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Methodology for Establishing Risk Criteria for Dams in Developing Countries, Case Study of China

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Abstract Despite the rapid development of risk analysis, there is a relative absence of risk criteria for dams in developing countries recently, which restrained the practical application of the research results. This paper proposes guidelines for establishing risk criteria of dams in developing countries in considering the coordination of social, economic and engineering factors, then establishes a method of targeted analysis and demonstrates relevant parameters selected according to the ALARP principle and F-N curves, using China as an example. Different individual life risk criteria are established based on different safety levels for existing dams and newly built dams. Social life risk criteria and economic risk criteria are established on the basis of the different safety levels of all size reservoirs, the seriousness of the consequences of accidents, and the acceptability of social risks. The process of establishing risk criteria of dams and the analysis of the parameters demonstrated in this paper are meaningful to provide a reference and promote the required level of management for developing countries.

Keywords Dams · Risk criteria · Developing countries · ALARP principle · *F-N* curves

1 Introduction

Risk assessment is primarily used for analyzing the probability of accidents under all kinds of conditions, and the consequences of these potential accidents, such as loss of life and economic

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loss, and negative impact on society and the environment. In addition to the risk criteria, determining whether the public can accept or tolerate the risk is also part of the assessment. As a result, a reasonable system for developing risk criteria is the key to obtaining an accurate and reliable risk assessment. Researchers from developed countries (notably Canada, Australia and the Netherlands) have carried out many investigations regarding the determination of risk criteria (Lind 2002), and the management decision making based on the risk criteria (Alipour 2015; Goda and Hong 2006). Their research results have been widely used in numerous areas, including dam management (Australian National Committee on Large Dams 2003; Canadian Dam Association 2009; Bottelberghs 2000).

In recent decades, decision makers in many developing countries began to change their outdated management concepts, which focused too much on the safety of the dam's structure, and began to apply what they learned from the developed countries. Some of researchers in developing countries also carried out their own explorations of risk assessment, but they mostly neglected the research on risk criteria and instead focused on analysis of the various theories of risk assessment (Gu 2011; Toosi and Samani 2012; Huang et al. 2013; Chitsaz and Banihabib 2015; Zhang et al. 2016). Moreover, in light of the different social, environmental and political conditions between the developed and developing worlds, the direct adoption of the developed countries' risk criteria into the risk assessment for developing countries is not a wise option. Therefore, in order to advance developing countries' dam management concepts and accelerate the practical application of the research results, it is imperative to conduct research on dam risk criteria that are suitable to the unique conditions of the developing countries.

Many world renowned dams are currently being constructed or have already been built in China. Due to the rapid growth of the industry of dam building, China still falls short in terms of dam risk management when compared with developed countries. Consequently, China's data will be used to establish dam risk criteria in this paper. Similar approach outlined in this paper can be adopted by other developing countries.

2 Concepts and Definitions of Risk Criteria for Dams

2.1 ALARP Principle

The determination of risk criteria necessitates a careful calculation of a country's political, financial, cultural and public psychological factors, as different factors will be considered to be more or less important in different countries, and consequently countries will adopt different sets of risk criteria. The concept of ALARP (i.e., the risks should be "as low as reasonably practicable"), which grew out of the so-called safety case concept first developed formally in the United Kingdom, is unique amongst the world's legislations and has served its intended purpose well (Kletz 2005; Marszal 2001; Health and Safety Executive 1992). In fact, the first formal definition of ALARP was provided by the English courts in the 1949 Court of Appeal case *Edwards v. National Coal Board*. The ALARP region partition method, which has been the most widely applied in the field of dam risk assessment (Jones-Lee and Aven 2011; Ale 2005), is adopted here. The principle is demonstrated in Fig. 1.

The diagram above divides risk into three regions: the intolerable region, the ALARP region (or tolerability region) and the acceptable region. If the risk is above the "tolerable risk level" then the risk should be reduced or the activity giving rise to it should be discontinued,

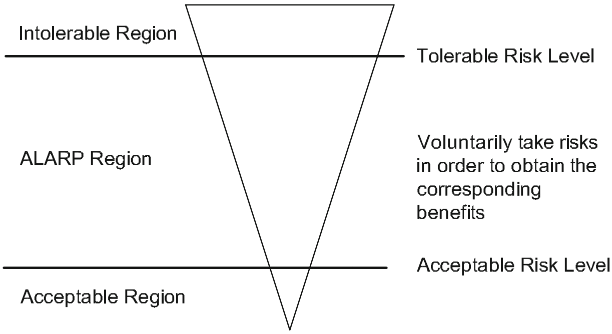


Fig. 1 Risk levels and ALARP principle

regardless of the cost. The ALARP principle is relevant only if the risk concerned is between the "tolerable risk level" and the "acceptable risk level." It refers to the willingness to live with a risk to secure certain benefits, in the confidence that risk is being properly controlled. To tolerate a risk means that we do not regard it as negligible or something that can be ignored, but rather as something we need to keep under close watch and reduce it further if and when we can. If the risk is below the "acceptable risk level," no action is needed.

It then becomes obvious that the values used for the "tolerable risk level" and the "acceptable risk level" are the key to risk assessment and management. Consequently, the establishment of the values corresponding to these risk levels is the focus of this study.

2.2 Definitions and Determination of Risk Criteria

Dam risk mainly involves loss of life and economic losses from damage caused by a dam failure, and these have adverse impacts on society and environment. During the early phases of risk management in developing countries, in order to avoid over-complications, social and environmental impacts (particularly those affecting the quality of life and natural scenery), can be simplified into financial analysis from an economic perspective. Therefore, the overall risk criteria for dams include both life risk criteria and economic risk criteria.

2.2.1 Life Risk Criteria

Two measures are incorporated into the life risk criteria: the individual life risk and the social life risk.

The first measure is the individual life risk (*IR*), as used by the Dutch Ministry of Housing, Spatial Planning and Environment (Jonkman et al. 2003). It is defined as the probability that an average unprotected person, continuously present at a certain location, is killed due to an accident resulting from a hazardous activity (Bottelberghs 2000; Laheij et al. 2000).

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

Where P_f is the probability of failure and $P_{d/f}$ is the probability of dying of an individual in the case of failure, assuming the continuous presence of an unprotected individual.

Individual life risk criteria vary by country. In the United Kingdom, the Health and Safety Executive determines the respective individual tolerable risk criteria (Health and Safety Executive 1992) for the public, $IR = 10^{-4}/a$ (where "a" is year); for workers, $IR = 10^{-3}/a$; and $IR = 10^{-6}/a$ is where the risk becomes widely acceptable. In the Netherlands, the Technical

Advisory Committee on Water Defenses sets the individual acceptable criteria at $\beta = 10^{-4}/a$ (β = 0.01 ~ 10), based on feedback from the public opinion (Jones-Lee and Aven 2011). In Australia, the Australian National Committee on Large Dams (ANCOLD) sets the individual tolerable risk criterion for existing dams at $10^{-4}/a$ and the tolerable risk criterion for new dams or expansion of existing dams at $10^{-5}/a$, according to its domestic mortality rate (Australian National Committee on Large Dams 2003).

The second measure is social life risk, which is defined by the relationship between the numbers of specific groups who suffered fatality from accidents and their corresponding probability. It is expressed in Eq. (2) (Jones-Lee and Aven 2011; Laheij et al. 2000).

$$P_f(x) = P(N > x) = \int_x^{\infty} f_N(x)dx \tag{2}$$

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.

In 1967, Farmer (1967) used probability theory to establish a curved graph representing the limits of a variety of risks and accidents, a graph that was later referred to as the *F-N* curve. Presently, *F-N* curve is widely applied in practice, and its limit lines are used for establishing risk criteria caused by dam failure (Australian National Committee on Large Dams 2003; Gu 2011). The criteria can be described in the following general formula:

$$1-F_N(x) < \frac{C}{x^n} \tag{3}$$

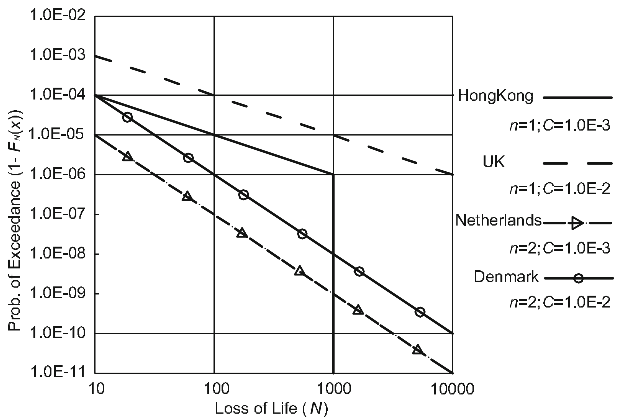
Where $F_N(x)$ is the probability distribution function of the number of fatalities per year, signifying the probability of less than x fatalities per year; n is the steepness of the limit line; and C is the constant that determines the position of the limit line.

The values of the coefficients for some international criteria and the *F-N* limit lines (Bottelberghs 2000; Marszal 2001; Laheij et al. 2000) are shown in Fig. 2.

2.2.2 Economic Risk Criteria

Because economic risk is greatly influenced by local economic development, the developed countries tend to allow individual business owners set their own criteria, based on their own expertise and abilities to bear risk (Jonkman et al. 2003). ALARP

Fig. 2 Some international criteria in *F-N* format



and *F*-*N* curves can also be used to establish economic risk criteria. ANCOLD finalized the economic risk criteria based on risk assessments conducted for a massive number of dams (Australian National Committee on Large Dams 2003), as shown in Fig. 3.

3 The Guidelines for Establishing Risk Criteria

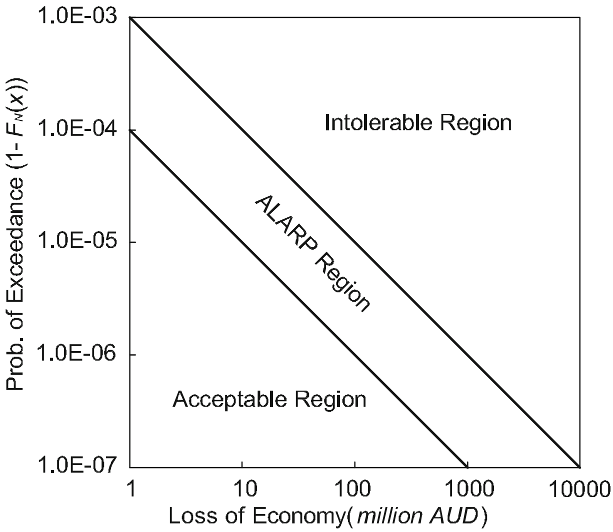
The determination of risk criteria is a delicate matter with far-reaching implications, as it not only involves technical difficulties but also social aspects (Rogers 1998). Many developed countries are relatively experienced in determining and applying the risk criteria, and the factors considered in the process as well as their problem-solving approach may have a particular significance or different implications for developing countries. Taking the many complicated scenarios of developing countries into account, the following general guidelines are proposed.

3.1 Social Perspective

Social and economic development within a country is the foundation of any risk management decisions. The risk criteria for dams in developing countries should not be set too high; the criteria should reflect the level of economic and social development, the policies regarding various energy sources, the value of human life, as well as the degree of importance attached to each of these aspects (Chen and Ren 2007).

Increased levels of education, awareness of environmental and development issues, and greater political maturity on the part of society generally leads to a much keener interest in establishing effective practices and policies for industrial risk management (Melchers 2001; Zhang and Tan 2014). The purpose of risk management is to reduce the risk to an acceptable level as perceived by the general public. Consequently, willingness of the public to accept risks is a key factor in establishing risk criteria.

Fig. 3 Economic risk criteria used in Australia



3.2 Technical Perspective

In general, the safety of dams in developing countries is not guaranteed to the extent it is in developed countries, and the funding for the management for dams is relatively lacking. One important aspect of ALARP is its reasonability, which means that the risk criteria must conform to actual safety conditions of the existing dams. Failing that, the risk criteria would be considered as unreasonable and unrealistic.

Change in management policy is a slow and gradual process. In the early stages of risk management for dams, decisions based on risk analysis can be considered as supplementary to current safety standards. Should the established risk criteria and the safety standards of existing dams fail to match, then it is very unlikely that the established risk criteria will be recognized officially. This type of situation would definitely not contribute to the risk criteria being accepted and applied in risk management.

4 Establishing Risk Criteria for China

4.1 Life Risk Criteria

4.1.1 Individual Life Risk Criteria

One of the tasks of a society is to protect individual members and groups from natural and man-made hazards, to an extent acceptable to its population and government agencies. In the past, the extent of the protection was mostly decided after the occurrence of the hazard had shown the consequences of accidents in manufacturing and other areas (Vrijling et al. 1998). Nevertheless, the potential damage caused by nuclear power plant failures, accidents in the manufacturing of hazardous products, and dam failures share certain traits in common. As a result, the risk criteria already established for the accidents for the industry mentioned above can serve as a reference in determining the individual life risk criteria for dams.

A total of 1,403,964 casualties resulted from accidents from 2000 to 2012 in China, and the annual average mortality rate is expressed as $0.82 \times 10^{-4}/a$.

In 2014, the Chinese government published "Individual and Social Acceptable Risk Criteria for Production and Storage Device with Dangerous Chemicals (Beta)" (State Administration of Work Safety of China 2014), in which individual acceptable risk criteria are set as shown in Table 1.

According to the individual life risk criteria established by ANCOLD, the tolerable risk criterion has increased by one order of magnitude more than the acceptable risk criterion. Considering the Chinese public's views in regard to the accident mortality rate, as well as the difference in safety levels between newly built dams and existing dams, the individual life risk criteria for dams in China can be determined. The recommended values are shown in Table 2.

Table 1 Individual acceptable risk criteria for production and storage of devices with dangerous chemicals in China

Risk criteria	Low population density region	High population density region
Newly built devices	$1 \times 10^{-5}/a$	$3 \times 10^{-6}/a$
Devices in service	$3 \times 10^{-5}/a$	$1 \times 10^{-5}/a$

Table 2 Individual life risk criteria for dams in China (recommended values)

Risk criteria	Tolerable criterion	Acceptable criterion
Newly built dams	1×10^{-4}/a	1×10^{-5}/a
Existing dams	3×10^{-4}/a	3×10^{-5}/a

4.1.2 Social Life Risk Criteria

Relative to individual life risk, the quantification of social risk is much more ambiguous, as the process involves a hypothetical approach, and any estimates are based on guesswork. Due to the fact that serious accidents occur so infrequently, it is generally very difficult to prove the hypotheses or estimates statistically. Consequently, some variables for different scenarios must be analyzed before deciding on the final value in the *F-N* curves.

4.1.3 The Value of C

C is a constant that determines the position of the limit lines. The expected value of the number of fatalities is much smaller than its standard deviation, which in general is true for accidents with low probabilities and high consequences (Henselwood and Phillips 2009). The factor *C* can now be written as a function of the national infrastructure level (N_A), the risk aversion factor (k), and the policy factor (β), as shown in Eq. (4) (Vrijling et al. 1995).

$$C = \left[\frac{\beta \times 100}{k\sqrt{N_A}}\right]^2 \tag{4}$$

Considering the management level, safety conditions and financial investment of Chinese dams, the tolerable risk criterion is suggested as $N_A = 1000$,$k = 3$,and $\beta = 0.1$, resulting in $C = 10^{-2}$.

Other industries have also given their input regarding the value of *C*, and these values were determined using the existing standards in their industries. The *F-N* curves presented in the Chinese "Individual and Social Acceptable Risk Criteria for Production and Storage Device with Dangerous Chemicals (Beta)" dictate that the tolerable risk criterion for dangerous chemical enterprises on land should be $C = 10^{-3}$. Most of the accidents involving dangerous chemicals are results from human error; on the other hand, uncontrollable natural factors during dam construction and functioning are major parts of the uncertainties for accidents in dams. This suggests that a higher value, 10^{-2}, should be used for *C* for dams.

Accordingly, the recommended tolerable risk criterion should be $C = 10^{-2}$; and the acceptable risk criterion can be one order of magnitude lower, which stands at $C = 10^{-3}$.

4.1.4 The Value of n

In risk assessment, *n* represents the preference of the degree of risk. A criterion with a steepness of $n = 1$ is referred to as "risk neutral." If the steepness is $n = 2$, the criterion is referred to as "risk averse." It means when the loss resulting from many small accidents becomes equal to the loss of one large accident, the center of attention tends to be focused on the large accident (Vrijling and Van Gelder 1997).

China has categorized its dams into five classes based on their reservoir capacity R (in m^3): Large (I) Type ($R \geq 1$ billion), Large (II) Type (1 billion$>R \geq 100$ million), Medium Type (100 million$>R \geq 10$ million), Small (I) Type (10 million$>R \geq 1$ million), and Small (II) Type (1 million$>R \geq 0.1$ million). Generally, the consequences of dam breaks of large and medium-sized dams are much more serious than those of the small-sized dams, in terms of the number of fatalities and the degree of economic loss. Thus, under similar circumstances, dam breaks in large and medium-sized dams receive relatively more attention. China is currently in the process of reinforcing its existing dams. In light of budget limits for dam management and maintenance, large and medium-sized dams generally receive more funding than small-sized ones, despite the fact that the probability of failure for large and medium-sized dams is lower than that for small-sized dams. Based on the above consideration, for large and medium-sized dams, $n = 2$; for small-sized dams, $n = 1$.

4.1.5 The Extreme Lines

Most countries have extreme lines integrated into the *F-N* curves for their risk criteria. In some countries, such as Australia, the extreme lines indicate that if the probability of an accident is lower than a certain value, then no consequences need to be considered and all potential risks in this scenario are acceptable. In other places, such as Hong Kong, if the extreme lines indicate that the loss from an accident is higher than a certain value, then it does not need to consider the probability of an accident, as any risk is considered to be intolerable. The safety of dams and their management level, as well as the social and economic development level in developing countries, may be quite behind those for developed countries, which makes setting accident loss using extreme lines unviable. So that developing countries should consider using accident probability extremes lines in their risk criteria.

From 1982 to 2000, the average dam break rate in China was 2.54×10^{-4}, in which the rate for large and medium-sized dams is 0.88×10^{-4} and the rate for small-sized dams is 2.62×10^{-4}. As recommended by ANCOLD, 10% and 1% of the annual dam break rate can be taken as the extreme lines of the tolerable risk level and acceptable risk level, respectively. Thus, for large and medium-sized dams, the extreme lines of the tolerable and acceptable risk probability should be 0.88×10^{-5} and 0.88×10^{-6}, respectively; for small-sized dams, they should be 2.62×10^{-5} and 2.62×10^{-6}, respectively.

Some existing reliability standards in China specify the degree of safety for dams. For dams of different sizes, a reliability index value of β is established to ensure that the main hydraulic structures under maximum design load after a long period of time would without sudden or difficult-to-repair damages occurring: Large (I) Type is 4.2, large (II) and Medium Type is 3.7, and Small Type is 3.2. The aforementioned reliability index values can become the foundation upon which the risk criteria are established (Aven 2009; Li et al. 2015). According to the reliability theory, assuming the function of reliability theory is a random variable of normal distribution, then$P_f = 1 - \Phi(\beta)$. The current Chinese reliability standards are somewhat congruent to the dam safety conditions, which is why 10% and 1% of the function of P_f can be taken as the extreme lines of tolerable and acceptable risk level, respectively. Since the consequences for failure of both large-sized dams and medium-sized dams are extremely serious, in order to avoid overcomplicating the risk criteria, medium-sized dams can potentially have the same criteria as large-sized dams. Thus, for both large and medium-sized dams, the extreme lines of tolerable and acceptable risk level should be 1.34×10^{-6} and 1.34×10^{-7}, respectively; and the extreme lines of tolerable and acceptable risk level for small-sized dams are 7×10^{-5} and 7×10^{-6}, respectively.

In order to satisfy the extreme lines determined by both the safety conditions of dams and reliability standards simultaneously, their respective smaller values must be chosen as the risk criteria. Then for large and medium-sized dams, the extreme lines of tolerable and acceptable risk level should be 1.34×10^{-6} and 1.34×10^{-7}, respectively, as shown in Fig. 4.

For small-sized dams, the extreme lines of tolerable and acceptable risk level should be 2.62×10^{-5} and 2.62×10^{-6}, respectively, as shown in Fig. 5.

4.2 Economic Risk Criteria

In comparison to life risk, economic risk is much harder to determine accurately because of the indirect and implicit economic loss involved. The indirect economic loss can be expressed by multiplying the direct economic loss by a coefficient, and many different proportional coefficients have been proposed. American safety expert H. W. Heinrich (Heinrich et al. 1980) believes that the ratio between direct and indirect economic loss should be 1:4. This ratio differs from the ratio used in the American annual accident report, which stands at 1:1. Chinese experts believe the ratio to be 1:7. However, such a coefficient is strongly influenced by the accident type and the nature of the industry. Thus, it is very challenge to determine such a coefficient.

Understandably, assessing the value of a human life in financial terms is often considered to be heartless, as every life is considered to be priceless, and putting an economic value on human life can lead to strong criticism and opposition. However, the value of a human life can be reasonably used as a statistical term to enable the numerical relation of life loss and economic loss to be established for determining the economic risk criteria.

The Chinese government, based on the economic data collected in prior accidents, believes that each individual death caused by an accident is roughly equivalent to 3.3 million to 5 million Yuan of direct economic loss. Thus, a ratio of 1 person to 4 million Yuan is recommended for the determination of economic risk criteria for dams in China, as shown in Figs. 6 and 7.

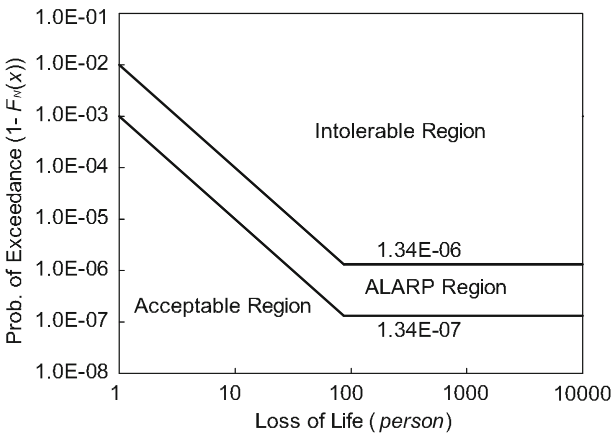


Fig. 4 Social life risk criterion for large and medium-sized dams in China (recommended value)

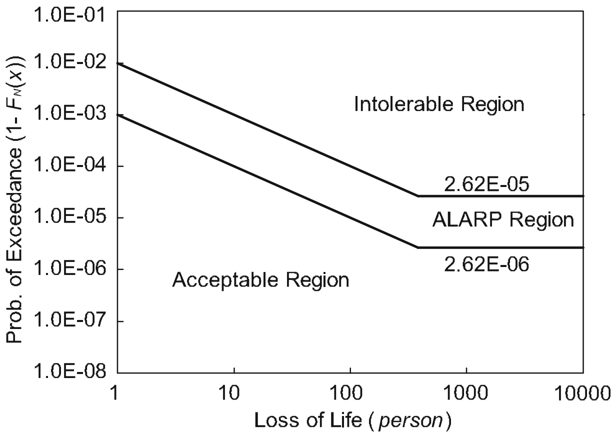


Fig. 5 Social life risk criterion for small-sized dams in China (recommended value)

5 Discussion and Conclusions

In risk management methods employed by many developed countries, the comprehensive consideration of the relationship between the project and people, as well as the project and society, is much more reasonable and scientifically sound than the methods employed by some developing countries, which tend to focus on the project safety alone. A reasonable system of risk criteria is the foundation and key to the risk assessment and risk management of dams. Some developed countries such as Canada and Australia have long since applied risk management to dam management and have formulated the corresponding risk criteria. Developing countries have a late start in this area, and they also lack research results coordinating with their domestic conditions as well. The experience of risk management in developed countries will have a significant influence on building a system of risk criteria and management in developing countries. It is critical for developing countries to apply these criteria and practices, so that the system will conform to their economic and social development as well as to the current conditions of their dams.

This paper presents guidelines and a suggested methodology for establishing a process for determining risk criteria for dams in developing countries. In China, for example, a method of

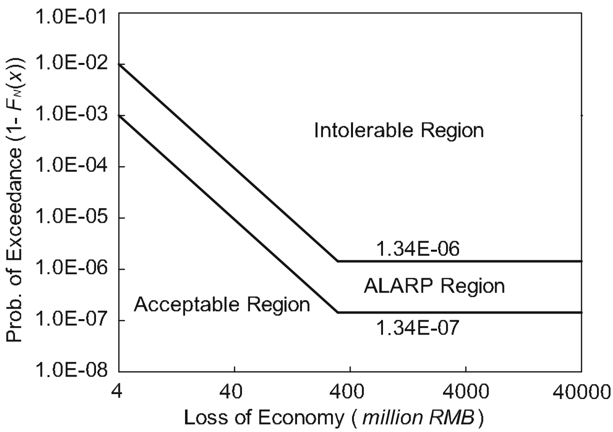


Fig. 6 Economic risk criterion for large and medium-sized dams in China (recommended value)

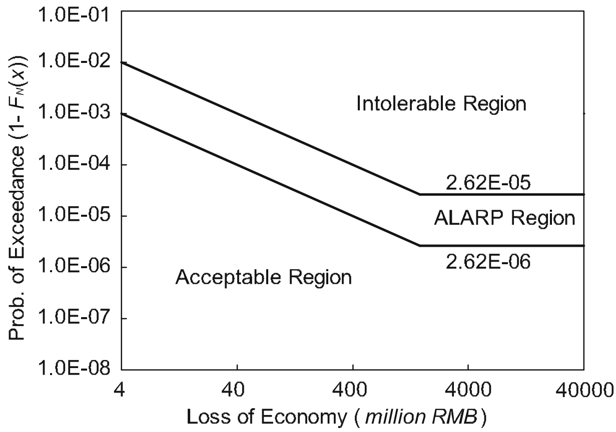


Fig. 7 Economic risk criterion for small-sized dams in China (recommended value)

targeted analysis and demonstrates relevant parameters selected is established according to the ALARP principle and *F-N* curves. The methodology, which is compatible with current safety standards in China, considers the current status of dam safety and other industry risk criteria, as well as economic and social growth, along with consideration of the degree to which the Chinese public will accept these risks. The aforementioned process of establishing risk criteria and the analysis of the parameters can provide a reference for other developing countries.

The determination of dam risk criteria is still in its infancy in developing countries, especially since these criteria have not yet been used in any application. Further verification to the risk criteria established in this research is still needed. However, it is important to define risk criteria to aid in determining risks to existing and newly built dams.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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