Study on the Probability Model of Ship-Bridge Collision

Guangnian Yu, Weidong Gan
Tianjin Research Institute for Water Transport Engineering, M.O.T, Tianjin, China
e-mail: yugn_tiwte@tom.com

Abstract. Based on the comprehensive analysis of the existing major ship collision probability models, this paper combined the advantages of the AASHTO model and the KUNZI model and improved AASHTO model by using the ship simulator to obtain the ship’s track probability distribution curve to replace the original geometric probability distribution curve. It also introduced ship stopping probability function to make up for the shortcomings of the AASHTO model in which the influence of human factors is not considered. Finally, this paper predicts the collision probability of the Longjiang Bridge in 2025 with the improved model.

1. Introduction
Studies on ship-bridge collision problems have started in the late 1960s, but the initial progress was slow. It didn’t bring great attention to the international engineering community until the collapse of the Sunshine Bridge in the United States in 1980. Afterwards, the authorities of the United States compiled the first guide specifications in 1991--The Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges, which is the first universally recognized and instructive specifications. In 1993, Ole Damgaard Larsen systematically summarized the existing researches on ship-bridge collision in his Ship collision with bridges: The interaction between vessel traffic and bridge structures, which further promoted the studies in this field. Since then, some European countries have also formulated some standards or norms for the ship-bridge collision problems. China has two sets of standards for anti-collision of ship and bridges, one is Code for Design on Railway Bridge and Culvert (TB 10002-2017), and the other is General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015). The design principals of the above two sets of standards are basically unified, that is, define ship-bridge collision as an accidental event, determine the anti-ship collision force in the form of an empirical formula according to the actual conditions of the channel and the passing ships and the impulse theorem principle, and use the transverse and longitudinal directions to quantify.

In fact, the time, position, velocity and energy of ship-bridge collision are highly random, and a single impulse theorem cannot fully reflect its mechanism. Therefore, it is inevitable to introduce the concept of ship-bridge collision probability in the study of bridge collision avoidance standards [2, 3].

2. Project Overview

2.1. Analysis of existing models
In recent decades, many countries have carried out a lot of exploration and research work on anti-collision design for bridges, and proposed several calculation methods of ship-bridge collision probability based on the special research of some bridges, wherein the most widely used are AASHTO model [4] and KUNZI model [5]. According to AASHTO model for calculating collision probability,
determine the yaw rate (\(PA\)) of the ship first, then multiply the yaw rate by the probability (\(PG\)) that the ship enters the bridge collision zone, and then multiply it by the annual traffic volume of this type of ship to calculate the annual impact rate of this type of ship. Obviously, in AASHTO model, the collision probability of the ship remains the same once it enters the bridge collision zone, and no human factor is considered in the model. The KUNZI model introduces the stopping distance parameter, it integrates various factors such as the shape of the ship, the shape of the bridge, the water flow and the quality of the driver, and considers that the minimum sufficient distance required to avoid the bridge obstacles is a normal random variable. Although the influence of human factors is considered in KUNZI model, the lateral distribution of ships is ignored, which causes a large deviation in the accuracy of the estimation results [6].

The AASHTO model includes 10 parameters in three aspects: bridges, currents and ships. The KUNZI model requires 9 parameters on both the bridge and the ship, and the water current data is reflected by the ship’s yaw angle. In terms of parameter, the AASHTO model is more comprehensive in terms of natural condition parameters of bridges, water flows, and ships, but lacks the influence of human factors, while the parameters in KUNZI model are not so comprehensive, but the influence of human factor is considered; in terms of parameter values, the correction coefficients required in the AASHTO model are mainly derived from the statistics of a large number of inland river vessel accidents, while the KUNZI model only gives suggested values and reference values on ship parameters. The specific application needs to be confirmed based on actual conditions.

Based on the above analysis, the existing models for calculating ship-bridge collision probability have their own advantages and disadvantages. Therefore, this article will combine the advantages of the AASHTO model and the KUNZI model and make improvements based on these models.

2.2. Improvements to the AASHTO model

2.2.1. Improvement of geometric probability distribution curve
When the geometric probability \(PG\) is calculated in the AASHTO model, the track distribution curve of the ship shows an ideal distribution with the centerline of the channel as the center of the normal distribution and the ship length as the standard deviation, ignoring the influences of wind, current and humans [7]. In this study, the author establishes a mathematical model of ships, takes the influences of wind, current, terrain and human factors into consideration, and obtains the ship’s track zone distribution on the ship simulator [8, 9]. Figure 4 shows that under the influence of wind, current and humans, the normal distribution center of the track zone is not located on the centerline of the channel, which means the geometric probability of ship-pier collision will be affected greatly (The shaded part is the geometric probability of ship-pier collision).

![Figure 1. Comparison of the track distributions](image-url)
2.2.2. The stopping probability function is introduced
If the ship yaws and enters the geometric collision zone, a collision event will be avoided if the ship can stop before it hits the bridge pier, and a collision event will certainly occur if it cannot stop before hitting the bridge pier. Therefore, the stopping probability function $F_S$ from KUNZI model is introduced. In the function, the ship’s mechanical performance, tonnage, average speed, overall dimensions, the average quality of drivers, current characteristics at the bridge location, and overall dimensions of the bridge piers are taken into consideration, so it is a more comprehensive distribution function.

$$F_S = \int_0^s f(s)ds \quad f(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} e^{-\frac{(s-\mu_s)^2}{2\sigma_s^2}}$$

In the formula, $f(s)$ is the distribution function of the stopping distance, and the values of the mean $\mu_s$ and variance $\sigma_s$ are obtained through the mathematical model of the ship.

From the above analysis, it is not difficult to conclude that the probability of hitting a bridge pier in a yaw situation is the product of the yaw probability and the probability that the ship does not stop after yaw, that is, $F_{65} = F_{\theta} \cdot (1 - F_S)$, $F_{65}$ is the probability of hitting the pier after yaw, and $F_{\theta}$ is the probability of entering the pier zone after yaw, and $1 - F_S$ is the probability that the ship cannot stop before hitting the pier.

Therefore, the calculation formula for the probability of collision between ship and bridge in the AASHTO model can be expressed as follows:

$$P = P_A \times P_G \times P_S$$

Where, $P$ is the probability of collision between ship and bridge; $P_A$ is the ship’s yaw probability; $P_G$ is geometric probability of collision; $P_S$ is probability that the ship fails to stop.

2.3. Calculation steps
① Investigate the data of old bridges, representative navigable ship types, the natural conditions of the bridge area, the current status of the channel and the implementation of the channel planning; ② Use a two-dimensional flow mathematical model to calculate the navigable flow conditions of the bridge area; ③ Use a ship simulator to study the representative ship type, the probability distribution of the track zone under the combined action of wind and current and the stopping distance of upward and downward ships, etc.; ④ The ship hitting bridge probability calculation model is used to determine the collision probability.

![Figure 2. Navigation diagram of Longjiang Bridge](image)

3. Calculation of the probability of ship collision on Longjiang Bridge

3.1. Calculation of yaw probability
The Shunde Waterway Longjiang Bridge is located at the upstream of the slightly curved river section, with an channel angle of about 10°. The representative navigable ship is a 1000 t inland river cargo
ship, the water flow component parallel to the route is 2.2 m/s, and the water flow perpendicular to the route is 0.1 m/s. The ship traffic density is moderate. According to the improved AASHTO standard calculation model, the values of each parameter are shown in Table 1:

| Ship type  | $B_R$     | $R_B$ | $R_C$ | $R_{XC}$ | $R_D$ |
|------------|-----------|-------|-------|----------|-------|
| Cargo ship | $0.6 \times 10^{-4}$ | 1.22  | 1.11  | 1.054    | 1.3   |

The yaw probabilities of ships:

$$P_A = B_R \times R_B \times R_C \times R_{XC} \times R_D = 1.116 \times 10^{-4}$$

**3.2. Geometric probability**

The results of the track distribution of the mathematical model of the ship are shown in Figure 3. The figure shows that the frequencies of the ship track are high in the middle and low on both sides, which can be regarded as a normal distribution.

$$f(x) = \frac{1}{\sqrt{2\pi \sigma_x}} e^{-\frac{(x-\mu)^2}{2\sigma_x^2}}$$  \hspace{1cm} (1)

Perform statistics on the upward and downward track band data, calculate the expectation and mean square error of these discrete data, substitute the calculated expectation and mean square error into Equation 1, and thus the track band distribution fitting is completed.

Upward ship, the expectation value is 8.336, and the mean square error is 9.730; Downward ship, the expectation value is 1.165, and the mean square error is 14.104.
As shown in Figure 2, the upward ship is considered to hit the 7# and 8# piers, and the downward ship is considered to hit the 8# and 9# piers. According to the AASHTO specification, the geometric collision probability is:

\[
\text{Upwards: } P_G = \int_{x_1}^{x_2} \frac{1}{\sqrt{2\pi} \times 9.73} e^{-\frac{(x-8.336)^2}{2 \times 9.73^2}} dx
\]

\[
\text{Downwards: } P_G = \int_{x_1}^{x_2} \frac{1}{\sqrt{2\pi} \times 14.104} e^{-\frac{(x-1.165)^2}{2 \times 14.104^2}} dx
\]

The geometric probability of each bridge pier being collided by a ship and the corresponding upper and lower limits of the integral of the calculation diagram are shown in Table 2.

| Item | up | down |
|------|----|------|
| X1   | 16 | -16  |
| X2   | 37.1 | -35.6 | -35.6 | 37.1 |
| PG   | 0.2139 | 0.00619 | 0.1072 | 0.141 |

3.3. Probability that the ship fails to stop

According to the recommendation from KUNZI and the results of the ship simulator test, the stopping distance of the downward ship is 300m, and the mean square error is 45m; the stopping distance of the upward ship is 200m, the mean square error is 45m, and the stopping distance integral path D is 350m. Then the probability that the ship fails to stop is:

\[
\text{Upwards: } P_S = 1 - F_S = 1 - \int_0^D f(s)ds = 0.0247
\]

\[
\text{Downwards: } P_S = 1 - F_S = 1 - \int_0^D f(s)ds = 0.1543
\]

3.4. Calculation of the collision probability of each bridge pier

By 2025, the annual cargo volume of the Shunde Waterway will exceed 8.9 million tons, and the annual traffic volume of the Longjiang Bridge will exceed 41,200. The probability of each bridge pier being collided by the ship is as follows:

\[
\text{Upwards: } P_7 = 17600 \times 1.116 \times 10^{-4} \times 0.2139 \times 0.0247 = 0.01034
\]

\[
\text{P8 = 17600 \times 1.116 \times 10^{-4} \times 0.00619 \times 0.0247 = 0.0003}
\]

\[
\text{Downwards: } P_8 = 23600 \times 1.116 \times 10^{-4} \times 0.1072 \times 0.1543 = 0.0435
\]

\[
\text{P9 = 23600 \times 1.116 \times 10^{-4} \times 0.141 \times 0.1543 = 0.0573}
\]

Therefore, the annual frequency of collisions of the Longjiang Bridge by upward ships is about 0.01064 times per year, and the annual frequency of collisions by downward ships is about 0.1008 times per year.

4. Conclusion

Based on the comprehensive study on the probability models of ship-bridge collision, the author of this research improved the AASHTO model while combining the advantages of the AASHTO model and the KUNZI model. The author used the ship simulator to obtain the ship’s track probability distribution curve to replace the original geometric probability distribution curve, and introduced ship stopping probability function to make up for the shortcomings of the AASHTO model in which the
influence of human factors is not considered. The collision probability of the Longjiang Bridge in 2025 with the improved model was also predicted in this paper.

References
[1] M.A.Knott. (1998) Vessel collision design codes and experience in the United States. Ship Collision Analysis, Gluver&olsen. 75-84.
[2] Dai T Y, Liu W L, Nie W. (2003) Probability analysis and prediction of ship impacts against bridges. Journal of Harbin Engineering University. 24(1): 23-25, 29.
[3] Geng B, Wang J J, Wang H, Fan L C. (2007) Risk assessment system for bridges against vessel impacts. CHINA CIVIL ENGINEERING JOURNAL. 40(5): 34-40.
[4] AASHTO. (2009) Guide Specification and Commentary for Vessel Collision Design of Highway Bridges. Second Edition. American Association of State Highway and Transportation Officials, Washington.
[5] Kunz C U. (1998) Ship bridge collision in river traffic. Analysis and Design Practice. Ship Collision Analysis. Denmark: Rotterdam.
[6] Tang Y, Jin Y L, Zhao Z Y. (2010) Comparison and Application of Probability Models of Ship-Bridge Collision. JOUINAL OF SSSRI. 33(1): 28-33.
[7] Wang C A, Tong S C, Jiang P F, Tang X Y. (2020) Numerical simulation of ship maneuvering motion under wind and current effects. Journal of Dalian Maritime University. 46(3): 50-59.
[8] Zheng Y F, Chen H. (2015) Marine Simulator Based Multi-track Overlay Research and Application. JOURNAL OF GUANGZHOU MARITIME INSTITUTE. 23(4): 9-12.
[9] Huang W Y, Li Z H. (2021) Calculation method of channel track width based on ship simulator. Port & Waterway Engineering. 579: 58-63.