, which is not consistent with the concept of risk. Li et al. (2006) took both sides of risk definition of all dam-break modes into consideration, and yet, the relevance of qualitative description and quantitative conversion probability is coarse and the accuracy of the result worths discussing. Due to the complexity and uncertainty of earth dam overtopping, how to connect the relationship between the probability and loss, and how to assess the risk level from two aspects of the risk definition, are the focal points and difficulties. For this reason, in this paper, both two sides of risk definition (failure probability and harmful consequence) are introduced to research the risk assessment method of earth dam overtopping, in order to build up a widely applicable risk evaluation system as well as provide a reference for similar theories and engineering applications. First, we consider gate failure

in the practical operation and randomness of flood limited water level to improve the traditional probabilistic models; then, simplify the estimation methods for life losses, economic losses, socioeconomic and environmental impacts; finally, we propose the thresholds of various types of losses that suit to the national conditions.

2 Evaluation process of dam flood overtopping risk

Flood overtopping risk contains the probability that the water level exceeds the dam and the associated consequences caused by the dam accidents, in the design reference period. From the view of probability theories, it synthesizes disciplines of reliability math, stochastic hydrology, stochastic hydraulics, engineering economics, and social statistics and so on, to make the best of the balance between flood control and flood utilization benefits. The evaluation process of flood overtopping risk is shown in Fig. 1.

3 Calculation of dam overtopping probability

Based upon the principle of dam overtopping (see Fig. 2), the probability of dam failure caused by flood overtopping can be represented by Eq. (1) (Kuo et al. 2007; Hsu et al. 2011),

$$P[\ln(H_c/H_{max}) < 0] \tag{1}$$

where H_C refers to the height of the dam or parapet wall, and H_{max} the highest water level.

Among them, H_{max} is affected by inflow flood, discharge, the shape of reservoirs, stormy waves and other factors. Sun and Huang (2005) and Mo et al. (2008) gave some discussions on overtopping risk including these factors. However, the randomness of operation and management is also important for overtopping risk models, the lapse of shaft spillway, deep hole spillway tunnel and spillway gate will prevent flood discharges, thus will raise the water level drastically. Flood storage capacity is also affected by the deviation between actual initial water levels and flood control levels in operation scheduling. The paper considers the gate failures in accident, operation and time-varying factors, etc.

Let l be the number of failure gate, Z_0 be the initial water level in a particular flood control scheme. Then, the probability of flood overtopping can be expressed as the function of l, Q_T, Z_0 in the design reference period, as follows:

$$P(l, Q_T, Z_0) = P\{\ln[H_c/(Z_0 + H_L(l, Q_T))] < 0\} \tag{2}$$

where Q_T is the peak discharge during the design benchmark period, H_L is the water level rise caused by many kinds of uncertain factors. Those factors include flood control level in the initial conditions, the relation of capacity and water level in the boundary conditions, inflow flood process in the hydrological conditions, the capacity of flood discharge in the hydraulic conditions, and the maximum effective wind during the flood season and gate failure of actual operation in the outside conditions, etc. Considering the differences among effect mechanisms, we divide H_L into the water level rise H_{L1} that caused by the flood, and the water higher value H_{L2} that caused by the wind and waves. It is supposed that H_{L1} and H_{L2} are independent factors, and the dam overtopping probability can be expressed as Eq. (3):
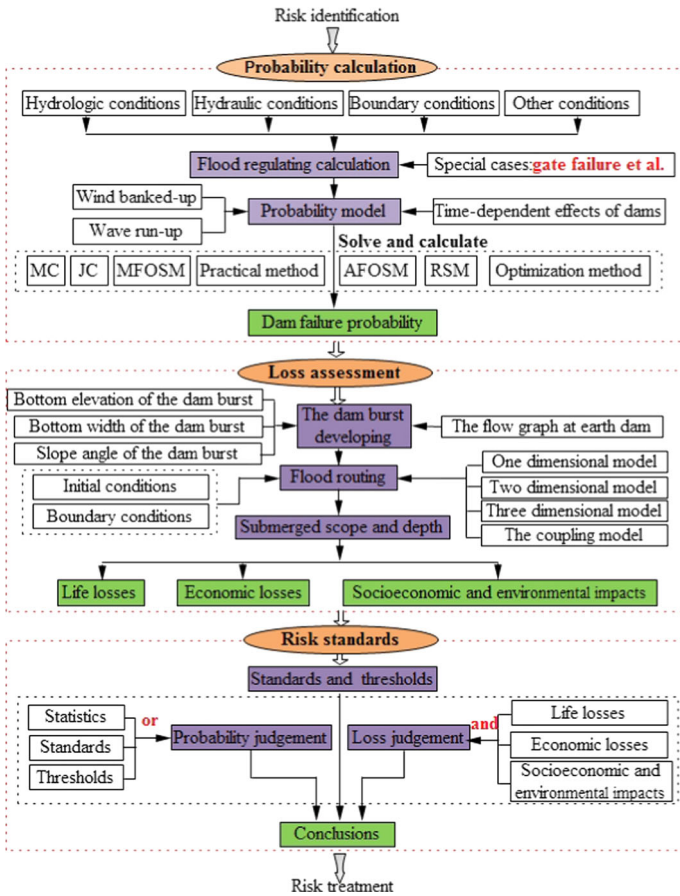
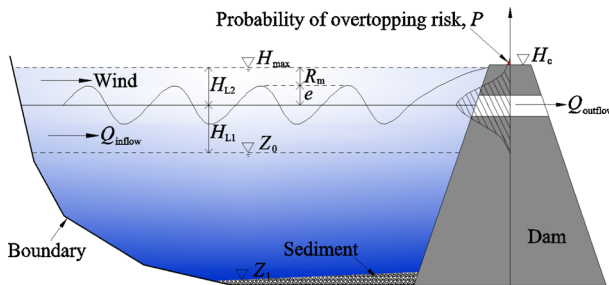**Fig. 1** Evaluation process of dam flood overtopping risk

Fig. 2 Probability calculation theory of flood overtopping

$$P(l, Q_\text{T}, Z_0) = P\{\ln[H_\text{c}/(Z_0 + H_{\text{L}1}(l, Q_\text{T}) + H_{\text{L}2})] < 0\} \tag{3}$$

$H_{\text{L}1}$ is a random process that determined by inflow flood Q, flood discharge q and real reservoir area F. Since the flood discharge flow during actual operation period is affected

by gate failure, the actual flow through the gate is related to gate shape and water level. We bring $q(z)$ between water level and discharge flow under all solutions to simplify the complex solving process, then obtain the relationship among Q, q and F as:

$$Q(t) - q(z) = F(z)\mathrm{d}z/\mathrm{d}t = F(z)f(z, t) \tag{4}$$

where z is water level elevation at the time t, and $f(z, t)$ is the probability density function (PDF) of water level z at time t. Since $Q(t)$, $q(z)$, $F(z)$ are all random functions, they are divided into linear difference equation, then are transformed into the Runge–Kutta format to solve the stochastic differential equation in flood routing operation as Eq. (5) (Mo et al. 2008),

$$\begin{cases} Z(t_{i+1}) = Z(t_i) + h[M_1 + 2(M_2 + M_3) + M_4]/6 \\ M_1 = \{Q(t_i) - q[Z(t_i)]\}/F[Z(t_i)] \\ M_2 = \{Q(t_{i+1/2}) - q[Z(t_i) + 0.5hM_1]\}/F[Z(t_i) + 0.5hM_1] \\ M_3 = \{Q(t_{i+1/2}) - q[Z(t_i) + 0.5hM_2]\}/F[Z(t_i) + 0.5hM_2] \\ M_4 = \{Q(t_{i+1}) - q[Z(t_i) + hM_3]\}/F[Z(t_i) + hM_3] \end{cases} \tag{5}$$

where $Z(t_i)$, $Q(t_i)$, $q[Z(t_i)]$ and $F[Z(t_i)]$ means the reservoir water level, water inflow, outflow and real reservoir area separately at time t, h is the computing time.

H_{L2} contains the wind banked-up e and the wave raising height R_m. It is generally believed that probabilistic distribution type of maximum wind speed obeys extremum I in a certain period, so does e. The mean of wind banked-up $\bar{e}$ and the standard deviation σ_e can be represented by Eq. (6) (Hydrochina Xibei Engineering Corporation 2008),

$$\begin{cases} \bar{e} = [KW^2D/(2gH)]\cos\beta \\ \sigma_e = [KW^2D/(2gH)]\cos\beta\sigma_w \end{cases} \tag{6}$$

where K is the synthetic friction factor (generally $K = 3.6 \times 10^{-6}$), W is the wind speed above the water surface, D is the fetch of reservoir, H is the average depth, β is the angle of wind and water area (conservatively $\beta = 0°$), and σ_w is the standard deviation of wind array.

The wave raising height R_m is a series of random waves which currently conform to Rayleigh distribution; its distribution function and probability density function are defined by Eq. (7):

$$\begin{cases} F(x) = 1 - \mathrm{e}^{-x^2/(2u^2)} \\ f(x) = (x/u^2)\mathrm{e}^{-x^2/(2u^2)} \end{cases} \tag{7}$$

The relationships between the distribution coefficient u and the mean $M(x)$ and mean-square deviation $\sigma(x)$ (Ma 2004) are given out in Eq. (8):

$$\begin{cases} M(x) = \sqrt{0.5\pi}\mu \\ \sigma(x) = \sqrt{0.5(4 - \pi)}\mu \end{cases} \tag{8}$$

Then, the mean value $\overline{R_m}$ and standard deviation σ_R of the wave raising height can be calculated by Eq. (9):

$$\begin{cases} \overline{R_m} = \left[0.06145K_m/\sqrt{(1 + n^2)gH}\right]\sqrt{W^{4.25}D^{0.4}} \\ \sigma_R = \left[0.03214K_m/\sqrt{(1 + n^2)gH}\right]\sqrt{W^{4.25}D^{0.4}} \end{cases} \tag{9}$$

where K_m is the rough permeability coefficient of dam upstream slope, and n is the corresponding slope coefficient.

However, the functional relations of dam performance will change over time and present some time-varying effects. Time-dependent effects of dams may be caused by structural factors or non-structural factors (Fan and Jiang 2007). Flood overtopping, seepage failure (piping, flowing soil) and slope instability of risk rates for flood control of dams may be related to these effects. In detail, the flood overtopping is caused by three main reasons, the first is the reduction of the effective flood regulating capacity, which is caused by the sediment deposition; then, the aging of flood gate will lower the dam flood discharge capacity; and the last, sedimentation deformation will reduce the dam crest height, these factors together will determine the risk of flood overtopping. There is no doubt that these slowly varying functions will increase the risk of flood overtopping in the whole running period. Therefore, time-varying influence of dam flood control is mainly induced by dam settlement. The time-varying characteristics of dam crest elevation can be represented by Eq. (10) (Jiang and Fan 2006),

$$H_c(t) = H_c(t_0)\varphi_t = H_c(t_0)\left(1 - k\frac{t}{N}\right)^2 \tag{10}$$

where t is the operation time, t_0 is the initial computation time, N is the dam design reference period, and k is a coefficient that often consults relevant engineering experience for determination. For example, when the random variables $X(50)$ decay to a pre-defined percentage of the initial value, t is assumed to equal N. In case, the settlement of the earth-rock dam is tending toward stability in the first 5 years running, and the total settlement is one percent of dam height, then $N = 5$, φ_5 equals to 99 %, and the coefficient k is 0.005.

With the consideration of gate failure in accident conditions, operation scheduling and time-varying effect, the dam overtopping probability could be obtained by combining Eqs. (3) and (10). There are many methods to calculate the risk, such as, Monte Carlo (MC) method, Latin hypercube sampling Monte Carlo (LHS-MC) method, Mean First Order Second Moment (MFOSM), Advanced First Order Second Moment (AFOSM), JC and Response Surface Method (RSM) etc. (Zhang and Yan 2011). This paper mainly uses Monte Carlo and JC Methods to solve practical problems. Among all random factors, the initial water level of reservoir Z_0 and dam crest elevation H_c can be regarded as Gaussian distribution (Ma 2004). While the wind banked-up e treats as extremum I, and the wave raising height R_m conforms to the Rayleigh distribution, which needs to be normalized in calculations.

4 Loss assessment of dam overtopping

The loss types caused by flood inundation include life losses, economic damages, socio-economic and environmental impacts, as shown in Fig. 3. For the sake of counting influence scopes of dam overtopping and estimating all the losses, the information of dam-break flow, water level hydrographs, the flow, water levels, flow velocities, flooding durations, scopes can be acquired by the process of flood routing.

4.1 Estimate of life losses

According to a large number of historical statistics of the disaster caused by foreign dam failures, life losses have very close relationship with risk population, alarm time and flood intensity. Dekay and McClelland (1993) deduced an empirical equation of life losses on the basis of disaster data, as follows:
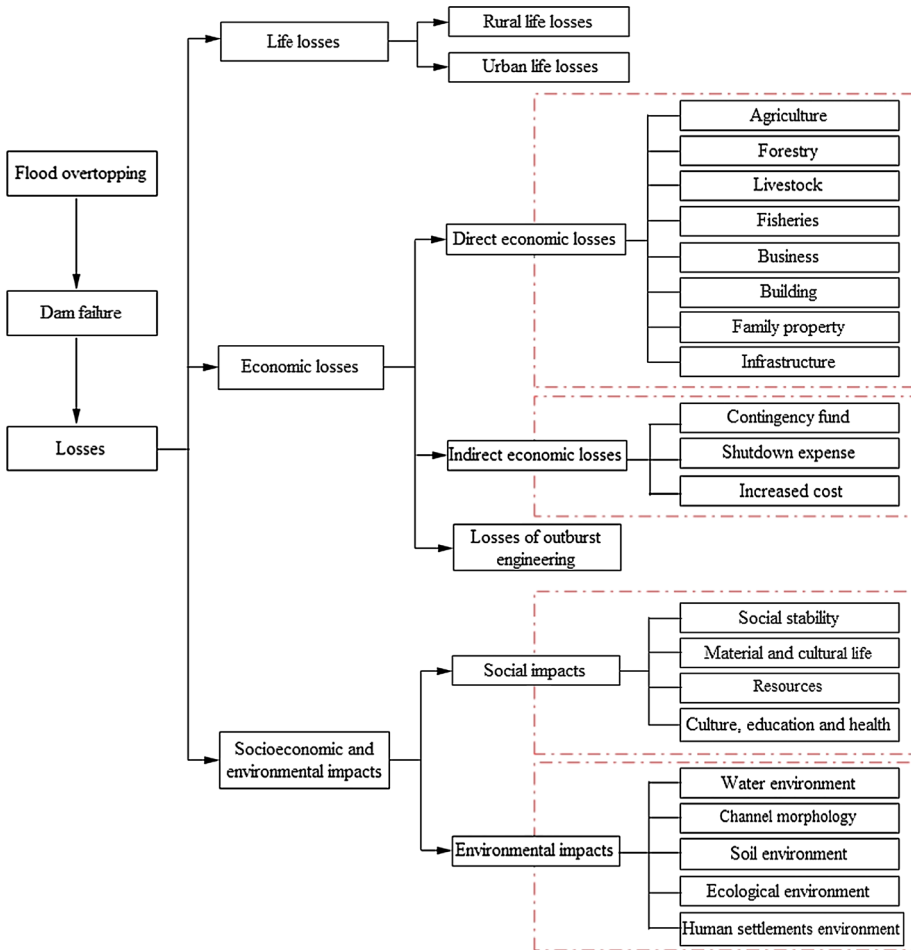
Fig. 3 The type of losses caused by flood overtopping

$$L_{OL} = 0.075 P_{AR}^{0.56} \exp[-0.759 W_T + (3.790 - 2.223 W_T)F_C] \qquad (11)$$

where L_{OL} is life losses, P_{AR} is risk population, W_T is warning time and F_C is the intensity of the flood. According to some engineering experience, F_C equals to 1 in canyon areas and 0 in plain areas. Figure 4 shows life losses in plain areas at a high hydraulic risk and in canyon areas at a low hydraulic risk in different alarm time.

To predict life losses more accurately, on the basis of the above factors, we add more factors as understanding of dam-break flood, young adults proportion of risk populations, weather, occurrence time of dam failure, the distance from the dam site, emergency plans, downstream gradients, dam heights, storage capacities and the anti-scouring ability of the projects (Li 2011), improve support vector machine (SVM) to solve the problem and estimate of life losses in Eq. (12). In practical applications, in order to obtain kernel function and parameters of SVM, we should quantify all these 13 factors to build a sample data set. If some factors are difficult to quantify, we could divide them into different grades
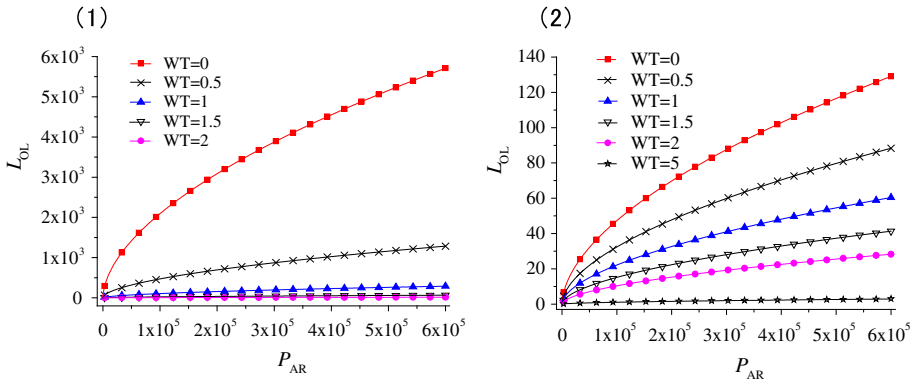
Fig. 4 Relation between life losses and risk population: **1** plain areas; and **2** canyon areas

in line with its seriousness. Real data (Zhou 2006) show that, statistical learning with small samples can solve the problem of information lacking effectively, then the improved SVM model is significantly better than the original SVM model and improved Graham method.

$$L_{OL} = P_{AR} \cdot d \cdot (m_1 + bm_2) \tag{12}$$

where d is death rate of risk populations, and b is the constant coefficient of impact factors, suggesting $0.50 \le b \le 0.80$, m_1 and m_2 are disaster severity factors of direct and indirect influences respectively, just as Eq. (13) and Eq. (14):

$$m_1 = \sum_{i=1}^{4} \xi_i \theta_i \tag{13}$$

$$m_2 = \sum_{j=1}^{9} n_j r_j \tag{14}$$

where ξ_i ($i = 1 \sim 4$) is the influence degree of risk population, understanding of dam-break flood, alarm time and flood intensity to population mortality risk with $\xi_i \le 1(\forall_i)$, and θ_i is the weight of corresponding factors, with $\sum_{i=1}^{4} \theta_i = 1$; and n_j ($j = 1 \sim 9$) is the influence degree of other factors with $n_j \le 1(\forall_j)$, and r_j is the weight, $\sum_{j=1}^{9} r_j = 1$.

4.2 Estimate of economic losses

Economic losses S mainly consist of three parts: direct economic losses S_D, indirect economic losses S_I and losses of outburst engineering S_E.

4.2.1 Direct economic losses S_D

S_D includes aspects of agricultures (crop, animal husbandry, fishery and forestry), industries and commerces, personal property, infrastructures (roads, telecommunications, communications and embankments), which can be further subdivided according to specific situation. Assume survey data are sufficient, S_D can be divided into physical losses, agricultural income losses and industrial & commercial transport services losses (Shi 1998). When data acquisition is limited, we combine with empirical coefficient methods to

Fig. 5 Relationship between loss rates and flood depths
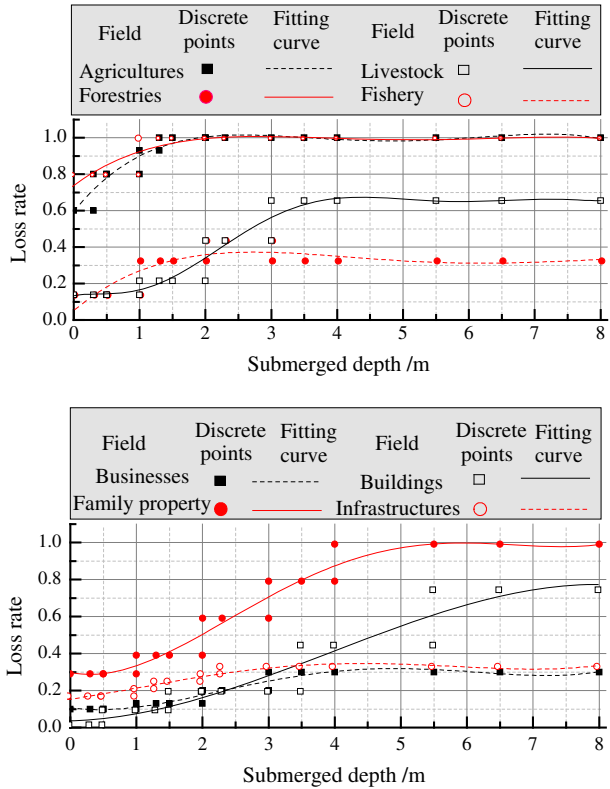
determine loss rates (Li et al. 2006), and relationship between loss rate of properties and floodwater depth is shown in Fig. 5.

4.2.2 Indirect economic losses S_I

S_I includes contingency costs, losses caused by decreased agricultural productions and suspended operation of factories, and the increasing costs of socioeconomic operation. By means of sample surveys and analysis of large amounts of data, indirect economic losses associate with direct economic losses in Eq. (15) (Li et al. 2006).

$$S_{Ii} = k_i S_{Di} + b_i \tag{15}$$

where S_{Ii} and S_{Di} are indirect and direct economic losses caused by dam failure on some department, respectively, k_i and b_i are loss coefficients. Generally speaking, after synthesizing loss relations of many industries, $k_i = 0.63$ and $b_i = 0$.

4.2.3 Losses of outburst engineering S_E

Revaluation of engineering assets are used to analyze S_E dynamically, with consideration of engineering construction cost deducting capital recovery as S_E in $(s - r)$ years of usage.

$$S_E = \sum_{i=1}^{r} C_i (1 + \delta)^{(s-i)} - \sum_{i=1}^{s} B_i (1 + \delta)^{(s-i)} \qquad (16)$$

where s is the year of usage before the dam failure, r is the year after dam building, δ is the social discounting rate, C_i is invested cost of projects after some years, and B_i is the net benefit of projects.

4.3 Estimate of socioeconomic and environmental impacts

Dam overtopping will affect people's daily life, work and entertainment, and even the political stability, this is defined as the social impact. At the same time, the damages caused to the water environment, soil environment, ecology environment and living environment are termed as the environmental impact (He et al. 2008). The influence of dam-break on society and environment cannot be ignored. Due to the complexity of influencing factors, social impact mainly takes into account the characteristics of risk population, social stability, material and cultural life, resources, facilities, culture, education and health, etc. Environmental impact considers the evaluation indicators of river, water environment, soil environment, ecological environment, and human settlements environment. Above all these factors, we simplify eight quantitative indexes as risk population factor Y, the regional importance coefficient C, facilities importance factor I, cultural relics coefficient V, the channel morphology coefficient R, soil and water environment coefficient M, ecological environment factor B, living environment factor L, introduce the social and environmental influence index f to comprehensively reflect the consequences of dam failure (Li et al. 2006), as follows:

$$f = Y \cdot C \cdot I \cdot V \cdot R \cdot M \cdot B \cdot L \qquad (17)$$

To calculate the value of f, the value of the factors is classified into five levels as extremely low, low, middle, high and extremely high, and each grade is assigned a number to express these effects quantitatively. Experts combine engineering practice and assign the corresponding grade referring to Table 1 (Li et al. 2006). When various influence factors are mild, $f = 1.0$; if all these factors are extremely serious, $f = 10,000$. For this reason, social and environmental influence index f varies between 1 and 10,000.

5 Thresholds of risk assessments

Risk calculation of dam overtopping aims at judging whether the risk is acceptable or not. For this reason, an overtopping risk evaluation standard is necessary, and risk criteria should be determined in the light of the risk levels widely adopted by the society (Mo et al. 2008). In general, there are two ways to assess dam overtopping risk. The first way estimated the probability of dam failure based on statistics data, such as the probability of dam failure in America is 5.03×10^{-5} per year and that of the world average is 5.45×10^{-5} per year (USCOLD 1988), and on the basis of data from the Australian Bureau of Statistics, the mortality rate of the Australian population is approximately 1.0×10^{-4} per year. The second way refers to Guideline on Risk Assessment (ANCOLD 2003), including the relationship between failure probability and losses which contain life losses, economic losses, socioeconomic and environmental impacts, respectively. Different countries and regions have come up with allowable risk criteria to adapt their own situations (Rettemeier et al. 2000). Especially, David indicated the risk of dam failure should be at a magnitude of 1×10^{-4} for

Table 1 Various factors assignment reference of social and environmental impacts

Category	Factors	Extremely low Condition	Value	Low Condition	Value	Middle Condition	Value	High Condition	Value	Extremely high Condition	Value
Social influence	Y	$1-10$	1.0–1.2	$10-10^3$	1.2–1.6	10^3-10^5	1.6–2.4	10^5-10^7	2.4–4.0	$>10^7$	4.0–5.0
	C	Retail investors	1.0	Village	1.3	Township	1.6	City	2.0–3.0	Provincial capital	4.0–5.0
	I	General facilities	1.0	General important facilities	1.2	Municipal facilities	1.5	Facilities at the provincial level	1.7	National infrastructure	2.0
	V	General	1.0	County level	1.2	Provincial level	1.5	National level	2.0	World class	2.5
Environmental impact	R	Minor damage	1.0	Stream damage	1.3	River damage	1.6	Serious damage	2.0–3.0	River diversion	4.0–5.0
	M	Mountain Forest	1.0	Agricultural clusters	1.2	Town	1.6	City	2.0–3.0	Provincial capital	4.0
	B	Average creature	1.0	Valuable	1.2	More precious	1.5	Rare animal and plant	1.7	Endangered species	2.0
	L	Minor damage	1.0	Municipal damage	1.2	Provincial damage	1.5	National damage	1.7	World cultural landscape	2.0

the sake of ensuring dam safety, whereas the risk of dam overtopping caused by inadequate flood discharge should be 1×10^{-5} (Zhu et al. 2003).

By the definition of risk, evaluation criteria of flood overtopping should be quantitative judgments that are widely acceptable by the society, which should also consider synthetically the failure probability P and the corresponding consequence c, and is further specified as the value of tolerable risk $R^* = P \cdot c$ (Fan and Jiang 2005). Based on the above criteria, we advise the adoption of risk standards that include the impacts on lives, economies, society and environment, so as to appraise the risks separately. The overtopping risk is termed as intolerable risk once any one of the risk component cannot conform to risk requirements. This paper comes up with the risk threshold of flood overtopping in China, according to the international general risk criteria of life losses and social and environmental impacts enacted by the F–N methods, and the economic risk standards set by ANCOLD (2003) and B.C Hydro (Li et al. 2006), as shown in Table 2. Risk assessment for the specific project should comply with the local risk tolerances. In Table 2, the max and min items represent the upper and lower limits of the acceptable risk, respectively. When the actual risk is larger than the upper limit, it will be labeled as high risk that is intolerable; for the case, the actual risk is lower than the lower limit, the case will be labeled as low risk, which means acceptable or tolerable. Figure 6 shows the relations between the failure probability and harmful consequence in this situation.

6 Case study

The Lianghekou hydropower station is located at the main stream of Yalong River in YaJiang County, Sichuan Province of Southwest China, 480 km away from Chengdu City (capital of the Sichuan Province). The dam site is located downstream of the confluence of the Yalong River and tributaries Xianshui River about 2 km of the river, some 25 km above YaJiang County. The Lianghekou Dam is a top concern because it is a considerable large reservoir and thousands of people living downstream. The earth dam has a total length of 668.70 m, a maximum height of 295.00 m, and a parapet wall of 1.2 m. The normal water surface is 2,866.30 m (P = 0.1 %), the restricted water level in flood season is 2,870.27 m (PMF).It has a total capacity of 10.8 billion m^3 and regulates a storage of 6.56 billion m^3. It belongs to a large reservoir (type I), with approximately 8,200 m^3/s of largest discharge quantity and 670 m^3/s of average flow for years at the dam site. The main function of the power station is electric power generation and navigation. Figure 7 shows the location of Lianghekou Dam and Table 3 gives random variables and their statistics.

6.1 Failure probability computations

In order to discuss the rise of water level under different initial values, the uncertain relations among inflow flood, discharge volume, storage capacity and the area of the reservoir are considered, and flood routing are investigated. Figure 8 shows the results of flood regulation calculation under different original water levels when the reservoir is affected to the PMF, where (1) means changing curves between inflow flood and its release, and (2) indicates variable courses of water levels. As seen in the figures, the flood discharge and ascent value of water level changes in unison, the maximum discharge is within the range of 186 and 204 h after the PMF arrival. If the reservoir begins to discharge under the initial water level of 2,865.00 m, the possible highest water level is 2,870.33 m at the dam site.

Table 2 Risk thresholds of dam flood overtopping

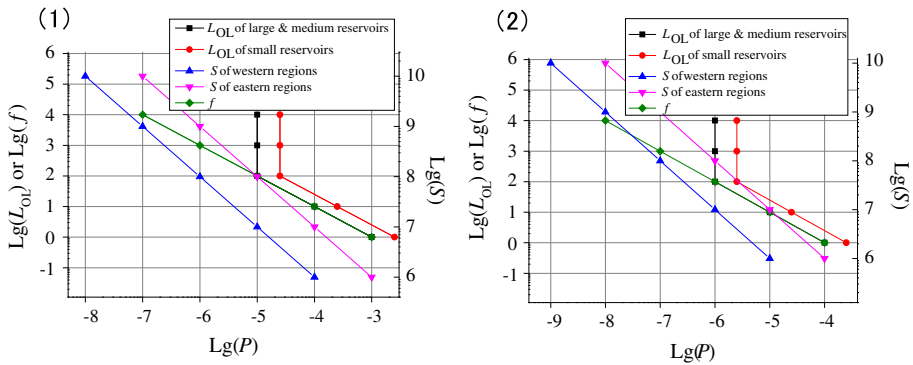| Types of losses	Extreme value	Large and medium reservoirs		Small reservoirs	
		Eastern regions	Western regions	Eastern regions	Western regions
L_{OL} One/(year × dam)	Max	1.0×10^{-3}	1.0×10^{-3}	2.5×10^{-3}	2.5×10^{-3}
	Min	1.0×10^{-4}	1.0×10^{-4}	2.5×10^{-4}	2.5×10^{-4}
S CYN/(year × dam)	Max	1.0×10^{3}	2.5×10^{2}	1.0×10^{3}	2.5×10^{2}
	Min	1.0×10^{2}	25	1.0×10^{2}	25
f 1/(year × dam)	Max	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}
	Min	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}

Fig. 6 Relation between failure probability and harmful consequence in risk thresholds: **1** Max; and **2** Min

According to the maximum mean wind speed of 22 m/s and fetch length of 2,030.00 m, the wind banked-up and wave run-up are calculated. Comparing to the reservoir depth, the quantitative values of the wind banked-up and wave run-up are small, so do the mean values and the standard deviations. Thus, the two variables are taken as constant values. What is more, the former is obedient to Extreme I distribution, the latter Rayleigh distribution. Comprehensively considering the uncertainty of flood, discharge, wind, wave, storage capacity and crest elevation (or wave wall elevation), the risk model of flood overtopping is built in accordance with formula (3). Then, Monte Carlo and JC method programs are used to solve the model based on MATLAB tools and DELPHI. When the dam is in the condition of PMF, failure probability under different initial water levels is shown in Table 4.

As the result shows in Table 4, when the dam encounters a PMF under normal water level of 2,865.00 m, and all gates are normal running, overtopping probability is the order of 10^{-9} magnitude (no consideration of wave wall), as well as 10^{-8} magnitude when consider the wave wall, all the data are small. The results by method of Monte Carlo and JC stay the same, indicating that there is a sufficient accuracy. In the light of security evaluation criteria, when the failure probability is less than 10^{-8} magnitude, the risks are acceptable in spite of large losses, thereby the role of losses is ignored. Based on the above observation, in the case, the failure of spillway gates is taken into account, and only flood
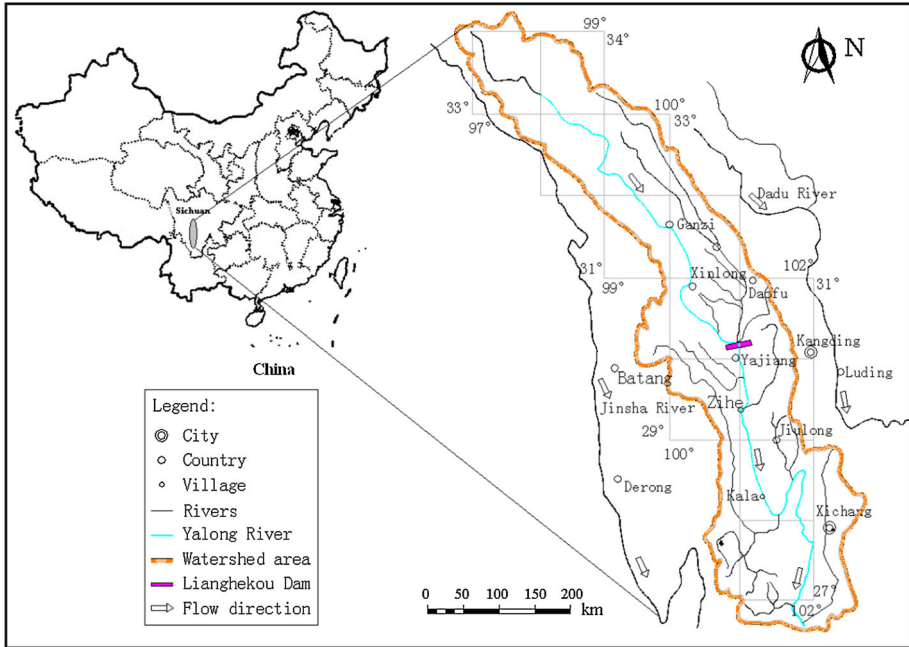
Fig. 7 Location of the Lianghekou hydropower station in China

Table 3 Random variables and their statistics

Random variable	Distribution type	Mean	Standard deviation
Dam crest H_C(m)	Gaussian	2,875.00	0.1
Elevation of parapet wall H_C'(m)	Gaussian	2,876.20	0.1
Flood limit level Z_f(m)	Gaussian	2,845.00	0.1
Normal water level Z_c(m)	Gaussian	2,865.00	0.1
Mean wind speed v(m/s)	Extreme type I	22	4.4

discharge tunnels are in operation (gate failure), the probability of flood overtopping is 3.39×10^{-6} when doing flood routing under the initial water level of 2,865.00 m.

6.2 Losses assessments

The flood evolution of dam break is simulated based on the above condition, and the model is shown in Fig. 9. The dam should start to flood overflow 111 h after the PMF comes. If the dam break is a quarter linear development, whose bottom elevation is 2,801.25 m, three-fourths of the dense residential area in the downstream Gala country will be flooded 5 h after the dam collapse. The minimum water depth will be 7.6 m and the average depth 42 m. At the same time, all the low regions of Hekou town will be submerged with a minimum water depth of 10 m and an average depth of 37 m, as shown in Fig. 10. Then, different types of losses are estimated on this condition.
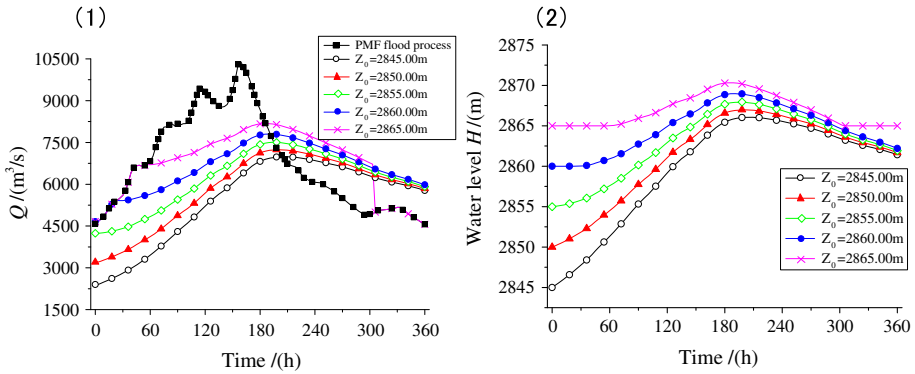
Fig. 8 Results of flood routing under different initial water levels: **1** relation between time and water flow; **2** relation between time and water levels

Table 4 Failure probability of Lianghekou hydropower station in the condition of PMF

Initial water level (m)	Highest flood level (m)	No consideration of wave wall		In consideration of wave wall	
		MC	JC	MC	JC
2,845.00	2,866.07	$<10^{-9}$	4.67×10^{-14}	$<10^{-9}$	2.59×10^{-16}
2,850.00	2,867.00	$<10^{-9}$	1.67×10^{-12}	$<10^{-9}$	1.54×10^{-14}
2,855.00	2,867.95	$<10^{-9}$	4.29×10^{-11}	$<10^{-9}$	6.63×10^{-13}
2,860.00	2,869.00	$<10^{-9}$	9.63×10^{-10}	$<10^{-9}$	2.64×10^{-11}
2,865.00	2,870.33	2.40×10^{-8}	2.42×10^{-8}	1.31×10^{-9}	1.37×10^{-9}

6.2.1 Life losses

According to the range of area submerged and the downstream rural and urban residents, the population risk P_{AR} is analyzed based on the technology of geographic information system (GIS). Thirteen factors are considered, among them, occurrence time of dam break, weather, understanding of dam-break flood, and alarm factors are obtained by reasonable assumption, the remaining factors calculated by the statistics and data analysis. We adopt the method of improved SVM to estimate life losses and apply the trial methods to confirm Gaussian radial basis function as the kernel function of life losses evaluation models. After numerous experiments, the penalty factor is set to 100, the insensitivity parameter 0.00001 and the kernel function parameter 10. The results of the P_{AR} estimation are shown in Table 5. Through analysis, life losses of dam break are significantly greater when taking place at night than in the daytime, and the later at night, the higher the life losses as a result of decreasing of comprehensive ability to flooding, with the maximum losses of life of 299.

6.2.2 Economic losses

In light of family property statistics of rural and urban residents in Sichuan province, the rural property value is set to 93800 CYN and urban residents 160900 CYN for each household, of which 30 % are house property and are 70 % financial assets. With the aid of
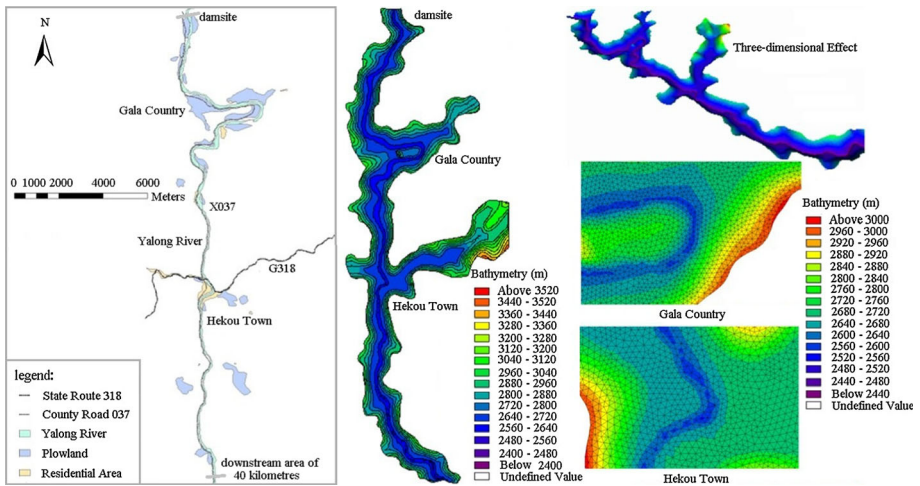
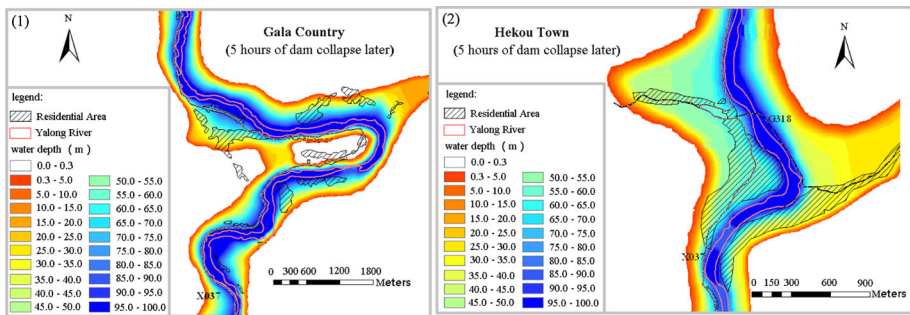**Fig. 9** Numerical models and simulation ranges of dam-break flood evolution

Fig. 10 Flooding depth distribution after five h of dam collapse later: **1** Gala Country; and **2** Hekou Town

GIS, the economic losses in the flood submerged region are calculated. Totally, 971 agricultural populations, 1,201 non-agricultural populations, 34-km Rural Road No.037, 8-km National Highway No. 318, 6,095 acres of crops will be inundated and the average water depth of all losses will be greater than 30 m, the rate of losses thus is taken as 100 %. As a result, the economic losses of personal property, houses, crops, livestock and highways are 0.199 billion CYN, 0.0853 billion CYN, 0.3 million CYN, 1 million CYN and 68.5 million CYN, respectively, in which a direct economic loss of 0.3541 billion CYN and indirect economic loss of 0.2231billion CYN. If the project starts to recover investment incomes without losses of outburst engineering, the total economic losses S is 0.5772 billion CYN.

6.2.3 Socioeconomic and environmental impacts

For the socioeconomic losses, the dam failure will cause a population risk P_{AR} of 6,472, and inundates area including Yajiang County and National Highway No. 318, but no historical sites, cultural relics and artistic treasures will be damaged. As for the impact on

Table 5 Estimated result of life losses

Away from the dam site (km)	P_{AR}	Daytime	Early time at night		Late time at night	
			Workday	Holiday	Workday	Holiday
5.00–9.00	432	1	3	4	6	8
9.00–16.00	2,354	21	31	35	52	62
16.00–20.00	586	8	9	10	12	13
20.00–23.00	200	4	4	5	5	6
23.00–26.00	2,800	24	25	31	42	59
26.00–30.00	100	3	3	3	3	3
Total	6,472	62	76	86	120	151

the environment, the dam failure will cause soil and water environment pollution involving Yajiang County and the surrounding agricultural area and will harm some provincial protected fish in the downstream. At the same time, only slight damage on the natural human landscape and little damage on the river form. Combined with Table 1 and expert advices, the coefficient is 1.69, 2.0, 2.0, 1.5, 1.3, 1.6, 1.5 and 1.0 in Eq. (17), respectively, so the social and environmental influence index f is 31.64.

6.3 Risk assessments

Assume that the dam is affected by the PMF under normal water level of 2,865.00 m, the dam break is a quarter linear development with the failure of spillway gates and only flood discharge tunnels is working, the single risk of life is less than 10^{-5} magnitude, which will meet the requirement of acceptable risk criterion. When appraising by means of risk thresholds of flood overtopping in Table 2, the social risk of life is tolerable, the economic risk (in the western region of China) is intolerable, the socioeconomic and environmental impact is within the acceptable level. As a whole, dam overtopping risk in the certain condition is intolerable, relevant departments should take effective measures to prevent flood overtopping.

7 Conclusions

Owing to the complexity of the dam break and limitation of knowledge, risk assessment and management of hydraulic engineering are necessary. In this paper, two aspects in the definition of the risk are considered at the same time, the probability of dam failure and the loss estimation as well. The loss estimation and evaluation criteria are adopted to explore the risk of earth dam overtopping comprehensively, which turns out to be more in line with the connotation of risk assessment.

Based on previous studies, a full consideration of various uncertainties could improve the risk model of flood overtopping. The model not only analyzes the risk of overtopping under the random inflow flooding and initial water levels, but considers the gate failure and time-varying effects during the run-time of hydroelectric station, thus better reflects the failure probability of flood overtopping according to the actual operation conditions.

The consequence of dam failure is divided into life losses, economic losses, socio-economic and environmental impacts. The paper adopts the improved SVM model to

estimate the life losses, so as to effectively overcome the problem of lack of data. The evaluation of economic losses, social and environmental impacts can simplify many complex factors reasonably, hence to reveal the extent of the dam break quantificationally.

The paper combines the F–N method and the ALARP principle to determine the risk threshold, further researches are required to reach a widely acceptance.

This paper aims at proposing the systematic and analytical methods for risk assessment of flood overtopping. The result of the engineering application shows that the probability of failure is well connected with various losses estimation and their criteria, with a wide range of applications and references. The risks are closely related to the probability and all kinds of losses, so more attention is required when doing similar work. Taking the complexity, randomness and variability of overtopping risk into account, analytical techniques and methods call for more in-depth researches.

References

ANCOLD (1994) Guidelines on risk assessment. Australian committee on large dams, Sydney

ANCOLD (2003) Guidelines on risk assessment. Australian committee on large dams, Sydney

Chadwick WL (1976) Chairman of independent peal to review cause of Teton dam, failure of Teton dam. Report to US Department of the Interior and State of Idaho, Idaho

de Béjar LA (2011) Probability of flood-induced overtopping of barriers in watershed-reservoir-dam systems. J Hydrol Eng © ASCE 9:699–709

Dekay ML, McClelland GH (1993) Predicting loss of life in case of dam failure and flash flood. Risk Anal 2:193–205

Fan Z, Jiang S (2005) Application of tolerance risk analysis method in decision-making of flood prevention. J Hydraul Eng 36(5):618–623

Fan Z, Jiang S (2007) Researches on time-varying risk rate for flood control of dams. J Hydraul Eng 38(supply):168–173

Graham WJ (2001) A simple procedure for estimating loss of life from dam failure. RES CDAM-LOL Helsinki 6(19):1–7

He X, Sun D, Huang J (2008) Assessment on social and environmental impacts of dam break. Chin J Geotech Eng 30(11):1752–1757

Hege K (1997) Dam safety evaluation and risk analysis. Exp Water Res Hydropower Inf 18(9):1–6

Hsu Y, Tung Y, Kuo J (2011) Evaluation of dam overtopping probability induced by flood and wind. Stoch Environ Res Risk Assess 25:35–49

Hydrochina Xibei Engineering Corporation (2008) Design specification for rolled earth-rock fill dams. National Development and Reform Commission, China

ICOLD (1998) ICOLD guidelines on risk assessment for dams. Attachment by: Williams, A: ICOLD chairman's 1997/1998 progress report for New Delhi meeting, vol 11, pp 1–28

Jiang S, Fan Z (2006) Influence of time varying effect on flood control risk rate for dams. J Hydraul Eng 37(4):425–430

Jin Y (2008) Study on the analysis approach for the dangerous situations of dam breach. Hohai University, Nanjing

Kreuzer H (2000) The use of risk analysis to support dam safety decisions and management. ICOLD 20th Congress, Beijing

Kuo J, Yen B, Hsu Y et al (2007) Risk analysis for dam overtopping-Feitsui reservoir as a case study. J Hydraul Eng ASCE 8:955–963

Kwon H, Moon Y (2006) Improvement of overtopping risk evaluations using probabilistic concepts for existing dams. Stoch Environ Res Risk Assess 20:223–237

Li S (2011) Key technology research and system development of dam safety risk management. Tianjin University, Tianjin

Li L, Wang R, Sheng J et al (2006) Dam risk evaluation and risk management. China water conservancy and hydropower press, Beijing

Li C, Wang S, Wang W et al (2012) Overtopping risk analysis using LHS-MC method. J Hydroelectr Eng 32(1):5–9

Lou JK (2000) Dam safety risk management of Canada BC Hydro corporation. Dam Saf 4:7–11

Ma R (2004) Risk analysis methods and applications of earth-rock dam. Science Press, Beijing

Mo C, Liu F (2010) Study on evaluation method for overtopping risk degree of reservoir earth dam. J Hydraul Eng 41(3):319–324

Mo C, Liu F, Yu M et al (2008) Risk analysis for earth dam overtopping. Water Sci Eng 6(1):76–87

Rettemeier K, Falkenhagen B, Köngeter J (2000) Risk assessment—new trends in Germany. The proceedings of 21th international congress on large dams. The international commission on large dams, Beijing, pp 625–641

Shi G, Zhu H, Xun H (1998) Study on reservoir dam-break loss and its calculation methods. J Catastrophol 13(4):28–33

Sun Y, Huang W (2005) Risk analysis on overtopping for operation management of reservoir. J Hydraul Eng 36(10):1153–1157

USCOLD (1988) Committee on failures and accidents to large dams. Lessons from Dam Incidents, USA, ASCE, New York

Yang S, Pan Y, Dong J et al (2013) A systematic approach for the assessment of flooding hazard and risk associated with a landslide dam. Nat Hazards 65:41–62

Zhang S, Yan L (2011) Operation safety risk analysis method of hydropower project considering time-dependent effect. Eng Sci 13(12):51–55

Zhang S, Sun B, Yan L et al (2013) Risk identification on hydropower project using the IAHP and extension of TOPSIS methods under interval-valued fuzzy environment. Nat Hazards 65:359–373

Zhong D, Sun Y, Li M (2011) Dam break threshold value and risk probability assessment for an earth dam. Nat Hazards 59:129–147

Zhou K (2006) Study on the analysis method for loss of life due to dam breach dissertation. Nanjing Hydraulic Research Institute, Nanjing

Zhu H, Chen Z, Zhou Z (2003) Risk analysis on dam overtopping of Taihe Reservoir. Dam Saf 4:11–14