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A case study to reservoir dam failure events in China

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An innovative methodology for establishing societal life risk criteria for dams: A case study to reservoir dam failure events in China

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ABSTRACT

Because of the uncertainty regarding the potential loss of life, it is difficult to use societal life risk criteria for dams established based on existing methods and the related research. Based on existing dam safety standards, dam safety conditions, and the opinions of the public on dam risks, an innovative methodology, i.e. *P–P* curve, was proposed to establish societal life risk criteria for dams. The annual probability of dam failure, population at risk, and dam height, which have the most significant and direct impacts on the potential loss of life, were selected as the basic indices. Taking China as an example, societal life risk criteria for the dams of five types of reservoirs were established; in these criteria, the heights of 30 m and 70 m were proposed as the bases for upgrading the risk criteria for the dams of small-type reservoirs, medium-type and large (2)-type reservoirs, respectively. The proposed methodology was designed to be more practical in determining the risk levels for dams because the values of the basic indices are considerably easier to determine than those of risk criteria based on the existing methods.

1. Introduction

Dams play extremely important roles in flood control, power generation, water supply, irrigation, and so on. However, they also pose significant threats to the downstream areas as a result of the water that they block [1]. Despite the increasing safety of dams resulting from the improved engineering knowledge and better construction quality [2], a full non-risk guarantee is not possible and accidents can occur owing natural hazards, human actions or dam aging [3,4]. Effective methods for evaluating threats have attracted the attention of both dam engineers and the public. Recently, risk management has begun to serve as a strong basis for informed decision making [5,6], with dam risk criteria being key factors in assessing and evaluating such risks [7,8].

The societal life risk is characteristic for a hazardous activity in combination with the surrounding population [9–11]. Due to the differences in social and economic conditions [12,13], both the potential consequences caused by dam failure and the social vulnerability differ considerably between countries. Thus, the risk criteria used in one country may not be practical in others [14]. Therefore, the relevant research is ongoing. Jonkman et al. [15] presented the results of a research project that evaluated the potential roles of two risk metrics, individual and societal life risks, to support decision making on new flood safety standards and presented preliminary estimates of the nationwide levels of societal life risk. Gu [16] established integrated dam failure risk criteria that comprehensively considered the risks caused by dam failure in the areas of life, economy, environment, and society. Bowles [17] summarized risk evaluation principles that included the topics of risk perception, individual and societal concerns, equity and efficiency, and pure and applied criteria. From a technical perspective, Chitsaz and Banihabib [18] adopted the societal criterion named Expected Average Number of Casualties per year as the highest priority among the criteria used to make decisions on flood management. Li et al. [7] proposed societal life risk criteria based on the safety conditions of dams in China, public safety and the acceptance of dam risks, historical dam breach data and current design standards. Ge et al. [14] proposed guidelines for establishing risk criteria for dams in

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developing countries and demonstrated the selection of relevant parameters based on the "As low as reasonably practicable" (ALARP) principle and *F–N* curve, using China as an example. Both the methods and parameter values proposed in the aforementioned studies serve as useful references and promote the required level of dam management. However, in addition to the failure probability, the potential loss of life (*LOL*) caused by dam failure is also essential to establish societal life risk criteria [19]. These criteria are very difficult to apply in a risk assessment during practical engineering, because dam risks cannot yet be reliably quantified [20].

In theory, the potential *LOL* can be determined by allocating the risk caused by dam failure to individual hazard scenarios or hazardous events [21]. This practice requires the number of scenarios or events to be estimated. Unfortunately, such estimates are often no better than guesses [22,23]. Due to the uncertainties of influencing factors and different levels of social vulnerability [24], the values for the potential *LOL* caused by dam failure calculated using the different existing methods vary within an order of magnitude [25].Furthermore, no procedure is currently available to accurately predict the number of fatalities resulting from a dam failure [26]. Consequently, compared with traditional standards that mainly pertain to dam safety conditions, dam risk criteria are less frequently implemented. For example, in Australia [27] and Canada [28], dam risk criteria are only regarded as supplements to traditional standards. Despite the relatively large amount of research progress, the *LOL* has not been considered separately in the current safety standards for flood defence standards in the Netherlands, which are largely based on the outcomes of cost-benefit analysis [15].

Therefore, based on an analysis of the characteristics of the commonly used expressions for dam risk criteria, a *P–P* curve that considers the annual dam failure probability, population at risk, and dam height, was proposed to establish societal life risk criteria for dams. The three key indices in this new method are easy to determine, ensuring that the established risk criteria are more practical than the existing methods.

2. Methods and materials

2.1. ALARP principle

Several principles are often used to guide the establishment of risk criteria, e.g., "As low as reasonably practicable" (ALARP), "As low as reasonably achievable" (ALARA), "Globalement au moins aussi bon" (GAMAB), "Minimum endogenous mortality" (MEM), "Mindestens gleiche sicherheit" (MGS), and "Nicht mehr als unvermeidbar" (NMAU). ALARP principle, which evolved from the so-called safety case concept first developed formally in the United Kingdom, is now widely applied in safety decision-making [29]. The principle divides risk into three regions, i.e., intolerable region, ALARP region (or tolerability region), and acceptable region, according to the tolerable risk level and acceptable risk level, as shown in Fig. 1.

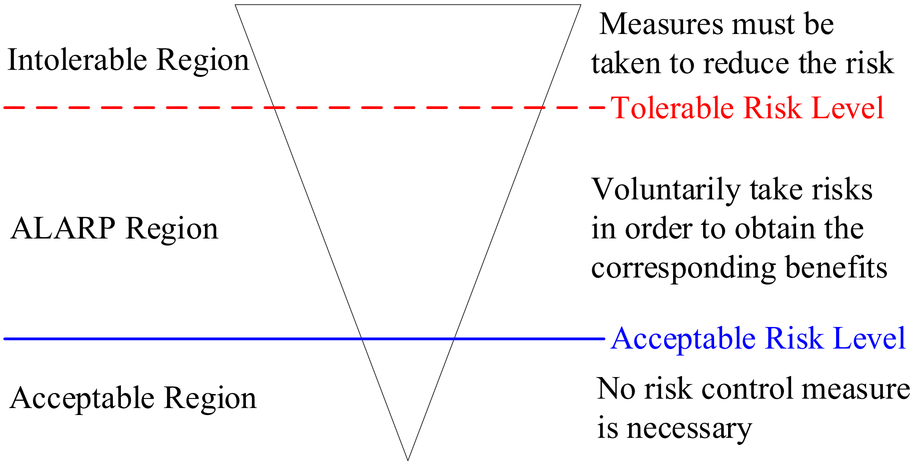


Fig. 1. ALARP principle.

2.2. Commonly used methods for establishing dam risk criteria

2.2.1. Expected loss

Risk metrics are essential for expressing, communicating and using the results of risk analysis in risk-informed decision-making [30]. Expected loss, which indicates the fatalities caused by one dam failure per year, is often used to evaluate the dam risk level. Individual risk is generally defined as the probability that an average unprotected person, permanently present at a certain location, is killed due to an accident resulting from a hazardous activity [9], as shown in Equation (1).

$$IR = P_f \times P_{d/f} \tag{1}$$

where *IR* is individual risk, P_f is the probability of failure, and $P_{d|f}$ is the probability of an individual dying in the event of failure, assuming permanent unprotected presence of the individual.

Expected loss can be determined as follows [31].

$$E(N) = \iint_A IR(x,y)m(x,y)dxdy \tag{2}$$

where $E(N)$ is expected *LOL*, $IR(x, y)$ is the individual risk at location (x, y), $m(x, y)$ is the population density at location (x, y), and A is the area where the population at risk is located.

In practical applications, expected loss caused by dam failure can be determined as follows.

$$E(N) = PAR \times P_f \times P_{d/f} \tag{3}$$

where *PAR* is population at risk.

British Columbia Hydro in Canada has proposed dam risk criteria based on expected loss, as shown in Equation (4) [32].

$$E(N) < 10^{-3}(\text{fatalities / year}) \tag{4}$$

2.2.2. Risk matrix

Although a consensus has not yet been reached, a risk matrix based on the combination of the severity of the consequence occurring in a certain accident scenario and its frequency has been widely used in practice [33,34].

A risk matrix is often used in a semi-quantitative way and its assessment results are often generated by two key elements [35]: the severity and probability. Generally, the elements are divided into three levels: low (L), medium (M) and high (H) [36], as shown in Fig. 2.

2.2.3. F–N curve

Because of the objective and subjective uncertainties that arise from the random character of the assessment process and limited and partial knowledge [33], both the probability and potential *LOL* caused by dam failure contain randomness. Therefore, societal life risk criteria are most often expressed in terms of the frequency distribution of multiple casualty events [37], as shown in Equation (5) [15].

$$P_f(x) = P(N > x) = \int_x^{\infty} f_N(x)dx \tag{5}$$

where $P_f(x)$ is the probability of more than x fatalities per year, and $f_N(x)$ is the probability density function of the number of fatalities per year.

Presently, an *F–N* curve is used to represent the limits of a variety of risks and accidents, as shown in Equation (6) [16].

$$1 - F_N(x) < \frac{C}{x^n} \tag{6}$$

where $F_N(x)$ is the probability distribution function of the number of fatalities per year, signifying the probability of less than x fatalities per year, n is the steepness of the limit line, and C is the constant that determines the position of the limit line.

NSW Dams Safety Committee [27], U.S. Army Corps of Engineers (USACE) [38] and U.S. Bureau of Reclamation (USBR) [39] have proposed corresponding risk criteria based on the *F–N* curve method for their dams, as shown in Fig. 3.

When the loss resulting from several small accidents becomes equal to the loss due to a single large accident, the attention tends to be focused on the large accident [14]; this cannot be reflected by expected *LOL* established based on the basic concept of risk, i.e., Risk = Probability × Loss. Societal life risk represented by a risk matrix or an *F–N* curve, shows the frequencies of accidents of different magnitudes for a given activity [40]. Both the failure probability and potential *LOL* differ significantly under different working conditions, which may cause the dam risk calculation results to be located in distinct regions, i.e., low, middle, high; and acceptable, ALARP, intolerable for the risk matrix and *F–N* curve graph, respectively. This will result in conflicts, as shown in Fig. 4(a) and Fig. 4(b).

2.3. Innovative methodology for establishing dam risk criteria

2.3.1. Selection of indices for dam risk criteria

According to Equation (3), three variables determine the risk due to dam failure. Population at risk (*PAR*) and dam failure probability (P_f) are basic variables, whereas the probability of an individual dying in the case of failure ($P_d|_f$) is not. $P_d|_f$ is determined by the flood severity, societal characteristics, and individual characteristics [41].

Based on the theory of disaster science, the main objects of disasters can be divided into three categories: the disaster-causing factor, disaster-prone environment and disaster-affected body [42], which corresponding to the floods caused by dam failure, societal characteristics, and individual characteristics in dam risk management, respectively. Generally, the disaster-causing factor, which possesses significant uncertainty, is the key to determining the loss rate. Therefore, the dam height, which is a basic property of a dam and has the most direct effect on flood severity, can be selected as a basic index. The disaster-affected body and disaster-prone environment [43], which remain relatively constant for a period in a certain region, can be considered as the important factors that determine the values of variables in the criteria rather than as basic indices, ensuring that the criteria will not be too complex to be applied.

Therefore, three variables, i.e., the population at risk, annual probability of dam failure and dam height, were selected as basic indices for establishing dam risk criteria.

2.3.2. Methodology for establishing dam risk criteria

According to ALARP principle and the risk matrix and *F–N* curve concepts, a *P–P* curve (annual probability of dam failure-population at risk) was proposed to establish the dam risk criteria. A typical *P–P* curve graph is shown in Fig. 5.

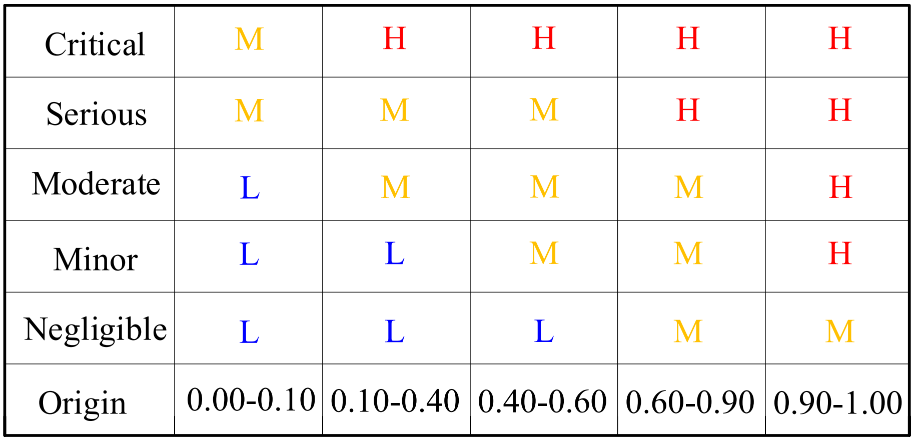
Generally, under the same conditions, i.e., both the population at risk and dam failure modes are same, the failure of a higher dam will cause much more fatalities than that of a lower one. Therefore, the stricter criteria should be followed for a higher dam.

2.3.3. Determination of index values for P–P curve graph

(1) Combined with existing dam safety standards

Safety standards for dam design and management are followed worldwide [44]. In the early stages of dam risk management, the decision based on risk criteria can be considered to be an effective supplement to current safety standards [14]. Changes to the existing standards must be gradual and minor to prevent anxiety and distress among the users of the standards. If a revision of the existing standards were to change the safety level by 10%, it is very unlikely that the established risk criteria would be officially accepted and applied in practice [45]. Therefore, the existing standards are useful bases for determining the values of the indices in *P–P* curve.

(2) Consistent with dam safety conditions



Critical	M	H	H	H	H
Serious	M	M	M	H	H
Moderate	L	M	M	M	H
Minor	L	L	M	M	H
Negligible	L	L	L	M	M
Origin	0.00-0.10	0.10-0.40	0.40-0.60	0.60-0.90	0.90-1.00

Fig. 2. Typical risk matrix.

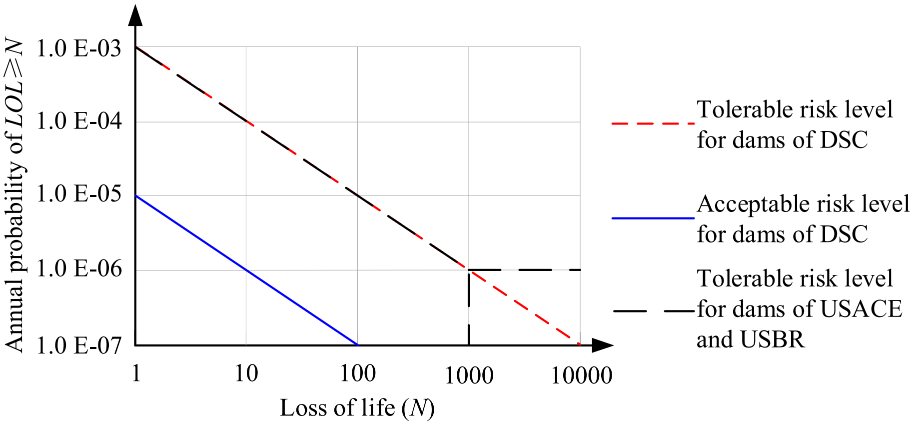
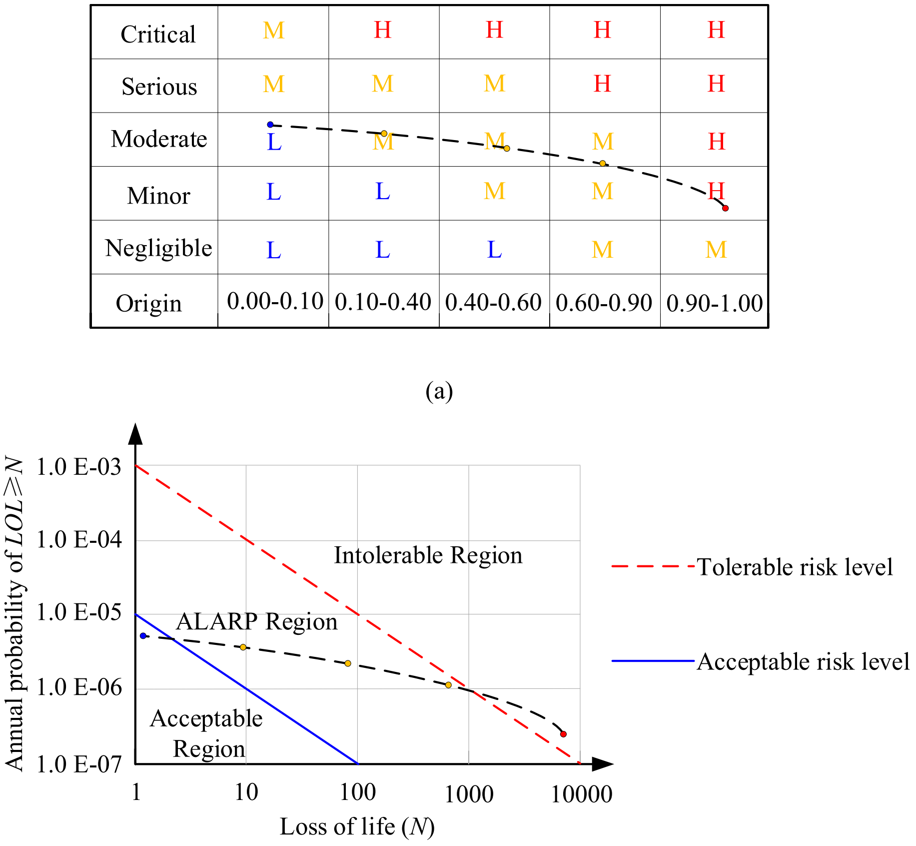


Fig. 3. Some societal life risk criteria for dams.



Critical	M	H	H	H	H
Serious	M	M	M	H	H
Moderate	L	M	M	M	H
Minor	L	L	M	M	H
Negligible	L	L	L	M	M
Origin	0.00-0.10	0.10-0.40	0.40-0.60	0.60-0.90	0.90-1.00

(a)

(b)

Fig. 4. (a). Potential conflicts in risk matrix, (b). Potential conflicts in F–N curve graph.

One important aspect of ALARP principle is its reasonability, which means that the criteria should be neither too high nor too low. Failing that, the risk evaluation results for most dams would be located in the intolerable region or those of almost all dams would be located in acceptable region, which is not conform to the actual safety conditions of existing dams [14]. Dam safety conditions contribute in two ways. They can assist in determining the values of indices for criteria when the existing safety standards are not available or are unreliable. They can also be used to verify the reasonability of the criteria based on the ALARP region that most dams located in.

(3) Considering opinions of the public on dam risks

The key to evaluating the risk level of a dam is determining the intuition of public regarding dam safety, because the public directly bears the risk caused by the dam. Furthermore, the willingness of the public to accept the risk in order to obtain the corresponding benefits should be considered fully [46]. Public opinions on dam risks can be adopted as the basis for determining whether the criteria are reasonable or not, and for adjusting the values of the indices in the P–P curves. Generally, the public has a relatively stable long-term attitude toward LOL. Therefore, it is unnecessary to adjust the previously established

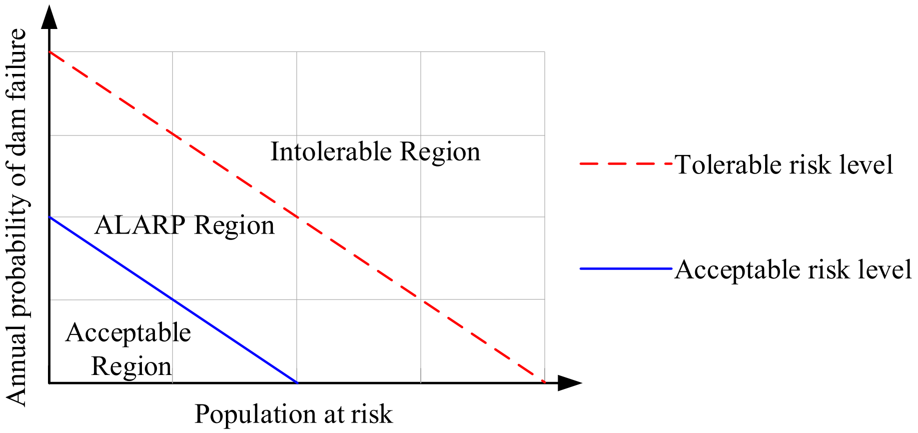


Fig. 5. Typical *P–P* curve graph.

criteria unless the public is not satisfied with the current dam safety situation [47].

3. Results

China, which has the largest number of dams in the world and continues to build dams for many other countries, can be used as a representative example for the establishment of dam risk criteria.

3.1. Dams in China

At the end of 2011, there were more than 98,000 dams in China [48]. China has categorized its dams into five classes based on their reservoir capacity, as shown in Table 1.

3.2. Societal life risk criteria based on P–P curve for dams in China

3.2.1. Preliminary determination of index values according to the existing safety standards

According to Ministry of Housing and Urban-Rural Development of the People's Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China [49] and The Ministry of Water Resources of the People's Republic of China [50], some existing standards in China are used to specify the flood control and rank classifications of water projects, as shown in Table 2.

For the dams of different types of reservoirs, Ministry of Housing and Urban-Rural Development of the People's Republic of China and General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China [51] set a reliability index of β to ensure that no sudden or difficult-to-repair damages would occur to the main hydraulic structures under the maximum design load over a long period of time. Because of the impacts of dam height on the flood severity and potential *LOL*, it is necessary to upgrade the reliability for much higher dams, i.e., small-type reservoir dams with heights greater than 30 m and medium-type and large (2)-type reservoir dams with heights greater than 70 m [50]. The reliability index can be converted to the probability of failure as the safety degree for a dam, according to Equation (7) [7,14], and the results are shown in Table 3.

Table 2
Existing standards for flood control and rank classifications of water projects in China.

Project rank	Reservoir class	Capacity (Million m^3)	Population at risk (thousand persons)	Level of main hydraulic structure
I	Large (1) type	[1000.0, ∞)	[1500, ∞)	1
II	Large (2) type	[100.0, 1000.0)	[500, 1500)	2
III	Medium type	[10.0, 100.0)	[200, 500)	3
IV	Small (1) type	[1.0, 10.0)	[50, 200)	4
VI	Small (2) type	[0.1, 1.0)	[0, 50)	5

$$p_f = 1\Phi(\beta) \tag{7}$$

According to the existing standards in China, the failure probability of a dam is not allowed to be higher than the corresponding value in Table 3; this means that relevant control measures must be adopted to reduce the risk. Therefore, the first line in the *P–P* curve graph can be preliminarily determined as the tolerable risk level. According to NSW Dams Safety Committee [27] and Ge et al. [14], the acceptable risk levels are often an order of magnitude lower than the corresponding tolerable risk levels.

Consequently, risk criteria for the dams in China based on the *P–P* curve can be determined, as shown in Fig. 6(a) and Fig. 6(b).

Table 3
Reliabilities for different levels of main hydraulic structure.

Level of main hydraulic structure	Reliability index of β	Failure probability
1	4.2	1.34×10^{-5}
2 and 3	3.7/4.2 (dam height>70 m)	$1.08 \times 10^{-4}/1.34 \times 10^{-5}$
4 and 5	3.2/3.7 (dam height>30 m)	$6.87 \times 10^{-4}/1.08 \times 10^{-4}$

Table 1
Classifications of dams in China.

Reservoir	Large type			Medium type	Small Type		
	Sub total	Large (1)	Large (2)		Sub total	Small (1)	Small (2)
Number	756	127	629	3938	93308	17947	75359
Total capacity (Billion m^3)	749.985	566.507	183.478	111.976	70.351	49.638	20.713

Fig. 6(a) can be used to determine the risk levels of small-type reservoir dams with heights of ≤30 m, as well as medium-type and large (2)-type reservoir dams with heights of≤70 m. Fig. 6(b) can be used to determine the risk levels of small-type reservoir dams with heights of>30 m, as well as medium-type and large (2)-type reservoir dams with heights of>70 m. Both Fig. 6(a) and (b) can be used to determine the risk levels of large (1)-type reservoir dams. Should the risk of a dam be located in the intolerable region, it must be reduced regardless of the cost. Should the risk of a dam be located in the acceptable region, no action is needed. Should the risk of a dam be located in the ALARP region, a cost-benefit analysis can be used to provide the basis for determining whether or not to adopt risk control measures.

3.2.2. Validation of the risk criteria based on dam safety conditions and the public opinions

The dam safety conditions were used to verify the reasonability of the preliminarily determined dam risk criteria. There were 3529 reservoir dam failure events in China from 1954 to 2014 [52], as shown in Table 4.

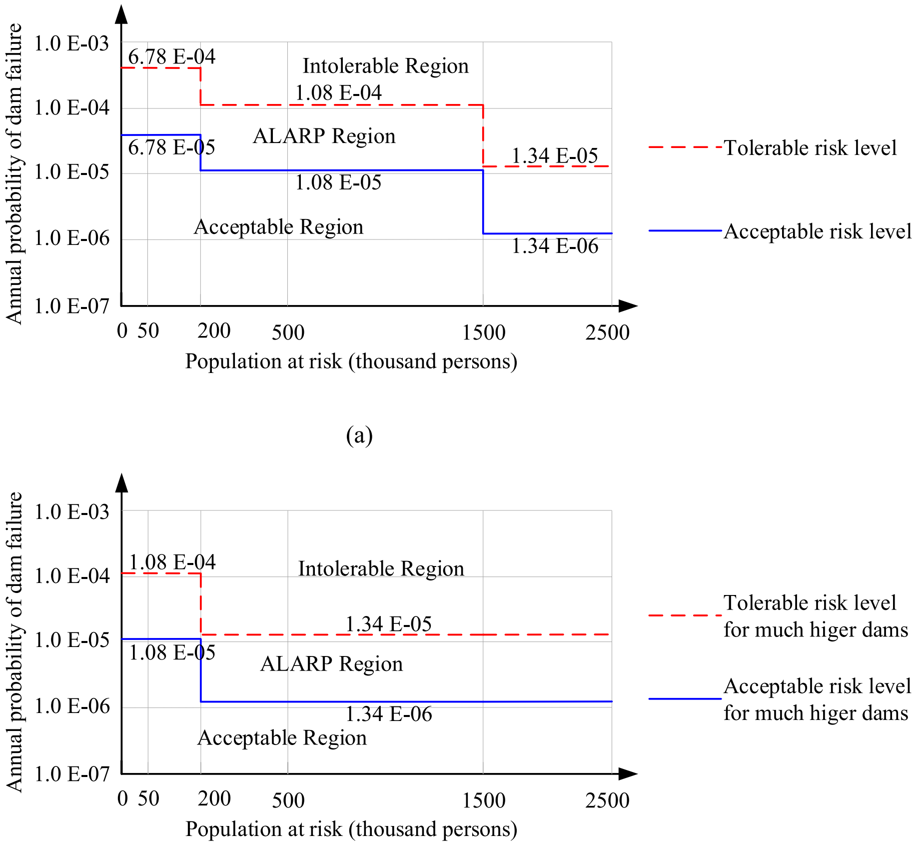
According to the statistics, most of the failure for small-type reservoirs, and medium-type and large (2)-type reservoirs were for dams lower than 30 m and 70 m, respectively. Therefore, the dam risk levels in the different periods determined based on the previously established risk criteria are shown in Fig. 7.

Currently, the public feels less anxious about the potential risks caused by dam failure than about those from earthquakes, traffic accidents, and dangerous chemicals, indicating that dam safety conditions might seem satisfactory.

4. Discussion

(1) According to Fig. 7, the dam risks of large-type (PAR≥500,000 persons) reservoirs were located in the acceptable region, except for the period of 1966–1976, when Banqiao Reservoir dam and Shimantan Reservoir dam collapsed (August 1975). The dam risks of both medium-type (200,000 persons ≤ PAR < 500,000 persons) and small-type (0 person ≤ PAR < 200,000 persons) reservoirs have significantly decreased since 1977 as a result of the constant reinforcement of reservoir dams and improvements in management ability. The results are consistent with the conclusions drawn by official dam authorities [52], showing that the proposed criteria established based on the P–P curve are applicable for assessing dam risk levels. However, the dam risks of medium-type reservoirs are still located in the ALARP region rather than the acceptable region, indicating that cost-benefit analysis are necessary to determine whether or not to take further control measures to reduce the risk.

(2) The three basic indices, i.e., the annual dam failure probability, population at risk and dam height, of the innovative methodology for establishing the dam risk criteria are much easier to determine than the potential LOL and its corresponding probability, and have no direct connections with the social development of dam downstream areas [53]. Furthermore, the important role of the potential LOL was fully considered based on the application of the population at risk and dam height, which most directly and significantly affect the flood severity, reflecting the concept of risk management. Hence, the societal life risk criteria for dams established based on the innovative methodology, i.e., the P–P curve, which are both scientific and practical, can be used as an



(a)

(b)

Fig. 6. (a). Risk criteria for dams in China based on *P–P* curve, (b). Risk criteria for much higher dams in China based on *P–P* curve.

Table 4
Reservoir dam failure events in China.

Reservoir dam	Failure condition	1954–1965	1966–1976	1977–1999	2000–2014
Large (1) type	Failure number	0	1	0	0
	Failure probability	0	7.16×10^{-4}	0	0
Large (2) type	Failure number	0	1	0	0
	Failure probability	0	1.44×10^{-4}	0	0
Medium type	Failure number	87	20	16	5
	Failure probability	1.84×10^{-3}	4.62×10^{-4}	1.77×10^{-4}	8.47×10^{-5}
Small (1) type	Failure number	282	231	155	16
	Failure probability	1.31×10^{-3}	1.17×10^{-3}	3.76×10^{-4}	5.94×10^{-5}
Small (2) type	Failure number	410	1425	829	51
	Failure probability	4.53×10^{-4}	1.72×10^{-3}	4.78×10^{-4}	4.51×10^{-5}

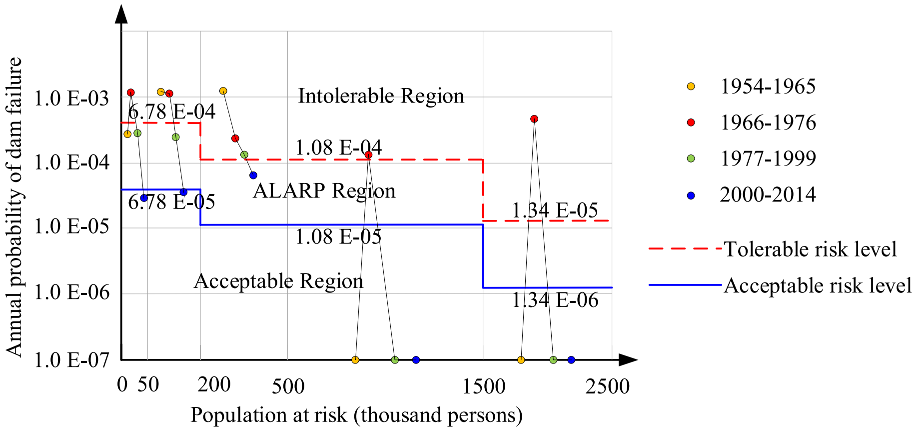


Fig. 7. Dam risk levels in different periods based on *P–P* curve.

effective transition between the traditional safety standards, which pay much less attention to downstream social conditions than to the safety status of the dam itself, and the risk criteria based on the potential LOL, which is difficult to accurately calculate.

(3) The existing dam safety standards were taken as the key bases for determining the index values of the dam risk criteria established based on the P–P curve, which ensures that the risk criteria can easily be officially accepted and conveniently applied. Because the concept of risk is heavily tied to probabilistic methods [54], the reliabilities of the Chinese Standard (GB 50199–2013) [7], which have the same level of safety measured by the annual probability of failure as Eurocode 7 [55], can be transferred to failure probabilities for establishing the risk criteria for dams in China. This verify the methodology can be applied not only in China but also in other countries.

(4) Combined with the existing dam safety standards and consensus in the field of dam engineering [50], the heights of 30 m and 70 m were preliminarily proposed as the bases for upgrading the risk criteria for small-type reservoir dams, and medium-type and large (2)-type reservoir dams in China, respectively. However, most countries do not have reference specifications for dams with heights greater than 200 m [56]. The proposed risk criteria may not be suitable for ultrahigh dams (>200 m), whose risk levels should be analyzed specifically.

5. Conclusions

Dam risk criteria established based on the existing methods are not adequately practicable, because of the difficulties in determining the potential *LOL* and its corresponding probability. Therefore, an innovative methodology, i.e., the *P–P* curve, was proposed herein. The annual probability of dam failure, population at risk, and dam height, which consider both the safety condition of the dam itself and potential consequences, were selected as the direct basic indices to establish societal life risk criteria for dams. Consideration was given to ALARP principle and the risk matrix and F–N curve ideas, which concern the potential *LOL* rather than the population at risk. Furthermore, the existing dam safety standards, dam safety conditions, and the opinions of the public on dam risks were fully considered. The proposed methodology was applied to establish risk criteria for the dams of five types of reservoirs in China, to provide examples and references for other counties; however, this methodology was not suitable for dams with heights greater than 200 m.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2020.101663.

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