Stoch Environ Res Risk Assess (2008) 22:303–313
DOI 10.1007/s00477-007-0116-3

ORIGINAL PAPER

Dam overtopping risk assessment considering inspection program

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Published online: 13 March 2007

Abstract Safety inspection of large dams in Taiwan is conducted every 5 years. The practice does not take into consideration uncertainty of dam conditions. The goal of this study is to determine the optimal dam inspection interval under the consideration of overtopping risk incorporating uncertainty gate availability. In earlier studies, assessment of overtopping risk only considered the uncertainties in reservoir properties and natural randomness of hydrologic events without giving much thought to the availability of spillway gates. As a result, the overtopping risk could be underestimated. In this study, an innovative concept is proposed to evaluate dam overtopping by taking into account spillway gate availability. The framework consists of three parts: (1) evaluation of conditional overtopping risk for different numbers of malfunctioning spillway gates; (2) evaluation of spillway gate availability; and (3) dam inspection scheduling. Furthermore, considerations are given to overtopping risk, inspection cost, and dam break cost for determining the optimal inspection schedule. The methodology is applied to the Shihmen Reservoir in Taiwan and to evaluate its time-dependent overtopping risk. Results show that overtopping risk considering the availability of the spillway gates is higher than the one without considering the availability of the spillway gates.

Keywords Dam safety · Dam inspection · Overtopping risk · Gate availability · Fault tree

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1 Introduction

Taiwan is located in a region plagued by frequent occurrences of typhoons and earthquakes. Dam safety is a major concern to the general public. As dam failure does not occur suddenly, signs of deterioration could be detected by regular inspection. Therefore, a dam owner has to consider the trade-off between facing a high risk of dam break and engaging in a program of more frequent inspections.

According to the International Commission on Large Dams (ICOLD 1973), overtopping causes about 35% of all earth dam failures; seepage, piping, and other causes make up the rest. Various studies (Langseth and Perkins 1983; Resendiz-Carrillo and Lave 1987; Karlsson and Haimes 1988a, b, 1989; Haimes et al. 1988) have proposed procedures to assess the safety of dams. The National Research Council (NRC 1988) has recommended general approaches to estimating probability distributions associated with extreme precipitation and runoff. In earlier studies (Askew et al. 1971; Cheng et al. 1982; Afshar and Marino 1990; Meon 1992; Pohl 1999; Hsu and Kuo 2004; Kwon and Moon 2006), overtopping risk that is assessed without considering the possible occurrence of malfunctioning spillway gates could result in potential underestimation of the risk. In this study, a method that takes into account the availability of spillway gates is proposed to evaluate overtopping risk. The overtopping risk is assessed by considering the random numbers of malfunctioning spillway gates that are not operable during flood events.

Numerous studies using risk and uncertainty analysis have been conducted over the years for safety evaluation of hydraulic structures. Tung and Mays (1981) applied the first-order second-moment (FOSM) method to estimate static and time-dependent reliability for a storm sewer system. Cheng et al. (1982) and Cheng (1993) applied the advanced first-order second-moment (AFOSM) method and fault tree analysis to evaluate dam overtopping risk. Yeh and Tung (1993) applied the FOSM method to evaluate the uncertainty and sensitivity of a pit-migration model.

In this study, reservoir routing, flood frequency analysis, availability model (Tang and Yen 1991), and various uncertainty analysis methods, such as the mean-value FOSM (MFOSM) and the Harr's (Harr 1989) point estimation (HPE) methods, are applied to estimate overtopping risk. This study consists of three parts (see Fig. 1): (1) evaluation of time-dependent availability of a single spillway gate; (2) evaluation of overtopping risk under the condition of multiple malfunctioning spillway gates; and (3) determination of optimal inspection scheduling considering overtopping risk by minimizing the annual total expected cost.

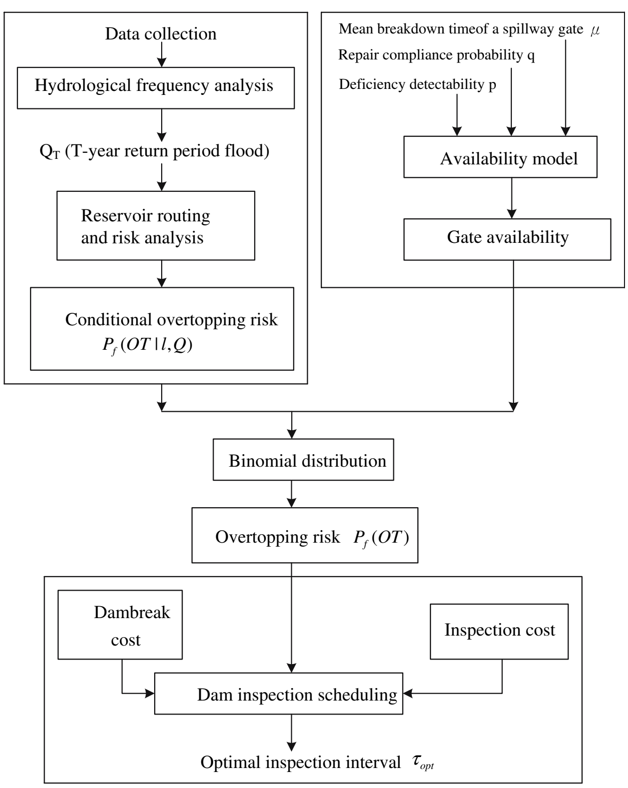


Fig. 1 Flow chart for evaluating the optimal inspection interval. Note: Here P_f (OT|l,Q) represents overtopping risk varying with flood frequency due to the number l of malfunctioning spillway gates; and P_f (OT) represents overtopping risk

2 Availability model

A system is classified as available if the operational condition of a system is satisfactory; otherwise, it is considered unavailable (see Fig. 2) and requiring repair. The availability of a system is defined as the fraction of time that the system is operating satisfactorily. The availability A of a dam system in an inspection cycle can be expressed as (Tang and Yen 1991):

$$A = P_S(\tau) + \frac{X'}{\tau + \tau_r} P_F(\tau), \tag{1}$$

where $P_S(\tau)$ and $P_F(\tau)$ are the probabilities of a dam system operating under satisfactory state S and unsatisfactory state F, respectively; X' is the time-to-breakdown in an inspection cycle which includes a breakdown; τ and τ_r are the inspection interval and repair time, respectively. Generally, the availability model could be applied to different systems and it is applied herein to a spillway gate system. The availability of a spillway gate is the probability of it working under satisfactory conditions; conversely, unavailability is the probability of a spillway gate being inoperative.

If a spillway gate system is operating in multiple breakdown-repair cycles, the expected availability $\overline{A}$ can be written as (Tang and Yen 1991):

$$\overline{A} = 1 - \frac{\tau_r}{\tau + \tau_r} F_X(\tau) - \frac{1}{\tau + \tau_r} \int_0^{\tau} F_X(x) \mathrm{d}x, \tag{2}$$

where $F_X(x)$ is the cumulative distribution function of unsatisfactory time.

Since all deficiencies might not be identified completely, Ang and Tang (1984) considered imperfect detection and

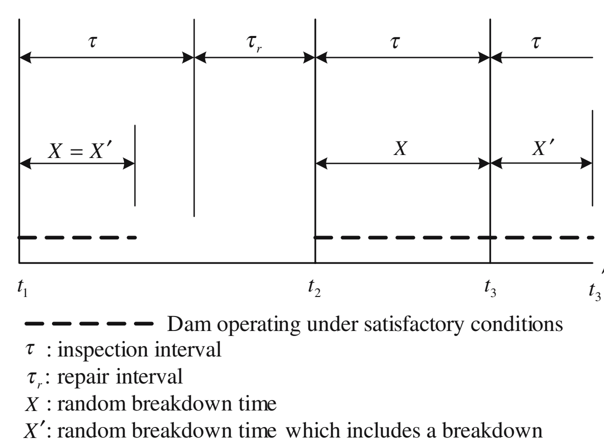


Fig. 2 Scenario of dam operations

derived the expected availability, assuming that the deficiency detectability increased exponentially with the inspection frequency, as (Ang and Tang 1984; Tang and Yen 1991):

$$A = P_S(\tau) + P_F(\tau)\left\{\left[\frac{X'}{\tau+\tau_r}pq + \frac{X'}{2\tau+\tau_r}p(1-q)q^{1/2} + \cdots\right] + \left[\frac{X'}{2\tau+\tau_r}(1-p)p^{1/2}q + \frac{X'}{3\tau+\tau_r}(1-p)p^{1/2}(1-q)q^{1/2} + \cdots\right]\right\} \quad (3)$$

where p is the deficiency detectability; and q is the repair compliance probability. Each term in Eq. 3 corresponds to a path in Fig. 3, representing the probability of the corresponding path. The first term is the probability $P_S(\tau)$ corresponding to the upper path. The second term is related to the path F-D-R in Fig. 3, where its availability is $X'/\tau + \tau_r$ with path probability $P_F(\tau)pq$. By collecting terms, Eq. 3 becomes

$$A = P_S(\tau) + P_F(\tau)\left\{p\left[\frac{X'}{\tau+\tau_r}q + \sum_{n=2}^{\infty}\frac{X'}{n\tau+\tau_r}q^{1/n}\left[\prod_{i=1}^{n-1}\left(1-q^{1/i}\right)\right]\right] + \sum_{m=2}^{\infty}p^{1/m}\left[\prod_{j=1}^{m-1}\left(1-p^{1/j}\right)\right]\left[\frac{X'}{m\tau+\tau_r}q + \sum_{n=2}^{\infty}\frac{X'}{[n+(m-1)]\tau+\tau_r}q^{1/n}\prod_{i=1}^{n-1}\left(1-q^{1/i}\right)\right]\right\}. \quad (4)$$

Assuming that X' has an exponential distribution with a mean value μ for a single spillway gate that does not age; the expected availability (Tang and Yen 1991) can be expressed as:

$$\overline{A} = e^{-\tau/\mu} + \left[1 - e^{-\tau/\mu}\left(\frac{\tau}{\mu}+1\right)\right]\left\{p\left[\frac{q}{\frac{\tau}{\mu}+\frac{\tau_r}{\mu}} + \sum_{n=2}^{\infty}\frac{q^{1/n}\prod_{i=1}^{n-1}\left(1-q^{1/i}\right)}{n\frac{\tau}{\mu}+\frac{\tau_r}{\mu}}\right] + \sum_{m=2}^{\infty}p^{1/m}\left[\prod_{j=1}^{m-1}\left(1-p^{1/j}\right)\right]\left[\frac{q}{\frac{m\tau}{\mu}+\frac{\tau_r}{\mu}} + \sum_{n=2}^{\infty}\frac{q^{1/n}\prod_{i=1}^{n-1}\left(1-q^{1/i}\right)}{\frac{(n+m-1)\tau}{\mu}+\frac{\tau_r}{\mu}}\right]\right\}. \quad (5)$$

In some cases, a system might age due to internal and external deterioration of its physical conditions. The treatment of aging systems can be found in Ang and Tang (1984).

3 Overtopping risk assessment incorporating gate availability

Referring to Fig. 4, evaluation of overtopping risk involves uncertainty analysis in reservoir routing by considering uncertainties in the operation policy, flow input, reservoir geometric information, and others. In earlier studies of overtopping risk, the unavailability of the gates was not considered rendering an underestimation of overtopping risk.

In this study, a procedure for evaluating overtopping risk is proposed which involves (a) collection of annual

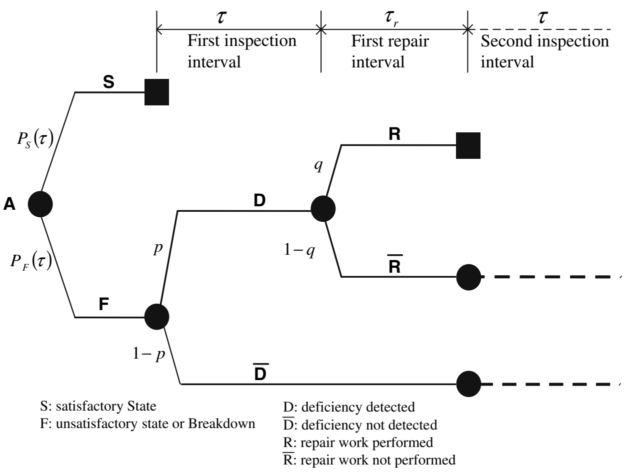


Fig. 3 Event tree of deficiency-detection-repair scenario in dam inspection

peak discharge data and establishment of the flow-frequency relationship; (b) using reservoir routing to calculate the highest water level for floods of varying frequencies under different numbers of malfunctioning gates; and (c) defining the performance function for risk analysis. Note that the rating curve of flow release facilities needs to be defined according to the number of malfunctioning gates. The details of the procedure are described as follows.

3.1 Reservoir routing

The reservoir routing is done according to the discrete form of the continuity equation:

$$\frac{I_t + I_{t+1}}{2} - \frac{O_t + O_{t+1}}{2} = \frac{S_{t+1} - S_t}{\Delta t}, \tag{6}$$

where I_t and I_{t+1} represent reservoir inflows at times t and $t+1$; O_t and O_{t+1} are reservoir outflows; S_t and S_{t+1} are reservoir volumes; and Δt is the routing interval. Using Eq. 6, one can compute the water level hydrograph and the highest level in the reservoir during a flood event. Under different numbers of malfunctioning gates the reservoir water surface hydrograph can be computed by adjusting the rating curve of water release facilities corresponding to the number of malfunctioning gates on the spillway.

3.2 Risk analysis

The failure of an engineering system can be defined as the loading to the system (L) exceeding the resistance of the system (R). The reliability of a hydraulic infrastructure can be defined as the probability that $R > L$, i.e.,

$$\alpha = P[L \le R], \tag{7}$$

where $P[\,]$ represents the probability. Therefore, the risk α' can be represented as:

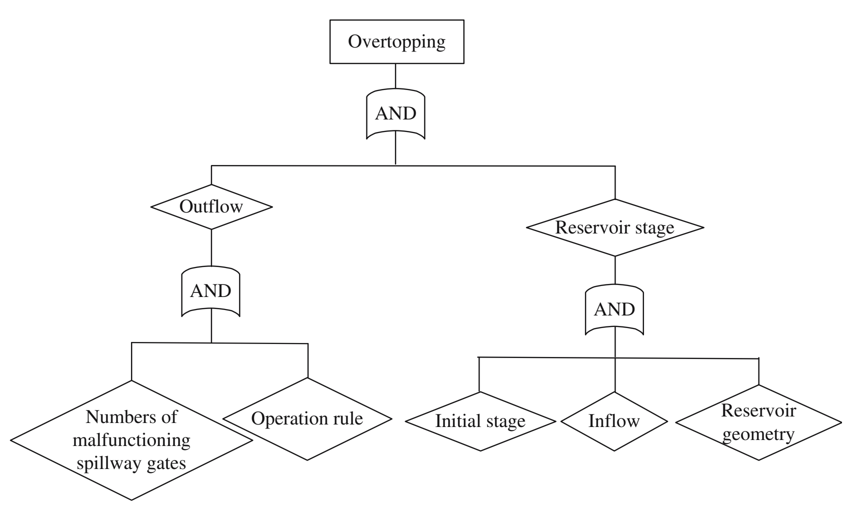
$$\alpha' = P[L > R] = P[Z < 0] = 1 - \alpha. \tag{8}$$

The reliability can also be written as $P[Z \le 0]$ in which Z is the performance function definable by $Z = R - L$, $(R / L) - 1$, or $\ln(R/L)$. Let $P(\mathrm{OT}|l, q)$ represent dam overtopping risk under a specific flood with peak discharge q and l malfunctioning gates. Then, Eq. 8 can be expressed as

$$P(\mathrm{OT}|l, q) = P[Z(l, q) < 0] = P[H_C - H_W(l, q) < 0], \tag{9}$$

where H_C and H_W represent dam crest height and the highest water level during a flood event, respectively. Note that randomness of H_w, under specific q and l, is due to uncertainties in reservoir geometry, spillway rating curve,

Fig. 4 Simple fault tree of dam failure due to overtopping considering malfunctioning spillway gates



etc. The annual dam overtopping risk conditional on l malfunctioning gates can be calculated by

$$P(\mathrm{OT}|l) = \int_0^\infty P[Z(l,q)<0] f_Q(q)\mathrm{d}q, \tag{10}$$

where $f_Q(q)$ denotes the probability density function of the annual peak discharge Q. Equation 10 can be approximated in discrete form as

$$P(\mathrm{OT}|l) \cong \sum_{n=1}^{\infty} P[Z(l,q)<0]\Delta F_Q(q_n), \tag{11}$$

in which $\Delta F_Q(q_n)$ represents the nth incremental probability.

Assuming the number of malfunctioning spillway gates follows a binomial distribution, the dam overtopping risk incorporating gate availability can be calculated as

$$P(\mathrm{OT}) = \sum_{l=0}^{K} C_l^{K-l} \times \overline{U}_{\mathrm{gate}}^{l} \times \overline{A}_{\mathrm{gate}}^{K-l} \times P(\mathrm{OT}|l), \tag{12}$$

where $P(\mathrm{OT})$ is the annual overtopping risk; C_l^{K-l} the binomial coefficient; K and l the total number of spillway gates and number of malfunctioning gates, respectively; $\overline{U}_{\mathrm{gate}}$ and $\overline{A}_{\mathrm{gate}}$ the unavailability and availability of a single gate that can be determined by Eq. 5; and $P(\mathrm{OT}|l)$ is the conditional overtopping risk under l malfunctioning gates on the spillway.

3.3 Uncertainty analysis of overtopping performance function

The main purpose of uncertainty analysis is to quantify the statistical features of system outputs or responses as affected by the stochastic basic parameters in the system. The selection of appropriate method depends on the nature of the problem at hand, including availability of information, model complexity, and type and accuracy of results desired (Tung and Yen 2005). In this study, the MFOSM and HPE method are used to obtain the first two moments of the performance function defining dam overtopping risk.

3.3.1 Mean-value first-order second-moment (MFOSM) method

The MFOSM method assumes that the uncertainty features of a random variable can be represented by its first two statistical moments. This method is based on the Taylor series expansion of the performance function linearized at the mean values of the random variables.

For a performance function Z involving k random variables as

$$Z = g(\mathbf{X}), \tag{13}$$

where $\mathbf{X}^t = \left(X_1, X_2, \ldots, X_k\right)$ is a row vector containing k random variables. Its Taylor series expansion at the mean values of the k random variables can be expressed as:

$$Z = g(\overline{\mathbf{x}}) + \sum_{i=1}^{k}(X_i - \overline{x}_i)\left.\frac{\partial g}{\partial X_i}\right|_{\mathbf{X}=\overline{\mathbf{x}}} + \sum_{i=1}^{k}\sum_{j=1}^{k}(X_i - \overline{x}_i)(X_j - \overline{x}_j)\left.\frac{\partial^2 g}{\partial X_i \partial X_j}\right|_{\mathbf{X}=\overline{\mathbf{x}}} + \text{H.O.T.}, \tag{14}$$

in which $\overline{x}^t = (\overline{x}_1, \overline{x}_2, \ldots, \overline{x}_k)$ represents a row vector containing the mean values of k random variables; H.O.T. represents the higher-order terms; the partial derivative terms are sensitivity coefficients denoting the rates of change in the model output Z with respect to the unit change of the corresponding variable at $\overline{\mathbf{x}}$. For most practical applications information on higher-order moments and cross-product moments are not easily available and, thus, the first-order approximation of Z is used (Tung and Yen 2005).

$$Z \approx g(\overline{\mathbf{x}}) + \sum_{i=1}^{k}(X_i - \overline{x}_i)\left.\frac{\partial g}{\partial X_i}\right|_{\mathbf{X}=\overline{\mathbf{x}}}. \tag{15}$$

Hence, the mean and variance of Z by the first-order approximation can be approximated, respectively, as

$$E(Z) \approx \overline{z} = g(\overline{\mathbf{x}}), \tag{16}$$

$$\mathrm{Var}(Z) \approx \mathrm{Var}\left\{\sum_{i=1}^{k}\left[\frac{\partial g}{\partial X_i}\right](X_i - \overline{x}_i)\right\}. \tag{17}$$

3.3.2 Harr's point estimation (HPE) method

Harr (1989) proposed an alternative probabilistic point estimation method, which requires $2k$ model evaluations for a performance function involving k random variables. A multivariate model $Z = g(\mathbf{X})$ involving $2k$ points for function evaluation by the HPE method is:

$$\mathbf{x}_{i\pm} = \overline{\mathbf{x}} \pm \sqrt{k}\mathbf{D}_x^{1/2}\mathbf{v}_i \quad \text{for } i = 1, 2, \ldots, k, \tag{18}$$

in which $\mathbf{x}_{i\pm}$ represents the vector of coordinates of the $2k$ points for function evaluation in the parameter space corresponding to the ith eigenvector $\mathbf{v}_i$; $\overline{\mathbf{x}} = (\overline{x}_1, \overline{x}_2, \ldots, \overline{x}_k)^t$, a vector of means of k basic random variables; and $\mathbf{D}_x$ is a diagonal matrix of variance of k random variables.

Based on the $2k$ points determined by Eq. 18, the performance function values at each of the $2k$ points can be computed. Then, the rth-order moment of the performance function Z can be calculated by

$$\overline{z_i^r} = \frac{z_{i+}^r + z_{i-}^r}{2} = \frac{g^r(\mathbf{x}_{i+}) + g^r(\mathbf{x}_{i-})}{2} \quad \text{for } i = 1, 2, \ldots, k; r = 1, 2, \ldots, \tag{19}$$

$$E(Z^r) = \frac{\sum_{i=1}^{k} \lambda_i \overline{z_i^r}}{k} \quad \text{for } r = 1, 2, \ldots, \tag{20}$$

where λ_i is the ith eigenvalues associated with the correlation matrix.

4 Dam inspection scheduling

The expected total annual cost (TC) used herein for a dam inspection program can be expressed as

$$\mathrm{TC} = P(\mathrm{OT})C + \frac{wp^d}{\tau}, \tag{21}$$

in which C is the annual damage cost; τ the inspection interval; p the deficiency detectability; w and d being constants. The first term is the expected annual damage cost and the second term is the annual inspection cost with wp^d being the total inspection cost. The expected TC varies with the inspection interval τ; the optimal inspection interval can be determined by minimizing TC.

Equation 21 indicates that the inspection cost goes up with the increasing p-value. For $p = 1.0$, w is the cost associated with perfect (or nearly perfect) detectability, which is rarely achievable in practice.

5 Relevant parameters in dam inspection scheduling

5.1 Deficiency detectability p

Deficiency detectability p could be determined from the records of dam-safety inspections or from experienced dam inspectors. Generally, deficiency detectability depends on factors including, but not limited to, cost, manpower, experience of the inspectors, equipment used, and/or the uncertainties involved in the dam system. In practice, it is practically impossible to detect all deficiencies in dam safety inspection, i.e., there is no perfect detection, no matter how costly the inspection is. This indicates that an upper limit exists for p.

Ang and Tang (1984) proposed a deficiency detectability p to describe the detection probability of an inspection. The value of p can be estimated from inspection cost, the past experiences, and the quality of the inspector. An assessment method was first proposed by Kuo et al. (2004) to evaluate the deficiency detectability from the information on cost, the past experiences, and the quality of the inspectors. The value of the deficiency detectability p used in this study is 0.74 estimated by Kuo et al. (2004).

5.2 Repair compliance probability q

Repair compliance probability q is the degree of willingness of dam owners to do the repair work as suggested by inspection. It can be determined from the repair records of a dam or from the degree of importance that the dam owner assigns to that repair. A greater value of q means that the dam owner would commit sufficient funds to repair the dam quickly. A small value of q, conversely, indicates the dam owner is less willing to repair the dam.

In the study of Kuo et al. (2004), the repair compliance probability was estimated according to the ratio of the repaired items to the total suggested repair items. If more items are being repaired in a short period of time, the value of q will be larger. Conversely, if items are not being repaired in a short time, the value of q will be small. The value of the repair compliance probability q used in this study is 0.73 estimated by Kuo et al. (2004).

5.3 Dam break cost C

The dam break cost includes the cost of the dam and the economic losses associated with the incidence. Economic losses can be tangible and intangible. Tangible losses include direct and indirect losses whereas intangible damages include losses, which could not be measured in monetary terms, such as human life, productivity, psychological trauma, etc. Direct losses mainly are the damage to properties including crops, buildings, facilities, goods, and

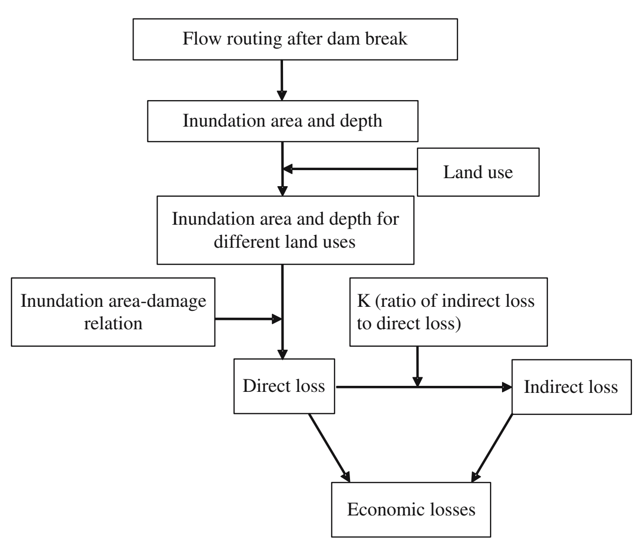


Fig. 5 Flow chart for estimating economic losses due to inundation

Table 1 Key information on the Shihmen Dam

Facility	Crest elevation or capacity
Non-overflow section	252.1 m
Overflow section	235.0 m
Height	133.0 m
Crest length	360.0 m
Spillway	11,400 m^3/s
Tunnel spillway (diameter 10 m)	2,400 m^3/s

materials, etc. Indirect losses involve those caused indirectly by floods including plant shutdown due to losses of electricity, decline of land value or rental fee, etc. In this study, only tangible losses are considered in the estimation of the economic losses due to dam failure.

Economic losses, generally, increase with inundation depth and the extent of the flooded area. Depending on the scale effect and landform, one can use a 1D or 2D model to simulate the inundation area and depth. Depending on the land use and gross domestic product, the economic losses will be different in residential, commercial or industrial areas at the same inundation depth. The procedure to assess the cost of inundation is shown in Fig. 5, which involves (1) dam break flow routing; (2) estimating the inundation area and depth; and (3) estimating economic losses.

6 Case study

6.1 Shihmen Reservoir

The Shihmen Reservoir, in operation since 1964, is located in the upstream reaches of Dahan Creek, a tributary of the Tanshui River in northern Taiwan. The reservoir has a drainage area of 763.4 km^2 and an active storage of 2.5×10^8 m^3 making it the third largest reservoir in Taiwan. The functions of the reservoir include irrigation, domestic water supply, hydropower generation, and flood control. Relevant information on the Shihmen Dam is can be found in Table 1.

6.2 Spillway gate availability

Considering the spillway gate system as a non-aging system, the time-dependent availability or unavailability of a single gate can be evaluated by Eq. 5. To illustrate the proposed procedure the mean breakdown time of a single gate on a spillway considered was assumed to be 20, 30, and 40 years, along with the deficiency detectability p = 0.74, and repair compliance probability q = 0.73 (Kuo et al. 2004). Figure 6 indicates that the unavailability or breakdown probability of a single spillway gate increases with time and the overtopping risk would increases with it as a result. With a larger deficiency detectability, the availability of a single spillway gate can remain at a higher value than for cases with smaller deficiency detectability (see Fig. 6).

Assuming the occurrence of malfunctioning spillway gates follows a binomial distribution, it can be calculated by the terms between the summation sign and the term of overtopping risk in Eq. 12. Knowing the binomial coefficients, namely, the total number of spillway gates, the number of the malfunctioning gates, and gate availability, and unavailability, the occurrence of malfunctioning spillway gates can be evaluated. For illustration, some of the results are shown in Fig. 7. The occurrence probability of zero-malfunctioning gate decreases with time while that of non-zero malfunctioning gates increases with time due to the time-dependent decreasing availability and increasing unavailability of spillway gates. Consequently, overtopping risk increases with time due to the decreasing availability of spillway gates.

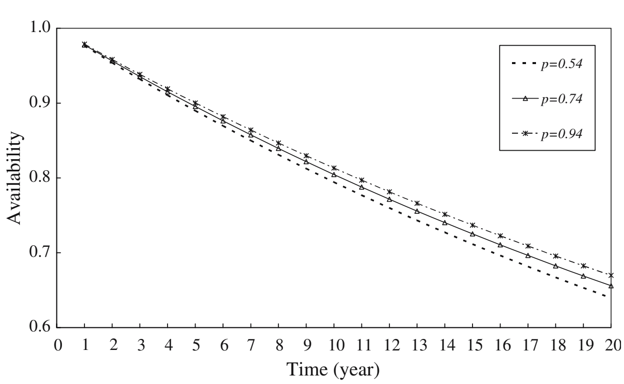


Fig. 6 Availability of a single spillway gate with μ = 30 years and a repair compliance probability q = 0.73

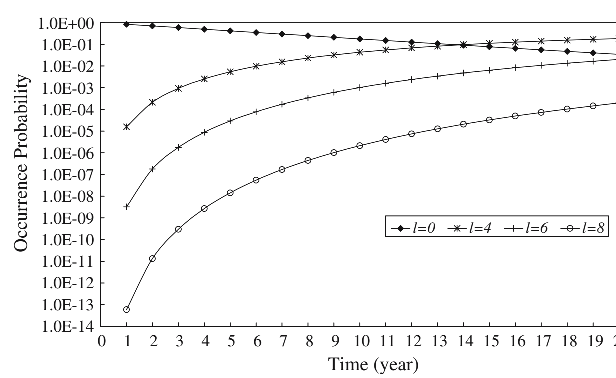


Fig. 7 Time-dependent occurrence probability of l malfunctioning gates

6.3 Overtopping risk

In this study, the annual peak discharge records were collected from 1962 to 2002 by the Shihmen Reservoir Operation Administration. Using chi-square test the best fit distribution is the Gumbel distribution.

Peak discharges of different return periods found by frequency analysis were converted into hydrographs by the unit hydrograph derived according to the records collected from 1962 to 2002. The hydrograpghs of different return periods were then routed through the Shihmen Reservoir considering current operation rules. The highest reservoir water levels under floods of different return period were evaluated for different numbers of malfunctioning spillway gates. The MFOSM and HPE methods with consideration of three uncertain factors (namely, reservoir geometry, spillway rating curve, and the error of the reservoir routing model) are adopted to calculate the dam overtopping risk by Eqs. 9–11. Table 2 shows the conditional overtopping risk increases due to an increase in the number of malfunctioning spillway gates, in which the risk values are the average calculated by the MFOSM and HPE methods. Figure 8 demonstrates the comparison of overtopping risk values with and without considering malfunctioning spillway gates and it clearly indicates an underestimation of overtopping risk by neglecting consideration of malfunctioning spillway gates.

Since the time-dependent availability of a single gate on spillway and the dam overtopping risk under different numbers of malfunctioning gates have been evaluated, the annual overtopping risk of Shihmen Dam can be computed by Eq. 12. Figure 9, which depicts the results under $p = 0.74$ and $q = 0.73$ for three mean gate breakdown times: $\mu = 20$, 30, and 40 years, shows that the overtopping risk increases with time due to increasing time-dependent unavailability of the spillway gates. Moreover,

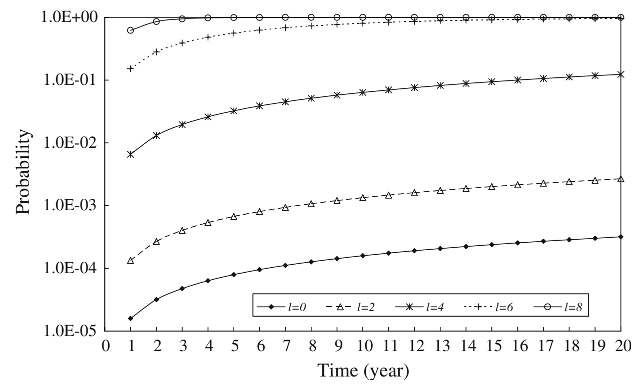


Fig. 8 Comparison of overtopping risk with and without considering malfunctioning spillway gates

Fig. 9 shows that the mean gate breakdown time influences the availability of spillway gates and the overtopping risk with time.

6.4 Cost of dam break

The cost of dam break consists of two components: the reconstruction cost of Shihmen Dam and economic losses due to down-stream inundation. The reconstruction cost of Shihmen Dam is estimated by calculating its present value considering a 5% interest rate. Shihmen Reservoir was completed in 1964, and its total present value in 2000 is estimated to be NT$ 18.6 billion.

The economic losses include direct and indirect losses. The values of direct and indirect losses in different areas affected by dam failure are concluded in Table 3. Total economic losses due to inundation are NT$ 4.26 billion. Detail calculation of the cost associated with Shihmen Dam failure can be found in Kuo et al. (2004). Therefore, the total dam break cost is estimated to be NT$ 22.86 billion.

Table 2 Overtopping risk considering l malfunctioning spillway gate(s)

Numbers of malfunctioning spillway gates, l	Overtopping risk due to malfunctioning gate(s), $P(\mathrm{OT}|l)$
0	1.5909×10^{-5}
1	3.3575×10^{-5}
2	1.3409×10^{-4}
3	1.2349×10^{-3}
4	6.5962×10^{-3}
5	4.9830×10^{-2}
6	1.6478×10^{-1}
7	5.3245×10^{-1}
8	9.7167×10^{-1}

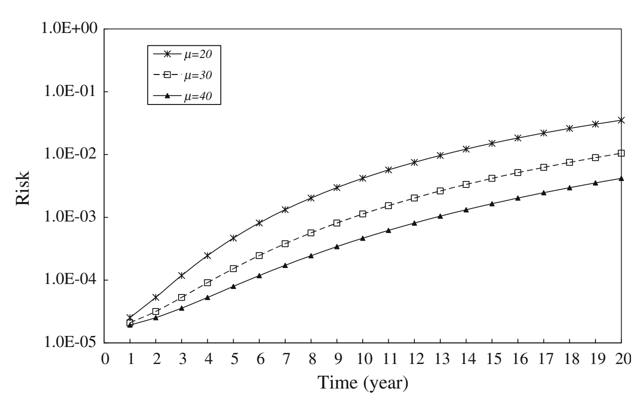


Fig. 9 Time-dependent overtopping risk considering malfunctioning spillway gate under $p = 0.74$, $q = 0.73$, and $\mu = 20$, 30, and 40 years

Table 3 Economic losses due to inundation in different regions (unit: million NT$)

Losses	Taipei county	Taipei city	Taoyuan county	Summation
Direct	1,543.33	291.01	1,417.35	3,251.69
Indirect	505.86	96.73	408.43	1,011.02
Total	2,049.19	387.74	1,825.78	4,262.71

6.5 Inspection scheduling

In determining dam inspection scheduling, the annual total cost TC for Shihmen Dam can be expressed as Eq. 22.

$$\mathrm{TC} = P(\mathrm{OT}|\tau, p, q)C + \frac{4.6 \times \mathrm{e}^{9.52p}}{\tau}, \qquad (22)$$

where $P(\mathrm{OT}|\tau, p, q)C$ is the product of TC of dam break and overtopping risk evaluated by Eq. 12; the second cost component is the annual inspection cost, a function of inspection cost which is roughly adjusted and estimated based upon the inspection records of six different large dams in Taiwan collected by Kuo et al. (2004); and τ is the inspection interval. TC is an U-shaped curve from which one can determine optimal inspection interval τ_{opt}, corresponding to the lowest point on the TC-curve. Adopting an inspection interval shorter than τ_{opt} indicates that a lower risk of dam failure but a higher value of inspection cost; conversely, adopting an inspection interval longer than τ_{opt} indicates that a higher risk of dam failure but a lower value of inspection cost.

With $p = 0.74$, $q = 0.73$, and a mean breakdown time $\mu = 30$ years, the optimal inspection interval for Shihmen Dam is about 5.3 years (see Fig. 10) corresponding to the minimum TC. One can observe that for an inspection interval between 5 and 8 years (see Fig. 10) the total cost curve around the minimum is rather flat. However, a larger inspection interval is would be associated with taking a higher risk of dam failure. One should consider the trade-off between the two.

Figure 10 shows that the optimal inspection interval increases with deficiency detectability p under a fixed repair compliance probability q. Considering the effect of the mean gate breakdown time, a longer mean gate breakdown time results in a longer optimal inspection interval for a fixed p and q. Furthermore, Fig. 10 also shows that a higher p-value flattens the bottom of U-shaped TC-curve for a fixed q and mean gate breakdown time. This implies that one can determine a more flexible inspection interval as the total cost curve is rather constant around the minimum. Similarly, Fig. 11 shows that the inspection interval increases with repair compliance q under a fixed deficiency detectability p. The optimal inspection interval varies from 4.4 to 6.0 years with q-values varying from 0.6 to 1.0. Moreover, the annual cost of dam break increases with a decrease in q-value. Therefore, with higher values of p and q, the optimal inspection interval increases.

Dam break cost C is the other important factor. Figure 12 shows the optimal inspection interval varies from 4.8 to 5.5 years with dam break cost varying from 0.8 to 1.2 times of C for $p = 0.74$, $q = 0.73$, and a mean breakdown time of 30 years for a single gate. Some suspect that dam break cost would be much higher than expected; Fig. 13 shows the optimal inspection intervals with dam break cost varying from 0.2 to 5 times of C. The results show that a higher dam break cost C would result in decreasing optimal inspection intervals. Table 4 shows that

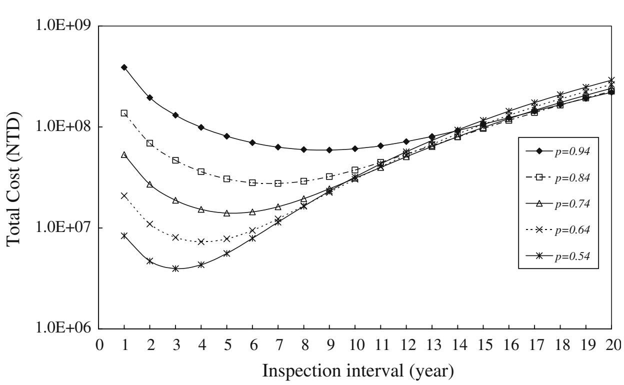


Fig. 10 Sensitivity of optimal inspection interval for Shihmen Dam with respect to deficiency detectability under $q = 0.73$ and $\mu = 30$ years

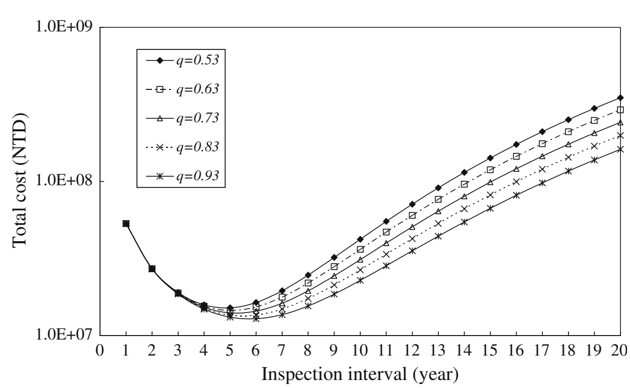


Fig. 11 Sensitivity of optimal inspection interval for Shihmen Dam with respect to repair compliance probability under $p = 0.74$ and $\mu = 30$ years

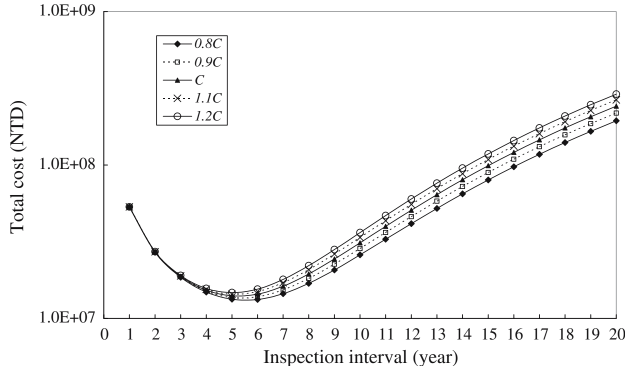


Fig. 12 Sensitivity of optimal inspection interval for Shihmen Dam with respect to total cost under $p = 0.74$, $q = 0.73$, and $\mu = 30$ years

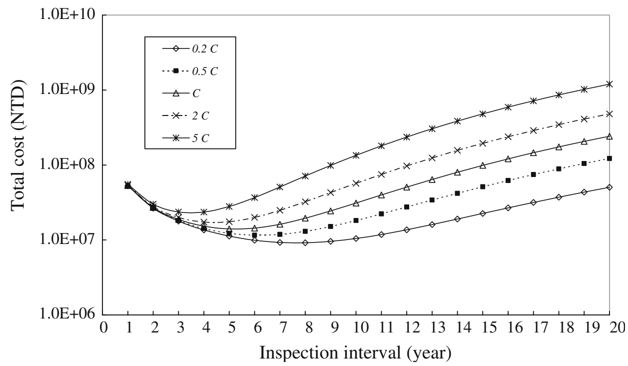


Fig. 13 Optimal inspection interval for different breakdown cost from 0.2 to 5 *C* with values of $p = 0.74$, $q = 0.73$, and a mean gate breakdown time of 30 years

the sensitivity of the inspection interval to *p*, *q*, and *C* ranges from 80 to 120%. Results show that *p* is the most sensitive factor because a larger value of *p* would correspond to higher inspection cost. Figure 14 shows that the optimal inspection interval would increase with increasing *p* and *q*-values.

7 Summary and conclusions

Earlier studies on the assessment of dam overtopping risk that consider only the uncertainties in the reservoir properties and natural randomness of hydrologic events without taking into account the spillway gates availabilities could underestimate dam overtopping risk. In this study, a framework is proposed to evaluate time-dependent overtopping risk considering the availabilities of spillway gates. The framework includes (1) evaluation of conditional overtopping risk under different numbers malfunctioning spillway gates; (2) evaluation of spillway gate availability; and (3) dam inspection scheduling. The time-dependent overtopping risk is assessed by considering the random numbers of malfunctioning spillway gates that are not operable during flood events. Furthermore, considerations are given to overtopping risk, inspection cost, and dam break cost for determining the optimal inspection schedule.

Table 4 Sensitivity interval to analysis of the inspection *p*, *q*, and *C*

Factor	Inspection interval (unit: years)					Rank
	20%	10%	0%	–10%	–20%	
p	8.7	6.6	5.3	5.1	4.2	1
q	5.7	5.4	5.3	4.9	4.7	2
C	5.6	5.4	5.3	5	4.7	3

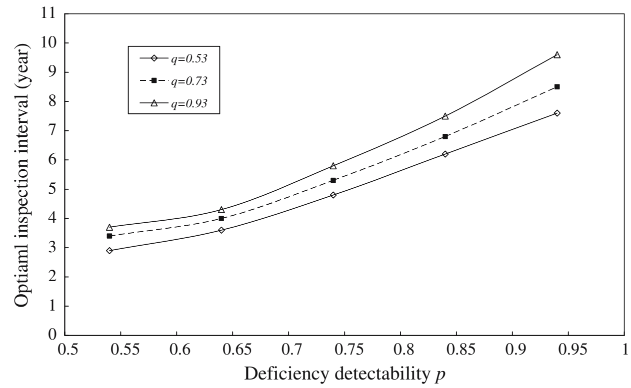


Fig. 14 Optimal inspection interval for different *p* and *q* with a mean gate breakdown time of 30 years

Results show that overtopping risk considering the availability of spillway gates is greater than the risk computed without considering the availability of spillway gates. Moreover, the optimal inspection interval for Shihmen Reservoir is estimated to be about 4.7, 5.3, and 6.6 years for $p = 0.74$, $q = 0.73$, and the mean gate breakdown time of $\mu = 20$, 30, and 40 years, respectively.

In Taiwan, government policy requires a dam inspection interval to be carried out every 5 years. Based on this study, an optimal inspection interval can be determined according to different conditions for a dam.

8 Recommendations

Two types of error associated with flood frequency analysis (quantile estimation) are not considered in this study. The first type arises from the assumption that the observations follow a particular distribution. The second type is the error inherent in the parameter estimates from small samples. The uncertainties for each return period of flood might affect overtopping risk and then affect the optimal dam inspection interval. Therefore, one can consider the uncertainties in flood frequency analysis for further study.

The optimal inspection interval is determined from the expected availability; however, availability of a system, in fact, deteriorates due to external forces with time. From this point of view, a dam system may face a larger risk if inspection program is implemented infrequently, and then the users down-stream of this dam system have to pay more if dam break occurs. Conversely, the availability of a system will be more certain if inspections and repair works are conducted more frequently, but the users also have to pay more for the work required. Therefore, the uncertainty of system availability is another important topic for further study.

Acknowledgments This study was based on the work supported by the Water Resources Agency, Ministry of Economic Affair (MOEA). The assistances from the Shihmen Reservoir Administrative Bureau and other reservoir administrative bureaus are gratefully acknowledged. We also thank the editor and referees for very helpful suggestions.

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