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Research Article

A New Approach for Probabilistic Risk Assessment of Ship Collision with Riverside Bridges

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The configuration of riverside bridges, such as the spatial distribution, wading status, and ship accessibility of piers, is generally different from river-crossing bridges. Thus, the ship collision risk of riverside bridges cannot be assessed using conventional assessment methods applicable to river-crossing bridges. The aim of this paper is, therefore, to develop a new probabilistic method for assessing the risk of ship collision with riverside bridges. First, a fully probabilistic framework for assessing the ship-bridge collision risk is presented. Second, a new probabilistic hazard analysis model of ship collision with riverside bridges is proposed, based on a combined study of riverside bridge characterization and an improved yaw ship collision model. A simplified empirical model for evaluating ship-bridge collision force is then adopted, and the probabilistic distribution of the collision force is obtained based on Monte Carlo simulation. Furthermore, finite element simulation is conducted to estimate the collapse probability of piers. Finally, the method developed is applied to the probabilistic assessment of ship collision risk with riverside bridges located at Shabin Road, Chongqing, China. The results show that the risk of ship-bridge collision at Shabin Road is low to moderate. The example demonstrated indicates that the methodology introduced in this paper is capable of assessing the ship-bridge collision risk in a concise and rapid way.

1. Introduction

Because of rapid economic development, there are massive existing riverside bridges which are parallel with the river direction in the Yangtze River valley of China. The extensive distribution of riverside bridges inevitably increases the risk of ship-bridge collision. The piers of the riverside bridge are commonly small in size and densely distributed in space, as shown in Figure 1. Most of the piers are waded in the wet season, inevitably increasing the risk of ship-pier collision. Besides, with the economic development of China, the number of ships travelling through the Yangtze River has been increasing rapidly. According to incomplete statistics, within 5 recent years, more than 100 ship-bridge collision accidents have occurred on the Yangtze River, Pearl River, and Heilongjiang River in China. It is, therefore, an important topic to evaluate the ship-pier collision risk for urban wading bridges in an accurate and realistic way.

There are several existing methods for assessing the ship-bridge collision risk, which can be broadly classified into three categories, namely, the fault tree method [1], fuzzy integrated method [2, 3], and probability-based method. The fault tree method is purely dependent on empirical data; yet, comprehensive historical data are usually difficult to obtain in engineering practice. Besides, Wang and Ma [2] and Ouyang and Chen [3] developed the fuzzy integrated method to assess the risk of ship-pier collision, which is a subjective approach greatly relying on experts' knowledge. Specifically, the probabilistic method, including hazard analysis of ship collision with riverside bridges and the

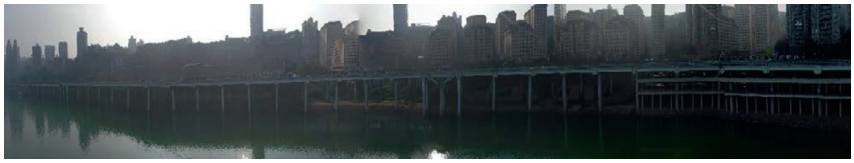

Figure 1: Riverside bridges located at Shabin Road, Chongqing, China.

damage assessment of ship-bridge collision, is currently widely used in engineering applications. For instance, Macduff [4] calculated the theoretical probability of collision between ships based on the statistical results of ship-ship collisions, and Fujii and Shiobara [5, 6] studied the ship grounding in several Japanese channels based on statistical analyses. The two works above laid the foundation for the study of ship-bridge collision. American Association of State Highway and Transportation Officials (AASHTO) wrote the guide specification and commentary for vessel collision design of highway bridges [7], establishing the framework of probabilistic risk assessment of ship-bridge collision. Based on the relative position of ship and bridge before collision occurred, KUNZI [8] developed a probabilistic model with two random parameters for evaluating the ship-bridge collision. Given the general trend of the construction of waterways and bridges in China, X. H. Fan and L. C. Fan [9] suggested conducting systematic research on the theory of ship-bridge collision based on a risk-based design concept. Ning et al. [10] investigated the demand of shear-critical reinforced concrete columns, and Gen et al. [11] developed a risk assessment system for bridges against vessel impacts.

The probability-based method provided by AASHTO is widely used for assessing the risk of ship-pier collision, which, however, is not suitable for the risk assessment of ship collision with riverside bridges. There are two major differences between cross-river bridges and riverside bridges: (i) the axial direction of riverside bridges is the same as the direction of ship heading and (ii) the piers of riverside bridges generally do not wade in the dry season, yielding no risk of the ship-pier collision. Thus, this paper aims to develop a new approach for probabilistic risk assessment of ship collision with riverside bridges, based on a combined study of the probabilistic risk assessment framework of ship-bridge collision developed by AASHTO and the wading probability of riverside bridge piers. Moreover, the method developed is applied to the probabilistic collision risk assessment for riverside bridges located at Shabin Road, Chongqing, China.

2. Framework of Fully Probabilistic Risk Assessment

The methodology of assessing ship-bridge collision risk developed by AASHTO mainly includes the probability (PA) of the ship's yaw, the probability (PG) of yaw ship collision with bridges, and probability (PC) of bridge collapse after ship-pier collision. Besides, the adjusting coefficient (PF) is employed to consider the function of anticollision measures (the coefficient (PF) is equal to 1 if a bridge lacks anticollision measures). The expression of calculating the probability AF of ship-bridge collision risk is, therefore, as follows:

$$\mathrm{AF} = \sum_{i}^{n} N_i \times \mathrm{PA}_i \times \mathrm{PG}_i \times \mathrm{PC}_i \times \mathrm{PF}_i, \quad (1)$$

where the N_i is the annual average number of the navigable ships of the i type.

Based on the framework of collision assessment developed by AASHTO, a new approach, which incorporates the wading probability and an improved yaw ship collision model, is developed to assess the risk of the collision between ship and riverside bridges. The detailed procedures for the risk assessment of ship-bridge collision are as shown in Figure 2.

3. Probabilistic Hazard Analysis

The determination of ship-collision probability (i.e., the hazard analysis of ship-bridge collision) is the most important part in the risk assessment of ship-bridge collision. However, the required sample size of ship collision accidents is a shortage for statistical analysis in most areas of China. Besides, the actual ship test cost is high and the factors considered are incomplete. This section, therefore, gives the probabilistic hazard analysis of ship-bridge collision based on existing mathematical models.

The AASHTO model [7] and KUNZI model [8] are the widely used methods to calculate the probability of ship-bridge collision. The parameters of the AASHTO model are determined empirically based on the US inland river statistics, so it is vague whether the parameters could be used for the analysis of ship-bridge collision over the Chinese inland river. Compared with the AASHTO model, the KUNZI model's theoretical derivation is more complete, and the parameters can be determined more accurately. Consequently, the KUNZI model is suitable to assess the probabilistic analysis of ship collision with riverside bridges in China.

A new probabilistic hazard analysis model of ship collision with riverside bridges is, therefore, proposed based on a combined study of riverside bridge characterization and an improved KUNZI model, in which the interval of ship trajectory integration is extended to the transverse distance from ship to pier, and the yaw angle θ_2 of the original model is directly set to 90 degrees. As shown in Figure 3, the improved KUNZI model includes three random parameters, namely, trajectory distribution, yaw angle, and stopping distance. Based on the improved model, the formulation of

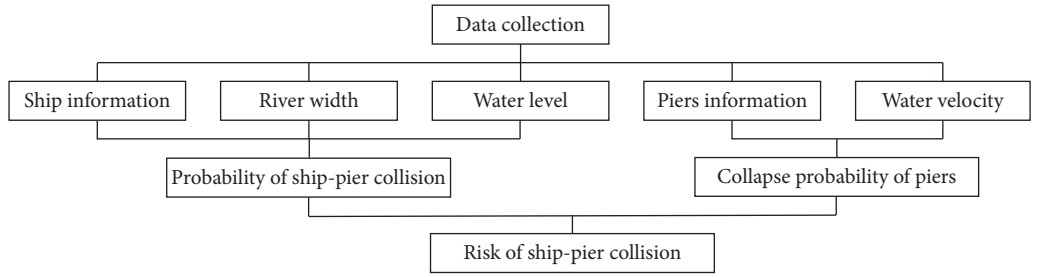

Figure 2: Framework of full probabilistic risk assessment of ship collision with riverside bridges.

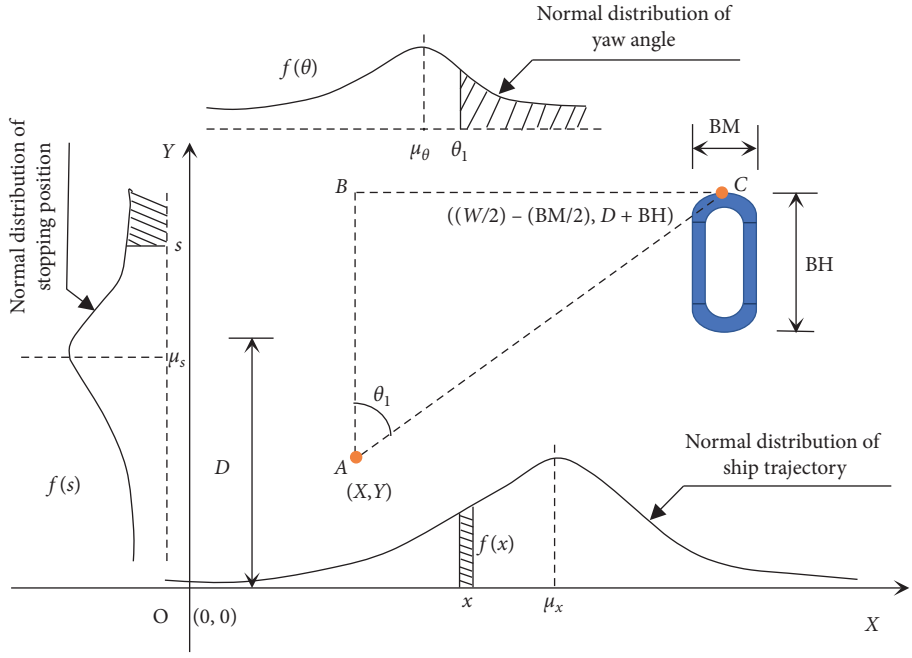

Figure 3: Principle of the KUNZI model.

annual probability of ship collision with riverside bridges under the i-th water level can be expressed as follows:

$$P_{wi} = \sum_{j=1}^{n} N_j \int_{-(W/2)}^{W/2} f(x) \int_0^D \lambda(s)[1 - F(s)] \cdot \int_{\theta_1}^{90} f(\theta) \mathrm{d}\theta \, \mathrm{d}s \, \mathrm{d}x, \tag{2}$$

where P_{wi} is the annual probability of ship collision with riverside bridge under the i water level; N_j is the annual navigation of the j type of ship; W is the channel width; $f(x)$ is the density function of ship trajectory; $\lambda(s)$ is the failure probability of ship in the unit sailing distance; $F(s)$ is the probability to stop the ship; $f(\theta)$ is the density function of yaw angle; n is the type of ship; W is the transverse distance between ship and collision point C; D is the integral path length of ship; and θ_1 is the threshold of yaw angle defined as follows:

$$\tan\theta_1 = \frac{(W/2) - (\mathrm{BM}/2) - X}{D - Y + \mathrm{BH}}, \tag{3}$$

where X and Y are the horizontal and vertical coordinates of the trajectory of the ship's bow, respectively; BH is the equivalent ship length; and BM is the equivalent ship width.

According to the characteristics of the riverside bridge and the parameters of the KUNZI model, the process of probabilistic hazard assessment of ship collision with riverside bridges can be summarized as follows:

(i) Determine the parameter values of the type of ship n, the annual navigation of the j type of ship N_j, the equivalent ship length BH, and the equivalent ship width BW in the assessment area

(ii) Determine the position of the customary wake in the assessment area, and estimate the mean and standard deviation of the transverse geometric distribution of the wake

(iii) Determine the yaw probability of ship in the assessment area, and estimate the mean and standard deviation of yaw angle

(iv) Determine the unit voyage accident rate and the distance to stop the ship in the assessment area, and estimate the mean and standard deviation of the distance to stop the ship and the unit voyage accident rate of ship

(v) Determine the navigable width at different locations in the assessment area

(vi) According to equations (2) and (3), calculate the probability P_{Gi} of ship-bridge collision and obtain the hazard map of ship-bridge collision in the assessment area

(vii) Determine the wading probability of each bridge pier in each month based on the water level change

(viii) Compute the total ship-bridge collision probability of each pier as

$$P_c = \sum_{i=1}^{m} \beta_i P_{Gi}. \tag{4}$$

4. Probabilistic Model of Ship-Bridge Collision Force

Several empirical formulas have been developed to estimate the ship-bridge collision force in the literature [7, 12–17]. This section then selects the most appropriate empirical formula by comparisons and analyses the distribution characteristics of the empirical value of the ship-bridge collision force by using Monte Carlo simulation.

4.1. Comparison of Empirical Formulas. Table 1 shows the comparison of the considered factors in empirical formulas. Figures 4 and 5 show the comparisons of the collision forces in empirical formulas, respectively (in the cases, the ship tonnage and ship velocity assigned as are 3000 t and 3.5 m/s), respectively. Based on these comparisons, these results can be obtained. The results of the Norwegian Public Roads Administration model (NPRA model) and Nordic Road Engineering Federation model (NREF model) are rough because of the absence of ship velocity. In contrast, the factors considered in the Chencheng model are too comprehensive to use for risk assessment of the large-scale area. Although the factors considered for other models are also simple and reasonable, the calculated results of ship-bridge collision force are smaller than the calculated result of the AASHTO model. In other words, the calculated result of the AASHTO model is reasonable and safe. Therefore, this paper uses the AASHTO model to forecast the ship-bridge collision force.

4.2. Monte Carlo-Based Approach for Probabilistic Distribution Characteristics. The governing equation of the AASHTO model for ship-bridge collision force is given as follows:

$$P = \alpha (\mathrm{DWT})^{1/2} \left(\frac{V}{8}\right), \tag{5}$$

where P is the ship-bridge collision force, V is the ship's impacted velocity, DWT is the ship's impacted tonnage, and α is the coefficient used to quantify the influence of other factors. Note that the ship's impacted tonnage is different from the ship tonnage because of the loaded cargo. In order to consider such specific situation, the uniform distribution model is used to simulate the distribution of ship collision tonnage. Based on the statistics of actual ship masses, the probabilistic uniform distribution of ship tonnage can be expressed as follows:

$$f(x) = \begin{cases} \dfrac{1}{1.35\mathrm{DWT} - 0.45\mathrm{DWT}}, & 0.45\mathrm{DWT} \le x \le 1.35\mathrm{DWT}, \\ 0, & \text{others.} \end{cases} \tag{6}$$

The ship's impacted velocity prior to ship collision against bridges is shown in Figure 6, and it can be observed that the ship velocity decreases as the distance between midline of waterway and impacted pier increases. Moreover, the maximum ship's impacted velocity is the common ship velocity; at the position where the distance between midline of waterway and impacted pier is 3 times the ship length, the ship's impacted velocity is minimum (equivalent with the flow velocity).

The coefficient α is used to consider the influence of other factors including collision angle, ship rigidity, and pier rigidity. Then the probabilistic distribution of the coefficient α can be descripted using triangular distribution.

In order to obtain the probabilistic distribution of the collision force, the Monte Carlo method is used in this paper. The process of the Monte Carlo-based approach modeling the probabilistic distribution characteristics of ship collision force is shown in Figure 7. First, three matrices with 10,000 random numbers of collision tonnage DWT, collision velocity, and coefficient α are generated, based on the uniform distribution, normal distribution, and triangular distribution, respectively. Second, the random matrix of ship collision force is calculated by equation (6). Finally, the probabilistic distribution of the ship collision force is simulated.

5. Collapse Probability of Piers

In order to assess the risk of ship-bridge collision, the collapse probability of pier after ship-bridge collision should also be evaluated. In this section, the ship-bridge collision is numerically simulated in ABAQUS, and the anticollision force from FE simulation is combined with the collision force from the AASHTO model to determine the collapse probability.

The plastic damage model is employed to model the concrete material. The double broken line model is chosen to model the reinforcement material. Reinforced concrete (RC) bridge pier is simulated using the method that the reinforces with the element attributes of two-dimension are embedded into the solid element attributes of three-dimension. The concrete model is mashed using the C3D8R element in

Table 1: Comparison of factors considered in various models.

Empirical formulas	Tonnage	Velocity	Yaw angle	Rigidity	Pile cap
TB10002 [12]	√	√	√	√	—
JTGD60 [13]	√	√	—	—	—
AASHTO [7]	√	√	—	—	—
Eurocode 1 [14]	√	√	—	√	—
Chencheng [15]	√	√	√	—	√
NPRA [16]	√	—	—	—	—
NREF [17]	√	—	—	—	—

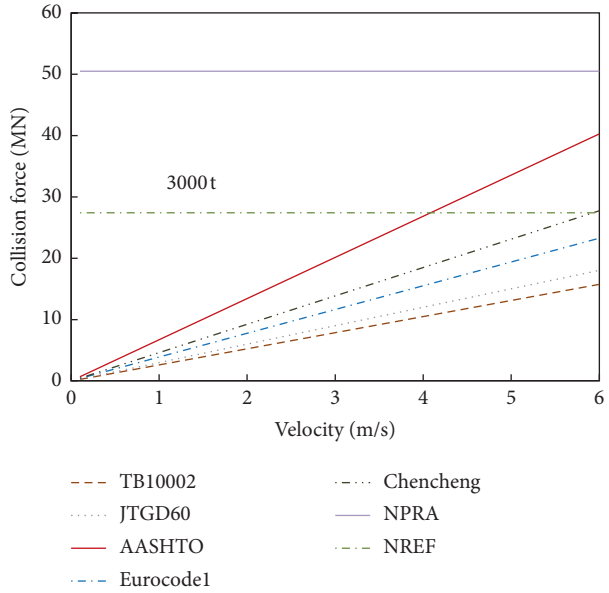

Figure 4: Comparison of relationship between ship impact force and ship impact velocity for various models.

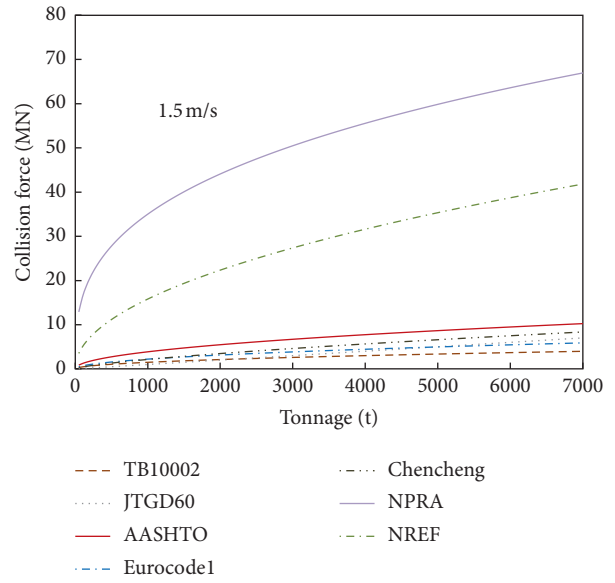

Figure 5: Comparison of relationships between ship impact force and ship impact tonnage for various models.

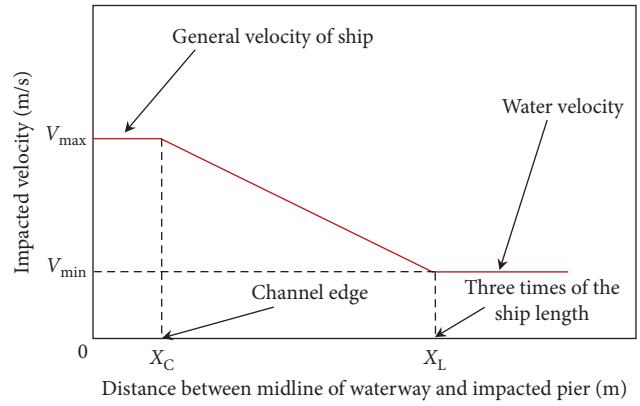

Figure 6: Determination of impacted velocity based on references.

ABAQUS, and the reinforcement model is mashed by selecting truss element T3D2 in ABAQUS. In order to simulate the ship-bridge collision, the interaction between the contact surfaces is modeled by using "hard contact" in ABAQUS. The ship bow adopts the shell element S4R in ABAQUS, with the elastic modulus assigned as 2.1×10^{11} Pa, the yield strength assigned as 235×10^6 Pa, and the rest of the parts modeling assigned as a rigid body. It is worth noting that the direction of collision between ship and bridge is assumed to be perpendicular for simulating the worst-case collision scenario of the impacted pier. This is because the actual collision angle is an unknown variable in reality; therefore, the maximum yaw angle (i.e., the perpendicular collision scenario) is considered in the AASHTO model to yield a reasonably conservative assessment about the ship-bridge collision force.

The finite element model of ship-bridge collision is shown in Figure 8.

The equivalent collision force is adopted as the representative value of the bridge pier anticollision force for evaluating the ability of pier anticollision. The concept of equivalent collision force is illustrated in Figure 9, according to the maximum moment M_{max} of the pier during the collision to derive the static force P_e on the collision point, and the static force P_e is the equivalent collision force.

The analysis process of collapse probability of pier after ship-bridge collision is as follows:

(i) To model the ship with initial velocity collision with the bridge pier in ABAQUS, and afterwards, monitor the concrete compressive strain ε_c in the core area of concrete of pier bottom

(ii) If $\varepsilon_c < \varepsilon_{cu}$, where ε_{cu} is the ultimate compressive strain of constrained concrete, one may increase the initial ship-bridge collision velocity until $\varepsilon_c > \varepsilon_{cu}$

(iii) The maximum moment $M_{max,u}$ at the bottom section of pier can be assigned as the representative value while the ε_c just more than ε_{cu}, and then to calculate the equivalent collision force $P_{e,u}$ (i.e., anticollision force of pier) by using the following equation:

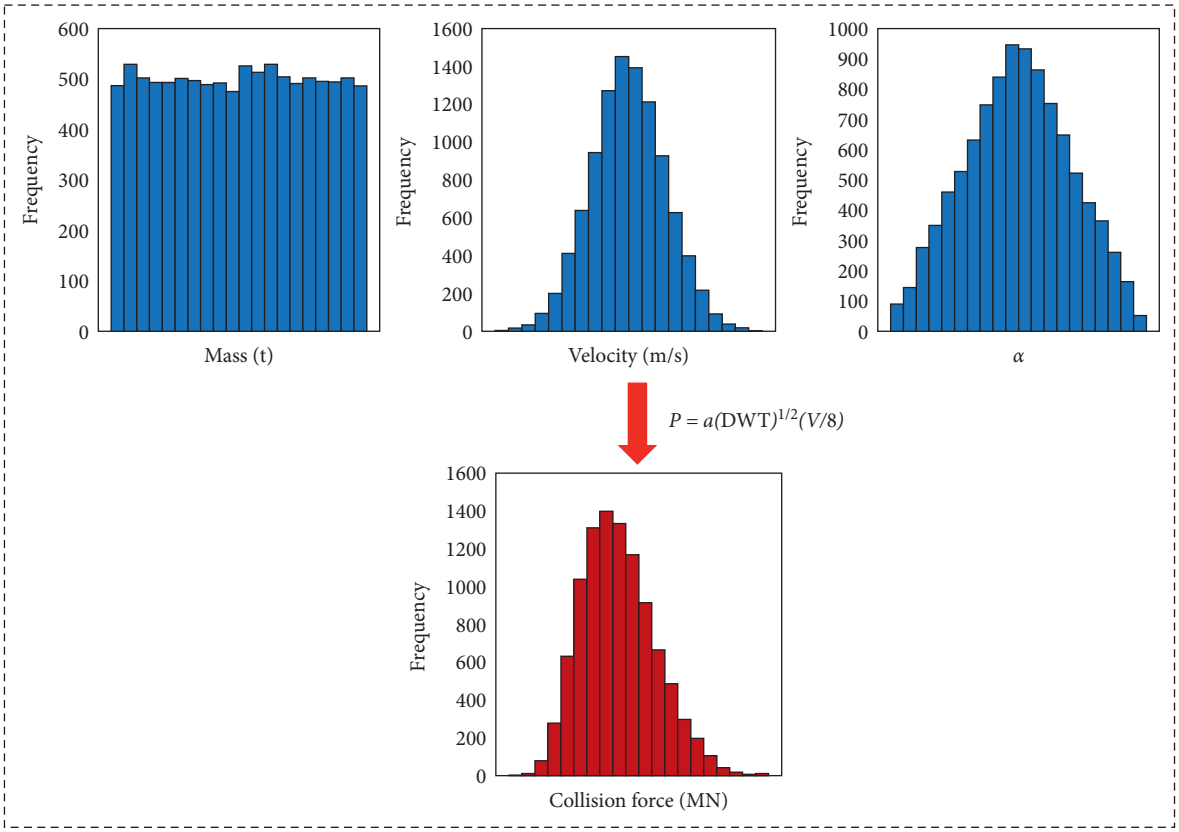

Figure 7: Evolution of probabilistic distribution of ship impact force based on Monte Carlo simulation.

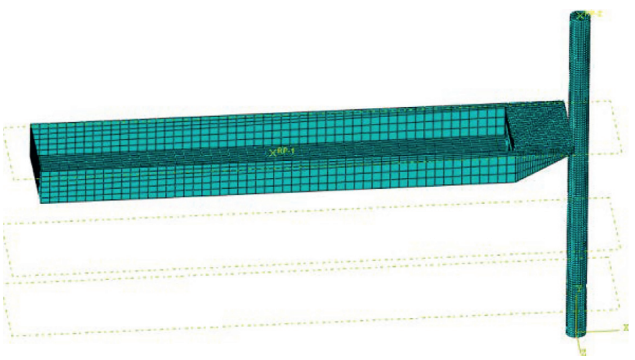

Figure 8: Finite element simulation of ship-bridge collision in ABAQUS.

$$P_e = \frac{(M(t))_{\max}}{H_2} = \frac{M_{\max}}{H_2}. \quad (7)$$

(iv) The impact force and the anticollision force are brought into the empirical formula of AASHTO to calculate the collapse probability P_C of pier after ship-bridge collision:

$$P_C = \begin{cases} 0.1 + 9 \times (0.1 - H/P), & (0.0 \le H/P \le 0.1), \\ 0.11\,(0.1 - H/P), & (0.1 \le H/P \le 1.0), \\ 0.0, & (1.0 \le H/P), \end{cases} \quad (8)$$

where H is the anticollision force of bridge pier and P is the collision force of ship.

6. Application of the Proposed Approach for Risk Assessment

6.1. Description of Risk Assessment Area. The riverside bridges located at Shabin Road, Chongqing, China, are considered as the risk assessment area, which is shown in Figure 10. The riverside bridges are 16.8 km in length, and the average of navigable span is 513.47 meters. Figure 11 shows the monthly water level in the study area in 2018. There are 8 types of ships in total according to statistics. Table 2 shows the equivalent ship parameters (i.e., DWT, BM, and BH) and the number of annual ship voyage considered in this study. Besides, three parameters, namely, the trajectory distribution, yaw angle, and stopping distance of the KUNZI model, can be reasonably assumed to be normally distributed in Chongqing City based on the study of Gen et al. [18]. According to statistics of navigation habit of

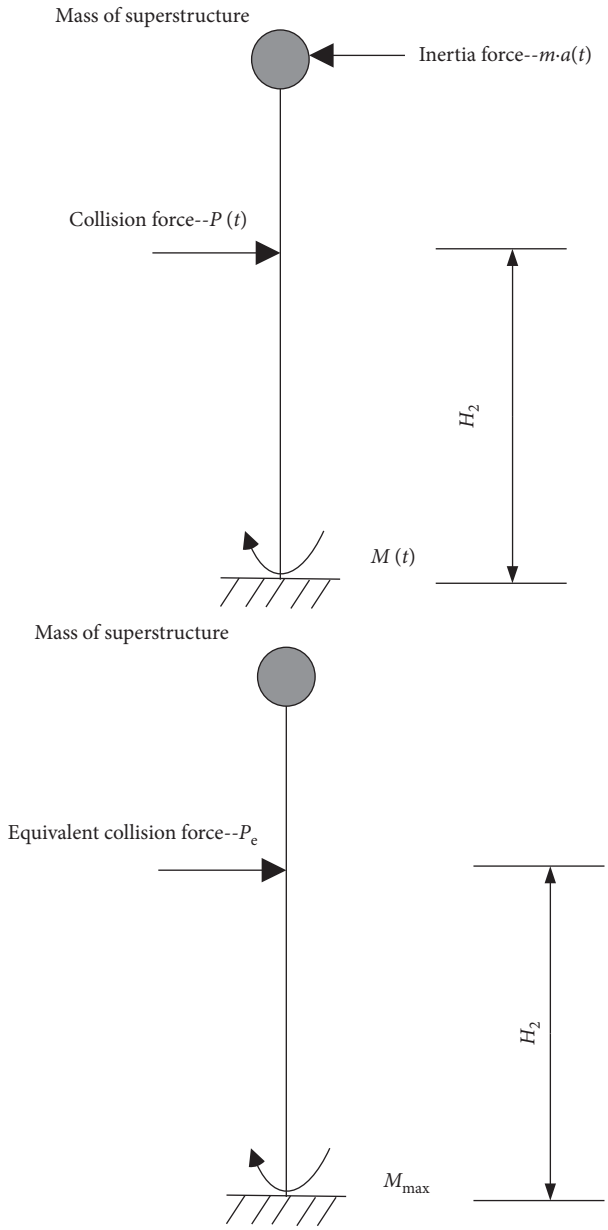

Figure 9: Schematic diagram of the calculation of equivalent collision force.

the ship in the study area, the unit voyage accident rate is 2.13×10^{-8}; the mean and standard deviation of the yaw angle are 7° and 4°, respectively, and the mean and standard deviation of the wake are 0.2 times and 0.1 times of the river width, respectively. The river width of the study area is illustrated in Figure 12. As suggested by the KUNZI model, the mean and standard deviation of the distance to stop the ship are 550 m and 60 m, respectively.

6.2. Hazard Analysis of Collision between Ship and Riverside Bridges. The hazard analysis of the ship-bridge collision at the study area can be conducted by taking the detailed information of riverside bridges into the probabilistic model of ship-bridge collision as introduced in Section 2. According to the spatial location of piers, we can obtain the probability of ship collision with piers. By adding into the monthly probability of wading of piers, the monthly probability of ship collision with piers can then be estimated. Finally, the annual probability of ship collision with piers is the mean value of the monthly probability of ship collision with piers. The resultant risk assessment of ship collision with bridge piers is illustrated in Figure 13. From this figure, it is observed that the probability of the ship-bridge collision at Shabin Road is low to moderate. Specifically, the probability of ship-pier collision at sections B, C, D, and E of Shabin Road is notably higher compared with the other sections. Moreover, the minimum probability of ship-pier collision occurs at the Shimen overpass.

6.3. Probabilistic Model of the Ship Collision Force. In order to assess the ship-bridge collision force, information regarding the ships' tonnage and velocity should be obtained. First, the ships' tonnage was obtained according to the navigation rules in the study area. Furthermore, the impacted velocity of ship was defined as the water flow velocity because the bridges are located on the riverside. The estimated values of the water velocity are given in Table 3, and the predicted values of the ship collision force with 84% rate guarantee are summarized in Table 4 based on the model of the ship collision force.

6.4. Analysis of Bridge Piers against the Ship Collision. Based on the information of the monthly water level in the study area, the impacted point of piers can be determined. Subsequently, a series of ship collision tests have been numerically conducted on a bridge pier in ABAQUS. Typical reinforcement and concrete parameters are assigned to each of the bridge sections, as summarized in Table 5. The change of position of the piers caused by the collision is illustrated in Figure 14. Part of the analyzed results is shown in Figure 15, and the ability of anticollision of bridges is shown in Table 6. Based on the method developed in Section 4, the collapse probability of bridge piers can then be derived, and calculated results are enlisted in Table 7.

6.5. Probabilistic Risk Assessment. By integrating the above results into the framework of risk assessment of ship collision with riverside bridges, the risk of ship-pier collision at Shabin Road in Chongqing is assessed. The risk map of ship collision with piers then is shown in Figure 16. Moreover, we classify the risk of ship collision with riverside bridges into three levels based on the criterion of AASHTO, namely, the low probability of risk below 10^{-4}, the moderate probability of risk between 10^{-4} and 10^{-3}, and the high probability of risk above 10^{-3}, respectively. Based on the above rules of classification, we qualitatively assess the risk of ship collision with the riverside bridges. It was shown that the maximum risk of piers subjected to ship collision is 2.3×10^{-4}. Therefore, the risk of ship-bridge collision at Shabin Road is at the low-to-moderate range. To further ensure the safety of riverside bridges, anticollision installation can be employed.

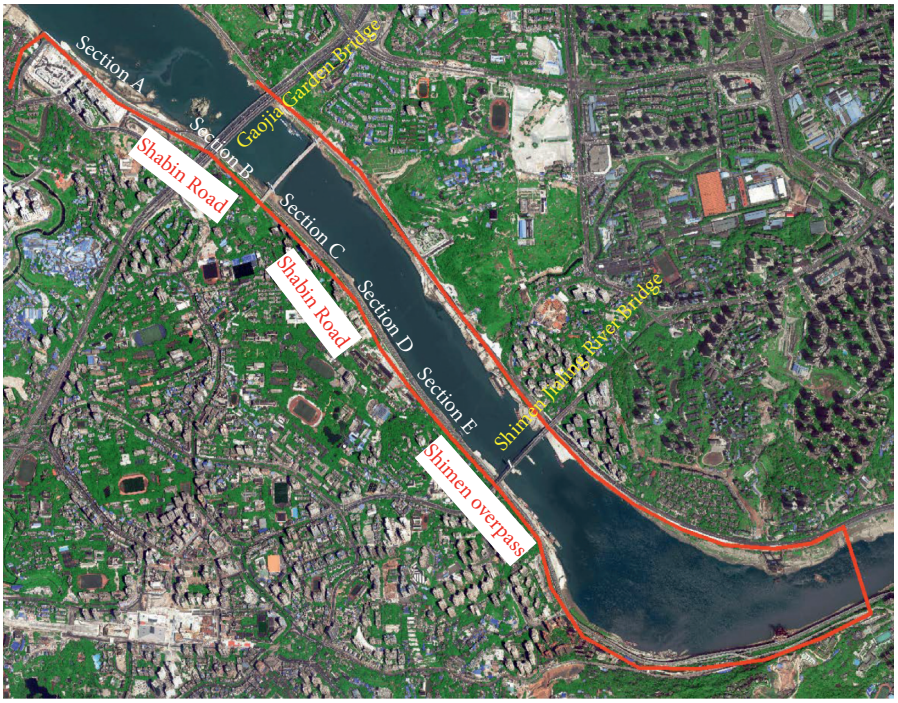

Figure 10: GIS map of the analyzed area (Shabin Road, Chongqing).

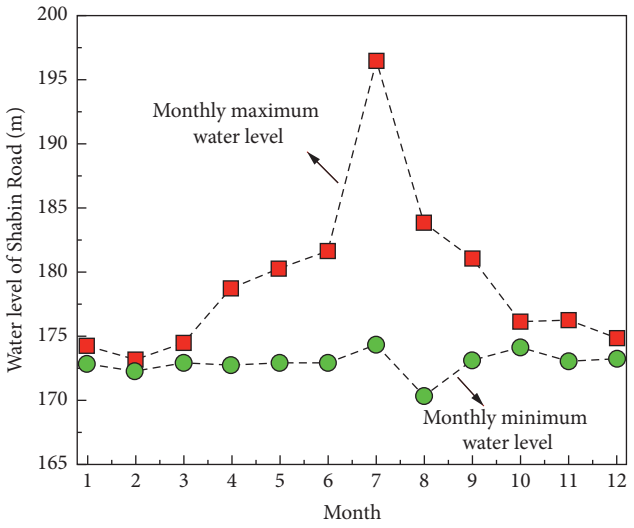

Figure 11: Monthly water level of Shabin Road in 2018.

Table 2: Equivalent ship parameters in the assessed area.

DWT (t)	BM (m)	BH (m)	Number of annual ship voyage
50	4.07	23.61	459
200	6.27	36.92	423
600	8.84	52.74	360
1600	12.04	72.64	102
3000	14.68	89.27	56

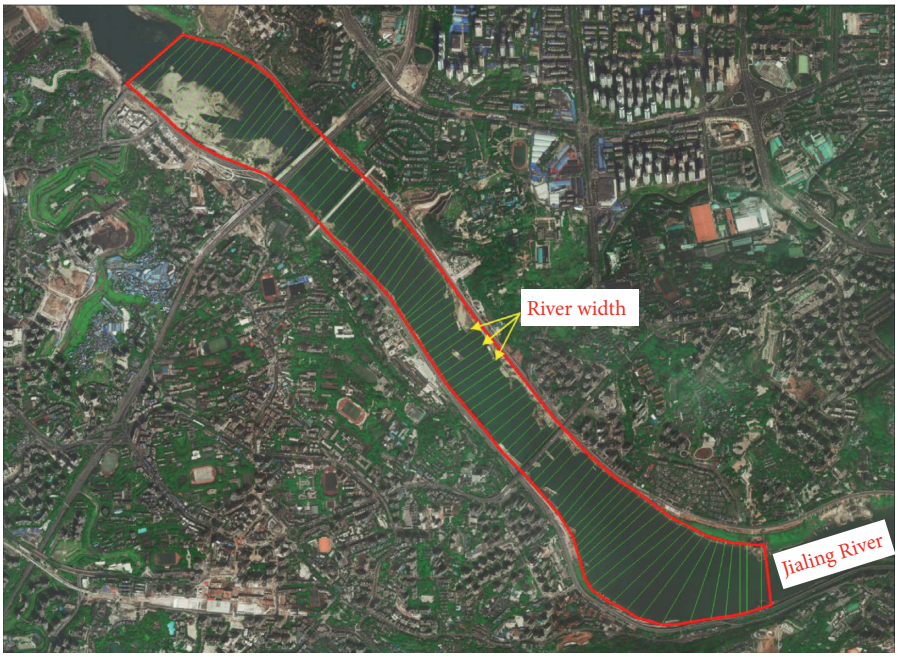

Figure 12: River width in the assessed area.

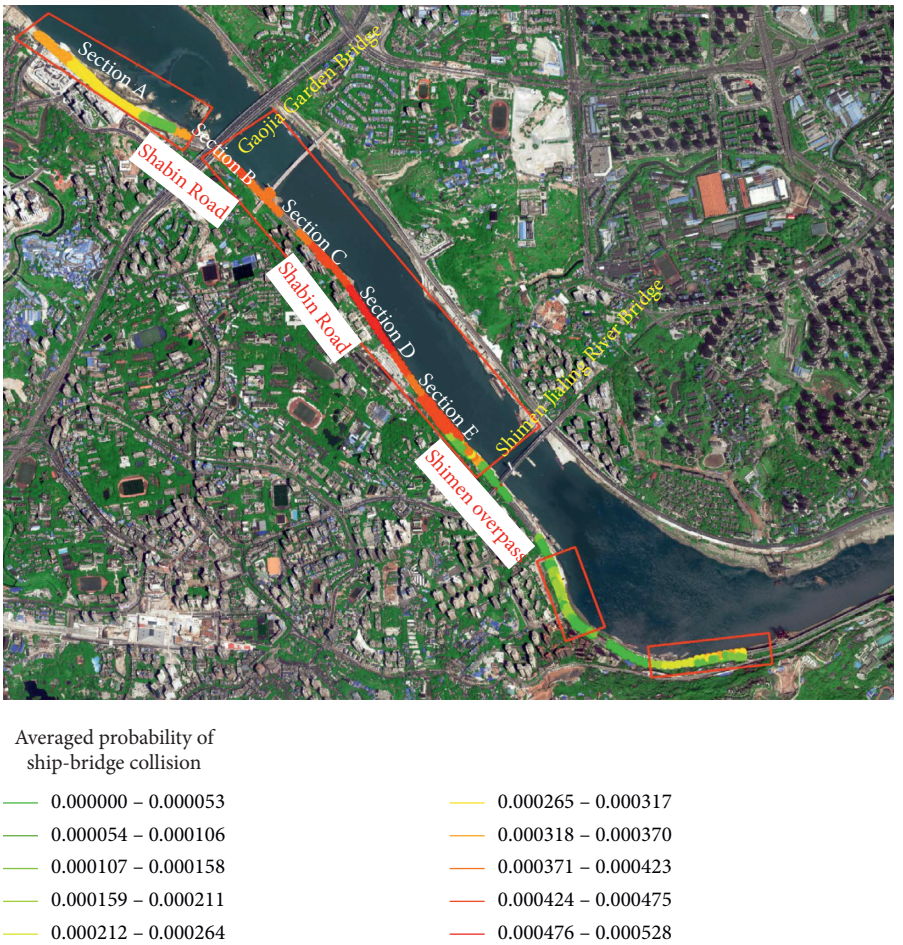

Figure 13: Averaged probability of ship-pier collision in the study area.

Table 3: Water flow velocity at Shabin Road in Chongqing City.

Water level	Mean of flow velocity (m/s)	Variable coefficient	Time (months)
Dry	2.5	0.2	3
Median	3.5	0.2	6
Flood	5	0.2	3

Table 4: Predictive values of ship collision force with 84% rate guarantee.

Tonnage (t)	Ship collision force (MN)		
	Dry (2.5 m·s^{-1})	Median (3.5 m·s^{-1})	Flood (5 m·s^{-1})
50	2.34	3.25	4.65
200	4.63	6.58	9.34
600	8.05	11.36	16.18
1600	13.22	18.63	26.39
3000	18.00	25.30	36.00
5000	23.19	32.72	46.69
6000	25.64	35.59	51.11

Table 5: Material properties of bridge piers.

Bridge sections	Pier size (mm)	Longitudinal reinforcement diameter (mm)	Transverse reinforcement diameter (mm)	f_y (MPa)	f_c' (MPa)
Section A~section E	2200	32	14	360	14.3
Shimen overpass	1500	25	8	360	14.3

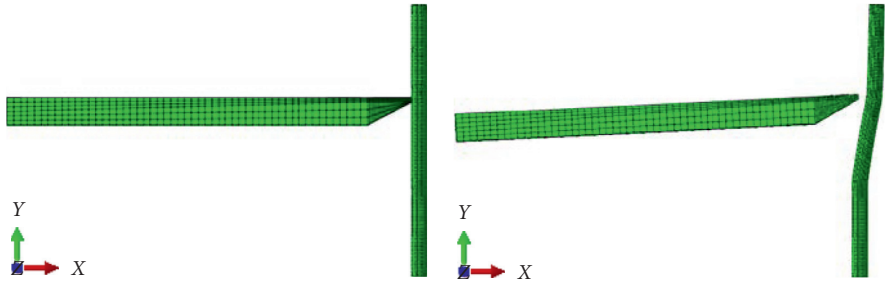

Figure 14: The positions of the pier (a) before the ship-pier collision and (b) after the collision.

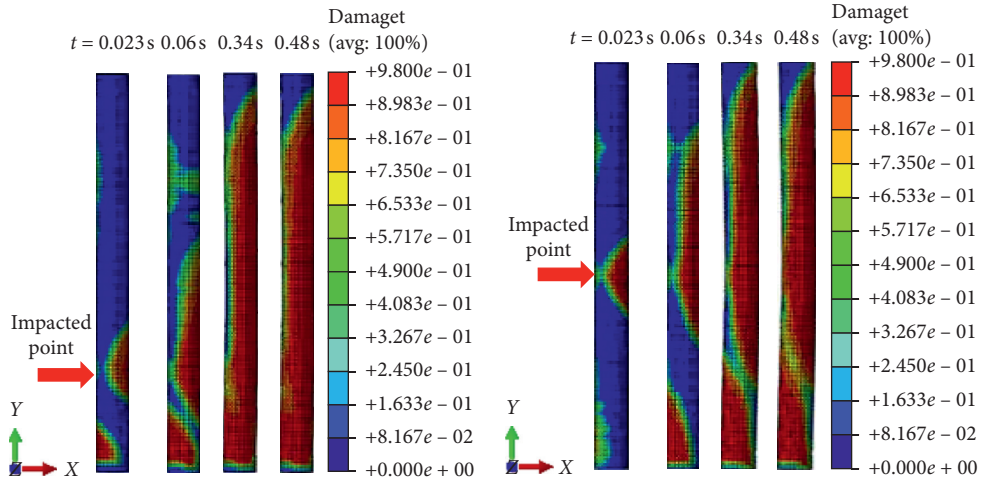

Figure 15: Tensile damage of the impacted pier based on FEM analysis.

Table 6: Capacity of anticollision of the pier of bridge sections.

Bridge sections	Monthly ability of anticollision of bridge sections (kN)											
	1	2	3	4	5	6	7	8	9	10	11	12
Section A	757.1	767.6	719.4	638.4	590.3	542.8	424.7	566.6	527.5	544.8	653.2	714.7
Section B	851.0	864.2	803.6	703.9	645.8	589.4	452.7	617.6	571.4	591.8	721.9	797.8
Section C	996.3	1014.6	932.1	800.5	726.3	655.7	490.8	690.8	633.4	658.6	823.9	924.2
Section D	996.3	1014.6	932.1	800.5	726.3	655.7	490.8	690.8	633.4	658.6	823.9	924.2
Section E	477.3	481.5	462.1	427.3	405.2	382.2	319.6	393.9	374.5	383.2	433.8	460.1
Shimen overpass	469.5	482.7	424.9	342.1	299.8	262.2	182.8	280.6	250.8	263.7	356.1	419.6

Table 7: Calculated collapse probability of the pier of bridge sections.

Bridge sections	Collapse probability of the pier											
	1	2	3	4	5	6	7	8	9	10	11	12
Section A	0.12	0.11	0.20	0.23	0.26	0.39	0.47	0.38	0.30	0.29	0.22	0.13
Section B	0.10	0.10	0.18	0.20	0.22	0.37	0.44	0.36	0.27	0.26	0.20	0.10
Section C	0.09	0.09	0.15	0.18	0.20	0.34	0.41	0.32	0.23	0.21	0.17	0.10
Section D	0.09	0.09	0.15	0.18	0.20	0.34	0.41	0.32	0.23	0.21	0.17	0.10
Section E	0.21	0.21	0.34	0.36	0.38	0.51	0.58	0.50	0.39	0.39	0.36	0.22
Shimen overpass	0.21	0.21	0.36	0.42	0.47	0.64	0.73	0.62	0.54	0.52	0.41	0.25

Figure 16: Resultant risk map of ship collision with riverside bridge piers of Shabin Road.

7. Conclusions

This paper developed a new approach for the risk assessment of ship collision with riverside bridges considering the wading probability of piers and the modified model of ship-bridge collision. The models for predicting collision forces were compared, and the determination of the AASHTO model was employed. The probabilistic distribution of the collision force was then obtained based on Monte Carlo simulation. Afterwards, the collapse probability of piers was obtained by extensive numerical analysis in ABAQUS. Finally, the method developed in this paper was applied to assessing the risk of ship collision with riverside bridges located at Shabin Road, Chongqing, China. The conclusions were summarized as follows:

(i) By introducing the wading probability of piers and the modified model of ship-bridge collision, the method developed can better evaluate the ship-(riverside) bridge collision risk compared to the conventional method

(ii) The employment of Mote Carlo simulation can appropriately model the collision force in a probabilistic way

(iii) The process of risk assessment of ship collision with riverside bridges is straightforward, so it is easy to use in application for risk evaluation of large-scale bridge piers

(iv) Based on the risk map developed, it is clear that the risk of the ship-bridge collision at Shabin Road, Chongqing, is at the low-to-moderate range

Data Availability

The research data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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