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Interval Analysis of the Loss of Life Caused by Dam Failure

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Abstract: Both hydrodynamic factors and social factors have large impacts on the loss of life caused by dam failure. Relatively large uncertainty intervals of the influencing factors lead to changes in the potential loss of life. Based on an analysis of the formation mechanism of loss of life, the influencing factors were identified. Combined with interval theory, a method for calculating loss of life and determining the impacts of the influencing factors on loss of life was proposed. The intervals of the exposure rate of the population at risk and the mortality of the exposed population, which are impacted by the major influencing factors such as the flood severity, warning time, understanding of dam failure, and building vulnerability, were recommended. Furthermore, a range of correction coefficients caused by the minor influencing factors, such as the dam failure time, rescue ability, and age distribution, was analyzed. The proposed method was validated by analyzing the losses of life in 21 flooded regions after 10 dam failure events and 2 flash river floods, in which the intervals of the estimated results all contained the actual loss of life. In addition, the ratios of the upper bounds to the corresponding lower bounds of the intervals were all less than 10, which is in accordance with the characteristic that the results of different existing methods vary within an order of magnitude. This is the first work that pays careful attention to the uncertainty intervals of loss of life estimates, and the proposed method effectively determined the severity of the potential loss of life caused by dam failure. **DOI: 10.1061/(ASCE)WR.1943-5452.0001311.** *© 2020 American Society of Civil Engineers.*

Author keywords: Loss of life; Uncertainty intervals; Dam failure; Influencing factors; Formation mechanism.

Introduction

Many countries have constructed a large number of dams for specific purposes such as water supply, flood control, irrigation, navigation, sedimentation control, and hydropower. For example, there are more than 98,000 and approximately 85,000 dams in China and the United States of America, respectively (Ho et al. 2017; Ge et al. 2017). Despite the increasing safety of dams due to improved engineering knowledge and better construction quality, it is not possible to guarantee no risk, because an accident can be triggered by natural hazards, human actions, or a loss of the strength capacity of the dam due to its age (Viseu and de Almeida 2009; Kalinina et al. 2018; Li et al. 2019). In recent years, there have been many serious dam failure accidents (Wu et al. 2019). As of July 24, 2018, at least 20 people had been killed and more than 100 had gone missing in the floods caused by the collapse of a dam under construction as part of the Xe-Pian Xe-Namnoy hydroelectric power project in southeast Laos (BBC News 2018). Twenty people were killed and eight went missing because of the failure of the dam associated with the Sheyuegou Reservoir on August 1, 2018, in Xinjiang, China (Beijing News 2018). More than 188,000 people were evacuated due to the threat of floods caused by local damage to both spillways of Northern California's Oroville Dam in July 2017 (Cable News Network 2017). Consequently, the potential loss of life caused by dam failure has always attracted the attention of researchers.

Originally, regression analysis was often used to establish models for analyzing the potential loss of life based on historical dam failure events. Brown and Graham (1988) established a calculation model for loss of life based on the analysis of population at risk and warning time. DeKay and McClelland (1993) developed procedures for assessing different losses of life caused by floods with different degrees of severity. Zhou et al. (2007) proposed an evaluation model for the loss of life due to dam failures in China based on eight historical dam failure events. Ge et al. (2019) proposed a method for rapidly evaluating the potential consequences of dam failure based on catastrophe theory. Because of the poor availability of data in historical data sets, however, most early studies were often limited (Jonkman et al. 2008).

Recently, physical models, which are a major component in analyzing the formation mechanism of dam failure and the loss of life,

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have gradually become a research hotspot. Assaf and Hartford (2002) outlined the modular architecture of a virtual reality approach [BC Hydro's life safety model (LSM)]. Aboelata and Bowles (2008) developed LIFESim to estimate the fatalities resulting from a wide range of levee failure scenarios in Greater New Orleans and for several dams under a range of failure and exposure scenarios. Jonkman et al. (2008) estimated loss of life based on the characteristics of floods, the evacuation of populations at risk, and mortality of exposed populations. Peng and Zhang (2013) analyzed human risks due to dam failure-induced flooding on the basis of Bayesian networks. Zhang and Tan (2014) improved the support vector machine (SVM) to estimate loss of life. Huang et al. (2017) established a calculation method for loss of life that considers more influencing factors than previous methods. However, to match the analysis results with the statistics of historical events, most existing methods have complex calculation processes and formulas, resulting in relatively poor practical applicability (Huang et al. 2017). Furthermore, due to the uncertainties in the influencing factors and their mechanisms of action (Baecher 2016; Fu et al. 2018), estimations of the potential loss of life caused by dam failure are more likely to be a most probable range rather than a definite value (Judi et al. 2014).

The wide variations in influencing factors and their impacts should be fully considered during the analysis process (Judi et al. 2012). Therefore, interval theory was introduced to analyze the potential loss of life caused by dam failure.

Methods

Interval Theory and its Arithmetic

Interval Theory

Interval analysis was originally developed to model the propagation of round-off errors through computerized calculations (Alefeld and Mayer 2000). Moore (1966) published a monograph entitled "Interval Analysis" in 1966, in which interval theory was systematically expounded. Since then, interval theory has attracted the interest of mathematicians in developing the foundations of numerical computation (Moore 1979).

Definition 1. An uncertain variable X is represented by a closed, finite interval, of which $\underline{x}$ and $\bar{x}$ are the lower bound and upper bound, respectively. X is defined on the real line R and is expressed as

$$X = [\underline{x}, \bar{x}] = \{x \in R | \underline{x} \leq x \leq \bar{x}\} \tag{1}$$

Interval theory can effectively solve two kinds of problems: (1) when the original data are vague but their boundaries are clear, and (2) when the theoretical principle of a given process is incomplete but the approximate describing equation is known (Su and Wen 2013). Recently, interval theory has been applied to risk analysis (Tsaur 2011), structure calculations (Santoro et al. 2015), and the multicriteria selection of complex systems (Grishko et al. 2018), and meaningful achievements have also been reported (Xue et al. 2019).

Interval Arithmetic

The core of interval arithmetic consists of the generalization of scalar arithmetic operators to interval arithmetic operators (Degrauwe et al. 2010). The basic operators of interval arithmetic are expressed as

$$X + Y = [\underline{x} + \underline{y}, \bar{x} + \bar{y}] \tag{2}$$

$$X - Y = [\underline{x} - \bar{y}, \bar{x} - \underline{y}] \tag{3}$$

$$X \times Y = [\min\{\underline{x}\,\underline{y}, \underline{x}\,\bar{y}, \bar{x}\,\underline{y}, \bar{x}\bar{y}\}, \max\{\underline{x}\,\underline{y}, \underline{x}\,\bar{y}, \bar{x}\,\underline{y}, \bar{x}\bar{y}\}] \tag{4}$$

$$X \div Y = X \times \frac{1}{Y} \tag{5}$$

$$\frac{1}{Y} = \begin{cases} \phi, & Y = [0, 0] \\ \left[\frac{1}{\bar{y}}, \frac{1}{\underline{y}}\right], & 0 \notin Y \\ \left[\frac{1}{\bar{y}}, \infty\right), & \underline{y} = 0 \text{ and } \bar{y} > 0 \\ \left(-\infty, \frac{1}{\underline{y}}\right], & \underline{y} < 0 \text{ and } \bar{y} = 0 \\ (-\infty, \infty), & \underline{y} < 0 \text{ and } \bar{y} > 0 \end{cases} \tag{6}$$

According to interval arithmetic, a variable may take different values in the same function, resulting in the extension of the interval analysis results. Taking the interval $X = (1, 2)$ as an example, the evaluation of $Y = X–X$ according to Eq. (3) leads to

$$Y = X–X = (1, 2) - (1, 2) = (-1, 1) \neq (0, 0) \tag{7}$$

When the variables of a function appear more than once in operation, the extension of the interval analysis result will be serious (Li and Xu 2018). The fewer the interval parameters appear, the weaker the correlation among the interval arithmetic operators will be. If each interval parameter appears only once, the interval arithmetic operation can obtain a more accurate interval solution, ensuring the practicability of the result (Degrauwe et al. 2010).

Analysis of Loss of Life Caused by Dam Failure

Identification of the Influencing Factors of Loss of Life

According to disaster theory, the concepts and principles of disaster-causing factors, disaster-prone environments, and disaster-affected bodies were used to identify the influencing factors of loss of life (Li et al. 2018).

1. Disaster-causing factors

   Floods caused by dam failures are the most direct influencing factors that lead to loss of life (Peng and Zhang 2013). Both the depth and the velocity reflect the severity of a flood (Qi and Altinakar 2012). Therefore, the two indexes of floods, namely, the depth and velocity, can be synthesized into one index, such as the flood severity (S_F), and expressed as

   $$S_F = D \times V \tag{8}$$

   where D and V = depth and velocity of the flood, respectively.
2. Disaster-affected bodies

   Without a population at risk, there is no loss of life regardless of how serious a flood is. The warning time and the two main properties of a population at risk, such as the understanding of dam failure and age distribution, have great impacts on the evacuation of populations at risk (Sun et al. 2014).

   Understanding of the dam failure refers mainly to whether the population at risk correctly understands the severity and area of flooding caused by the dam failure and whether they can take timely and correct escape measures and paths. Considering the great differences in the escape capabilities of different age groups, the age distribution was used to reflect the percentages of young and middle-aged people among the population at risk.

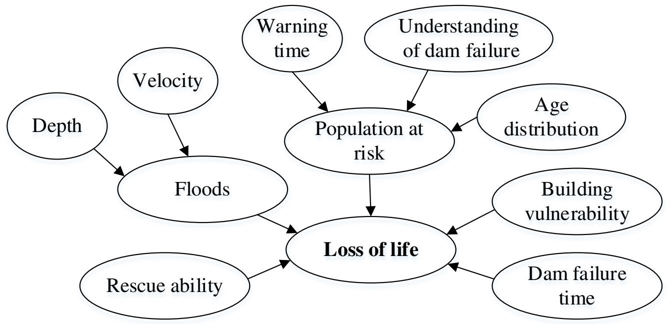

Fig. 1. Relations between the loss of life and influencing factors.

3. Disaster-prone environments

Disaster-prone environments, which include both societal and engineering conditions, also impact loss of life in addition to disaster-causing factors and disaster-affected bodies. Buildings provide the main shelters for populations at risk, and thus, building vulnerabilities are of great importance. Furthermore, the rescue ability and dam failure time are other intuitive influencing factors of loss of life.

The relations between the loss of life and influencing factors are shown in Fig. 1.

Interval Analysis of Loss of Life

Due to the extension of the results of interval arithmetic, the recurrence of influencing factors should be avoided when analyzing the loss of life by interval theory. Therefore, the key influencing factors and their functional links should be clarified to ensure the accuracy of an interval analysis of loss of life (Maijala et al. 2000).

Rescue actions are expected to have a limited effect on the fatalities incurred during the direct impact phase (Jonkman et al. 2008). In addition, the age distribution of the population at risk and dam failure time are less important than the other influencing factors (Li et al. 2018). Therefore, except for the population at risk (PAR), the other influencing factors can be divided into two categories: (1) the major influencing factors, such as the warning time (T_W), understanding of dam failure (U_B), flood severity (S_F), and building vulnerability (V_B); and (2) the minor influencing factors, such as the dam failure time (T_B), rescue ability (A_R), and age distribution (D_A). The formula used to calculate loss of life (LOL) is expressed as

$$LOL = (LOL_{\min}, LOL_{\max}) = PAR \times f \times c \tag{9}$$

where $LOL_{\min}$ and $LOL_{\max}$ = lower bound and upper bound of the loss of life interval, respectively; f = mortality interval of the population at risk caused by the major influencing factors; and c = correction coefficient corresponding to the minor influencing factors.

1. Interval analysis of the major influencing factors

The formation mechanism responsible for the loss of life caused by the major influencing factors is shown in Fig. 2.

According to Fig. 2, the loss of life can be calculated as

$$\begin{aligned} LOL &= PAR \times f_1 \times f_2 \times c \\ &= PAR \times f_1(T_W, U_B) \times f_2(S_F, V_B) \times c \end{aligned} \tag{10}$$

where f_1 = interval of the exposure rate of the population at risk influenced by the warning time and understanding of dam failure; and f_2 = mortality interval of the exposed population influenced by the flood severity and building vulnerability.

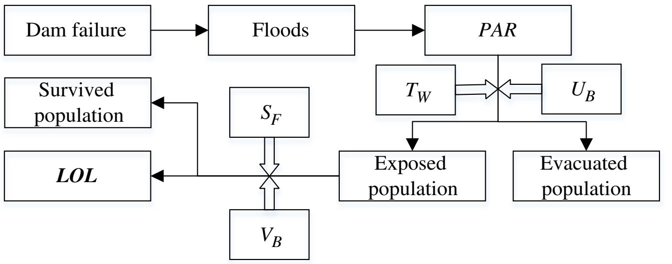

Fig. 2. Formation mechanism of the loss of life caused by the major influencing factors.

Table 1. Recommended intervals of the exposure rate influenced by the warning time

T_W (in hours)	f_{11} (T_W)
[0.00, 0.25)	(0.75, 1.00]
[0.25, 0.50)	(0.60, 0.75]
[0.50, 1.00)	(0.20, 0.60]
[1.00, 1.50)	(0.05, 0.20]
[1.50, ∞)	[0.00, 0.05]

The warning time is a key influencing factor of evacuation. On this basis, the understanding of dam failure also has a certain effect. Therefore, f_1 can be expressed as

$$f_1 = f_{11}(T_W) \times f_{12}(U_B) \tag{11}$$

where $f_{11}(T_W)$ = interval of the exposure rate of the population at risk influenced by the warning time; and $f_{12}(U_B)$ = interval of the influence coefficient of the exposure rate caused by the understanding of dam failure.

Based on the analysis of 24 major dam failure events and flash floods, Brown and Graham (1988) clarified the impact of the warning time on loss of life. However, the proposed formulas showed large discontinuities (Jonkman et al. 2008). According to DeKay and McClelland (1993), loss of life decreases very quickly when the available warning time increases. Combined with the normalized function of the warning time established by Wang et al. (2011) based on statistics, the recommended intervals of the exposure rate of the population at risk influenced by the warning time are shown in Table 1.

Generally, the clearer the understanding of dam failure is, the higher the evacuation rate will be, resulting in a lower exposure rate and a lower corresponding mortality. Combined with the studies of Graham (1999) and Zhou et al. (2007), the recommended intervals of the influence coefficient of the exposure rate caused by the understanding of dam failure are shown in Table 2.

Table 2. Recommended intervals of the influence coefficient of the exposure rate

U_B	f_{12} (U_B)
Unknown	(0.80, 1.00]
Vague	(0.60, 0.80]
General	(0.40, 0.60]
Medium	(0.20, 0.40]
Precise	[0.00, 0.20]

Table 3. Recommended criteria of building damage

Building type	Partial damage (m^2/s)	Major damage (m^2/s)
Unanchored wood-framed	$S_F \geq 2$	$S_F \geq 3$
Anchored wood-framed	$S_F \geq 3$	$S_F \geq 7$
Masonry, concrete, and brick	$S_F \geq 7$ and $V \geq 2$	$S_F \geq 7$ and $V \geq 2$

Table 4. Recommended mortality intervals of the exposed population

		$f_2 = f_2(S_F, V_B)$		
Flood severity	S_F	Soil	Brick	Concrete
Slight	[0.00, 0.60]	[0.00, 0.10]	[0.00, 0.00]	[0.00, 0.00]
General	(0.60, 2.00]	(0.10, 0.30]	(0.00, 0.10]	[0.00, 0.00]
Moderate	(2.00, 3.00]	(0.30, 0.70]	(0.10, 0.30]	(0.00, 0.10]
Serious	(3.00, 7.00]	(0.70, 1.00]	(0.30, 0.70]	(0.10, 0.50]
Extremely serious	(7.00, ∞)	(1.00, 1.00]	(0.70, 1.00]	(0.50, 1.00]

Once damaged, buildings no longer serve as reliable shelters for exposed populations, causing loss of life. Building damage is influenced mainly by the characteristics of both the flood and the building. Under certain flood conditions, the ability of a building to provide shelter for a population at risk is mainly related to the type and height of the building.

Total destruction of masonry, concrete, and brick houses occurs as soon as the product of the water depth and flow velocity exceeds the following criteria simultaneously (Jonkman et al. 2008):

$$S_F \geq 7\ \mathrm{m^2/s} \quad \text{and} \quad V \geq 2\ \mathrm{m/s} \tag{12}$$

Maijala et al. (2000) presented the criteria for building damage, as shown in Table 3.

However, these criteria should be specified to avoid the excessive extension of the results caused by interval arithmetic. Combined with the mechanical properties of different types of building structures (Kang and Kim 2016), the mortality intervals of exposed populations influenced by the flood severity and building vulnerability are shown in Table 4.

2. Analyzing the range of correction coefficients caused by the minor influencing factors

Due to the correlation among the three minor influencing factors, the correction coefficient c can be expressed as

$$c = c_1 \times c_2 \times c_3 \tag{13}$$

where c_1, c_2, and c_3 = correction coefficients caused by the dam failure time, rescue ability, and age distribution, respectively.

Because people typically sleep and have poor sight at nighttime, the mortality of the population at risk is higher at night than during the daytime (Zhou and Li 2006). Although limited, the effect of the rescue ability on decreasing loss of life is positive (Jonkman et al. 2008). Intuitively, the more elderly people and children there are, the higher the mortality of the population at risk. However, the impacts on loss of life caused by these minor influencing factors are much less than those caused by the major influencing factors. Due to the lack of validation data, such effects can be preliminarily considered to be less than 20%. Therefore, the ranges of c_1, c_2, and c_3 are expressed as

$$\{c_1, c_2, c_3\} \in \{(0.80, 1.20), (0.80, 1.00), (1.00, 1.20)\} \tag{14}$$

Judging the Effectiveness of the Interval Analysis of Loss of Life

Except for including the value of actual loss of life, interval analysis results should be in a certain range, ensuring their ability to guide risk evaluation and management.

Neither the lower bound $\underline{x}$ nor the upper bound $\bar{x}$ of a loss of life interval can be less than 0. A, the ratio of $\bar{x}$ to $\underline{x}$, can be expressed as

$$A = \frac{\bar{x}}{\underline{x}}, \qquad \underline{x} \neq 0 \tag{15}$$

Considering the uncertainties of different influencing factors, there can be significant differences in the analysis results of loss of life using various methods. However, the difference in these results is within an order of magnitude (Judi et al. 2014). Therefore, when A is not larger than 10, the results of an interval analysis can be considered valid.

Results

Preliminary Data

The results of the proposed method were compared with the actual losses of life in 21 flooded regions, which were divided according to the distance from the corresponding dam sites or rivers of 10 dam failures in China and Laos and 2 flash floods in the United Kingdom that had similar characteristics to those of floods caused by dam failures (Penning-Rowsell et al. 2005). The relevant parameters of the 21 flooded regions are shown in Table 5.

Interval Analysis Results and Comparison

Based on the interval arithmetic and the interval analysis model of the loss of life caused by dam failure previously established, the intervals of the estimated results ($LOL_{\min}$, $LOL_{\max}$) were obtained for the 21 flooded areas. The actual loss of life (LOL) of each flooded region used for validation was adopted for comparison, as shown in Table 6.

Discussion

The interval analysis results and actual losses of life in the flooded regions used for validation are shown in Fig. 3.

In general, the more definite the results of a mathematical model are, the more accurate the analysis will be. However, due to the uncertainties of influencing factors, some of whose exact values are determined subjectively by human beings, this principle is not suitable for analyzing the loss of life caused by dam failure. Compared with definite values, intervals of the potential loss of life can also effectively reflect the severity of consequences caused by dam failure, which are relatively easy to determine objectively and are consistent with the uncertainties of the influencing factors.

According to Fig. 3, the intervals of the estimated results from the proposed method all contained the actual losses of life in the 21 flooded regions caused by dam failure events or flash floods, showing good correctness. The proposed method, which reflects loss of life by intervals rather than definite values, fully considers the uncertainties of the loss of life and the degrees of impact of various influencing factors.

According to Table 6, when the lower bound $\underline{x} \neq 0$, all ratios of the upper bound $\bar{x}$ to the lower bound $\underline{x}$ of the loss of life intervals in the 21 flooded regions were less than 10. Combined with the section "Judging the Effectiveness of the Interval Analysis of Loss

Table 5. Relevant parameters of the 21 flooded regions

Dam/village	Year	Country	Region	T_W/h	U_B	S_D	V_B	c_1	c_2	c_3
Liujiatai	1960	China	1	1.00	Vague	Extremely serious	Soil	1.10	1.00	1.00
Liujiatai	1960	China	2	1.00	Vague	Serious	Soil	1.10	1.00	1.00
Liujiatai	1960	China	3	1.00	Vague	General	Soil	1.00	1.00	1.00
Liujiatai	1960	China	4	1.00	Vague	Slight	Soil	1.00	1.00	1.00
Hengjiang	1970	China	1	0.25	Precise	Extremely serious	Brick/soil	0.80	1.00	1.00
Hengjiang	1970	China	2	0.25	Precise	Serious	Brick/soil	0.80	1.00	1.00
Hengjiang	1970	China	3	0.25	Precise	Moderate	Brick/soil	0.80	1.00	1.00
Hengjiang	1970	China	4	0.25	Vague	General	Brick/soil	0.80	1.00	1.00
Hengjiang	1970	China	5	0.25	Vague	Slight	Brick/soil	0.80	1.00	1.00
Dongkoumiao	1971	China	1	0.00	Vague	Moderate	Brick/soil	1.00	1.00	1.00
Lijiazui	1973	China	1	0.00	Vague	Serious	Soil	1.10	1.00	1.00
Shijiagou	1973	China	1	0.40	Vague	Serious	Soil	1.00	1.00	1.00
Gouhou	1993	China	1	0.00	Vague	General	Brick/soil	1.05	0.95	1.00
Xiaomeigang	1995	China	1	0.00	Vague	General	Brick/soil	1.05	0.95	1.00
Shenjiakeng	2012	China	1	0.00	Medium	Moderate	Brick/concrete	1.05	0.90	1.10
Sheyuegou	2018	China	1	0.00	Medium	Moderate	Brick/concrete	1.00	0.90	1.00
Xe-Pian Xe-Namnoy	2018	Laos	1	>8.00	Vague	Serious/moderate	Brick	1.00	0.90	1.00
Lynmouth	1952	UK	1	0.00	Medium	Extremely serious	2-story homes[a]	1.00	0.95	1.00
Lynmouth	1952	UK	2	0.00	Medium	Serious	2-story homes	1.00	0.95	1.00
Lynmouth	1952	UK	3	0.00	Medium	Moderate	2-story homes	1.00	0.95	1.00
Gowdall	2000	UK	1	Limited[b]	Medium	Slight	2-story homes	1.00	0.90	1.00

[a] According to Peng and Zhang (2013), the vulnerability of a 2-story home is similar to that of a brick structure.

[b] According to Penning-Rowsell et al. (2005), a limited warning time indicates that the warning played an insufficient role in guiding people to evacuate. Combined with Table 1 and $f_{11}(T_W) = (0.20, 0.60)$.

Table 6. Interval analysis results and actual losses of life

Dam/village	Region	*PAR*/person	$f \times c$	Actual $f \times c$	$(LOL_{\min}, LOL_{\max})$	Actual *LOL*	*A*
Liujiatai	1	2,784	(0.132, 0.528]	0.189	(367, 1,470]	525	4.00
Liujiatai	2	3,395	(0.092, 0.528]	0.104	(314, 1,793]	352	5.71
Liujiatai	3	11,929	[0.000, 0.080]	0.005	[0, 954]	60	—
Liujiatai	4	46,833	[0.000, 0.024]	0.000	[0, 1,124]	0	—
Hengjiang	1	1,250	[0.000, 0.120]	0.000	[0, 150]	0	—
Hengjiang	2	2,500	[0.000, 0.102]	0.000	[0, 255]	0	—
Hengjiang	3	7,250	[0.000, 0.060]	0.006	[0, 435]	41	—
Hengjiang	4	60,000	(0.014, 0.096]	0.015	(864, 5,760]	900	6.67
Hengjiang	5	15,000	[0.000, 0.024]	0.000	[0, 360]	0	—
Dongkoumiao	1	4,700	(0.023, 0.160]	0.040	(106, 752]	186	7.11
Lijiazui	1	1,034	(0.347, 0.880]	0.499	(358, 910]	516	2.54
Shijiagou	1	300	(0.262, 0.630]	0.270	(76, 180]	81	2.38
Gouhou	1	3,060	[0.022, 0.160]	0.011	[69, 488]	320	7.11
Xiaomeigang	1	1,400	(0.018, 0.144]	0.024	(25, 201]	34	8.00
Shenjiakeng	1	300	(0.011, 0.100]	0.037	(3, 30]	11	9.14
Sheyuegou	1	5,600	(0.003, 0.300]	0.005	(18, 170]	28	9.64
Xe-Pian Xe-Namnoy	1	13,000	[0.000, 0.018]	0.010	[0, 234]	134	—
Lynmouth	1	100	(0.100, 0.380]	0.085	(10, 38]	34[a]	5.11
Lynmouth	2	100	(0.043, 0.266]		(4, 27]		6.93
Lynmouth	3	200	(0.014, 0.114]		(3, 23]		8.00
Gowdall	1	250	[0.000, 0.000]	0.000	[0, 0]	0	—

[a] The total loss of life and mortality of the population at risk in the three flooded regions of Lynmouth caused by flash floods were 34 and 0.085, respectively, and the corresponding interval analysis result is (17, 88).

of Life," these results show that the goal of avoiding the extension of intervals was realized by clarifying the key functional links and refining the intervals of the influencing factors.

The interval analysis results in some calculation regions, such as Liujiatai 4, Hengjiang 1, and Hengjiang 2, still had large ranges due to the relatively rough division of the calculation region caused by the limited availability of basic materials and parameters. The interaction between the wide intervals of influencing factors and the interval extension caused a difference reaching up to 4 orders of magnitude when the lower bound $\underline{x} = 0$. With the development of flood routing analysis, the interval analysis results will be narrowed and become more accurate because of the narrower intervals of the basic parameters resulting from a more detailed division of the calculation region, which will provide more meaningful guidance for dam risk management while fully considering all kinds of uncertainties.

Conclusion

The uncertainties of various influencing factors lead to significant differences in the losses of life caused by dam failures. Combined

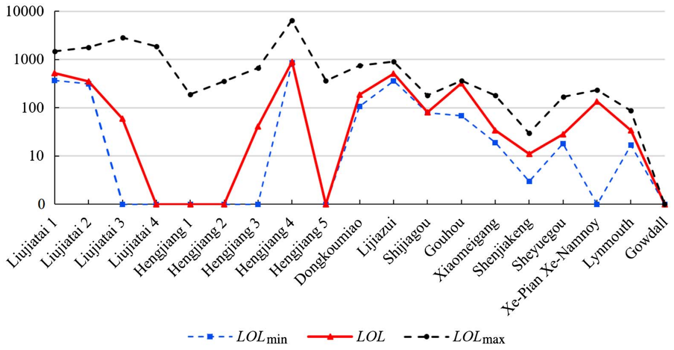

Fig. 3. Comparison between the interval analysis results and actual loss of life.

with a review of existing methods, a new evaluation method was proposed based on interval theory. According to disaster theory and an analysis of the formation mechanism of the loss of life due to dam failure, except for the population at risk, the other seven influencing factors—warning time, understanding of dam failure, flood severity, building vulnerability, dam failure time, rescue ability, and age istribution—were identified and divided into two categories: major influencing factors and minor influencing factors. The intervals of the impacts on loss of life caused by the major influencing factors and a range of correction coefficients caused by the minor influencing factors were clarified. Seventeen regions that flooded due to nine dam failure events and four regions that flooded as a result of two flash floods were adopted for validation; the results were in accordance with a judgment of the effectiveness of the interval analysis of loss of life, thereby verifying the accuracy of the proposed method and its effectiveness at evaluating the severity of dam failure.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published paper.

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