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# Using FSA framework, research on maritime safety management of the highway bridge water area on the Yalu River

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# USING FSA FRAMEWORK, RESEARCH ON MARITIME SAFETY MANAGEMENT OF THE HIGHWAY BRIDGE WATER AREA ON THE YALU RIVER

By

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**The People's Republic of China**

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## DECLARATION

I certify that all the material in this research paper that is not my own work have been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

Signature: Han Jing

Date: June 28, 2021

**Supervised by: Professor Fu Yuhui**

**Dalian Maritime University**

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**Assessor:**

**Co-assessor:**

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## ABSTRACT

Title of Dissertation: Using FSA Framework, Research on Maritime Safety Management of the Highway Bridge Water Area on the Yalu River

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Bridges are of great significance to economic development and social progress. But at the same time, they will also pose a threat to the safety of water traffic, increasing the risk of accidents in the bridge area. Since the late 1960s, scholars have made positive contributions to the project of preventing ship-to-bridge collision. But there are few pieces of literature to put forward suggestions and countermeasures for the maritime authorities to strengthen the management of navigation safety.

On the basis of studying the previous research results, this paper uses the FSA framework to evaluate the navigation safety of the Highway Bridge water area on the Yalu River. Based on the preliminary analysis of four respects of crew-ship-environment-management, this paper identifies the key factors that affect the traffic safety, and then finds out the weak links of the key risk factors or the potential hazards to navigation safety through in-depth analysis. Finally, this paper proposes effective and targeted risk control measures and safety management suggestions. In the process, literature study, questionnaire survey, expert interview, simulation test, empirical analysis and other methods are used.

The research results of this paper will provide a basis for Dandong MSA to improve the maritime safety management of the Highway Bridge water area. It will also provide a reference for the research on navigation safety assessment in similar navigable waters. At the same time, this paper will also provide reference value to

the site selection, design, planning, and construction of bridges in future.

**KEY WORDS:** Navigation Safety; Management Recommendations; Risk Assessment; Highway Bridge; FSA

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| | |
|---|---|
| AASHTO | American Association of Highway and Transportation Officials |
| AIS | Automatic Identification System |
| C | Calm |
| CCS | China Classification Society |
| CCTV | Closed Circuit Television |
| cm | Centimeter(s) |
| COVID-19 | Coronavirus disease 2019 |
| d | Days |
| DMU | Dalian Maritime University |
| DPRK | The Democratic People's Republic of Korea |
| DWT | Dead weight tonnage |
| E | East longitude (or East) |
| ENE | East-Northeast |
| ESE | East-Southeast |
| FHWA | Federal Highway Administration |
| FSA | Formal Safety Assessment |
| FTA | Fault Tree Analysis |
| h | Hour(s) |
| H | Height |
| IABSE | International Association of Bridge and Structural Engineering |
| IACS | International Association of Classification Societies |
| IMO | International Maritime Organization |
| km | Kilometer(s) |

| | |
|---|---|
| km/h | Kilometer(s)/hour |
| m | meter(s) |
| $m^2$ | Square meter(s) |
| $m^3$ | Cubic meter(s) |
| MEPC | Maritime Environment Protection Committee |
| min | Minute(s) |
| mm | Millimeter(s) |
| MOT | Ministry of Transport |
| MOU | Memorandum of Understanding |
| m/s | Meter(s)/second |
| $m^3/s$ | Cubic meter(s)/second |
| MSA | Maritime Safety Administration |
| MSC | Maritime Safety Committee |
| N | North latitude (or North) |
| NE | North -East |
| NNE | North-North-East |
| NNW | North-Northwest |
| NW | North-West |
| PIANC | Permanent International Association of Navigation Congresses |
| PSC | Port State Control |
| s | Second(s) |
| S | South |
| SE | Southeast |
| SSE | South-South-East |
| SSW | South-Southwest |

| | |
|---|---|
| STCW | International Convention on Standards of Training, Certification and Watchkeeping for Seafarers |
| SW | Southwest |
| t | tonnage |
| UAV | Unmanned Aerial Vehicle |
| VHF | Very High Frequency |
| W | West (or Width) |
| WNW | West-North-West |
| WSW | West- South West |

# Chapter I Introduction

## 1.1 Background, purpose, and significance of the study

### 1.1.1 Background of the study

With the development of port economy, the bridge across the waterway, as the throat node of railway, highway, urban road, canal, and other transportation channels, its construction pace is accelerating, and the number is increasing. According to data from the National Bureau of Statistics and the Huajing Industrial Research Institute, as of 2019, the total number of bridges in China's municipal districts was 76,157, an increase of 2,725 over 2018 year-on-year increase of 3.71 percent (Hu, 2021). Especially in recent years, China's bridge construction technology is becoming more and more advanced. The bridge is becoming bigger and longer, greatly improving the land traffic conditions, but at the same time, some new contradictions between the bridge and water transport come into being. The completion of the bridge will narrow the existing waterway, and the bridge piers will silt up, which will lead to the riverbed changes. The navigation environment, such as the flow velocity and direction will change to a large extent. At the same time, due to the limitation of navigable height and width, the bridge has become an obstacle to water traffic, which is a kind of damage and threat to the navigation safety of passing ships. Especially in recent years, with the increase of traffic density and the trend of large vessels, the contradiction between bridge and ship has become increasingly prominent. Therefore, when sailing through the water area of the bridge, ships must especially pay attention to collision avoidance. Otherwise, it is easy to cause dangerous situations or ship-to-bridge collisions, objectively increasing the probability of maritime accidents.

The occurrence of ship-to-bridge collision makes the water area of the bridge become an extremely "sensitive water area" for water traffic safety management. How to properly solve the water traffic safety problems in the bridge area to alleviate the conflict between ships and bridges is particularly important. This issue has become the critical research and management object of the maritime authorities. Since December 2020, the Ministry of Transport (MOT) of China launched a three-year action to control hidden risks of ship-to-bridge collision. The targets are bridges across inland waterways built and put into operation before December 31, 2019. The action aims to further improve the safety management responsibility system, improve navigation aids marks in bridge areas, improve the navigation service of waterways, standardize the navigation orders in bridge areas, establish and improve the long-term mechanism for preventing and defusing hazards and risks, and resolutely prevent the occurrence of severe accidents (MOT, 2020). The Highway Bridge on the Yalu River, the main part of which completed in 2014, was included in the scope of the three-year action. The Highway Bridge and its connection lines are a vital passage connecting China with the Democratic People's Republic of Korea, and an essential part of the Tokyo - Seoul - Pyongyang - Beijing - Moscow - London Eurasian international passage. It is of great significance to promoting China's foreign trade and economic cooperation (Sheng & Wu, 2021). As the competent authority, Dandong Maritime Safety Administration (MSA) has always maintained navigation safety in the Bridge area as the top priority in its work. Although Dandong MSA has accumulated some management experience in the supervision of water traffic safety, it has not yet carried out the systematic scientific research on the navigation risk factors in the Bridge area. It lacks the theoretical basis for formulating the navigation safety management measures in the Bridge area. Therefore, this paper chooses the navigation safety of the Highway Bridge water area on the Yalu River as the research object.

### 1.1.2 Purpose and significance of the study

This paper systematically analyzes the navigation environment characteristics and safety situation of the Highway Bridge water area on the Yalu River. It identifies the risk factors affecting navigation safety in the Bridge area, and makes a comprehensive evaluation. Through analysis and evaluation, this paper tries to put forward effective and targeted risk prevention and control measures and safety management countermeasures and suggestion. It is of great practical significance to study the navigation safety of the Highway Bridge water area on the Yalu River.

In respect of practical significance: (1) Through the study, the main risks affecting the navigation safety of the Bridge area are identified, so that the safety supervision in the future will be more focused on observing and tracking the dynamic situation of the key risk factors. Human intervention is more purposeful. Maritime safety supervision is more targeted. (2) It also provides a basis for the maritime authority to formulate the navigation safety management regulations in the Bridge area. (3) Given the status quo of the limited management resources, this paper puts forward a set of scientific and feasible risk management and control proposals, which is conducive to the rational distribution of limited human, material, financial, and other management resources, so that the limited resources can be invested in the most needed parts, saving unnecessary resource input and improving the efficiency of supervision.

From a theoretical perspective, the risk assessment of navigation safety generally exists in all bridge areas, and the management of hidden dangers of ship-to-bridge collision is a long-term work. This study summarizes the research achievement of the predecessors at home and abroad, identifies the common risk factors affecting the navigation safety of the bridge area, and proposes the research method of this kind of subject. All these works can provide a reference for the research on navigation safety in similar navigable waters. At the same time, this paper will also provide reference value to the site selection, design, planning, and construction of relevant bridges in the future.

In the long run, this paper is dedicated to better protect the safety of people's lives and property, and boost the development of the marine industry.

## 1.2 Research status at home and abroad

### 1.2.1 Foreign research status

The research on ship-to-bridge collision can be traced back to the late 1960s globally, but the study that proposed the concept of "risk" and used systematic risk assessment methods to deal with the problem began in the 1980s. In 1983, the International Association of Bridge and Structural Engineering (IABSE) held an academic conference on "Collisions between Ships and Bridges and Offshore Structures" in Copenhagen, Denmark, and risk assessment was first linked to bridge structures (Barratt, 1983). In 1991, the work report "The Interaction between Vessel Traffic and Bridge Structures: a review and guide" was adopted by the annual meeting of IABSE. The report treated the ship-to-bridge collision as a risk event. It established a relatively complete ship-to-bridge collision risk research system. Later, IABSE published a special book on "Ship Collision with Bridges" in 1993. The IABSE website gives further information (https://iabse.org/).

In 1991, the American Association of Highway and Transportation Officials (AASHTO) issued the first Guide Specification and Commentary for Vessel Collision Design of Highway Bridges after the collapse of the Sunshine Bridge in the United States in 1980. The Guide adopts the project results jointly invested by 11 states of the United States and the Federal Highway Administration (FHWA), which has been under study for many years. It proposes to adopt the risk analysis method based on probability. The second edition of the Guide was published in 2009, which has become one of the earliest design codes in the world to guide the bridge design to prevent ship collision (AASHTO, 2009).

In 1996, Hitoshi Furuta et al. developed a bridge damage fuzzy evaluation expert system by combining Genetic Algorithms and Neural Networks, aiming at the situation that it is difficult to obtain expert advice in the field of the bridge. The system can obtain new knowledge and judgment criteria based on the GA-NN combination method (Furuta et al., 1996). At the same time, a series of probability calculation models based on accident statistical analysis and considering risk factors were receiving increasing attention abroad. The following are representative:

In 1993, Larsen's IABSE model divided the causes of the ship-to-bridge collision into 4 yaw situations from the perspective of phenomenology. And he proposed a more general ship-to-bridge collision probability model (Larsen, 1993).

In 1995， working group No. 19, established by the Permanent International Association of Navigation Congresses (PIANC), took five years to build a database that contains 151 ship-to-bridge incidents. Through the analysis of the database, they concluded that the causes of ship-to-bridge collision accidents were 70% of human error, 20% of mechanical failures, and 10% of bad natural conditions. In the same year, a joint venture company in Europe studied the collision frequency model of the Orisan Bridge across Sweden and Denmark. Then it established a database covering 252 accidents (Karlsson et al., 1998). The PIANC website gives further information (https://www.pianc.org/).

In 1997, to calculate the probability of ship-to-bridge collision, Euro Code 1 provided an integral algorithm based on the failure path (Vrouwenvelder, 1998).

In 1998, Kunz from Germany proposed a ship-to-bridge collision probability model.

The model is based on the relative location of the pier before the accident, containing two random parameters: stopping distance X and ship yaw angle Ψ (Kunz, 1998).

In 2001, Japanese scholars established a ship collision analysis system by using the fault tree construction method and concluded that the human element accounted for a large proportion of ship collisions (Kita, 2001).

From 2004 to 2009, Gucma from Poland conducted many studies on ship-to-bridge collision risk through data statistics, simulators, etc (Gucma, 2005).

In 2005, IABSE annual meeting was held in Lisbon, Portugal. The bridge risk assessment was once again included as one of the topics of the conference (Perevoznikv & Seiverstov, 2001).

In general, the research in this field started earlier in foreign countries. The relevant Codes or Guides could well apply the risk management ideas to guide the collision avoidance design of bridges. Later, domestic scholars began to pay attention to the subject.

### 1.2.2 Domestic research status

In the early 1990s, research on the collision prevention between ships and bridges began in China. Liu Mingjun, Qi Chuanxin, and other scholars took the lead in studying the collision accident of Huangshi Yangtze River Bridge during the construction period, gradually understood the effect of the flow factors on the vessels sailing in the bridge area, and discussed the maneuvering scheme of the ships crossing the bridge in the curved reach (Liu et al., 1999; Qi, 1991).

In 2002, Dai Tongyu set up China’s first database of Ship Collision with Bridge, proposed a concept of “equivalent weight of consequence”, and proposed a simplified probability model for ship-to-bridge collision bride which was suitable for

China's reality. In particular, he proposed the concept of “equivalent weight of consequence” in the framework of risk analysis of ship-to-bridge collision, which laid a foundation for quantitative risk analysis (Dai, 2002).

In 2006, Lin Tieliang et al. from Tongji University put forward the fault tree analysis (FTA) method and constructed an FTA diagram of ship-to-bridge collision, the results of which could help to find the possible causes of accidents and their logical relations (Lin et al., 2006).

In 2008, Wang Zengzhong et al. compared the preventive measures and effects of passive and active collision prevention. Then they proposed the risk control and risk management guidelines based on life-cycle (Wang et al., 2008).

In 2011, Jin Yujuan proposed introducing corresponding impact factors to revise the previous calculation model of ship-to-bridge collision probability. She carried out simulation collision analysis on the anti-collision device of a certain main pier by ANSYS/LS-DYNA (Jin, 2011).

In 2012, Cui Guoping established a mathematical model with PS evaluation method (an evaluation method which combines fuzzy mathematics comprehensive evaluation method, analytic hierarchy process, and FSA method). He carried out a navigation risk assessment by determining the severity and probability of risk, through which he determined the risk level of the bridge area (Cui, 2012).

In 2016, Liu Shuang used the pressure sensor and the corresponding acquisition system to measure the force state of the ship when it passed through the bridge area at different flow rates. By changing the distance between ships and bridges, Liu Shuang analyzed the change of forces on vessels and discussed the safety characteristics of ships sailing in the bridge area (Liu, 2016).

In 2019, Xiao Yue took the bridge area of the Hong Kong - Zhuhai - Macao Bridge as the research object. Xiao Yue conducted a series of simulation experiments on various ship types under different wind and current conditions through a large ship handling simulator. Finally, Xiao Yue concluded that the bridge area of the Hong Kong - Zhuhai - Macao Bridge was 1000m above and below the axis of the bridge (Xiao, 2019).

In 2020, Liu Zhanhui et al. reviewed the bridge collision events and the current situation of scientific research in 2019, summarized the current analysis hotspots, introduced new materials, new structures, and new theoretical methods. The introduction of the peridynamic research method would help deepen the understanding of the nature of the collision and provide a new path to break through the bottleneck of traditional analysis of collision accidents (Liu et al., 2020).

To sum up the literature at home and abroad, with regard to research objects, the research focuses generally include the following aspects: Ship-to-bridge collision accident research; Ship-to-bridge collision risk analysis; Study on anti-collision design and facilities configuration of the bridge; Study on navigation safety assessment in bridge area. The research achievements mainly cover: (1) The establishment of the ship-to-bridge collision accident databases, such as the international database of 151 accidents built by PIANC Group No. 19, the database of 252 accidents built by an European consulting company, and the database of 213 accidents made by Dai Tongyu in China. (2) The publication of the common codes and standards for bridge design, such as Guide Specification and Commentary for Vessel Collision Design of Highway Bridges in the United States, the two codes for the design of highway and railway Bridges and culverts in China. (3) The introduction of the analytical research method and mathematical calculation model. In terms of research methods, the more mainstream are the FSA evaluation method, fuzzy mathematics comprehensive evaluation method, FTA method, analytic hierarchy process, artificial neural network evaluation method, extension matter element evaluation method, grey correlation degree analysis method, and so on. The accident probability calculation models mainly include the AASHTO model, IABSE model, Kunzi model, etc.

These studies have made positive contributions to the prevention of collision between ships and bridges from different aspects. However, due to the different navigation environments and conditions of each specific bridge, the relevant research results cannot be applied to any bridge area. Moreover, there are few pieces of literature that study on the maritime safety management of the bridge area. Therefore, this paper selects the maritime safety management of the Highway Bridge water area on the Yalu River as the research object, which has unique characteristics and practical application value.

## 1.3 Main work

### 1.3.1 Main research contents

(1) Summarize the domestic and foreign research results on the risk management of navigation safety of bridges;

(2) Conduct field research to collect the primary data of the natural environment, navigation environment, management environment, and bridge conditions of the Highway Bridge on the Yalu River;

(3) Conduct questionnaire survey to identify the navigation risk factors of the Bridge are; on this basis, identify the key risk factors employing expert interview and literature research;

(4) Based on the FSA theory, use literature study, empirical analysis, simulation experiments, and other methods to conduct qualitative and quantitative analysis of

the critical risk factors;

(5) From the perspective of maritime authorities, put forward countermeasures and suggestions for navigation risk management in the Highway Bridge water area on the Yalu River.

### 1.3.2 Technical route, key problems to be solved, and research methods

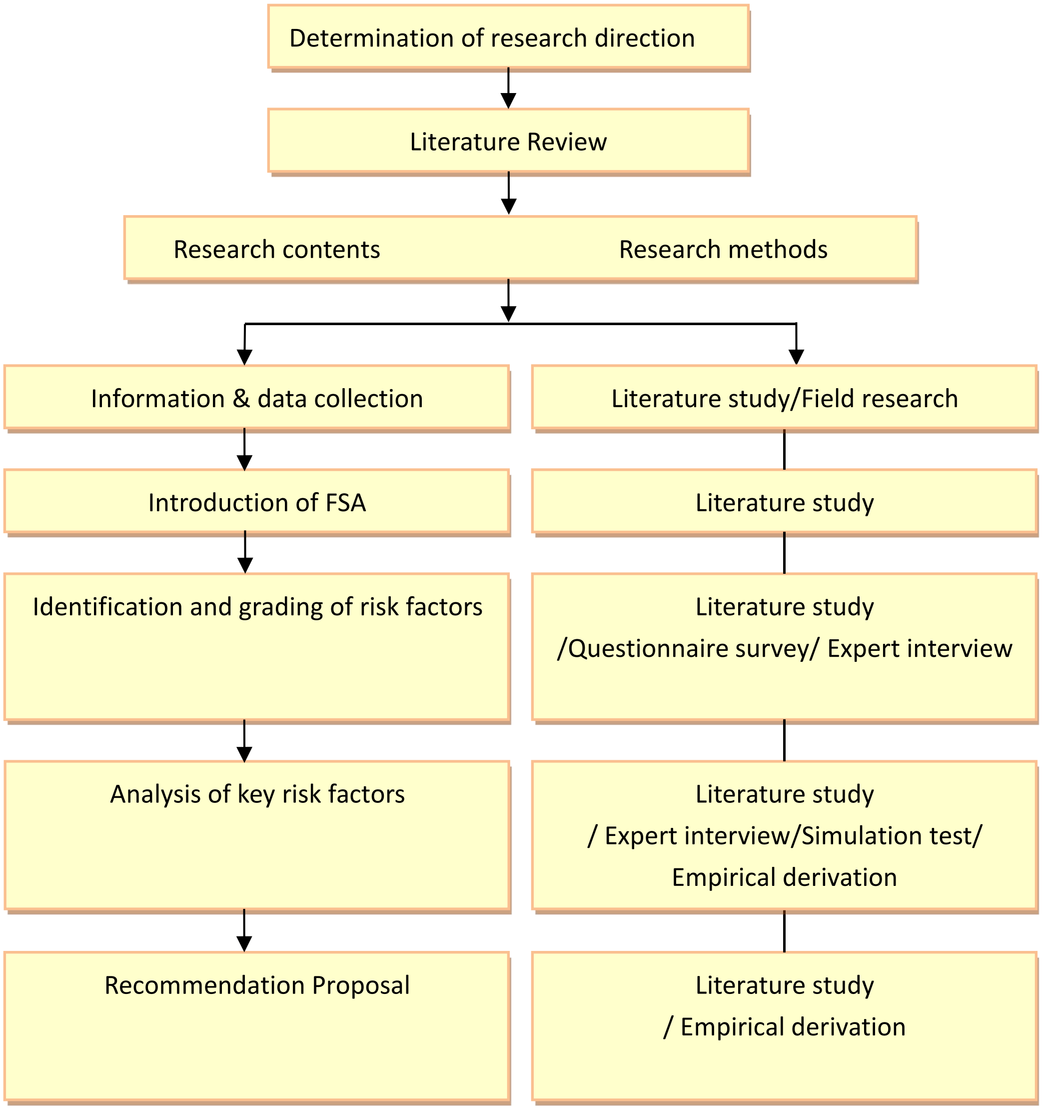



Figure 1 - Technical route

Source: Author.

The technical route is illustrated in Figure 1.

The fundamental problems to be solved: through identifying and analyzing the key risks of the navigation environment of the Highway Bridge water area on the Yalu River, this paper aims to put forward effective and targeted risk prevention and control measures and safety management countermeasures and suggestions from the perspective of maritime management.

This paper adopts the FSA framework for general risk evaluation, and uses literature study, field investigation, questionnaire survey, expert interview, simulation test, empirical analysis, and other research methods.

# Chapter II Overview of the environment of the Highway Bridge water area on the Yalu River

## 2.1 Highway Bridge on the Yalu River

Figure 2 - The Highway Bridge on the Yalu River

Source: Author.

The Highway Bridge on the Yalu River is located on the border river between China and the Democratic People's Republic of Korea (DPRK), connecting China's

Dandong City in Liaoning Province and Sinuiju City in North Pyongan Province of the DPRK, respectively. It is the largest boundary river bridge in China at present. The Bridge is shown in Figure 2.

The Bridge is a cable-stayed bridge with two towers and two cable-stayed steel box girders. It spans the inland waterway III-class of the Yalu River. The main bridge has a total length of 1266m. The main bridge hole is divided into five spans of 86+229+636+229+86m, and the main span is 636m (Ma & Zhou, 2016). The Bridge's main navigable span is a single-span two-way navigable span with a clear width of 398m and a clear height of 30.5m. The highest navigable water level is 5.837m, and the lowest navigable water level is -1.573m. 2000t general cargo ship was selected as the representative ship type for the calculation of the navigable clearance width of the Bridge, while the navigable clearance height was controlled by 3000t ship (Wang et al., 2013). According to the relevant standards and specifications, the basic data of the two types of ships are shown in Table 1.

Table 1 - Representative ship type

| **Ship type** | **Deadweight tonnage (t)** | **Main dimensions** | | | **Height above the no-load waterline to the maximum fixed point（m）** |
|---|---|---|---|---|---|
| | | Length overall (m) | Breadth molded (m) | Draft (m) | |
| **General cargo ship** | 2000 | 87.0 | 13.7 | 4.9 | 25.06 |

| | | | | | |
|---|---|---|---|---|---|
| **Seagoing vessel** | 3000 | 108 | 16.0 | 6.0 | 28.0 |

Source: Wang, J. Y. & Xi, G. H. & Yan, D. W. (2013). Overall design of China-SPRK Yalu River Boundary Highway Bridge. In *Proceedings of 2013 National Bridge Academic Conference* (pp. 3-10). Shenyang: China Highway Society Bridge and Structural Engineering Branch.

Considering the collision risk, the anti-collision grade of the piers of the main navigable span is designed according to 3,000t ships, while the anti-collision grade of other underwater piers is designed according to 1,000t ships.

### 2.2 Natural environment

#### 2.2.1Meteorological condition

Langtou Observation Station of Dandong Meteorological Observatory is located at 40°03 'N, 124°20' E, and an altitude of 15.1m. There are 30 years of complete meteorological observation data from 1951 to 1980, and the statistical analysis is as follows:

(1) Temperature

The local area is a temperate region with a monsoon climate and four distinct seasons. The main characteristic values of air temperature are as follows: the annual average temperature is 8.5°c; The annual average maximum temperature is 13.6°c; The annual average minimum temperature is 4.3°c; The annual extreme maximum temperature is 34.3°c (August 2, 1956); The annual extreme minimum temperature -28.0°c (February 3, 1952).

(2) Precipitation

Dandong is a region with high precipitation in the north of China. Precipitation was mainly concentrated in July to August, accounting for 54.3% of the total annual precipitation. The highest precipitation was in July, with an average of 296.2mm. Into the winter, the precipitation greatly reduced, and the average monthly precipitation is only 12mm.

(3) Wind regime

According to the data statistics of Langtou Observation Station of Dandong Meteorological Observatory for 30 years, the annual average wind speed is 3.2m/s. The yearly normal wind direction is NE with a frequency of 12%, and the subnormal wind direction is N, NNW with a frequency of 10%. The strong wind direction was N with a maximum wind speed of 20.0m/s (February 28, 1976). The annual average number of days with wind force ≥6 was about 41.1d. The annual average number of days with wind force ≥8 was about 15.9d. S wind predominates from April to August, NE wind predominates from August to October, and NW wind predominates in winter. Wind speed and wind direction frequency are displayed in Table 2, and wind roses are illustrated in Figure 3.

Table 2 - Wind Speed and Wind Direction Frequency in Dandong City (1951-1980)

| **Wind direction** | **N** | **NNE** | **NE** | **ENE** | **E** | **ESE** | **SE** | **SSE** | **S** |
|---|---|---|---|---|---|---|---|---|---|
| **Frequency （%）** | 11 | 8 | 12 | 2 | 1 | 1 | 5 | 7 | 8 |
| **Average wind speed （m/s）** | 6 .0 | 5.4 | 4.2 | 2.7 | 2.2 | 2.4 | 4.2 | 4.8 | 4.6 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Maximum wind speed （m/s）** | 20 | 18 | 12 | 8 | 7 | 8 | 16 | 14 | 16 |
| **Wind direction** | SSW | SW | WSW | W | WNW | NW | NNW | C | |
| **Frequency （%）** | 5 | 4 | 2 | 2 | 2 | 4 | 10 | 16 | |
| **Average wind speed （m/s）** | 4.2 | 3.7 | 2.3 | 2.7 | 3.0 | 4.9 | 6.2 | | |
| **Maximum wind speed （m/s）** | 13 | 14 | 10 | 14 | 14 | 18 | 18 | | |

Source: Dandong Maritime Safety Administration. & Dalian Maritime University. (2014). *Research Report on Navigation Safety Management Rules of the Bridge Area of China-DPRK Yalu River Boundary Highway Bridge (Exposure Draft)*.

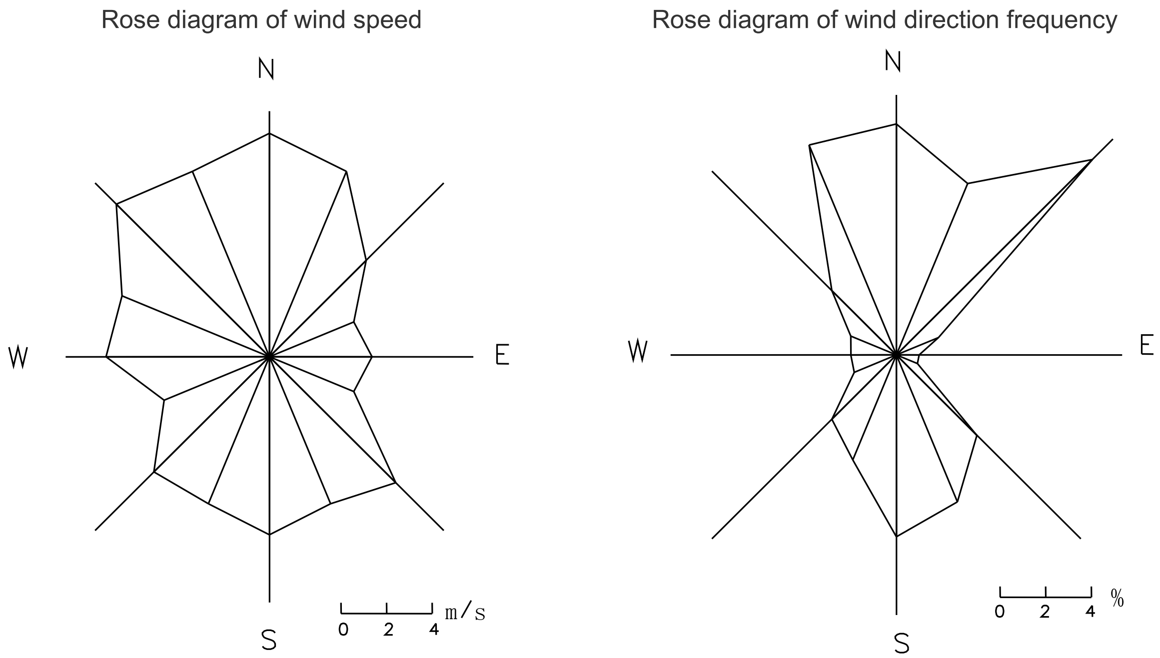



Figure 3 - Wind Rose

Source: Dandong Maritime Safety Administration. & Dalian Maritime University. (2014). *Research Report on Navigation Safety Management Rules of the Bridge Area of China-DPRK Yalu River Boundary Highway Bridge (Exposure Draft)*.

(4) Fog condition

The annual average number of fog days (visibility < 1km) was about 49.7d, with the maximum being 71d (1964) and the minimum being 26d (1954). Fog days are mostly concentrated in summer. Fog days are less frequent in winter, with an average of 1.8d per month.

(5) Freezing

The ice age is usually from early December to mid-March. The total glacial period is about 100d, and the maximum glacial period is about 45d. The thickness of floating ice is generally 5-15cm, and the thickness can reach more than 30cm. Floating ice flows with rising and falling tide. The maximum flow velocity of floating ice can reach 1.0m/s. The fixed ice is usually formed along the shore and is about 0.4m thick, up to 0.8m thick. Coastal ice usually accumulates to 2.0m to 4.0m.

Due to the large tidal difference between the two daily ebb and flows of the Yalu River, the water surface of the Yalu River has never been closed in winter. However, in winter, the floating ice on the river surface is severe, affecting the ships docked at the shore. Although the daily ebb and flow cannot form a frozen river surface, the ebb and flow of the Yalu River Estuary have been continuously thickening and increasing the floating ice on the river surface since January every year. At the location of the Highway Bridge, the thickness of the floating ice in winter in cold years can reach 2m-3m, and the area of a single ice block can reach $30m^2$-$40m^2$. Because the flow velocity of the ebb and flow is small, the maximum flow velocity of the floating ice is generally not more than 1.5m/s.

**2.2.2 Hydrological conditions**

The Bridge is located downstream of Langtou port. It is about 10km upward from the China-DPRK Friendship Bridge and about 25km downward from the river-sea boundary. This reach is a tidal reach of the Yalu River with curved and branching channels and a changeable riverbed. The channel is about 1.5km wide, and the landform along the river is low-lying tideland reclamation plain.

(1) Tides

There is no long-term tidal observation station in this basin. According to the measured data of Langtou tide station from June 1955 to 1968, the statistical characteristic values of tide level are demonstrated in Table 3.

Table 3 – Tidal data of Langtou tide station (Yellow Sea basic surface)

| | |
|---|---|
| Maximum tide level | 5.837m |
| Average high water level | 2.987m |
| Average low water level | -0.233m |
| Average tide level | 1.377m |
| Lowest tide level | -1.833m |
| Maximum tidal range | 4.90m |
| Average tidal range | 3.24m |
| Average flood tidal duration | 4h30min |
| Average ebb-tidal duration | 7h50min |

Source: Dandong Maritime Safety Administration. & Dalian Maritime University. (2014). *Research Report on Navigation Safety Management Rules of the Bridge Area of China-DPRK Yalu River Boundary Highway Bridge (Exposure Draft)*.

(2) Tidal flow

The data were collected from a temporary monitoring station located at Wen 'an Beach near the Highway Bridge between August 19 and August 26, 2008. It was a seven-day continuous observation with a fixed point on a single ship. The observation time was more than 27h, and two kinds of tidal patterns are selected for the test. The results show that the tidal flow near the Bridge area has the following characteristics: (1) During the spring tide, the average vertical velocity of the flood tide was greater than that of the ebb tide; The average vertical velocity of the neap tide is less than that of the ebb tide. (2) Flood tidal duration was generally 3-4h, and ebb-tidal duration was generally 8-9h. The specific data is described in Table 4.

Table 4 - Flow velocity and duration of ebb and flow near the Bridge area

| **Position** | **Average velocity** | **Maximum** | **Average** |
|---|---|---|---|

| | | **(m/s)** | | | **vertical velocity (m/s)** | | **duration (h:m)** | |
|---|---|---|---|---|---|---|---|---|
| | | Flood tide | Ebb tide | Average | Flood tide | Ebb tide | Flood tide | Ebb tide |
| **On the right side of Wen 'an Beach** | Spring tide | 0.94 | 0.92 | 0.93 | 1.84 | 1.74 | 3:20 | 9:04 |
| **On the right side of Wen 'an Beach** | Neap tide | 0.63 | 0.79 | 0.71 | 1.52 | 1.48 | 4:13 | 8:44 |

Source: Dandong Maritime Safety Administration. & Dalian Maritime University. (2014). *Research Report on Navigation Safety Management Rules of the Bridge Area of China-DPRK Yalu River Boundary Highway Bridge (Exposure Draft)*.

(3) Runoff

The heavy rain in the Yalu River Basin occurs from June to September, and the rainstorm is mostly from July to August. Floods in the Yalu River basin are caused by heavy rains, which also occur from June to September, especially from July to August. The Yalu River is a mountain river, and the intense and concentrated rainstorm causes the flood to rise and fall steeply. Since heavy rain lasts only 1-3d in a weather process and 70% of the rainfall falls a single day, floods are mostly single peak. The flood rises very fast, from the rise to the peak generally about 2d; the floodwaters gradually subside, generally about 9d. A flood lasts about 11d, and the bulk of its water is concentrated in just 3d. However, under the condition of large-scale exploitation and utilization of water resources in the Yalu River Basin, the flood characteristics of the river have been greatly changed compared with the natural state, and the flooding process tends to be gentle. The Bridge area is in a tidal reach, and the flood level is affected by both flood and tide.

(4) Waves

There is no fixed wave observation station in the Yalu River Estuary. For the wind and waves near the estuary, the maximum wave height observed in the short term seldom exceeds 1m and the maximum wave period is only 3.6s. There are a large number of shoal ridges and islands outside the estuary, which form a good natural cover, so it is generally difficult for the waves from the open sea to spread.

### 2.3 Navigation environment

#### 2.3.1 Waterways

The waterway located in the Bridge area is a part of the waterway from the China-DPRK Friendship Bridge to the river-sea boundary. It is the inland waterway III-class. The design scale of the waterway is 5.6×90×680m (waterway depth ×waterway width × bending radius).

#### 2.3.2 Navigation aids

Under relevant agreements between China and the DPRK, China is responsible for setting navigation aids in the following two areas: from the China-DPRK Friendship Bridge to the Yalu River Estuary; and the free navigation zone south of the Yalu River Estuary. At present, the Bridge is equipped with 10 bridge opening marks, 4 pier warning signs, 8 bridge column lights, 1 radar transponder, and 13 buoys. The buoys are red on the left red, and green on the right side in the direction of approach. Every year, the navigation buoys will be moved and replaced according to the actual situation of the waterways, and the adjusted situation will be released to the public.

Up to now, the setting and adjustment of navigation aids on the Yalu River in 2021 have completed. The buoys in the Bridge area of the Highway Bridge are shown in Table 5.

Table 5 - Information of the buoys in the Highway Bridge water area

| **Serial number** | **Type** | **Characteristics of lights** | | **Position** | |
|---|---|---|---|---|---|
| | | Light color | Period | North latitude | East longitude |
| **27** | starboard hand buoy | Green | Flash (3) for 10 s | 40°00′39.9″ | 124°22′22.6″ |
| **28** | port hand buoy | Red | Flash (3) for 10 s | 40°00′51.3″ | 124°22′22.5″ |
| **29** | starboard hand buoy | Green | Flash (3) for 10 s | 40°01′12.2″ | 124°22′35.6″ |
| **30** | port hand buoy | Red | Flash (3) for 10 s | 40°01′13.3″ | 124°22′27.0″ |
| **31** | starboard hand buoy | Green | Flash (3) for 10 s | 40°01′26.4″ | 124°22′35.6″ |
| **32** | port hand buoy | Red | Flash (3) for 10 s | 40°01′30.9″ | 124°22′28.0″ |

| | | | | | |
|---|---|---|---|---|---|
| **33** | starboard hand buoy | Green | Flash (3) for 10 s | 40°01′55.6″ | 124°22′37.0″ |
| **34** | port hand buoy | Red | Flash (3) for 10 s | 40°01′57.7″ | 124°22′29.2″ |
| **35** | starboard hand buoy | Green | Flash (3) for 10 s | 40°02′20.6″ | 124°22′12.5″ |
| **36** | port hand buoy | Red | Flash (3) for 10 s | 40°02′14.2″ | 124°22′05.8″ |
| **37** | starboard hand buoy | Green | Flash (3) for 10 s | 40°02′23.6″ | 124°21′52.9″ |
| **38** | port hand buoy | Red | Flash (3) for 10 s | 40°02′19.1″ | 124°21′46.1″ |
| **L01** | starboard hand buoy | Green | Flash (3) for 10 s | 40°02′23.9″ | 124°21′38.8″ |
| **L02** | starboard hand buoy | Green | Flash (3) for 10 s | 40°02′26.4″ | 124°21′27.9″ |
| **39** | starboard hand buoy | Green | Flash (3) for 10 s | 40°02′39.3″ | 124°20′20.7″ |

(The coordinate system is the national 2000 geodetic coordinate system)

Source: Liaoning Maritime Safety Administration, (2021). *Notice of adjustment of navigation buoys in*

*spring of 2021 in Dandong District.* Retrieved May 30, 2021 from the World Wide Web:

https://www.ln.msa.gov.cn/lnmsa-site/HangXingTongGao.init?SiteID=122&warnID=E853C849CB8B4AAABCB3745FD650F662

### 2.3.3 Traffic flow

There are sand quarries near the shore in the vicinity of the Bridge area, so there are lots of vessels used for dredging and sand mining. In addition, there are general cargo ships, bulk carriers, border trade ships, public service ships, fishing crafts, and so on. The tourist route along the river does not extend to the Bridge area, so no tourist ships are sailing through this area at present. Every year from the middle of March to the middle of November, especially from July to October, the traffic density is relatively larger. According to the statistics of April and May 2017, the number of ships passing through the Bridge was 738 and 771, respectively.

Since the Highway Bridge on Yalu River has been built for a short time and there have not been any ship-to-bridge collision accidents in the Bridge area, the statistical analysis of collision accidents in this paper is ignored.

### 2.3.4 Ports and berths

Langtou Port, a river port, is located in Langtou Town, 11km downstream of Dandong City, 28km away from the Yalu River Estuary, occupying less than 1km of the shoreline. The water depth in front of the shoreline is good, and the 8m isobath line is close to the shore. There are 5 production berths, including 1 1000t berth, 3 3000t berths, and 1 3000t oil berth. They mainly undertake the coastal bulk cargo transport, as well as meeting the border trade and river-sea cargo transport needs. The basic data and information of berths of Langtou Port are described in Table 6. However, due to the local silting of the waterway has a negative impact on the upgrading and reconstruction of the port, only 1000t ships can be berthed at present.

Figure 4 shows a panoramic view of Langtou Port.

Figure 4 - Overview of Langtou Port

Source: Author.

Table 6 - Status quo of berths in Langtou Port Area

| Name | Completion date | Cargo type | Water depth ahead of berth (m) | Length(m) | Berthing capacity (DWT) |
|---|---|---|---|---|---|
| **#1 Berth** | 1988 | General cargo | -8.0 | 126 | 3000 |

| | | | | | |
|---|---|---|---|---|---|
| **#2 Berth** | 1988 | General cargo | -8.0 | 122 | 3000 |
| **#3Berth** | 1988 | General cargo | -8.0 | 126 | 3000 |
| **Sand Berth** | 1972 | Sand | -8.0 | 68 | 1000 |
| **Oil Berth** | 1992 | Oil | -4.5 | 200 | 3000 |

Source: Dandong Maritime Safety Administration. & Dalian Maritime University. (2014). *Research Report on Navigation Safety Management Rules of the Bridge Area of China-DPRK Yalu River Boundary Highway Bridge (Exposure Draft)*.

**2.4 Management environment**

**2.4.1 Legal environment**

The domestic laws, regulations, and normative documents applicable to the maritime management of navigation safety of the Bridge area mainly include:

(1) Law of the people’s Republic of China on Work Safety (effective as of December 1, 2014);

(2) Regulations of the People's Republic of China on the Administration of Traffic Safety on Inland Waters (effective as of March 1, 2017);

(3) Rules for Preventing Collisions on Inland Waters of the People's Republic of China (effective as of January 1, 1992, revised on September 2, 2003);

(4) Measures of the People's Republic of China for the Administration of Water Traffic Safety in Bridge Areas (effective as of June 1, 2018);

(5) Provisions for the Administration of Pilotage of Vessels (effective as of January 1,

2002);

(6) Provisions of the People's Republic of China on the Administration of Navigation Safety for Water and Underwater Activities (effective as of March 1, 2011, revised on September 2, 2016);

(7) Provisions of Liaoning Maritime Safety Administration on the Administration of Entry and Exit Report of Inland River Vessels (effective as of May 5, 2019);

(8) Measures of Liaoning Maritime Safety Administration for the Implementation of Primary Responsibilities for Navigation Safety of Water and Underwater Activities (effective as of January 1, 2021);

(9) Provisions of Liaoning Maritime Safety Administration on Supervision and Administration of General Navigation Safety under Special Weather Conditions (effective as of June 6, 2019);

(10) Measures for the Implementation of Supervision and Inspection on Safety and Pollution Prevention of Shipping Companies of Liaoning Maritime Safety Administration (effective as of November 9, 2018).

Dandong section of the Yalu River has no regulations for water traffic management. It is currently supervised by referring to the Regulations of the People's Republic of China on the Administration of Traffic Safety on Inland Waters. So far, there are no traffic management regulations for the water area of the Highway Bridge. The maritime authorities of China and the DPRK jointly implement the management according to an agreement agreed by the two countries------Rules for Navigation of Vessels in the Frontier Rivers of China and the DPRK (1981).

### 2.4.2 Management authority and supervision mode

The Highway Bridge water area is jointly owned, shared, and managed by China and the DPRK. The DPRK maritime authority is the North Pyongan Maritime Administration, and the Chinese maritime authority is Dandong MSA. Langtou Maritime Department, as a dispatched agency of Dandong MSA, is responsible for the specific maritime administration and on-site supervision, including supervising the traffic order on the Yalu River; patrolling the water area under the jurisdiction; conducting ship registration and seaworthiness management; carrying out ship safety inspection and ship technical supervision, etc.

# Chapter III Identification of maritime risk factors

## 3.1 Introduction of FSA

This paper applies the FSA framework to evaluate the navigation safety of the Highway Bridge water area on the Yalu River.

### 3.1.1 Background of FSA

FSA is a structured and systematic analysis methodology, which is applied to ship engineering design, traffic and transportation management, navigation environment research, shipping safety management, and regulation formulation. The aim is to take into account all various factors affecting safety. Through risk assessment and cost-benefit assessment, researchers can propose reasonable technical requirements that can effectively control risks to continuously improve and enhance maritime safety (Zhou, 2015).

In the 1980s and 1990s, the UK developed a set of systematic safety assessment methods and theories, including FSA, on the basis of a lot of research work in the field of maritime security and achieved satisfactory expected results. To promote the development of maritime safety and anti-fouling work, the UK put forward a proposal on the application of FSA in the field of ship safety at the 62nd session of the Maritime Safety Committee (MSC) of the International Maritime Organization

(IMO) in 1993 (Zhao, 2005). The IMO attaches great importance to this proposal and proposed to introduce and apply FSA in the maritime sector in 2002 (Montewka et al., 2014). As a strategy, FSA has gradually been widely used in the formulation of maritime safety and marine environmental protection conventions and rules, in the safe operation management of ships, and in the design of ships. At the 68th MSC meeting held in May 1997, The IMO adopted Interim Guidelines for the Application of Formal Safety Assessment (FSA) to the IMO Rule-Making Process (IMO, 1997). Since then, the IMO has revised it many times, and now the latest version is Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-making Process (IMO, 2018). Another important international organization---the International Association of Classification Societies (IACS), set up an ad hoc FSA working group to follow up the IMO research to carry out FSA application research.

In China, researchers from the MSA, classification societies, research institutions, and colleges have carried out some preliminary studies on the FSA application. In 1999, according to Interim Guidelines for the Application of Formal Safety Assessment (FSA) to the IMO Rule-Making Process, China Classification Society (CCS) specially formulated and promulgated the Guidelines for Application of Formal Safety Assessment (1999). On this basis, CCS issued the Guidelines for Application of Formal Safety Assessment of Ships (2015). In recent years, some domestic experts and scholars have carried out lots of research on the application of FSA in the field of ship safety.

### 3.1.2 Applicability of FSA to this study

(1) FSA can play a preventive role. It not only can be used to post hoc evaluation after the accident but also can predict the possibility before the accident. FSA can systematically analyze the possibility of potential danger happening or the seriousness of results, and take the necessary measures to prevent the occurrence of

the accident or minimize the negative effect of the consequences. FSA aims to manage risk foreseeably, not just passively learn a lesson from the accident (Zhao, 2015). So this approach is particularly suitable in the area of maritime traffic, where the maritime authorities need to ensure the safety of people's lives and property, maintain a clean marine environment, rather than in the occurrence of casualties or ship pollution accidents and then take action to rectify.

(2) FSA is a comprehensive analysis and evaluation method. Through a structured and systematic analysis process, it comprehensively considers various factors affecting safety, finds out the relationship between them, and determines the contribution of each factor to the overall safety level of the evaluated object. Comprehensive analysis and evaluation can prevent the measures taken to eliminate the unsafe factors in a certain respect from leading to new potential hazards (Zhao, 2015). Through FSA, this paper weighs up the risk factors from all aspects of the crew, ship, environment, and management, and finally proposes holistic solutions.

(3) FSA includes a cost-benefit analysis. In general, to further reduce risk, the introduction of additional safety measures will increase safety costs. However, whether the additional costs are proportionate to the resulting benefits is a crucial factor in determining whether the additional investment is worth it. The purpose of cost-benefit analysis is to achieve the maximum safety benefit with the minimum safety investment, realizing the optimization of the proportion of input and output (Zhao, 2015). Although this paper does not carry out a professional quantitative cost-benefit analysis, it insists that the recommendations presented should be reasonable and feasible and should be in line with the actual financial situation of Dandong MSA.

(4) FSA is a combination of qualitative assessment and quantitative assessment, which has the advantages of both methods. Qualitative analysis is relatively

subjective, easy to understand and apply. Expert evaluation is a commonly used method in qualitative analysis. Quantitative analysis can provide quantitative conclusions for decision-makers, but its analysis and calculation process is relatively complex. In the evaluation process, a large amount of data and calculation formulas should be used. General navigation safety evaluation is a complex issue, and the affecting factors are numerous and complex. Qualitative analysis or quantitative analysis alone is not accurate enough. Generally, it is more scientific to combine qualitative analysis with quantitative analysis.

### 3.1.3 Implementation of FSA

FSA mainly consists of five standardized steps: Identification of hazards, assessment of risks, risk control options, cost-benefit assessment, and recommendation for decision-making, which can found on the IMO web site (https://www.imo.org). The basic process is shown in Figure 5.

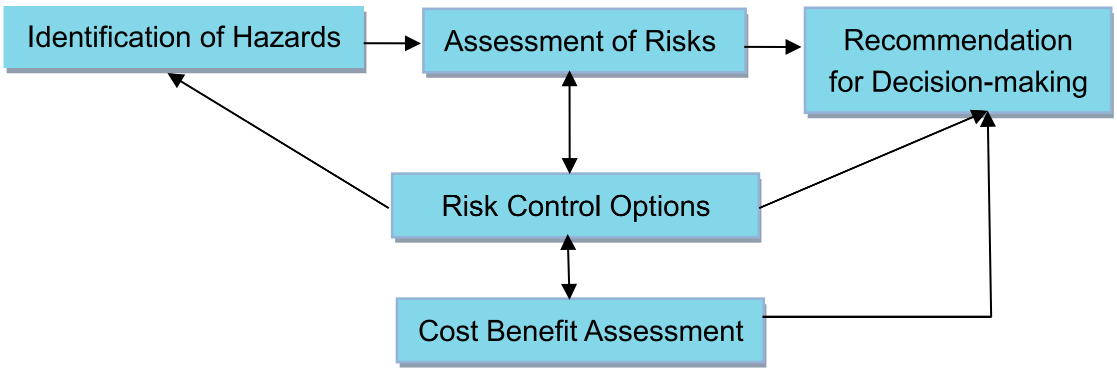



Figure 5 - FSA Flow Chart

Source: Ban, Y. J. (2017). Study on navigation safety evaluation of the bridge area on inland river based on FSA, *China Water Transport, 17*(2), 29-32.

(1) Identification of hazards: it is the initial step of FSA to identify all hazards or risks in the project and then arrange these hazards in a list according to different risk

degrees for further analysis of major hazards (Fang et al., 2004).

In the process of identification of hazards, relevant experts, scholars, and others study and discuss together through workshops and symposia. Identification of hazards should not only focus on the identification of subsequent or existing threats, but also take full account of the anticipated hazards that may occur or emerge (Fang et al., 2004).

(2) Assessment of Risks: first, the various factors that influence risk should be analyzed. Then find out the high-risk areas and key risk factors in the order of priority, and focus on the analysis and evaluation of these high-risk factors. Finally, the relationship between the occurrence of accidents and the consequences of accidents is analyzed to control the high risks within an acceptable range as far as possible (Fan, 2006).

(3) Risk Control Options: On the basis of risk identification and assessment, the third step is to put forward some risk reduction measures to prevent accidents or mitigate their consequences and effects. Then according to these measures to develop specific, practical, and feasible risk control options, such as formulating and modifying some rules and regulations; standardizing working procedures; strengthening training, etc. When formulating risk control options, we should fully pay attention to the new risks caused by the new measures (Fan, 2006).

(4) Cost-Benefit Assessment: the purpose of cost-benefit assessment is to estimate and evaluate the cost and benefit generated by each risk control option, in which the cost shall be all the costs generated during the whole assessment and implementation cycle, including direct and indirect costs. The benefits to be assessed may include a reduction in the number of fatalities and injuries, a reduction in the frequency of accidents, a reduction in the extent of environmental damage, a reduction in the loss

of third-party liability, and an increase in the average life of the ship (Fan, 2006). The main issues is to reduce the cost-benefit ratio, and then to make a reasonable ranking of the proposed options (Ban, 2017).

(5) Decision Making Recommendations: Based on the previous four steps, it puts forward reasonable, practical and feasible suggestions and measures with a better cost-benefit ratio shall be selected at last (Fan, 2006).

As Cost-Benefit Assessment involves very professional knowledge of economic disciplines, the fourth and fifth steps are not discussed and applied in this paper. This paper will mainly apply the first three steps to evaluate the navigation safety of the Highway Bridge water area on the Yalu River.

## 3.2 Identification of maritime risk factors

The navigation safety evaluation of the bridge area is system engineering with four elements of crew-ship-environment-management mutually coupling (Zhang, 2017). Each element also includes many specific indicators, such as ship element including ship size, ship type, ship age, and many other factors. Some factors are suitable for qualitative analysis, while others are suitable for quantitative analysis. In the process of navigation safety evaluation, experts' experience and opinions are adopted, and the research results of domestic and foreign scholars are cited to identify the maritime risk factors existing in the Highway Bridge water area on the Yalu River and identify the key risk factors through risk grade assessment.

### 3.2.1 Preliminary identification of risk factors

Identification of risk factors is the initial step to comprehensively evaluate the maritime risks in the Highway Bridge water area on the Yalu River, aiming at abstracting all the possible risk factors in the evaluation system. There are not only some risk factors that are recognized by domestic and foreign scholars in the general navigation field but also some risk factors that are applicable to a certain water area. In addition, some risk factors are identified by imagination, combined with some analysis. In order to have a general understanding of the navigation safety status and risk factors of the Highway Bridge water area on the Yalu River, this paper made an expert survey questionnaire (see Appendix 1 for details) and distributed it to the relevant experts. A total of 59 valuable questionnaires were recovered, including 15 copies from the maritime authorities; 6 copies from maritime support departments; 3 copy from the fishery administration departments; 5 from port enterprises; 8 copies from the shipping companies; 22 copies from the senior captain. The opinions collected from the questionnaire on the overall safety evaluation and risk factors of the Bridge area are summarized as follows:

(1) At present, the navigation safety situation on the Yalu River is at the best level in history, thanks to the following 3 aspects: first of all, the publicity, implementation and enforcement of laws and regulations by competent departments such as the MSA have improved the safety awareness of port enterprises, shipping companies and their crew members, and the safety management of each company is getting better and better. The accident rate has greatly decreased. Secondly, the investment and use of CCTV, AIS, and other modern scientific and technological equipment have effectively controlled navigation safety and effectively reduced the occurrence of illegal acts. Third, with the in-depth cooperation of relevant government departments such as the MSA, the transportation department, the fishery administration departments, the crackdown on illegal acts has been intensified, and the law enforcement efficiency has been effectively improved. Joint supervision has played a positive role in promoting navigation safety.

(2) Although the navigation situation of the Yalu River is good on the whole, due to the particularity of the Bridge area, there are still many hazards or risks. It is

necessary to identify and analyze these risk factors and put forward feasible control measures. The 16 risk factors affecting the navigation safety of the Bridge area fall into 4 categories, which are represented by tree diagram in Figure 6. The first category is human factors, including crew competence. The second category is ship factors, including ship size, type of ship, ship age, and load capacity. The third category is environmental factors, including ice, tidal current and runoff, wind, visibility, wave, traffic density, bridge location, channel depth, the swing of channel, and navigation aids. The fourth category is management factors, including maritime management. Moreover, the Yalu River is the border river between China and the DPRK, and almost all the experts who participated in the questionnaire survey mentioned the impact of bilateral maritime management between China and the DPRK on the navigation safety of the Bridge area, which will be discussed in the maritime management section.

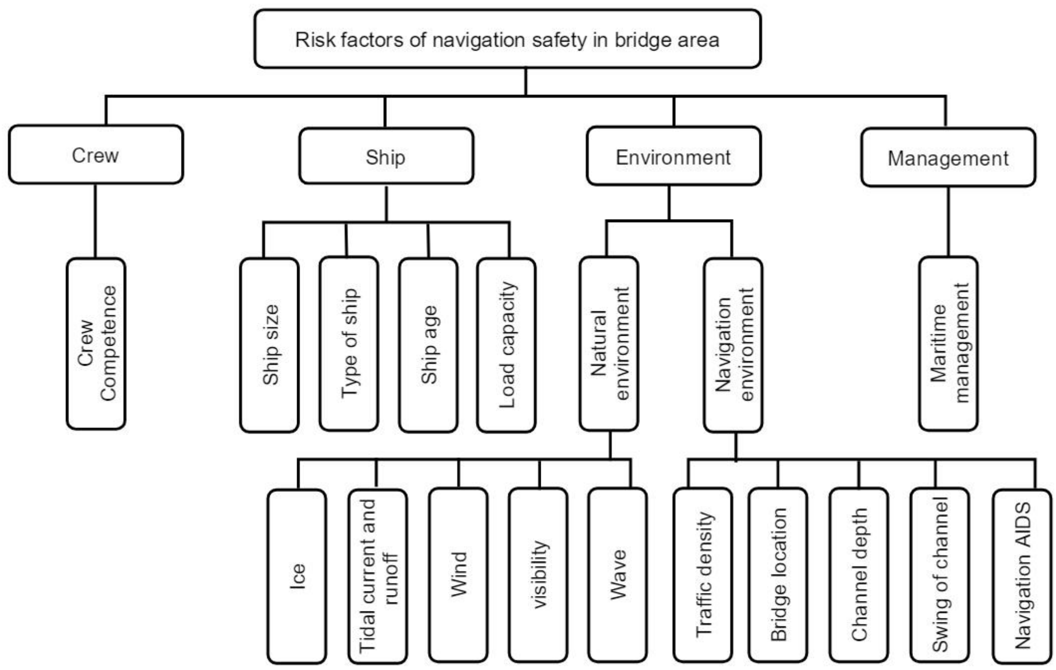



Figure 6 - Navigation safety evaluation factors of the Bridge area

Source: Author.

According to the statistics, all the risk factors mentioned in the order from the most to the least are shown in Table 7.

Table 7 - Questionnaire Statistics------risk factors

| Risk Factor | Times of Being | Risk Factor | Times of Being |
|---|---|---|---|
| Crew Competence | 49 | Navigation Aids | 28 |
| Channel Depth | 45 | Tidal Current and Runoff | 27 |
| Maritime Management | 44 | Swing of Channel | 19 |
| Ship Age | 38 | Ship Size | 18 |
| Type of Ship | 34 | Ice | 15 |
| Load Capacity | 31 | Bridge Location | 11 |
| wind | 30 | Traffic Density | 8 |
| Visibility | 29 | Wave | 4 |

Source: Author.

### 3.2.2 Identification of key risk factors

In the specific environment of the Highway Bridge water area on the Yalu River, it is unnecessary to take all factors into account. Some factors can be ignored if they do little harm to the navigation safety in the water area. Therefore, in this part, the risk factors will be evaluated and the key risk factors will be identified. However, due to the strong subjectivity of the questionnaire, there may be the possibility that a certain risk factor is mentioned too few times due to participants' temporary forgetting or different ways of language expression. Therefore, the questionnaire results are an important basis for the evaluation of key risk factors, but they are not the only basis. Further analysis is needed.

Experts from maritime authorities, veteran captains on the Yalu River, and professors from maritime universities participated in symposia. A total of 4 symposia were held, with a total number of 18 participants. Combined with the literature research results and basic theories at home and abroad, the 16 risk factors were deeply analyzed and classified as key risk factors, general risk factors, and ignorable risk factors according to the degree of hazard.

Key risk factors: represent the risk factors that have a great impact on navigation safety of the Highway Bridge water area on the Yalu River, and are in urgent need of great attention and strict control by maritime authorities;

General risk factors: represent the risk factors that have an impact on navigation safety of the Highway Bridge water area on the Yalu River, and need to be considered in the process of maritime management; but since the impact is small, there is no need for special attention;

Ignorable risk factors: represent the risk factors that have little influence on navigation safety of the Highway Bridge water area on the Yalu River, or represent those that have some influence but are ignored in this paper due to some reasons.

The classification of all risk factors is as follows:

(1) Human factors: the human factors in this paper mainly refer to the crew. More than 83% of participants in the questionnaire survey believed that crew competence played a very important role in ship safety. Participants of the symposia generally stressed that the navigable environment of the Highway Bridge water area on the Yalu River were complex, which required a high level of crew competence. The only ship traffic accident on the Yalu River in 2019 was caused by a crew member's

operation error, which resulted in the ship crashing into a reef. The IMO points out that human element are involved in about 80% maritime accidents (IMO, 2013). The handling capacity of the crew affects the accident rate (Hao et al., 2016). Therefore, crew competence is listed as a key risk factor.

(2) Ship factors:

- Ship size: according to the current situation of ships in Langtou port, most of the ships sailing near the Bridge are ships of 1000t and below, and the tonnage of ships in the DPRK is smaller than that of China. Based on the anti-collision design and safety facilities of the main piers, under the present condition, the collision between ships and piers has little effect on the safety of the Bridge. Therefore, ship size is listed as an ignorable risk factor.
- Ship age: the age of the ship has an impact on the safety of the ship. For ships with high age, due to aging, corrosion, and other reasons, the strength of hull structure and equipment performance generally decline, and the probability of failure and accident increases accordingly (Huang, 2000). Most of the DPRK's ships are old ships imported from China or Japan, and Chinese ships for sand mining are generally aged. In accordance with China's PSC inspection data in the first quarter of 2021, the older the ship, the higher the average number of defects and the higher the detention rate, especially for ships over 20 years of age (Zhang, 2021). So this factor is listed as a general risk factor.
- Load capacity: there are sand quarry near the shore in the vicinity of the Bridge area, sand carriers often sail nearby. These ships are often fully loaded, and most of them are overloaded, which greatly reduces the ships' maneuverability. If the ship sails downstream, the ships' maneuverability becomes worse. This factor is therefore classified as a general risk factor.

- Type of ship: ships passing in the Bridge area are mostly general cargo ships, bulk carriers，sand carriers, as well as a large number of fishing crafts. According to Annual Report on Port State Control in the Asia-Pacific Region 2020 from Tokyo Memorandum, the deficiency rate of different types of ships in PSC inspection is obviously different. From 2018 to 2020, the defect rate of general cargo ships and bulk carriers are both relatively high. Both are higher than the average deficiency rate of 2.93% for all types of ships (Tokyo MOU, 2021). Therefore, the type of ship is also a factor to be considered in accidents, so it is listed as a general risk factor.

(3) Environment factors:

Environment factors are usually the inductive factors of ship traffic accidents in bridge areas. Chinese scholar Shao Zheping has used mathematical models and simulation models to make a comprehensive quantitative analysis of relevant environmental factors that can affect ships' performance (Shao, 2000), and tested the relationship between these environmental factors and navigation safety.

- Ice: Due to the high latitude of the Yalu River, the sea area freezes every year. The sea ice has an impact on Dandong Port. In winter, the ice formed at the Bridge site has a small effect on river-related buildings such as revetment and wharf, but it has a bigger effect on docked ships. There has been an incident in which a block of tidal ice pushed the docked ship of the DPRK, causing someone to fall overboard. At the same time, ice also causes harm to navigation aids. When large ice surrounds the navigation aids, the large area of ice moves as a whole under the action of tidal current and wind, which makes the navigation aids move as a result of being squeezed, and the navigation safety of ships cannot be guaranteed. This factor is therefore classified as a general risk factor.

- Tidal current and runoff: the Highway Bridge is located 26.5km from the Yalu River Estuary and is greatly affected by tides. According to the data from August 19 to August 26, 2008, the tidal current velocity in the Bridge area is relatively high. Although the ships sail either upstream or downstream, there are turns in the channel near the Bridge. In the course of steering, the tidal current has a great influence on the navigation safety of ships. The effect of runoff on navigation safety is greater than that of the tidal current. The Yalu River floods in July and August. The water level is affected by rainfall, and the difference between flood and low water levels is 5-6m. During the flood, which is the worst in 50 years, the maximum flow velocity at the Bridge section is 3.81m/s. Under the flood which is the worst in 100 years, the maximum flow velocity at the Bridge section is 3.91m/s. The effect of runoff on ship navigation is similar to that of ebb-tidal current, but the impact of runoff on ship navigation is more remarkable because the flow velocity is much higher than that of the tidal current. Therefore, these factors are listed as key risk factors.
- Wind: wind is one of the well-recognized environmental factors that affect the safety of ship navigation. The wind will cause the ship to deviate from its route, run aground, drag anchor, etc. Crosswind can make the ship drift or heel. It is more difficult to operate the ship. For ships sailing in narrow waterways such as bridge areas, the greater the wind, the higher the risk is. Some researchers have shown that when the wind force exceeds magnitude 7, the probability of accidents is higher (Xiao, 2007). In this area, the wind direction is mainly S, NE, and NW. The direction of the channel near the Bridge is about NW/N, and there are turns near Liucao Island. The wind direction of S and NE has a great influence on the navigation and turning of ships in the channel. However, because the wind is light in the water area, the ship tonnage is small, and the

freeboard is low, the wind has little influence on the sailing of the ship. This factor is therefore classified as a general risk factor.

- Visibility: it is one of the most important factors affecting ship navigation, especially when no radar equipment is available. Rain, snow, fog, haze, dust storms, etc., as well as night, can lead to poor visibility. Studies have shown that visibility lower than 4km affects navigation safety to a certain extent, when visibility is 0-1km, the accident rate increases sharply, and this visible distance can be regarded as the danger area (Gao, 2010). Other studies have shown that the probability of collision accidents at night is 4.5-12 times higher than during the day (Tan, 2011). From the management practice of Dandong MSA, rain and fog have an impact on visibility, which is only concentrated in summer. This factor is therefore classified as a general risk factor.

- Waves: waves may cause the ship pitching and heaving, making it more difficult for the crew to handle the ship (Xiao, 2007). There are a large number of shoal ridges and islands in the Yalu River Estuary, which form a good cover for the waters in the Bridge area. In general, it is difficult for waves from the open sea to penetrate into the Bridge area. Therefore, waves basically have no impact on the navigation safety of ships at the Bridge location. Therefore, this factor is classified as an ignorable risk factor.

- Traffic density: to some extent, traffic density reflects the congestion degree of the water area and the risk degree of traffic. Generally speaking, a port with a high traffic density and terrain conditions has a greater risk of collision (Yoo & Kim, 2019). Due to the low traffic volume and traffic density of the Bridge area, this factor is ignored in this paper.

- Bridge location: the Highway Bridge on the Yalu River is very close to the tidal flats at the end of Liucao Island. The straight channel under the Bridge has a short distance, so both upstream and downstream vessels need to turn at this position, which increases the difficulty of ship maneuvering and is a test of the crew's maneuvering capability. As the site selection of the Bridge was determined by the Agreement between China and the DPRK, the Bridge has been completed and the Bridge site cannot be changed, so this factor is ignored in this paper. However, the navigational hazards posed by the turn of the channel will be considered from the perspective of crew competence.

- Channel depth: When sailing at sea, ships can ignore the water depth, while when sailing on inland rivers, they cannot. Because most of the channel is in the shallow water area, which has a great impact on the maneuverability of ships (He, 2019). According to the topographic survey data near the Bridge site, the natural water depth of the channel does not meet the navigation requirements within the designed width of two-way navigation for 2000t ships, so ships need to ride the tide for navigation. Therefore, this factor is classified as a key risk factor.
- Swing of channel: due to the influence of water flow and sand, the channel in the bridge area swings every year (Zhao, 2017). The river channel movement will cause the change of navigable clearance breadth, which will increase the risk of two-way navigation of ships and pose a threat to the safety of the Bridge. Therefore, the factor is classified as a key risk factor.
- Navigation aids: the navigation channel near the Bridge position swings every year, and the setting of navigation aids should be adjusted accordingly every year. So this factor is classified as a general risk factor.

(4) Management factors:

Maritime management: management factors are usually the deep causes of accidents. The discussion here mainly refers to the management from the maritime authorities. The management from the maritime authorities can be embodied in the management of the crew, the management of the ship and the management of the navigable environment. In fact, human factors, ship factors and environmental factors all include management factors. However, this paper specifically lists management factors as a separate item, so as to highlight and emphasize the importance of maritime authorities in maintaining navigation safety of the Bridge area. The purpose is to find out the weak points and hidden risks existing in the management of the maritime authorities and improve the management efficiency and effectiveness of the maritime authorities.

It should be noted that the Highway Bridge is located on the China-DPRK border river, and the navigation management of the Bridge area is in charge of China and the DPRK, which undoubtedly increases the difficulty of maritime management. Between 2017 and 2019, there were two collision accidents between Chinese and DPRK vessels. How to jointly manage and coordinate the ships of the two countries is one of the key issues to ensure the navigation safety of the Bridge area. So this factor is classified as a key risk factor.

To sum up, in light of the local conditions, survey results, the opinions of experts interviewed, the research achievements of domestic and foreign scholars, and basic theories, among the 16 risk factors collected in the early stage, the following 5 risk factors are classified as key risk factor: crew competence, tidal current and runoff, channel depth, the swing of channel, maritime management (including China-DPRK Maritime Management). Figure 7 distinguishes different levels of risk factors by color.

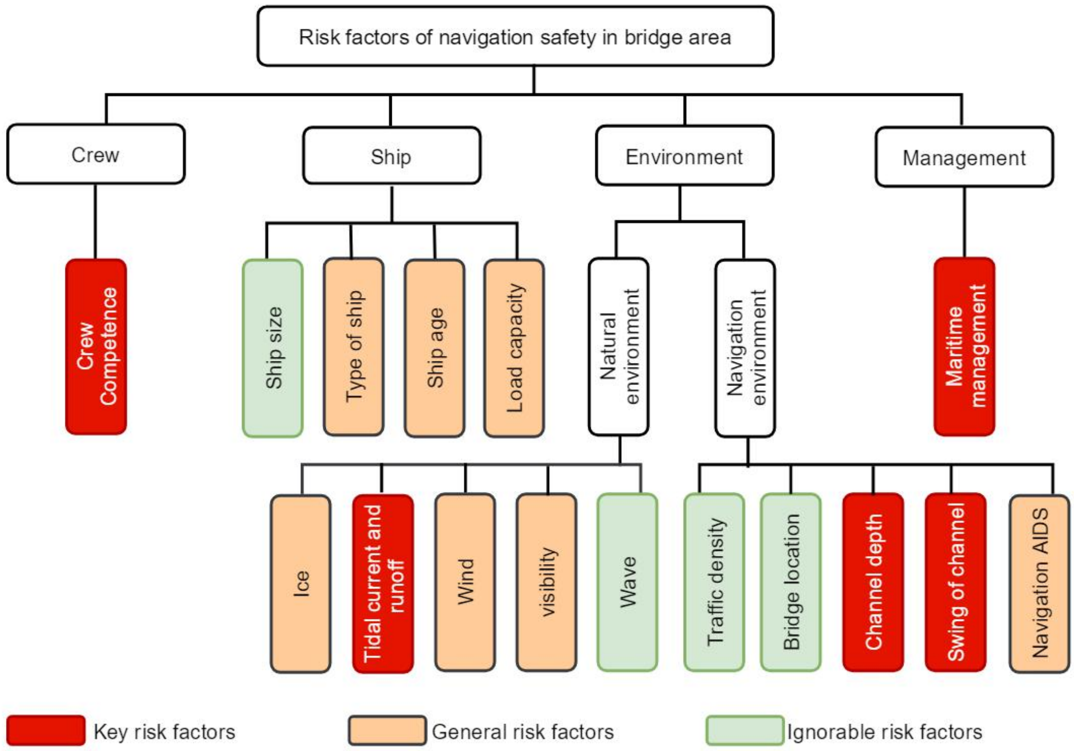



Figure 7 - Classification of navigation safety evaluation factors of the Bridge area

Source: Author.

## Chapter IV Analysis of the key risk factors

This chapter will carry out an in-depth analysis of 5 main risk factors, and find out the weak points of key risk factors and identify the potential hazards to navigation safety. For logical reasons, this chapter will proceed in the following order: analysis of tidal current and runoff; analysis of channel depth and channel swing; crew competence analysis; maritime management analysis.

### 4.1 Analysis of tidal current and runoff

To test the influence of tidal current and runoff on the navigation of ships in the Highway Bridge water area on the Yalu River, professors, and captains of Navigation College of Dalian Maritime University (DMU) were invited to conduct a simulation test on a large ship handling simulator. The simulation test selected the most unfavorable external force conditions for the safety of ship handling. The one-way navigation of 3000t class ships and the two-way navigation of 2000t class ships in the main navigable span were tested. In order to verify the accuracy of the simulation test, the simulation turning circle trial was carried out on the test ship type. The results were compared with the data of typical similar ship types, and the margin of error was within an acceptable range (10%). The specific test conditions are as follows.

(1) Test Vessel:

The dimensions of ships participating in the test are shown in Table 8.

Table 8 - Dimensions of Test Vessel

| **Ship name** | **Gross tonnage** | **Ship length (m)** | **Ship Breadth (m)** | **Load draught (m)** | **Volume of displacement ($m^3$)** |
|---|---|---|---|---|---|
| **GuoYu-5** | 2000 | 87.0 | 13.4 | 4.9 | 3414.2 |
| **Cargo3000W** | 3000 | 108 | 16.0 | 6.0 | 5875.0 |

Source: Dalian Maritime University. (2011). *Ship Maneuvering Simulation Test Report of the Highway Bridge water Area on the Yalu River.*

(2) Wind force and wind direction

The maneuvering environment was set up to be relatively difficult. The wind direction was set for N, NE, S, and NW. The wind force was set at Beaufort scale

5-6.

(3) Flow velocity and flow direction

In this simulation test, a simulated flow field near the Bridge was made according to two working conditions. One was flat beach flow, the velocity was 7000m$^3$/s. The other was 10-year flood flow, the velocity was 20400m$^3$/s. The specific parameters of the two flow fields are illustrated in Figure 8 and Figure 9.

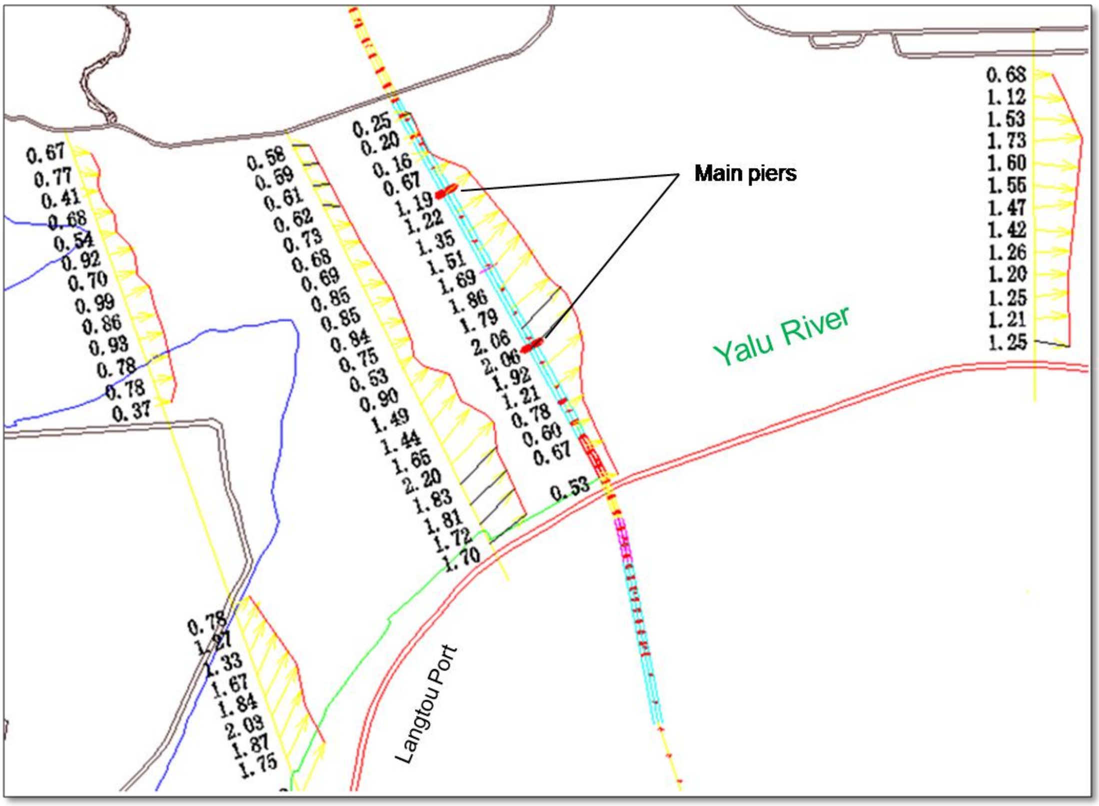



Figure 8 - The flat beach flow field

Source: Dalian Maritime University. (2011). *Ship Maneuvering Simulation Test Report of the Highway Bridge water Area on the Yalu River.*

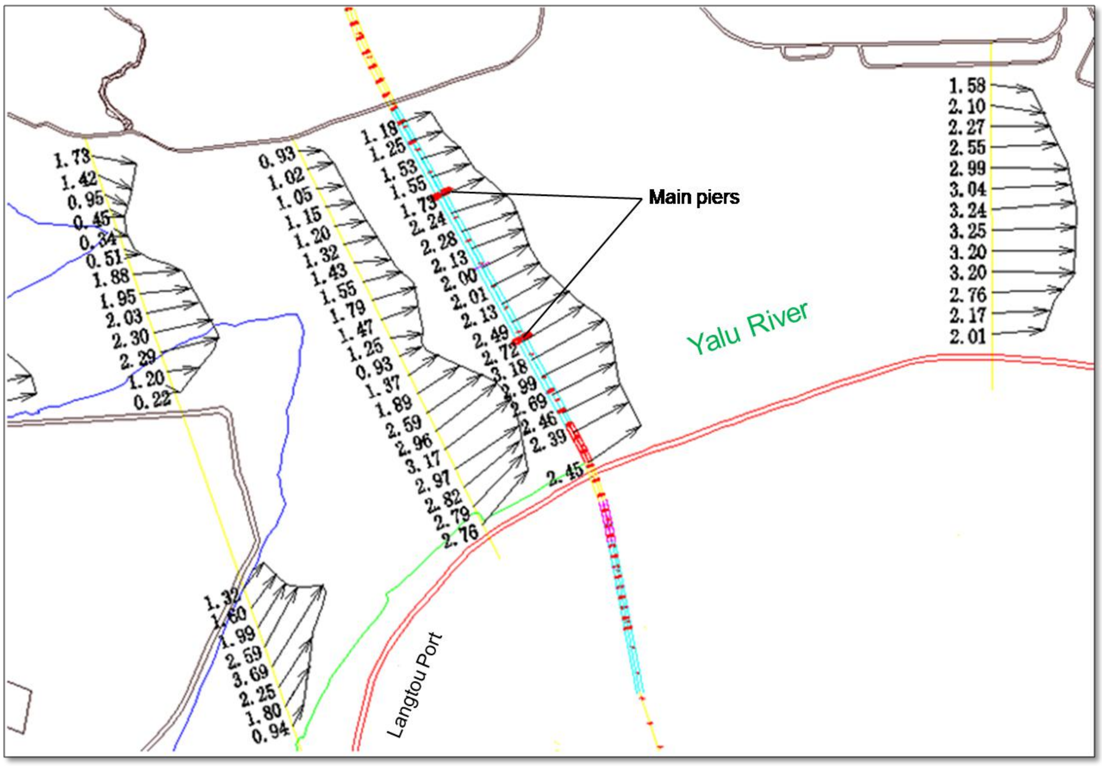



Figure 9 - The 10-year flood flow field

Source: Dalian Maritime University. (2011). *Ship Maneuvering Simulation Test Report of the Highway Bridge water Area on the Yalu River.*

(4) Test plan

A total of 18 simulation tests were completed according to the test plan listed in Table 9. During the test, the ship position, course, speed, and other motion parameters were recorded, and a large number of data about ship maneuvering and ship movement were obtained, which provided an objective basis for quantitative analysis.

Table 9 - State of the test vessel and external conditions

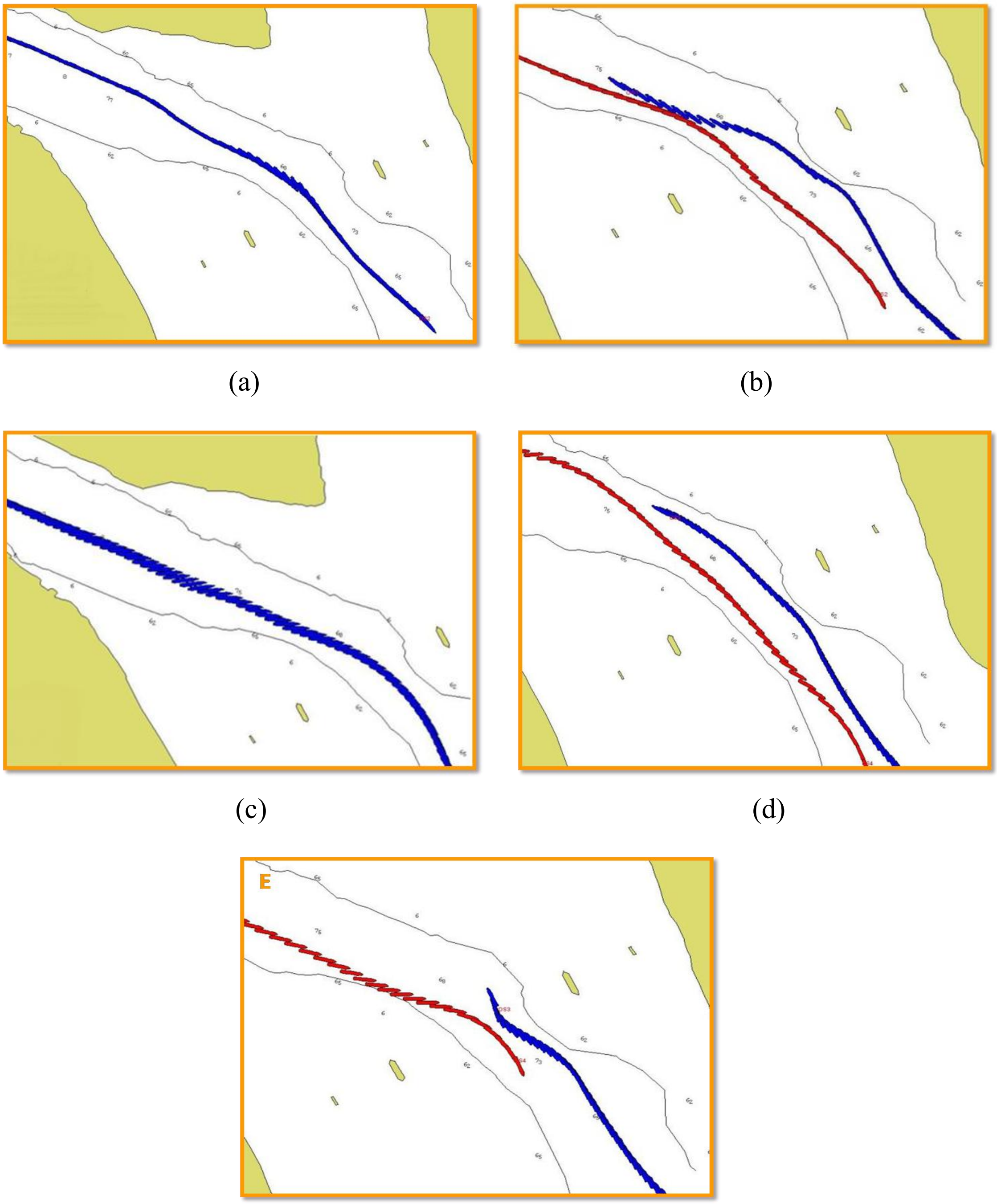
| Serial | Ship motion | Gross | Load | Wind | Flow field |
|---|---|---|---|---|---|

| number | | tonnage | state | direction and force | |
|---|---|---|---|---|---|
| **1** | Go upstream (flood tide) | 3000 | Full load | N-6 | Flow field 1 |
| | Go downstream (flood tide) | 3000 | Full load | N-6 | Flow field 1 |
| **2** | Go downstream (ebb tide) | 3000 | Full load | S-5 | Flow field 1 |
| | Go upstream (ebb tide) | 3000 | Full load | S-5 | Flow field 1 |
| **3** | Go upstream | 3000 | Full load | NE-5 | Flow field 2 |
| | Go downstream | 3000 | Full load | NW-5 | Flow field 2 |
| **4** | Go upstream (flood tide) | 2000 | Full load | N-6 | Flow field 1 |
| | Go downstream (flood tide) | 2000 | Full load | N-6 | Flow field 1 |
| **5** | Go upstream | 2000 | Full load | S-6 | Flow field 1 |

| | | | | | |
|---|---|---|---|---|---|
| | (ebb tide) | | | | |
| | Go downstream (ebb tide) | 2000 | Full load | S-6 | Flow field 1 |
| **6** | Go upstream (flood tide) | 2000 | Full load | S-5 | Flow field 1 |
| | Go downstream (flood tide) | 2000 | Full load | S-5 | Flow field 1 |
| **7** | Go upstream (ebb tide) | 2000 | Full load | NE-6 | Flow field 1 |
| | Go downstream (ebb tide) | 2000 | Full load | NE-6 | Flow field 1 |
| **8** | Go upstream | 2000 | Full load | NE-5 | Flow field 2 |
| | Go downstream | 2000 | Full load | NE-5 | Flow field 2 |
| **9** | Go upstream | 2000 | Full load | NW-5 | Flow field 2 |
| | Go downstream | 2000 | Full load | NW-5 | Flow field 2 |

Source: Dalian Maritime University. (2011). *Ship Maneuvering Simulation Test Report of the Highway Bridge water Area on the Yalu River.*

(5) Simulation test results and conclusions




(a) (b) (c) (d) (e)

Figure 10 - Some successful and unsuccessful test examples in flat beach flow field and 10-year flood flow field (a-e).

Source: Dalian Maritime University. (2011). *Ship Maneuvering Simulation Test Report of the Highway*

*Bridge water Area on the Yalu River.*

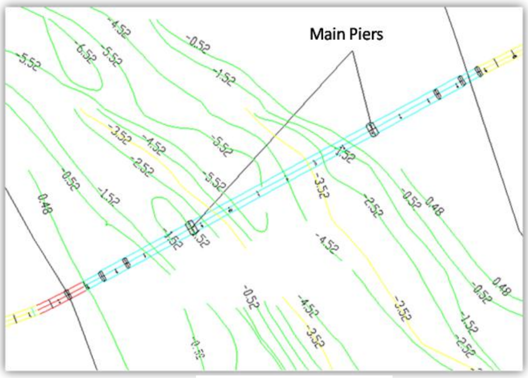
The test ships have completed all the simulation tests, and some test results are recorded in Figure 10. The results and data confirm the fact that the increase of runoff makes the ship difficult to operate. Through collective discussion of the professors and captains participating in the test, the following results and conclusions are drawn:

First, under the condition of flat beach flow, the success rate of one-way and two-way navigation is higher. Figure 10 (a) and (b) shows two examples of successful flat beach flow field tests, where A is the downstream test record chart of one-way navigation test and B is the record chart of two-way navigation test. The test results show that the channel can meet the safety of the one-way navigation of 2000-3000t ships and can basically meet the requirements of the two-way navigation of 2000t ships. When the ship is in two-way navigation, it is more difficult to operate the ship sailing downstream. When the ship meets, it is advisable for the ship sailing upstream to take evasive action as soon as possible to avoid the urgent situation of the two ships.

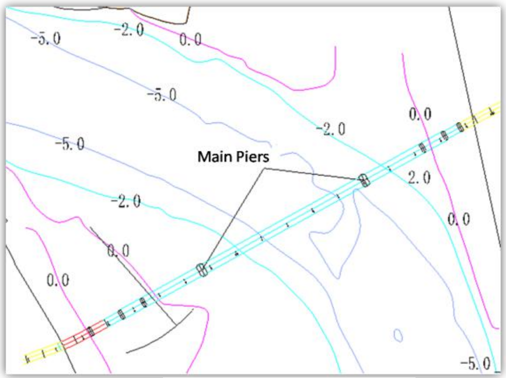
Second, with the increase of runoff, the success rate of both one-way and two-way navigation decreases significantly. Figure 10 (c) and (d) shows two examples of successful 10-year flood flow field tests, where C is the downstream test record chart of one-way navigation and D is the test record chart of two-way navigation. Figure 10 (e) records the failure of the ship's two-way navigation in the 10-year flood flow field test. During the test, the success rate of the simulation test for one-way navigation of 2000-3000t ships is relatively high. However, when the ship goes downstream, it is difficult to maneuver the ship because of the large difference in flow pressure, which reveals that the navigation is potentially risky. The probability of success and failure are close to each other in the simulation test of two-way navigation for 2000t ships, which indicates that there is a great risk of collision and grounding when ships meet in strong currents.

## 4.2 Analysis of channel depth and channel swing

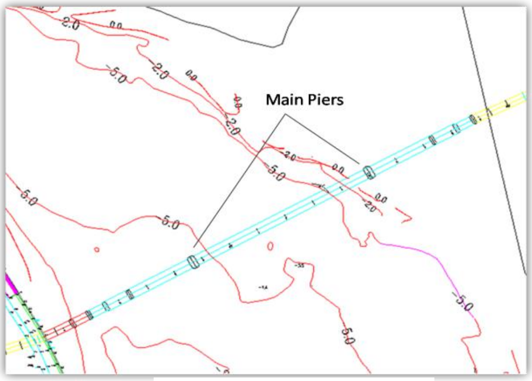
### 4.2.1 Analysis of channel depth



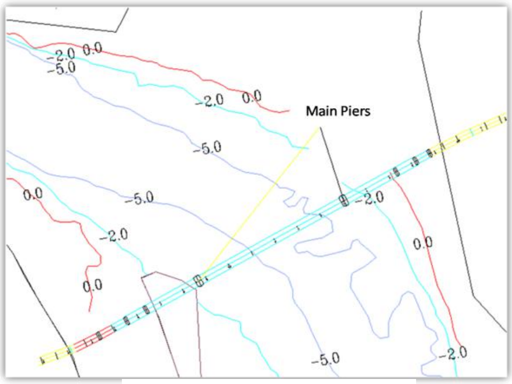

(a) In 2000




(b) In 2008




(c) In March 2010




(d) In October 2010

Figure 11 - Relationship between main piers and riverbed topographic maps (a-d)

Source: Dalian Maritime University. (2018). *Navigation safety Evaluation of improvement project of the water area of the Highway Bridge on the Yalu River (Exposure Draft).*

Recently, no water depth measurement has been carried out near the Bridge area. The water depth change of the channel and the swing of the navigation channel will be analyzed by referring to 4 river bed topography surveys in 2000, 2008, March 2010, and October 2010. Figure 11 shows the relationship between the main piers of the Bridge and the riverbed topographic map in 4 measurements.

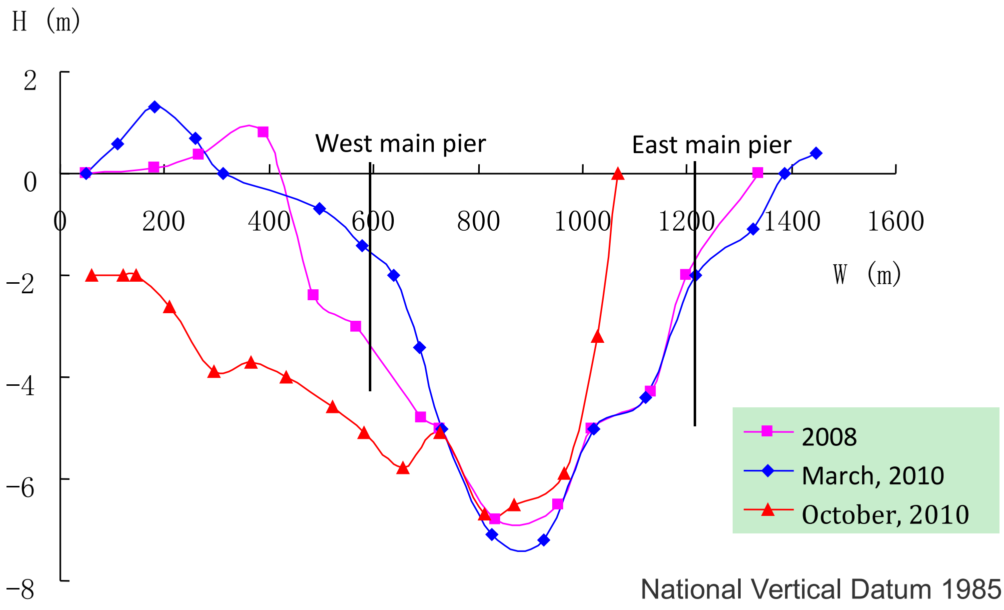



Figure 12 - Cross-section diagram of main span and riverbed topography

Source: Dalian Maritime University. (2018). *Navigation safety Evaluation of improvement project of the water area of the Highway Bridge on the Yalu River (Exposure Draft).*

In a normal year, the channel in the Bridge area basically follows the characteristics of curved flow and riverbed scouring and silting, namely, concave bank scouring and convex bank silting. During the 10 years from 2000 to March 2010, there was no major flood in the Yalu River. From the relationships between main piers and riverbed topographic maps, it can be seen that the west side (convex bank) of the river near the Bridge site formed a large range of shallow beaches by siltation. In contrast, the east side (concave bank) was relatively stable. However, after the flood in August 2010, the shallow shoal on the original west side (convex bank) was widely scoured. The topographic elevation of the west main pier was -2.4m in 2008 and -4.4m in October 2010. The topographic elevation of the east main pier was basically unchanged in 2008 and 2010, both of which were -4.2m. In October 2010, the topographic elevation was about 0.0m, as shown in Figure 12.

The main navigable span of the Bridge is bi-directional navigable, with a clear width of 398m. By analyzing the measured data of different years in Figure 12, the width of the waterway with a water depth greater than -4.0m basically meets the navigable clearance breadth. According to the requirements of "Specification for General Plan of Port", the navigable depth of 2000t ships is 5.6m, and the designed depth of the channel is 6.6m. Therefore, based on the water depth of -4.0m, the safe navigable tide level of ships is 2.0m near the Bridge. That is to say, although, in the simulation test, the main navigable span can allow the two-way navigation of 2000t ships under the condition of flat beach flow. However, in recent years, a large amount of sediment from the open sea and inland rivers has accumulated in the waterway, and the phenomenon of siltation in the waterway is very serious. The channel water depth has changed. Within the design width of the two-way navigation of 2000t ships, the natural depth of the channel does not meet the navigation requirements, so ships need to operate by the tide.

### 4.2.2 Analysis of channel swing

The main channel and shoal in the Bridge area are unstable. There is a great difference in riverbed evolution between the normal period and the extreme flood period. It can be said that the channel near the Bridge swings every year. According to the statistics of the waterway management department, from 2000 to 2009, the swing of the main waterway is shown in the Figure13.

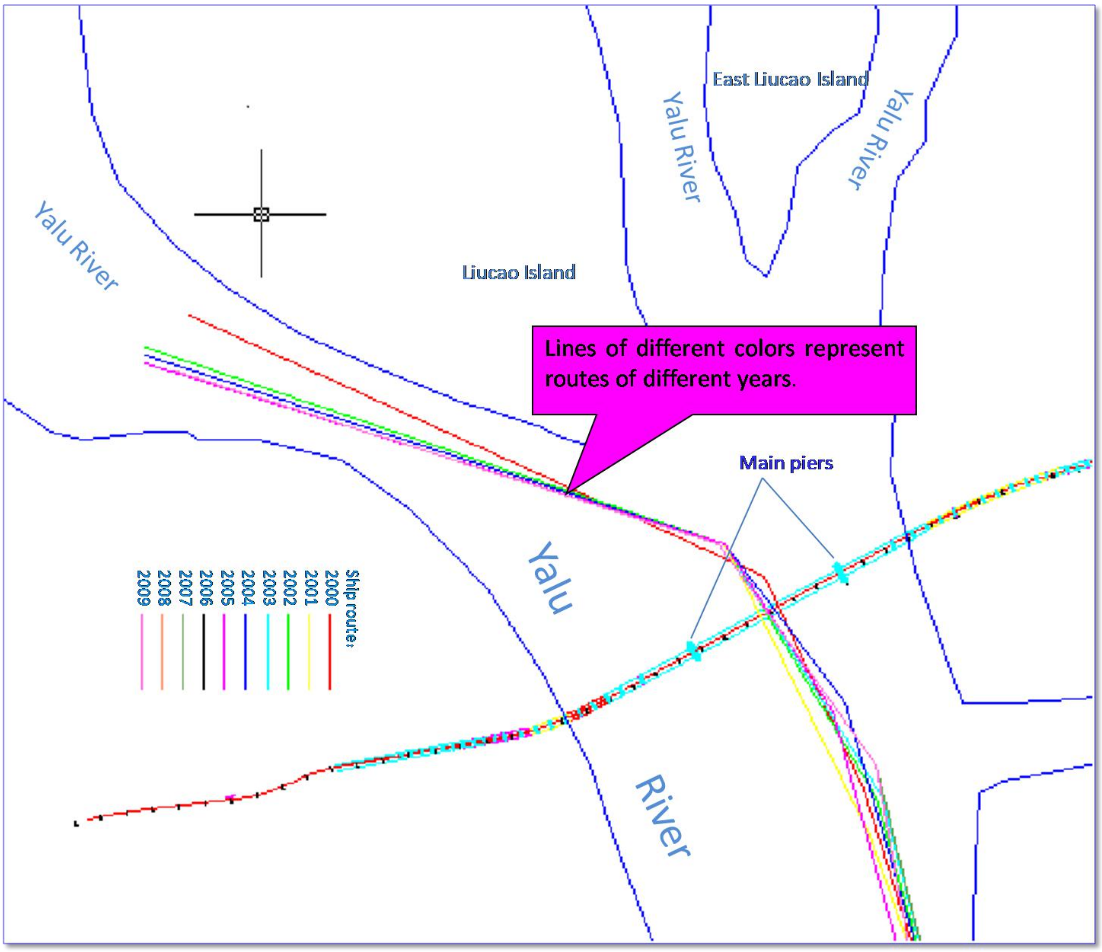



Figure 13 - Swing of the channel from 2000 to 2009

Source: Dalian Maritime University. (2018). *Navigation safety Evaluation of improvement project of the water area of the Highway Bridge on the Yalu River (Exposure Draft).*

The swing of the channel will bring many threats to navigation safety: (1) Excessive swing amplitude of the navigation channel will result in changes in navigable clearance breadth. The design clearance breadth of 398m was set considering the maximum swing of 146m of the channel during the non-flood period (2000-2009), which met the navigation requirements. When the channel swings more than 146m, the clearance breadth is insufficient, and the navigation of ships may pose a threat to the safety of the Bridge. (2) The swing of the channel will cause the change of flow velocity and flow direction in the deep-water channel, which increases the difficulty of ship maneuvering. (3) Channel swing will also cause deep troughs to move near the main pier, increasing the risk of collision. The designed main channel is located between the two main piers. There is shallow water near the main piers. The ship will not collide with the pier during normal navigation. However, if the channel changes, when the deep-water trough is located near one of the main pier, the distance between the ship and the main pier are very close. The ships and the Bridge are peculiarly prone to collisions.

### 4.3 Crew competence analysis

The human element is an essential subsystem of the risk factor evaluation system. On June 23, 1997, the MSC and the MEPC of the IMO issued the unified terminology of the human element, which highlighted the defects in the physiological, psychological and behavioral abilities of sailors from both subjective and objective perspectives (Xiao, 2019; Liu et al., 2020). The IMO has also emphasized the vital role of the human element in Resolution A. 947(23) and other documents, pointing out that the human element is a complex and multi-dimensional issue affecting marine safety, security, and marine environmental protection. It is very necessary to increase the input of human element in maritime safety and other issues (IMO, 2003; IMO, $2006_a$; IMO, $2006_b$), which shows the importance of the human element. There are many aspects involving the human element. This paper mainly discusses the crew's competence, which is mainly reflected in the crew's practical operational ability, emergency handling in response to urgent situations, familiarity with navigational conditions, etc.

According to the actual situation of the Highway Bridge water area on the Yalu River, the crew's competence plays a crucial role in the following aspects:

(1) As shown in Figure 13, the Bridge site is quite close to the tidal flat at the end of Liucao Island. The distance of the straight channel under the Bridge is short, and both the upstream and downstream vessels need to turn at this position. When the downstream ship turns into a straight channel, it must not only ensure its navigation in the channel, but also avoid the upstream ship. It is a test of the crew's maneuvering ability.

(2) The velocity of the tidal current in the Bridge area is relatively high. Although ships are sailing upstream or downstream, there are turns in the navigation channel near the Bridge. In the course of steering, the tidal current has great influence on the navigation safety of ships, which requires the high competence of the crew.

(3) Due to the swing of the channel of the Yalu River, the water depth of the channel changes unstably. During two-way navigation, especially in the dry season, because of the fear of grounding or collision with the pier, the ships hope to sail in the deep trough, resulting in a smaller encounter distance. A little improper maneuvering during the encounter of ships may lead to a collision.

The above 3 aspects all put forward high demands on the crew's competence. Once the crew takes wrong collision avoidance action when ships encounter or fail to change course at the channel’s turn and make the ship close to the Bridge, there may be an urgent situation, and even collision, grounding, and other accidents.

From the experience of on-site supervision, it can be seen that in addition to the qualification certificates of crew members, the service years on local ships and the number of voyages in the Highway Bridge water area are 2 important indicators for the competent authorities to evaluate the crew's competency. International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (2010) (STCW) provides a generally accepted minimum standard for the training, certification and watchkeeping of crew members. The Annex to the STCW Convention stipulates that one of the mandatory requirements for the certification of officers in charge of a navigational watch for ships of 500 Gross Tonnage or more is that they must have no less than 12 months of approved seagoing service. After seeking the approval of most experts, a crew with 5 years of working experience on a local ship can be considered to have rich experience in handling ships in the waters of the Yalu River. For the Highway Bridge water area on the Yalu River, most experts believe that the navigational experience of crossing the Bridge at least 10 times can be identified as having a high degree of water familiarity and good seamanship.

Of course, it is undeniable that psychological factors such as crew's sense of responsibility, caution, and safety consciousness have an impact on ship navigation safety. If the crew has no sailing experience in the Highway Bridge water area on the Yalu River, they will generally make full preparations out of a sense of responsibility, be familiar with the chart of the area in advance, and be careful in driving or require a pilot. They may get safe sailing results. On the contrary, the crew with rich sailing experience in these waters may take their minds lightly, leading to dangerous sailing results. However, psychological factors are applicable in any water area, not remarkable in the Highway Bridge water area on the Yalu River. So they are not considered in this study.

### 4.4 Maritime management analysis

#### 4.4.1 Introduction of Langtou Marine Department

Langtou Marine Department, as an agency of Dandong MSA, is the competent maritime authority in charge of the Highway Bridge water area on the Yalu River. There are 8 maritime officers, 2 maritime patrol vehicles, 2 maritime patrol ships, 1 CCTV terminal with 15 cameras distributed at 11 surveillance points.

The jurisdiction of Langtou Marine Department has a coastline of about 66 kilometers. There are more than 60 wharves in the area, such as tourism wharf, official wharf, border trade wharf, etc.; 3 ports under its jurisdiction, including one national first-class open port, namely Langtou Port, and two national second-class ports, namely Danzhi Port and Dataizi Port; 11 shipping companies; more than 300 boats; and more than 1000 crew members.

### 4.4.2 Problems in maritime management

(1) The number of maritime officers is insufficient.

The supervision task of Langtou Marine Department is characterized by a sizeable geographical span, rich business types, and various types of vessels. The shoreline is 66 kilometers long. There are more than 60 docks and more than 300 ships of all kinds within the jurisdiction. The work is a formidable one. In 2020, Langtou Marine Department conducted FSC on 33 ships, conducted the on-site inspection on 280 ships, disassembled 14 ships, and patrolled on the river for 4,734 nautical miles for a total of 376 hours. The above is only part of the work data, which shows the considerable workload. However, limited by the establishment of the administrative department, the whole department is only equipped with 8 maritime officers. Therefore, in the case of limited human resources, it cannot guarantee that all the supervision work is treated equally but can only guarantee that the highest priority work is completed first. Under such circumstances, it is difficult to guarantee the quality of supervision on the navigation safety of the Bridge area.

(2) There are drawbacks to traditional maritime supervision methods.

At present, the patrol supervision mode applied to the jurisdiction, including the Bridge area, is "AIS + VHF + CCTV + maritime patrol ship + maritime patrol vehicle", which has initially realized the transformation of maritime supervision from "sweat mode" to "intelligent mode" and improved the efficiency of on-site supervision. But its disadvantages are also apparent.

Langtou Marine Department is equipped with a CCTV terminal, and two cameras are set up upstream and downstream of the Highway Bridge. First of all, the functions of AIS and VHF are limited. They are a kind of assisting means for patrol but cannot be relied on completely. Moreover, some ships do not install AIS equipment. Secondly, as for CCTV, Langtou Marine Department is equipped with one CCTV terminal, and two cameras are set up upstream and downstream of the Highway Bridge. However, due to the harsh outdoor environment, the camera often malfunctions and cannot be used normally. Thirdly, from the point of view of maritime patrol ships, there are two patrol ships in the jurisdiction, one of which is 28 meters long and has a displacement of 140t, the other is 30 meters long and has a displacement of 121t. During each voyage of patrol, it is necessary to take into account several patrol tasks such as traffic order maintenance, ship inspection, ship operation activities, on-site inspection, and so on. As a result, the patrol can only focus on some aspects and ignore others in many cases. Meanwhile, due to the restriction of bad weather and sea conditions, as well as the high cost of fuel and maintenance of maritime patrol ships, the time and frequency of patrol are restricted, making it difficult to achieve very comprehensive supervision of the Bridge area. Last but not least, Langtou Marine department also has two maritime patrol vehicles, which can only be used as a supplement to the patrol on water due to the limited vision of patrol on land.

These problems have weakened the maritime supervision and service capacity to some extent. Especially in the face of bad weather and sea conditions, or dense ship traffic flow, or for the grounded and sunken ships that are difficult to obtain evidence, the traditional means of maritime supervision cannot meet the supervision needs of the waters of the Highway Bridge.

## 4.5 Analysis of China-DPRK Bilateral Maritime Cooperation

### 4.5.1 Background

In 1962, the China-DPRK Boundary Treaty was signed in Pyongyang, which established that the Yalu River is jointly owned by China and the DPRK and shall be jointly administered and used by the two countries. In 1981, China promulgated the Rules for Navigation of Vessels in the Frontier Rivers of China and the DPRK (1981), which apply to vessels sailing in the waters of the Yalu River. Since September 28, 2000, the Dandong section of the Yalu River has been under the jurisdiction of the Dandong MSA. As authorized by laws, Dandong MSA, on behalf of the state, performs administrative law enforcement functions such as traffic safety supervision and administration, pollution prevention from ships, and maritime security. In 2011, the maritime authorities of China and the DPRK signed the Agreement on Cooperation in Maritime Management of the Yalu River and established an annual exchange visits mechanism; meeting mechanism; joint patrol mechanism; search and rescue drill mechanism; accident investigation and handling mechanism; information linkage mechanism. A system of bilateral maritime management agreements between China and the DPRK has taken shape.

To make full use of the Frontier River to develop water transportation, the China-DPRK Frontier River Shipping Cooperation Committee was established by the Agreement between the Government of China and the Government of the DPRK on Frontier River Shipping Cooperation Committee (I960). At present, this Committee is in charge of shipping cooperation between the two sides, including maritime affairs. Since 1961, regular meetings have been held annually alternately in the two countries to discuss matters related to the joint regulation and full utilization of the waterway of the Yalu River.

### 4.5.2 Problems

(1) The personnel composition of the China-DPRK Frontier River Shipping Cooperation Committee is not scientific

The China-DPRK Frontier River Shipping Cooperation Committee serves as a platform for communication on shipping-related issues between the two sides as well as a responsible organization. All work and activities between the maritime authorities of the two sides need to be approved by the Committee. The Committee is composed of representatives from the two countries. The Chinese representative is headed by the personnel from the Water Transportation Bureau of the Ministry of Transport, together with relevant officials from the Transport Departments of Liaoning Province and Jilin Province. Since the first session in 1961, most of the meetings have been attended by 3 delegates, with an additional 2 to 6 delegates sitting on the meetings. The MSA official can attend only as a nonvoting delegate. Since the reform of the transportation system, MSA has been responsible for the supervision and management of traffic safety and the prevention of pollution from ships. Still, maritime officials have not been allowed to attend the meetings as delegates of the Committee. It is obviously not conducive to MSA to play its own professional advantages, not benefit to the maintenance of navigation safety of the Yalu River waters.

(2) Boundary river maritime management regulations have lagged behind

The Highway Bridge water area on the Yalu River is applicable to the Rules for Navigation of Vessels in the Frontier Rivers of China and the DPRK (1981). The Rules were approved by the 21st session of the China-DPRK Frontier River Shipping Cooperation Committee and have been implemented since September 1, 1982. All vessels sailing on the Yalu River should strictly abide by the Rules. However, since the rule came into effect nearly 40 years ago, the navigable environment of the Yalu River, navigable ships, and other factors have undergone tremendous changes, and the Rules are no longer applicable in many aspects.  For example, there are only six definitions of ships listed in Article 3 of the Rules, many of which are not mentioned. It is stipulated that there are altogether 11 kinds of navigation marks, including 6 signs to guide the navigation direction, 3 signs to indicate dangerous substances in the fairway, and 2 signs to signal. However, this classification method is fewer than the 18 kinds in GB5863-93 "Navigation aids for Inland Rivers" implemented in China on September 1, 1994, and the names of some navigation marks are not uniform (Gao, 2008). Many aspects of the content are not satisfied with the present situation of navigation. The rules need to be revised.

(3) The China-DPRK bilateral maritime cooperation mechanism needs to be further improved and implemented

Although China and the DPRK have established cooperation mechanisms in many aspects, in recent years, due to the impact of the Ebola virus and COVID-19 virus, the two sides have suspended the implementation of some cooperation mechanisms, which has hindered bilateral cooperation to a certain extent and adversely affected the shipping safety on the Yalu River. Moreover, the two countries have not yet established a unified navigation management mechanism and navigation rules. How to manage and coordinate the navigation vessels between the two countries is one of the critical issues to ensure the navigation safety of the Bridge area and vessels. When vessels from China and the DPRK meet under the Bridge, it is very challenging to manage and coordinate the navigation of vessels from the other country.

# Chapter V Suggestions and recommendations

Based on the analysis results of the main risk factors, this chapter puts forward the following targeted countermeasures and suggestions from the perspective of MSA to strengthen the navigation safety in the Bridge area.

## 5.1 Implementing integrated means to improve crew skills and experience

To the local crew, it is suggested that the local shipping company establish the relevant training mechanism. Captains with rich navigation experience in these waters and veteran professors from maritime colleges may be invited to preach the Rules for Navigation of Vessels in the Frontier Rivers of China and the DPRK (1981), to introduce the basic information of the channels, wharves, berths, and Navigation aids of the Yalu River, so that the crew can be familiar with the situation of the area and relevant navigation regulation. Making the best of the geographical advantages, carry out on-site operation training, especially on the ship turning in the Bridge site and ship encountering under the Bridge. Veteran captains will be invited to give practical demonstrations and impart operational experience to improve the crew's safe operation skills and the ability to deal with emergencies. Maritime officials should carry out warning education for the crew and report typical cases on a regular basis so that seafarers can learn lessons from accident.

As for the captain and crew of the ships making their first visit to the port, as well as the crew of non-local ships, they are not familiar with the Bridge area. They are recommended to apply for pilotage into and out of the waters of the Bridge area. If they don't apply for pilotage, it is recommended that the shipping company arrange skilled masters or crew members to steer the ship. Before sailing into the waters of the Yalu River, the captains should be familiar with the characteristics of the waters, including meteorological and hydrological conditions as well as navigable environment characteristics, especially the direction and flow of the waterway. In addition, they should carefully consult navigation information and make scientific navigation plans, which should include the rapid response to various emergencies. When necessary, maritime officers may carry out on-site patrol inspections and check the crew's practical operation ability.

### 5.2 Monitoring and improving the waterway conditions

#### 5.2.1 Establishing tidal observation stations (system)

It is suggested to set up a tidal observation station (system) near the Bridge to measure the water depth and velocity of the channel in the Bridge area. The observed velocity can be used as the basis for permission to navigate in the bridge area. During the summer flood discharge period, when the water level exceeds the designed navigable maximum water level or the flow rate is too large, the navigation of vessels shall be suspended temporarily. According to the observed tidal level data and the change of the width of the deep trough, the time of one-way or two-way navigation can be determined. In the winter dry season, when the water level does not meet the design requirements for two-way navigation, only one-way navigation is allowed to ensure the safety of ships and the Bridge. In addition, when the natural water depth near the Bridge area is not sufficient for the safe navigation of the designed ship type, the ship navigation needs to ride the tide. The establishment of the tidal observation station is helpful to improve the tide riding rate.

#### 5.2.2 Carrying out dredging projects for channels

To maintain the excellent state of the channel in the Bridge area, it is suggested to remove and dredge the silt deposited in the channel regularly. Before and after channel dredging, three other aspects of work should also be noted. First of all, an early warning mechanism for channel dredging should be established to closely monitor channel water depth and other parameters to determine whether the channel's function is normal and whether there is a blockage. As the so-called early detection and early prevention, an effective early warning mechanism can improve the safety, timeliness, and efficiency of dredging projects (Qi, 2021). Secondly, after the channel dredging is completed, the channel water depth and back silting should be monitored regularly during the trial operation period. On the basis of obtaining the dynamic conditions of water and sediment in the channel and the dynamic changes of riverbed scouring and silting, the characteristics and objective laws of channel maintenance should be studied, and the management mode should be explored. After accumulating a lot of practical experience, it is necessary to formulate targeted maintenance plans to maintain the channel smooth and stable (Zhao & Chu, 2021). Last but not least, after each dredging, confirm the change of the deep trough and move the Navigation aids in time to ensure the safety of the ships and the Bridge.

## 5.3 Strengthening maritime management capacity of Dandong MSA

### 5.3.1 Establishing the Yalu River Highway Bridge Marine Department

Considering the complex navigable environment of the Bridge area and the limited law enforcement resources of the existing maritime department, it is suggested to set up a new agency of Dandong MSA in the water area of the Highway Bridge. The agency can be called the Yalu River Highway Bridge Marine Department. At least two maritime officers shall be provided, and more officers can be allocated during the flood season and other critical periods. To facilitate communication and coordination with the ships and crew of the DPRK, at least one of the maritime officers should be able to speak Korean. The Yalu River Highway Bridge Marine Department shall also be equipped with necessary water traffic safety supervision equipment and facilities, such as maritime patrol boats, maritime patrol vehicles, telescopes, telephones, fax machines, VHF hand-held machines, basic office supplies, etc.

### 5.3.2 Purchase and use of Unmanned Aerial Vehicle (UAV)

UAV is an unmanned aircraft operated by radio remote control equipment and self-contained program control device. There is no cockpit on board, but it is equipped with an automatic pilot, program control device, and other equipment. The personnel of the remote control station of the ground, ship, or mother aircraft carries out tracking, positioning, remote control, telemetry, and digital transmission through radar and other equipment (Chen et al., 2019). As UAV technology continues to mature, it has been applied in many areas, including agriculture, communications, transportation, public safety, healthcare, and environmental protection (Alsamhi, 2021), providing replicable experiences.

Compared with the traditional supervision means by maritime patrol ships, UAV has the advantages of flexible take-off and landing, quick response, wide patrol area, strong real-time, simple operation, energy-saving, and environmental protection. Especially in terms of cost, compared with maritime patrol ships, which cost millions at a time, the operation and maintenance cost of UAV is much lower (Chen et al., 2019).

UAV will open a new chapter of intelligent patrol. UAV equipped with high-definition cameras can be used as mobile CCTV to patrol the navigation environment in the jurisdiction and transmit real-time field images such as the situation of ships, navigation order, and navigation aids to the electronic patrol room. UAV can also be used to carry high-power sirens and loudspeakers to correct the illegal behavior of ships in the Bridge area. If necessary, patrol vessels will be assigned to the scene. It has dramatically improved the accuracy and efficiency of maritime supervision. At present, the speed of the two maritime patrol vessels in the area is 10 knots, and the patrol speed of the UAV is generally above 30 knots (55km/h), which can reach the target area more quickly. In case of contingencies and accidents, UAV can be used to deliver life-saving facilities, food, and medicine, so that the area's emergency response capacity can be improved. Especially in the period of COVID-19 virus prevention and control, through the visual function of UAV to verify crew qualification, maritime officers do not need to board the ship for inspection. Through zero contact, the actual crew number and qualification on the ship can be quickly screened, which effectively reduces the possibility of COVID-19 virus infection and also greatly reduces law enforcement costs. When necessary, UAV can be stuffed with infrared cameras, synthetic caliber radar, laser rangefinder, etc., to play more roles for MSA. With the development of 5G technology, the combination of UAV and 5G can also be actively explored to give full play to the superiority of UAV. Combined with traditional patrol methods, the introduction and use of UAV will create an all-around integrated patrol mode covering water, land, and air.

It is suggested that at the initial stage, the competent maritime authority could purchase 2 UAVs and assign 2-4 maritime officers to take part in the exam for flying training and qualifications. Meanwhile, the competent maritime authority should promptly formulate internal working procedures and systems on UAV.

### 5.3.3 Setting up the broadcast system

Some vessels in this area are equipped with inadequate communication equipment, making it difficult to send and receive information well. Faced with this situation, it is suggested that broadcast systems should be installed at appropriate locations on both upstream and downstream of the Bridge to broadcast meteorological and sea conditions, navigation channel information, traffic density information, navigation announcements, and alerts, etc. in Chinese and Korean. The Passing ships can be well informed.

### 5.3.4 Formulating regulations for the administration of traffic safety in the Bridge area

Under the guidance of Measures of the People's Republic of China for the Administration of Water Traffic Safety in Bridge Areas and combination with the actual situation of the jurisdiction, the MSA should formulate the regulations for the administration of traffic safety in the Highway Bridge water area on the Yalu River, systematically and comprehensively expounding the requirements that ships should abide by when sailing in the Bridge area, such as the visibility limits, two-navigation restrictions, etc., to provide a clear basis for the maritime authorities to supervise and manage the water traffic safety in the Bridge area.

## 5.4 Deepening and improving China-DPRK maritime bilateral cooperation mechanism

(1) Rules for Navigation of Vessels in the Frontier Rivers of China and the DPRK (1981) are of great significance and function. Still, the Rules are not perfect for the current navigable environment and vessels. It is suggested to organize experts from maritime departments, transportation departments, and navigation colleges to revise the Rules as soon as possible so that they will continue to play an important role in the peaceful use of the border river waters between China and the DPRK and in ensuring traffic safety on the Yalu River.

(2) It is suggested to reform the China-DPRK Frontier River Shipping Cooperation Committee and apply for adding experts from MSA as representatives of the Committee to participate in the meeting so as to enhance the discourse power of the maritime department. MSA is the functional department for the supervision and management of water traffic safety. It has mastered the most comprehensive and

objective on-site supervision situation, including excellent practices and experience, as well as the difficulties and problems existing in the management. The joining of maritime members will be more conducive to the scientific and accurate decision-making of the Committee.

(3) It is proposed that China and the DPRK should further establish and improve the bilateral maritime cooperation mechanism between the two sides. The two sides should increase the areas of collaboration, earnestly implement the cooperation mechanism, hold regular meetings and exchange visits, maintain positive response to cooperation, etc.

## Chapter VI Conclusions

Based on in-depth study of domestic and foreign literature, this paper studies the navigation safety of the Highway Bridge water area on the Yalu River by using the FSA framework and draws the following conclusions:

(1) This paper identifies and determines the navigation risk factors of the Highway Bridge water area on the Yalu River. Utilizing literature study and questionnaire survey, a total of 16 risk factors are identified preliminarily, including crew competence, ship size, type of ship, ship age, load capacity, ice, tidal current and runoff, wind, visibility, wave, traffic density, channel location, channel depth, the swing of the channel, navigation aids and maritime management. On this basis, with the method of literature study and expert interview, 5 key risk factors that can mostly affect the navigation safety of the Highway Bridge water area on the Yalu River are identified, respectively are crew competence, tidal current and runoff, channel depth, the swing of the channel, and maritime management (including bilateral China-DPRK maritime management).

(2) This paper has completed qualitative and quantitative analysis and evaluation of

5 key risk factors through literature study, simulation test, and empirical derivation. This paper finds out the weak points or potential dangers of the key risk factors to navigation safety.

(3) Using the method of literature study and empirical derivation, this paper systematically puts forward the risk management countermeasures and maritime management suggestions to improve the navigation safety of the Highway Bridge water area on the Yalu River. The countermeasures and recommendations include implementing integrated means to improve crew skills and experience; monitoring and improving the waterway conditions; strengthening maritime management capacity of Dandong MSA; deepening and improving China-DPRK maritime bilateral cooperation mechanism and so on.

Different from most academic literature on navigation safety of the Bridge area, this paper not only carries out navigation safety evaluation but also puts forward safety management suggestions from the perspective of maritime authorities. Its fundamental purpose is to improve the water traffic safety management capacity of maritime authorities. The study is of great theoretical and practical significance.

Due to the limitation of personal knowledge, professional ability, and research time, the research process is not perfect, and there are still many deficiencies. In future research, further exploration will be made in the following aspects:

(1) First of all, it is impossible to take into account all the risk factors affecting navigation safety in the Bridge area. This paper only analyzes and studies a few key risk factors and ignores the general risk factors. For example, the analysis and study of human factors are not comprehensive enough. Especially the psychological factors such as the crew's sense of responsibility and caution have an impact on the ship's navigation safety. It is suggested to do further research.

(2) The paper lacks the collection of accident data samples. Due to the short construction time of the Bridge, there are little data in this aspect, and it is not of analytical value. It is suggested that in future supervision work, the collection of data samples should be strengthened.

(3) The identification and determination of risk factors are mainly obtained through questionnaire survey and expert interview, and the subjective component is relatively large. It is suggested that it should be further adjusted and perfected in future research.

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## Appendix 1

### Navigation safety status evaluation and risk factor investigation of the Highway Bridge water area on the Yalu River

Dear experts:

Hello! Thank you for taking the time to participate in this questionnaire survey.

Please fill in according to your cognition and experience.

Thank you very much!

1. Your overall evaluation of the navigation safety status of the Highway Bridge water area on the Yalu River;

______________________________________________________________

______________________________________________________________

2. In your opinion, the achievement or good experience of navigation safety management in the bridge area;

______________________________________________________________

______________________________________________________________

3. From the perspective of the crew, ship, environment, and management, what do you think are the prominent risk factors affecting the navigation safety of the bridge area (the factors are as detailed as possible);

______________________________________________________________

______________________________________________________________

4. Your advice and suggestions on the navigation risk control of the bridge area.

______________________________________________________________

______________________________________________________________

Your Occupation______________________

Your Position/Title_____________________