Study on Risk of Ship Collision in Bridge Life-cycle Based on Synergetic Theory

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Abstract

The study on the risk of ship-bridge collision has always been a significant subject in academic research. However, the study of ship-bridge collision risk is rarely mentioned from the perspective of the bridge life-cycle. This paper proposes the concept of "bridge-ship common safety" based on the synergetic theory and constructs a high-level cooperative platform to solve the problem of bridge-ship collision. It was given in this article by analyzing the interaction relationship among subsystems of environment, ship, and bridge. In this paper, it proposed the analysis method of the ship-bridge collision risk based on synergetic theory with order parameters, including ship-bridge collision probability and collapse probability of bridge. Finally, the Lanjiang Xiangnv Bridge project as the case study is demonstrated. The risk of bridges is evaluated by utilizing order parameters and synergetic degrees. The result shows that the model can reflect the risk of ship-bridge collision properly, which achieves great scientific significance and academic value for enriching the theory in bridge-ship collision avoidance and implementing the concept of " bridge-ship common safety ".

Keywords: ship-bridge collision; synergetic theory; bridge life-cycle; order parameters; rask

1 Introduction

1.1 Research Background

The Ministry of Transport's newly issued "Outline of Inland Waterway Shipping Development" which guides that we will basically build a modern and powerful inland waterway shipping system by 2035. According to incomplete statistics, by 2020, there will be about 2,600 bridges across the "two horizontal and one vertical, two networks and eighteen lines" of inland waterways in China, including the Qiongzhou Strait Project, the Yangtze River Estuary Crossing Project and the Pearl River Estuary Lingdingyang Project. Chinese President Xi Jinping pointed out that a modern and powerful country must possess a strong shipping industry. Although bridges have brought rapid development dividends to coastal transport and the economy, they have produced to some extent restricted water transport and brought certain safety risks to navigable ships and bridges themselves. The occurrence of ship collision has limited the development of China's shipping industry

In order to investigate and manage the safety hazards of ship-bridges collisions comprehensively, the General Office of the Ministry of Transport and the Comprehensive Department of the State Railway Bureau issued the "Three-year Action Plan for the Implementation of the Management of Hidden Hazards of Ship Collisions on Bridges" to focus on the risk of ship collisions on bridges. This action has alleviated the current safety hazards partly, but it has cost a lot of financial resources. As most bridges have been built for a long time, they were designed without taking into account the location and span of the bridge and the development of transport in the bridge area. The upgrading of waterways and the enlargement of vessels have created additional risks and hazards for existing bridges in navigable waters.

1.2 Research Methodology

Generally, three approaches can be used for ship-bridge collision analysis, the first being experimental studies with real ships, and the full-scale ship impact bridge tests were conducted by Consolazio et al. through barge impact experiments [1,2]. This type of method can directly obtain data on the impact loads of ships and structural damage of bridges. However, the available results are relatively limited by the experimental conditions and budget.

The second type of research is numerical calculation. Sha et al. studied the response of bridge deck girders under the action of ship deckhouse collision through numerical simulation and evaluated the resistance of bridge main girders to ship superstructure collision [3]. In addition, they calculated the barge-quay impact force-time course and checked the reliability of the numerical model [4]. Fan et al. developed a high-resolution finite element model of the ship-soil interaction and discussed force-deformation relationships in detail [5]. Not only compared three reinforcement methods based on ultra-high performance fibre concrete [6], but also proposed a general analytical method for rapidly estimating the force-deformation relationships of steel fender panels under various bow impacts [7]. Han F [8] used LS-DYNA software to establish a basic simulation model to study the influence of impact speed, ship tonnage and other factors on the collision process.

The third method is the empirical formula method. In 2000, Huang P et al. [9] obtained the ship collision probability of bridges by using a three-parameter path integral from the distribution characteristics of ship trajectories in the straight channel. In 2003, Dai T [10] applied artificial neural network method to estimate the ship collision probability of the bridge. In 2007, Geng Bo [11] used a modified KUNZI model to give a correctional probability of vessel impact, by taking into account the ship yaw angle, track distribution, stopping distance and other factors. Researchers, mainly Professor Wang J, have done plenty of theoretical research on the design and general framework of ship collision prevention for bridges, which has contributed greatly to the introduction of guidelines in China [12].

In summary, a wealth of research has been conducted in the world on the issue of vessel impact against the bridge. However, the research is still based on the respective fields, and focus on the analysis of the mechanism of a particular situation. while the design, construction, and operation of bridges are an one thing, the risk of ship collision is also in a dynamic process. Therefore, we need to consider that problem through life-cycle of bridge.

2 Bridge collision avoidance system based on synergistic theory

2.1 Synergetic Theory

The synergetic theory was founded by the famous physicist Haken, a professor at the Federal University of Stuttgart in Germany. It is based on systems theory, information theory, cybernetics, and mutation theory, and draws on the results of structural dissipation theory, using a combination of statistics and dynamics to explore the similarity of systems from disorder to order [13].

Traditional bridge design is usually considered in separated stages, focusing on cost and short-term performance, nevertheless neglecting the bridge as a navigational obstruction, which generates barriers to navigation in the bridge area. The design, construction, and operation of bridges should take into account the development of water traffic at all stages so that we can build a synergistic system of “bridge-ship common safety”.

Based on the theoretical view of synergetic theory, it is believed that the collision problem between bridges and ships can be effectively solved in a new platform by collaborating with the three subsystems of the environment, ships and bridges, and configuring the collision prevention system of bridges from the three stages of bridge design, construction and operation.

Shen [14] et al. systematically analysed the definition and basic connotations of water resources allocation based on synergistic theory. Frangopol [15] et al. outlined the concept of life-cycle management of bridge systems under uncertainty, which investigates the management of risk and sustainability of bridges under the impact of gradual and sudden deterioration. Li K [16] took the relevance of transport as well as coordinated economic development as the objective of his study, analysing the mechanism of their interaction. Gao M [17] synergistic objectives with the schedule, cost, and quality of the project, explores the relationship between each other. Previous research on synergy is mostly directed towards resource allocation, economic cost optimization, and synergistic relationship, but there is little research on bridge engineering project risks and control methods.

2.2 Bridge Collision Avoidance System

The collision avoidance system for bridges in this paper is based on the synergetic theory, including the bridge collision avoidance system, the environment subsystem, the ship subsystem and the bridge subsystem. The bridge collision avoidance system is set up to reduce the risk of vessel impact. The bridge collision avoidance system is designed based on the other three subsystems, which not only ensure the safety of bridges and ships but also provide environmental protection for the rational use of natural resources in the waters of the bridge area. The environmental subsystem provides the basis for the design of the bridge, and the external system also influences the state of the environmental subsystem, which creates the necessary environmental resources for the navigation of ships and the construction of the bridge. The bridge subsystem is the main object of the bridge collision avoidance system protection. The performance of bridges is affected by external systems which gradually deteriorate. It's significant for bridge subsystem to utilize environmental resources properly in its design, construction, and operation phase. The navigation safety of vessel is based on that. The ship subsystem needs to provide the necessary design basis for bridge in its life-cycle. The bridge collision avoidance system provides safety and development support to the other three subsystems. In contrast, the three subsystems are influenced by the external environment and provide real-time feedback to the bridge collision avoidance system. The interactions between them are shown in Figure 1.

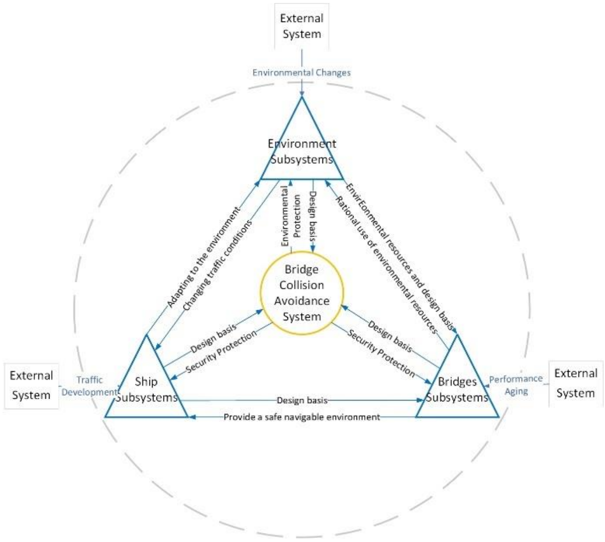

Figure 1. Interaction diagram of each system relationship

2.2.1 Design phase of bridge

The factors affecting bridge safety from the design phase of the bridge subsystem are analysed as follows. ① Meteorological and hydrological: The direction of the water flow in the channel affects the arrangement of the bridge axis. The weather conditions, as well as changes in historical maximum water levels, affect the dimension of navigation clearance. ② The condition of the waterway: this is an important factor in determining the location and siting of the bridge. The navigation safety is established on those aspects including straightness of the channel, ample water depth, and stability of the riverbed. ③ Traffic conditions: the dimension of navigation clearance is affected by those factors including typical ship type, density of vessel traffic, and vessel trajectory.

In the interaction process with other subsystems during design phase of bridge subsystem, it's indispensable to take critical factors into comprehensive consideration. For bridges in design phase, ① Consider whether the bridge location and bridge site is in synergy with the environment: the bridge axis should be orthogonal to the mainstream direction of the water flow as far as possible. Preferred sites for bridges are those with straight waterways. The chosen river bed has sufficient water depth to provide better navigational conditions for ship navigation. ② Consider the bridge span, navigational clearance and environmental synergy: for severe weather conditions, the span clearance of the bridge must be increased or one hole crossed. The navigational clearances shall be designed to match the historical maximum water levels in the bridge area. The navigational clearances shall be compatible with historic high water level and height above water of unladen ships. Consider the impact of the growing trend of vessel traffic on the risk of bridge collision for at least in the next 30 years. The bridge span shall be synergistic with the typical vessel width, vessel traffic flow trajectory and traffic density. ③ Consider the bridge collision avoidance structure: the bridge piers of the navigable holes should be designed with the necessary collision avoidance facilities, which can withstand the energy of ship collision, determined according to the typical navigation ship. As shown in Figure 2.

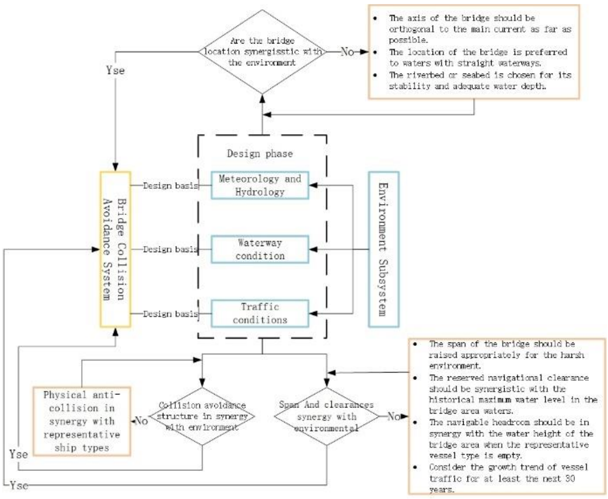

Figure 2. Bridge subsystem design phase interaction diagram

2.2.2 Construction phase of bridge

The factors affecting the safety of the bridge from the construction phase of the bridge are analyzed as follows. ① The construction of the bridge piers and foundations has caused a change in the original route of the navigation channel, interfering with the normal navigation of ships. ②A large number of engineering vessels traveling during the construction period. ③ The light source and noise from the construction site will interfere with the ship driver's judgment of the navigation.

In the process of interaction with other systems during the construction phase. ①Optimizing the navigation routes reasonably for engineering vessels contributes to minimizing interference with normal navigation vessels. ②Consider the change of the original navigation route, which must be readjusted. ③ Considering the light source and noise at the construction site, such pollution near the navigable area must be reduced n. As shown in Figure 3.

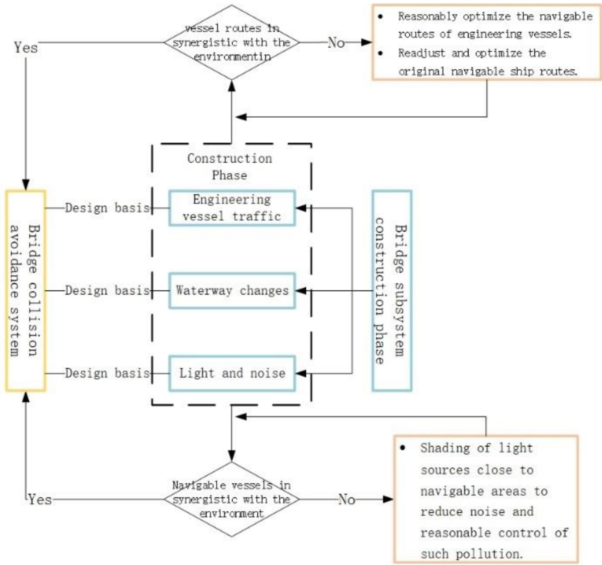

Figure 3. Bridge subsystem construction phase interaction diagram

2.2.3 Operation phase of bridge

The factors affecting the safety of the bridge from the operation phase are analyzed as follows. ① Changes in the water depth and current of the channel can bring the risk of yawing or overtopping the vessel. ②Irregularities in operation caused by human factors of navigable vessels can bring accident risks to bridges. ③The stability of the vessel equipment and structure can also increase the risk probability of bridge vessel collision.

For the bridge in the operation process: ①The safety training of ship drivers should be strengthened to conquer the hidden danger of human manipulation. ②The effectiveness of the ship's equipment should be checked regularly and the ship's collision avoidance structure should be adapted to the bridge type. ③ For those with hidden danger of ship deviation, electronic fence course deviation warning devices shall be arranged. If the ship has the potential of over-height, the bridge shall be equipped with the equivalent device of laser detection warning for over-height. As shown in Figure 4.

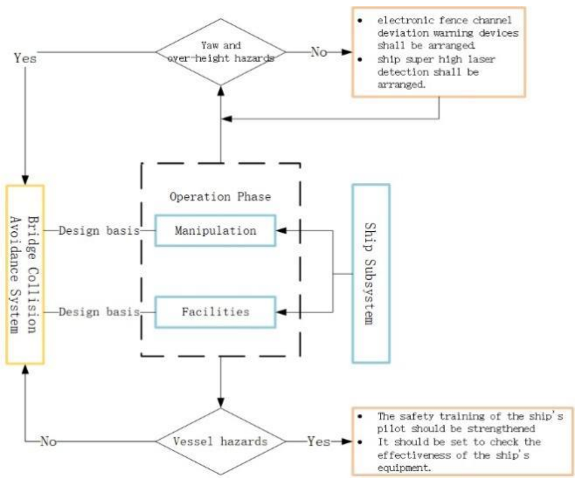

Figure 4. Bridge subsystem operation phase interaction diagram

3 Determination of order parameters

This paper adopts the vessel-bridge collision probability and the probability of bridge collapse frequency as order parameters to get the risk of bridge collision and the bridge's crashworthiness.

In order to determine the threshold values for the range of sequential parameters under the most unfavourable and ideal conditions, this paper determines the threshold values of sequential parameters for the three stages of bridge design, construction and operation from the perspective of acceptable levels of social risk.

Social risk [18] refers to the relationship between the number of people who suffer from an accident and the frequency of accidents. This paper is in accordance with the formula proposed by the UK's CIRIA regarding the acceptable guidelines for the failure of social risk structures.

$$p_{ft} = \frac{10^{-4}}{n_r} K_s n_d \tag{1}$$

Where p_{ft} is probability of failure over design life years. n_d is design life years. n_r is the number of people at risk events. K_s take values according to table 1.

Table 1. Table of values for K_s

Situation	Values
Public assembly, dams	0.005
Office, factory	0.05
Bridges	0.5
Towers	5

Taking the design life of the bridge to be 100 years, the above formula gives a range of acceptable guidelines for the different stages of the bridge's risk as shown in table 2.

Table 2. Table of values for K_s

Phase	Risk criteria
Design	5×10^{-5}～5×10^{-4}
Construction	5×10^{-3}～5×10^{-2}
Operation	5×10^{-5}～5×10^{-4}

At present, the most common models for calculating the probability of ship collision with bridge are the AASHTO code model in ship collision avoidance design, the Larsen (IABSE) model, the Eurocode model, the Kunz model, and the Wong Ping Ming straight road model, etc. The different models have different characteristics. Compared to the AASHTO model, which gives a target collapse frequency of 10^{-3} for general bridges and 10^{-4} for important bridges, the results calculated using the risk acceptance criteria proposed by CIRIA are within a reasonable range of values.

It's a whole process in the bridge life-cycle. In the design phase of the bridge, the risk of ship collision is influenced by many factors such as bridge site selection, bridge span length, etc. The initial risk state and the construction risk state of the numerical distribution obey some probability density function, which keeps changing with the variation of design. The risk state of the construction phase is influenced by the size of the bridge cofferdam and the number of piers in the water area accessible to the ship, etc. The bridge design also determines the risk of ship collision during the construction phase to a certain extent. The risk state of the bridge's operation phase is almost the same as the initial risk state, ignoring the development of ship traffic during the construction phase here. As time goes by, the risk of vessel ship collision is influenced by those factors including performance aging, variation of waterway traffic, etc. When the risk is close to the upper threshold, it requires us to take some mandatory measures to improve the anti-collision performance of bridge or reduce the ship collision probability of the pier. The risk change process is shown in Figure 5.

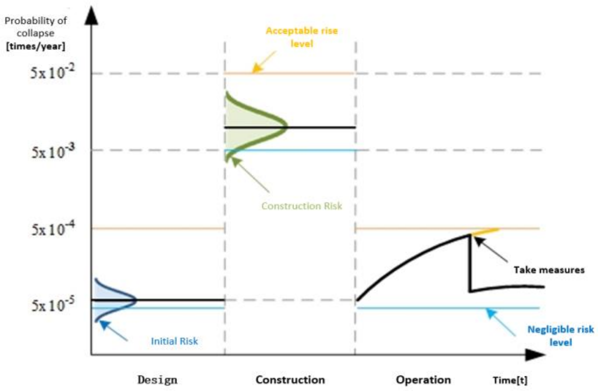

Figure 5. Bridge ship collision risk diagram for different stages

4 Calculation of ship collision risk for the whole life cycle of bridges

4.1 Case Background

In this paper, the risk calculation of ship collision bridge is carried out with the case of Lanjiang Xiangnv Bridge. Two options are proposed for different bridge types and economic budgets under the planning.

Case 1: The bridge adopts continuous steel structure bridge with mixed beam. The length of the bridge is 1348.2m. The width is 31.5m. The whole bridge is 110+260+110m, and the intersection angle between the bridge axis and the center line of channel is about 6.1°. the aerial view of the bridge is shown in Figure 6.

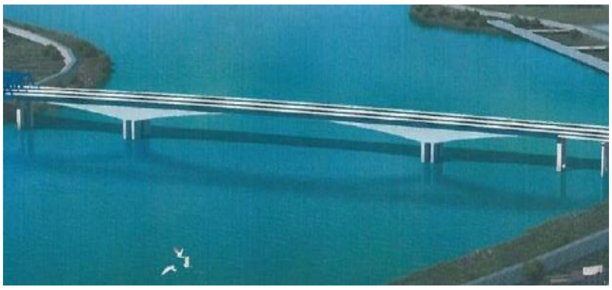

Figure 6. Bridge subsystem operation phase interaction diagram

Case 2: The bridge adopts ground-anchored steel box girder suspension bridge, with a length of 1348.2m, a width of 31.5m. the main tower height of 53.33m, and a span arrangement of 150+480+150m. The aerial view of the bridge is shown in Figure 7.

Figure 7. Bridge subsystem operation phase interaction diagram

The bridge design phase is expected to have 10,000 vessel through the bridge line position in 2021, where the number of upbound and downbound vessels is almost the same. During the operation and maintenance period of the bridge, considering the local economic development of Lanxi, it is expected to be 52,000 vessels in 2050, with 500t barges as the typical vessel type in 2021 and 1000t barges as the representative vessel type in 2050. The information of the vessel type is shown in table 3.

Table 3. Navigable representative ship information

Year	Barge [ton]	Length [meter]	Width [meter]	Volume [vessel]
2021	500	50	10.8	10000
2050	1000	67.5	10.8	52000

The average number of navigable days in a year is 345 days. The number of windy days is 13.5 days. The number of foggy days with visibility less than 1000m is 9 days. Due to the different conditions of navigation between China and foreign countries, so the AASHTO model is modified [19,20].

Table 4. Modifying Factors

Modified items	Value
Vessel type	0.04
Upward and downward	1.90
Winds	1.02
Fog	2.01

Cofferdams are required at the bridge piers during the bridge construction period. Considering the thin riverbed cover in the bridge area and the dense weathered rock layer underneath, the cofferdam size calculated in this paper is calculated according to the double-walled steel cofferdam [21]. The Specification for Collision Resistant Design of Highway Bridges (JTG/T 3360-02-2020), "Based on the consideration that the bridge has different collision resistance during the construction period and operation period, during the construction period, the bridge does not have the collision resistance required by the design", so the collision resistance of the bridge is neglected during the construction period.

The probability of bridge collapse in the phase of design, construction, and operation is calculated for the existing 2 cases respectively, so as to analyze the risk of ship collision at different stages.

Table 5. bridge collapse probability under different cases[times/year]

Phase	Case1	Case2	Negligible risk level	Acceptable rise level
Design	7.7×10^{-6}	6.4×10^{-7}	5×10^{-5}	5×10^{-4}
Construction	2.8×10^{-2}	1.7×10^{-3}	5×10^{-3}	5×10^{-2}
Operation	2.2×10^{-4}	1.9×10^{-5}	5×10^{-5}	5×10^{-4}

4.2 Calculation of the Synergetic Degrees in the Subsystems

The order degree in different phase reflects the order degree of the interaction between subsystem elements, which is calculated via the fuzzy mathematical method. The larger the value of the order parameter, the higher the order degree of the subsystem. By contrast, the smaller the order parameter is, the lower the order degree of the system. The older degree is calculated via formula (2).

The synergetic degree of different cases is affected by the order degrees of the design, construction and operation subsystems, and the synergetic degree is calculated via formula (3)[22].

$$F(e_{ij}) = (\alpha_{ij} - e_{ij})/(\alpha_{ij} - \beta_{ij}) \tag{2}$$

$$\begin{cases} D = \sum_{j=1}^{k} \gamma_{ij} F(e_{ji}) \\ \gamma_j > 0 \\ \sum_{j=1}^{k} \gamma_j = 1 \end{cases} \tag{3}$$

Where α_{ij} and β_{ij} are the threshold values of the i^{th} case of the j^{th} phase. The larger the $F(e_{ij})$ value is, the greater its contribution to the order degree of its subsystem. The γ_j is the influencing weight coefficient of the order degree of the j^{th} phase.

In this paper, it is considered that the reference values of both design and O&M of the bridge are equally important, and the construction phase of the bridge accounts for a smaller proportion of time and resources, so the impact weights of the three phases of bridge design, construction and operation are taken as follows. $\gamma_1 = 0.4$; $\gamma_2 = 0.2$; $\gamma_3 = 0.4$.

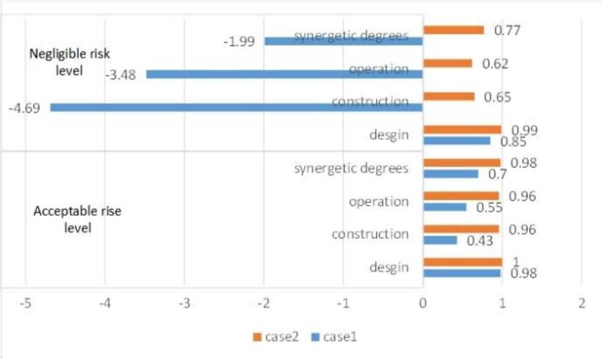

Figure 8. Comparison of the synergetic degrees of different cases

The results in the graphs show that both cases meet the requirements of the acceptable risk level, with case2 having a significantly better order than case1. In order to ensure that the ship collision risk is within a certain acceptable range, we prepare to optimize case1 in its life-cycle.

Different spans and different bridge types are adopted in the design phase of the bridge. Without changing the overall design idea and avoiding the initiative of higher construction cost, it is advisable to adjust the ship's route in the design phase and set navigation aids to correct the ship's track so that it passes through the central position of the navigable hole as much as possible. The bridge piers can be set as perpendicular to the intersection angle of the water flow as much as possible.

As the risk state during the construction period is influenced by factors such as the size of the bridge cofferdam and the number of piers. The risk is also influenced by the construction process and the environmental changes such as the water level in the bridge area, while the design of the bridge determines to a certain extent the risk of ship collision during the construction period. It is suggested to improve the construction process and reduce the pollution of light source and noise at the construction site .Setting up navigational aids to ensure the safety of ship navigation. Organizing training for the staff on the ship to enhance the safety awareness and navigation skills, etc.

At the initial stage of bridge operation, the risk of ship collision is less than 5×10^{-5} within the acceptable risk range. As time goes by, the risk of ship collision of the bridge gradually increases and approaches the upper limit of risk, it is appropriate to set up physical anti-collision facilities or active warning system of the bridge.

The physical anti-collision facilities should match the bridge piers and navigable representative ship bow stiffness to achieve both absorbing enough energy and protecting the safety of ships and bridge piers. Meanwhile, the physical anti-collision facilities are not easy to crowd the navigable headroom. Otherwise, it will increase the probability of ship collision to some extent [23]. The passive anti-collision energy absorption efficiency can reach 40%, which greatly reduces the probability of ship collision failure of the bridge [24]. The active warning system should be timely and reliable, making full use of microwave radar and other potential sensing equipment to comprehensively locate the ships entering the channel. At the same time, for different kinds of ships through different warning ranges in the bridge area waters, different degrees of warning measures can be taken to avoid false alarms and missed alarms [25], which can significantly reduce the probability of ship collision. After optimization, the risk and its synergetic degrees are recalculated.

Table 6. Ship collision risk before and after optimization in case 1[times/year]

Phase	Before	After
Design	7.7×10^{-6}	6.4×10^{-7}
Construction	2.8×10^{-2}	1.7×10^{-3}
Operation	2.2×10^{-4}	1.9×10^{-5}

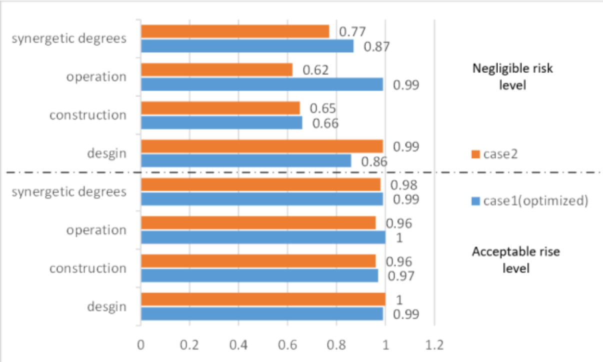

Figure 9. Comparison of the synergetic degrees of the optimized case

The optimized case is 0.29 and 2.86 higher compared with the original scheme. The synergetic degrees of case 1 is higher than that of case 2. In general, the construction cost of the bridge will gradually increase with the span of the bridge, whereas the risk of ship collision of the bridge shows a gradually decreasing trend. Both cases meet the safety requirements, but taking into account the budget of the bridge, the economic performance of the optimized case 1 is higher than that of case 2.

5 Conclusions

In this paper, the synergistic theory between ship, bridge, and environment among subsystems is systematically elucidated by applying the principle of synergy. The risk management measures for ship collision with bridges in different stages are given in above. From the perspective of social risk, the acceptance criteria are presented in the design, construction, and operation stages of bridge. The change process of ship collision risk in the whole life cycle of bridge is analyzed. The risk of ship collision at different stages of the bridge is calculated. The risk of bridge life-cycle is controlled based on synergetic degrees, so as to find a more reasonable way of bridge design, construction and operation.

The results show that this study can appropriately reflect the ship collision risk during the whole life cycle of the bridge, which helps us understand the risk level of bridges and provide support for vessel impact of bridge life-cycle. It has broad application prospects in the field of ship-bridge safety based on the idea and framework system of life- cycle in the future.

6 Acknowledgments

This research was supported by the National Natural Science Foundation of China, grant number 51509151, the Shandong Province Key Research and Development Project (SPKR & DP), grant number 2019JZZY020713, Shanghai Commission of Science and Technology Project, grant number 21DZ1201004, Anhui Provincial Department of Transportation Project, grant number 2021-KJQD-011.

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8 Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Yihua Liu, Xin Guo; data collection: Yihua Liu, Xin Guo; analysis and interpretation of results: Yihua Liu, Xin Guo; draft manuscript preparation: Yihua Liu, Xin Guo. All authors reviewed the results and approved the final version of the manuscript.

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