8-25-2013

Risk assessment of navigation environment in bridge waters

Haoqiang Rui

WORLD MARITIME UNIVERSITY

Dalian, China

RISK ASSESSMENT OF NAVIGATION ENVIRONMENT IN BRIDGE WATERS

By

RUI HAOQIANG

China

A research paper submitted to the World Maritime University in partial
Fulfillment of the requirements for the award of the degree of

MASTER OF SCIENCE

(MARITIME SAFETY AND ENVIRONMENTAL MANAGEMENT)

2013

DECLARATION

I certify that all the materials in this research paper that are not my own work have been identified, and that no materials are 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: 芮浩强

Date: 19 July 2013

Supervised by: Li Tieshan

Professor

Dalian Maritime University

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude first and foremost to the World Maritime University, Dalian Maritime University, International Maritime Organization and Quanzhou MSA for this priceless opportunity to study at MSEM program, which has great impacts on my life and career.

I would like to thank my supervisor professor Li Tieshan for his precious and patient guidance and supervision, who has helped me to overcome a lot of difficulties in writing and completing this dissertation.

My sincere thanks also go to all staff of Fengze Branch of Quanzhou MSA for their continuous support and encouragement.

I am also grateful to all the members of the MSEM 2013 for their invaluable help and support in learning the courses.

Lastly but most important and heartfelt gratitude goes to my family, especially, my wife Wang Suzhen and my son Rui Junzhe , who inspired me during my study at DMU.

ABSTRACT

TITLE: Risk Assessment of Navigation Environment in Bridge Waters

DEGREE: MSC

This thesis aims to research the risk assessment of navigation environment in bridge waters, which is based on the FSA methodology. First of all, four risk assessment methods are explained and identified in this study. Secondly, according to the process of FSA methodology, risk factors in navigation environment systems in bridge waters are identified and analyzed. And then based on the fuzzy synthesis evaluation method and AHP method, the risk assessment model of navigation environment in bridge waters is established to study the navigation environment of Quanzhou Bay Cross-Sea Bridge.

It is found out that FSA methodology is feasible to be used to in risk assessment of navigation environment of bridge waters, in the process of risk assessment, fuzzy synthesis model can be established to evaluate the risk level and the major risk sources can be further analyzed with mathematical model, for example, queuing model and PRA method. By studying the case, the risk level of Quanzhou Bay Cross-Sea Bridge is between low risk and moderate risk; the vessel traffic capacity of bridge fairway can meet the demand of navigation. However, there is a hidden danger of vessel-bridge collision. Therefore, countermeasures and suggestions should be made to evade and reduce risks.

KEYWORDS: Navigation environment; Risk assessment; Bridge waters; FSA.

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LIST OF ABBREVIATION

AIS	Automatic Identification System
APH	Analytic Hierarchy Process
CCS	China Classification Society
CCTV	Closed-Circuit Television
DHBC Code	General Code for the Design of Highway Bridges and Culverts
DMU	Dalian Maritime University
ETA	Event Tree Analysis
FMEA	Failure Mode and Effects Analysis
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
IACS	International Association of Classification Societies
IMO	International Maritime Organization
MMEM	Man –Machine –Environment –Management

MOC	Ministry of Communications of the People's Republic of China
MSA	Maritime Safety Administration
MSC	Maritime Safety Committee
PA	Probability of Vessel Aberrancy
PRA	Probabilistic Risk Assessment
TIO	Third Institute of Oceanography
VTS	Vessel Traffic System
WUT	Wuhan University of Technology

Risk Assessment of Navigation Environment in Bridge Waters

Chapter 1 Introduction

1.1 Background

With the rapid development of international economy and transportation, a large number of cross-river, cross-sea bridges have been built and put into use or are being planned, designed and constructed. There is no doubt that the construction of these bridges has offered convenience to land transport, promoting the development of regional economy, but they have caused varying degrees of negative effects to ship navigation and transportation. As the risk of ship-bridge collision is on an increase, a series of hot issues concerning ships safety navigation of in bridge waters are widely noticed. Only in recent years, a significant number of ship-bridge collision accidents have taken place in other countries in the world. In China, according to the records of maritime administration, more than 70 ship-bridge collision accidents have occurred to Wuhan Yangtze River Bridge since it was built, and of the accidents caused direct economic losses of more than one million RMB. It is said that about 30 accidents and incidents have taken place on the Nanjing Yangtze River Bridge waters since it was constructed. With the advancement of modern traffic, more or more bridges are being built or to be built, the ship size will be much larger than now and before. What is more, with the development of water transport, the traffic density in waterway is much heavier than before, which results in an increase of ship-bridge collision risk. Besides, the consequences of accidents may be more serious.

Bridge services as transport infrastructure for a country, which plays an important and irreplaceable role in the development of economy and society. However, once accidents occurred to the bridge, the consequences would be disastrous. More and more bridges are intensely built in the same waters, how to resolve the impressing issues of safety navigation in the bridge waters properly is particularly important. Therefore, risk assessment of navigation environment in bridge waters is one of the scientific and reasonable countermeasures. By risk assessment, we can better understand and grasp the risk factors as well as risk degree of navigation environment in bridge waters, in particular, the situation of major risk sources will be known well. And risk assessment is beneficial for maritime administrations to improve navigation environment in bridge waters and navigation management, and it can provide scientific basis for decision-making, which has practical values and far-reaching significance.

1.2 The Purpose and Meanings of This Research

Based on the fact that there are practical meanings to improve safety navigation in bridge waters, the author gets down to doing this research paper. In this thesis, the navigation environment system in bridge waters is the research objective. By studying the various risk factors in this system, risk assessment model of navigation environment in bridge waters will be established. Besides, Quanzhou Bay Cross-sea Bridge is taken as a studying case, and its navigation environment will be assessed by making use of the risk assessment model. Furthermore, risk probability of the major risk source will be analyzed. In the process of research, Formal Safety Assessment (FSA) method is applied to the risk assessment of navigation environment in bridge waters, which attempts to strengthen traffic safety supervision and management in bridge waters.

1.3 Research Methods and Its Main Contents

1.3.1 The main risk assessment methods applied in safety assessment of water traffic are compared and analyzed, and then FSA methodology and its ideas will be introduced, finally the feasibility and practicability of FSA methodology in the assessment of navigation environment in bridge waters are demonstrated.

1.3.2 FSA methodology is utilized in this research paper. In risk identification step, through the analysis and survey of literature, borrowing the ideas of system safety assessment theory and the merits of assessment methods in water traffic safety, the risk factors of navigation environment in bridge waters will be identified. Based on the results of the previous studies and expert investigation, the evaluation index system is established. At the risk assessment stage, fuzzy assessment methodology is applied, and the fuzzy synthesis evaluation model for navigation environment in bridge waters is established. Furthermore, Probabilistic Risk Assessment (PRA) method is used in the quantitative analysis of the major risk sources. In the decision-making and recommendations step, in accordance with Man–Machine–Environment–Management (MMEM) system theory, countermeasures and suggestions are put forward to the main parties related to the safety management and operation of navigation environment in bridge waters.

1.3.3 Take the Quanzhou Bay Cross-sea Bridge for example, the established fuzzy comprehensive evaluation model is utilized to evaluate the risk level of navigation environment and get the evaluation score. The risk assessment results will be given and depicted objectively. Then the queuing model is used to analyze the vessel traffic capability of the bridge waters. Finally, the PRA method is used to calculate the probability of ship-bridge collision. Moreover, ship collision force and hazards of ship-bridge collision for the ship under command in bridge waters are analyzed.

1.3.4 Through the case study, the existing common problems of traffic safety in bridge waters are pointed out, suggestions and solutions for improving traffic safety in bridge waters are proposed, thus providing advice to safety management work.

Chapter 2 Risk Assessment Method

2.1 Overview of Risk Assessment

Risk assessment, also known as safety assessment, the definition of which is to make use of the principles and methodologies of system engineering, make qualitative and quantitative analysis of the existing and latent risk factors in the systems to assess their probabilities of risk and their consequences in the system. Based on the analysis, the risk degree of system will be evaluated. And the corresponding measures for continual improvement will be put forward. The objective of risk assessment is to seek the lowest accident rates, minimum losses and optimize the efficiency of investment, and ultimately achieve the safety goal of system.

Risk assessment in marine traffic is a specific application of the risk assessment theory in marine domains. According to the definition of risk assessment theory, risk assessment in water traffic should include the following steps:

First, the hazards in the system should be identified and the unsafe factors in water traffic safety system should be analyzed qualitatively and quantitatively.

Second, the evaluation standards will be compared. And the probability and consequences of risk factors in system will be evaluated.

The third step, suggestions and countermeasures for improvements will be brought forward.

2.2 The Present Research Situation of Risk Assessment in Water Traffic in Domestic and International Marine Field

Risk assessment is an important issue for water traffic safety. Based on the goal of system safety, in accordance with the scientific procedures and methods, the probability of an accident and consequences of loss and damage will be analyzed and assessed. It will provide scientific basis to evaluate the safety system and to develop preventative measures.

2.2.1 Foreign Research on Water Traffic Safety

Water traffic safety, mainly referring to maritime safety, comes along with the water transport (Skjong & Soares, 2008, pp. 289-1291). A lot of research was done on water traffic safety in Western European, the research theory is systematic, extensive and in-depth, and great achievements have been made in water traffic safety research. Owing to the domestic needs of shipping development, Japan was engaged in the research in the 1960s or the 1970s, and a lot of achievements have been made in traffic safety field and the contents and methods of water traffic safety study are enriched to a great extent.

Initially, the foreign research derived from the analysis of cases of typical maritime accidents in water traffic and the lessons learned from them, because every major maritime disaster will bring concern to all walks of life, and their lessons are to be learned by the shipping industry and scholars to prevent the similar marine accidents from happening again (Zhang, S.K,&B, Y, &T, W.Y., 2003, pp.12-13). In the late 20th century, due to an increase in maritime accidents, based on statistical theory and principles, from the macro viewpoint, the Western European scholars began to study the numbers of traffic accidents in specific waters at specific period of time to determine the safety level of given waters, and then carry out maritime safety research. During this period, great progress has been made in the research from leading case analysis to macro statistics. Maritime safety, and all the changes in the process of implementation, has been accident-driven (Veiga, 2002, p.24). However, whether it is a case study of an accident or macro statistics of accident, both of them are carried out after the accident, which is very unfavorable for the high risk shipping industry. In the UK, Vldimierm.Trbojevic and Barryj.Carr proposed risk-based navigation safety management system in port. For vessel traffic safety, it is evaluated by safety analysis, and finally programs are launched to improve management (Zhao, 2005, PP. 77-78).

In 1989, the supertanker EXXON Valdez encountered serious average accident, which led to in-depth study on the analysis and management of risk. Subsequently, the PRA methods have been widely used in other areas of the world. PRA methods have been used in the risk analysis of ship safety. United Kingdom, after doing a large number of research work in the field of maritime safety, submitted the FSA concept to the IMO (International Maritime Organization) in 1993. And then it is introduced to the maritime field to promote maritime safety and pollution prevention. FSA is a risk assessment method relying on risk analysis and cost-effective assessment to improve the safety of life at sea, health, environment and property, which have the initiative, anticipatable, structured, standardized and systematic characteristics. FSA is considered as one of prime instruments for developing proactive policies. “Proactive means an early stage identification of factors that may adversely affect maritime safety and the immediate development of regulatory action to prevent undesirable events, as opposed to just an after-the-fact ad-hoc reactions to a single accident” (Psaraftis, 2002, p.5). Since the FSA method is adopted by IMO, the academic and industry world have focused on the research and development of the methodology, many countries and organizations have carried out intensive research, and it is also applied in the rule-making, ship design, survey, operation, management and other fields.(Fang,wang,&Datubo,2004,pp.1-5;Lee,Yeo, &Yang,2001,pp.651-667;Lois,etal,2004,pp.93-109;Wang&Foinikis,2001,pp.143-15).

In the 1960s or 1970s, a special maritime traffic research team was set up in Japan, and gradually the research results were developed into a discipline of modern maritime transportation, namely traffic engineering. In Japan, the maritime traffic engineering experts collected maritime traffic data through visual, radar, aircraft and other means. And the data will be analyzed, simulated and processed, and then the safety issues of marine traffic are studied to find solutions to improve maritime traffic safety.

In the field of water traffic safety research, great contributions have been made in Japan. The research did not only enrich the knowledge of systems theory, but also achieved fruitful results. The book *Marine Traffic Engineering* written by Fujii and his partners analyzed the relationship between maritime traffic elements and its safety system, and established systematical marine traffic engineering theory (Fujii, Y.1977, PP. 86-93).

2.2.2 Water Traffic Safety Research in China

The water traffic safety research started late in China, with the rapid growth of shipping industry, some progress has been made. Wu Zhaolin, participated in the field of maritime traffic safety research earlier in China, and made great contributions to the development of China's water traffic safety (Wu&Zhu, 2004). Chen Weijiong, combining the maritime safety systems with safety management disciplines, proposed the MMEM theory, and the typical model has four key elements such as seafarer, ship, environment and management (Chen, 1998). The large ship handling simulator, developed by the Institute of Nautical Science and Technology in DMU, has played a significant role in maritime safety domain, which makes use of computer simulation technology.

By analysis of domestic and international literature on water traffic safety, it is found that a number of scholars and experts are mainly concentrated on dynamic simulation of vessel traffic flow, the safety behavior of ship, maritime accident investigation and safety assessment of navigation waters (Furnes&Amdahl, 1980; Kokotos& Linardatos, 2011, pp.192-197; Merrick.et al, 2003, pp.119-132.). The ultimate goal of water traffic safety is to take appropriate measures to prevent and reduce maritime accidents. The premise of right decision-making is to make scientific and reasonable assessment of navigation environment. Therefore, in these research projects, the assessment of navigation waters is more widely researched (Debnath, & Chin, 2009, PP. 68-75).

2.3The Research Situation of Risk Assessment of Navigation Environment

The safety assessment of navigation environment is an important issue of water traffic safety. Because the degree of dangers hidden in navigation system, whether the risk level can be accepted and whether there is a need for increasing investment and improving management, all of these relied on safety assessment of waters navigation environment.

With regards to safety assessment of navigation environment, much work has been done by foreign scholars. Especially for the Japanese maritime traffic experts who have achieved essentially important results. For example, in the text of the ship handling characteristics and its impacts on the assessment of navigation environment, from the perspective of the ship handlers, the assessment indexes of ship handling difficulties are put forward. The natural environment elements were also researched, which have important impacts on ship maneuvering capabilities. Besides, various elements and indictors are quantitatively processed. Meanwhile, taking the actual situation into account, the impacts of natural navigation elements of waters on the ship handler's operational capacity are verified.

Domestic experts and scholars have also done a lot of work in the safety assessment on navigation environment. The Vessel Traffic Investigation and Safety Assessment Team in DMU, proposed safety indexes of safety assessment system, the method is based on the standardized processing and has been widely used in the safety assessment of many parts of coastal port waters in China (Wu& Zhu, 2004). Based on fuzzy mathematics theory, fuzzy assessment model was introduced in the assessment of maritime safety earlier in China (Zhao, Wu, &Wang, 1991, pp. 247-251). He Hui proposed the concept of the risk level of maritime traffic environment and established fuzzy assessment model which combined with the AHP analytical method (He, Wu &Fang, 1997, pp.36-41). It is noted that the corresponding assessment indicators and standards and applied gray poly classes and statistical assessment method of gray theory into quantitative analysis and assessment of risk level of navigation environment in port channel waters (Ma&Wu, 1998, pp.15-18). The application of systems engineering into the analysis of safety navigation environment system is also determined by using the fault tree analysis method, the navigation environment factors and their degrees of importance were specified (Weng&Wu, 2001,pp.1-4). Zheng Zhongyi, working in DMU, who uses the gray correlation degree and factor analysis methods to research navigation environment, and factors in port channel and marine accidents(Zheng,Wu,&Yang,1997,pp.61-64). And the historical data and navigation environment factors are associated with these mathematical methods. Besides, a lot of scholars have made great efforts in studying the navigation environment.

Through the analysis and research of previous work done in safety assessment of navigation environment waters, the main methods of safety assessment of navigation waters are as follows :

(1) The statistical methods are used based on the accident database, such as the probability of risk assessment.

(2)The dynamic observation of traffic flow analysis and assessment method.

(3) The computer simulation simulator assessment method.

(4) The macro comprehensive assessment method by use of mathematical model, for example, fuzzy comprehensive evaluation (Sii,Ruxton, & Wang, 2001,pp. 19-34)

Among the four main approaches to water traffic safety assessment, the third and the fourth one are widely used. In particular, the mathematical assessment model based on macro ideas is the most popular. The requirement of the breadth and accuracy of data is high in the first approach, but the current database can not meet this need in China. A lot of human and financial resources are occupied in the second idea, because it needs the aid of high-tech observation and processing technology. As the low cost and practicality of the third idea, it is widely used in the process of water project construction or transformation. Because the fourth approach is operational and simple, quantitative assessment is more direct, together with the other comparative advantages, it is more widespread.

Based on the fourth idea, the author tries to use the FSA method in the paper. Besides, fuzzy mathematical models and probabilistic risk assessment methods are used in the assessment of navigation environment in bridge waters.

2.4 Risk Assessment of Navigation Environment in Bridge Waters

Currently, ship-bridge collision is the key issue of safety navigation in the bridge waters. In the early 1980s, the international shipping countries started to research the ship-bridge collision system. In the last ten years, as a large number of river-crossing, cross-sea bridges were designed and constructed; ship-bridge collision issues have aroused wide attention. A lot of researches (Kong& Zou, 2003; Liu, Wu&Zou, 2003; Qiu&Zou, 2004, pp.84-89) on the ship-bridge collision have been carried out. Overall, a ship-bridge collision issue is primarily confined to the probability of risk assessment of ship-bridge collision, the methods to determine collision force, the dynamic analysis of bridge after collision (Kong, Zou& Mou, 2004, pp. 30-32).

The study on the assessment of navigation safety in bridge waters has something to do with navigation environment. However, the research on the risk assessment of navigation environment is very rare in domestic and international research sphere (Liang, 2011; Wang, 2005). As the particularity of bridge waters, accidents are prone to occur. Therefore, the research on navigation environment in bridge waters has very important and urgent significance.

2.5 The Main Risk Assessment Methods

2.5.1 Fault Tree Analysis

Fault Tree Analysis (FTA), also known as accident logical analysis, is a scientific method for the analysis and assessment of the effectiveness of system safety. This method can be not only used for qualitative analysis, but also for quantitative analysis; it is simple and user-friendly. And the existing and potential dangers of various systems can be identified and assessed with this method.

According to the accidents or incidents information provided to the system, FTA is the method to find root and contributing causes of the accidents in order to take effective measures to prevent accidents. This analysis method mainly includes five steps: First, the preparing phase, the system has to be identified and the accidents and incidents database of the systems will be collected and researched. The second step is to draw up the fault tree. It should be noted that the top event ought to be determined and all the reasons related to the top event have to be investigated before compiling fault tree. The third stage is qualitative analysis of the fault tree. Depending on the structure of fault tree identified in the previous step, the basic reasons for the events and their importance to the structure will be analyzed. The fourth stage is quantitative analysis of the fault tree. Its purpose is to calculate the probabilities of the basic events, and then analysis of the probability of system risk. The last stage is to sum up the FTA results and to determine their applications.

The advantages of FTA lie in the following aspects. First, from the fault tree, the visually simple and clear cause and effect relationship can be identified. The causes and logical relationship leading to disaster incidents can be comprehensively understood; therefore, the key points and responding measures to prevent accident or disaster will be got. Based on the probability of each basic event and accident, their degrees of importance to the structure will be determined. Through qualitative analysis, the consequences of basic events can be determined, and the appropriate control measures can be taken in advance, providing corresponding experience for formulating reasonable and scientific safety control measures. More importantly, the factors of system can be analyzed quantitatively. Based on the probability of the basic events, the probability of an accident can be calculated, some specific and practical indexes to control the system safety can be provided (IMO, 2007).

Of course, FTA method has its own drawbacks. First, this method can analyze the causes of an accident more accurately, but the likelihood of causes leading to accidents is difficult to determine. Second, its requirements of analysts are relatively high, so the analysts should be very familiar with the system and good at applying this method skillfully and accurately. Consequently, the fault tree analysis method is used by different persons, and the assessment results are not the same (Fang, & Datubo, 2004, pp.1-5). Besides, for the large and complex system, in the processes of preparing for fault tree analysis, the steps are complicated and cumbersome, making it more complicated to calculate, so that it is difficult to implement the following qualitative and quantitative analysis. Finally, if you can not determine the probability of each basic event beforehand, the quantitative analysis of system safety can not be completely made by fault tree analysis.

2.5.2 Probabilistic Risk Assessment

PRA is an important method of quantitative risk assessment, which is also a major component of the risk assessment. The PRA method mainly includes the identification of the types of risk, estimating the probability of occurrence and its consequences of its hazards to environment, public and safety. The starting point of this method is to research the individual components, based on the relationship between the elements and components, components and subsystems, subsystems and subsystem, finally, the overall probability of an accident will be estimated. In general, PRA includes three phases: identification of hazardous events, causal analysis and risk quantification. PRA can be carried out on different levels.

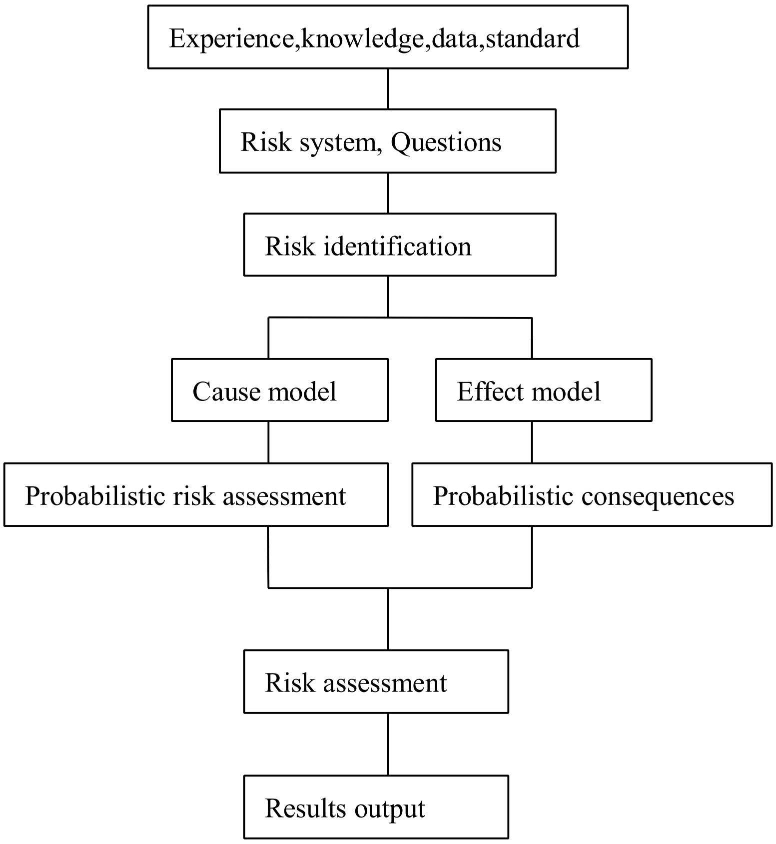


Figure 1- The general process of probabilistic risk assessment
Source: Zhang, S.K, &B,Y,&T,W.Y.(2003).Risk assessment in marine and ocean engineering . *Engineering risk analysis, Procedure of PRA* (p.6).Beijing: National defense industry press.

2.5.3 FSA

FSA is a tool adopted by the IMO in the rule-making process with the purpose to improve ship safety. It is a well structured, systematic approach to risk assessment. It is helpful to develop reasonable and feasible rules, as far as practicability, prevention or control measures are provided. In addition, the method can not only be used for post-analysis after an accident, but also can be used to predict before an accident. In short, it is a standardized risk assessment method. The applications of FSA method will have positive impacts on the improvement of water traffic safety management.

2.5.3.1 Research and Application of the FSA Method in Foreign Countries and China

The foreign countries started researching the FSA methodology earlier. Since the FSA is applied to the water traffic safety management, relatively good results are achieved in the United Kingdom. So far, in terms of maritime accident, vessels operating at sea and platform, many FSA experts and scholars have done in-depth study and propose suggestions for decision-making, which can effectively avoid or reduce risks to the largest extent. In addition, the FSA method is no longer recommended to be applied in ship safety field, considering the actual needs of maritime safety, the international research on the application of FSA method into bulk carriers was submitted by the United Kingdom at the 70th meeting of IMO Maritime Safety Committee (MSC) in 1998. Under the support of IMO, the United Kingdom, together with Japan, France, Norway, Australia and other countries began to carry out research work on this project. In addition to the application of FSA into bulk ship, the International Association of Classification Societies (IACS) has launched a series of research projects related to maritime safety and environmental protection with FSA method. At the same time, the application into operational management and special ship safety have been researched in some other countries, such as Northern Europe, Denmark, Finland, Norway and Sweden(Fan&Wang,2008,pp.2207-2212). Norway and the United Kingdom carried out a joint study on the safety assessment of Ro-Ro ships. United States and Sweden apply FSA method in ship safety operation management and other national research fields.

As early as in 1999, China started to research the applications of FSA methodology. According to the actual conditions in China and the provisions of IMO instruments, China Classification Society (CCS) specially formulated and issued Guidelines on the Applications of FSA in CCS. Then with the use of FSA method, risk assessment and risk analysis of high-speed ship navigating in the Yangtze River was conducted. And the application of FSA in the Ro-Ro passenger ship in the Bohai Bay was also carried out.

In addition, some experts and scholars began to study the FSA assessment methods in data processing and quantitative analysis, and the application of FSA in the hull strength, stowage, transport of noxious liquid substances and ship accidents made some progress. After the ferry ship *"Salam 98"* had an accident at sea, shipping companies in China attaches great importance to ship's safety navigation into specific waters and how to apply the FSA method in relevant research work is carried out.

In recent years, some Chinese experts and scholars have worked on the applications of FSA method in different fields of sea traffic safety. Mainly in the following aspects: First, in terms of navigation management, it is applied in port waters, vessel traffic management waters, dangerous goods terminal, navigation safety assessment are in-depth researched. With regard to ship management and shipping company management, its application in ships carrying dangerous goods, Ro-Ro passenger ships, oil spill risk management, safety management of shipping companies are widely studied. When it comes to Ship handing and Preventing Collisions, its applications in pilot safety, collision between commercial ship and fishing boat are researched. In respects of maritime and water transport management, FSA is used in many fields, such as risk control in maritime administration, maritime legislation, and safety management of water transport. FSA will play a more significant role in water traffic safety management in the world.

2.5.3.2 The Flowchart of FSA Methodology and Its Approaches

According to the guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process, the assessment method consists of five steps.

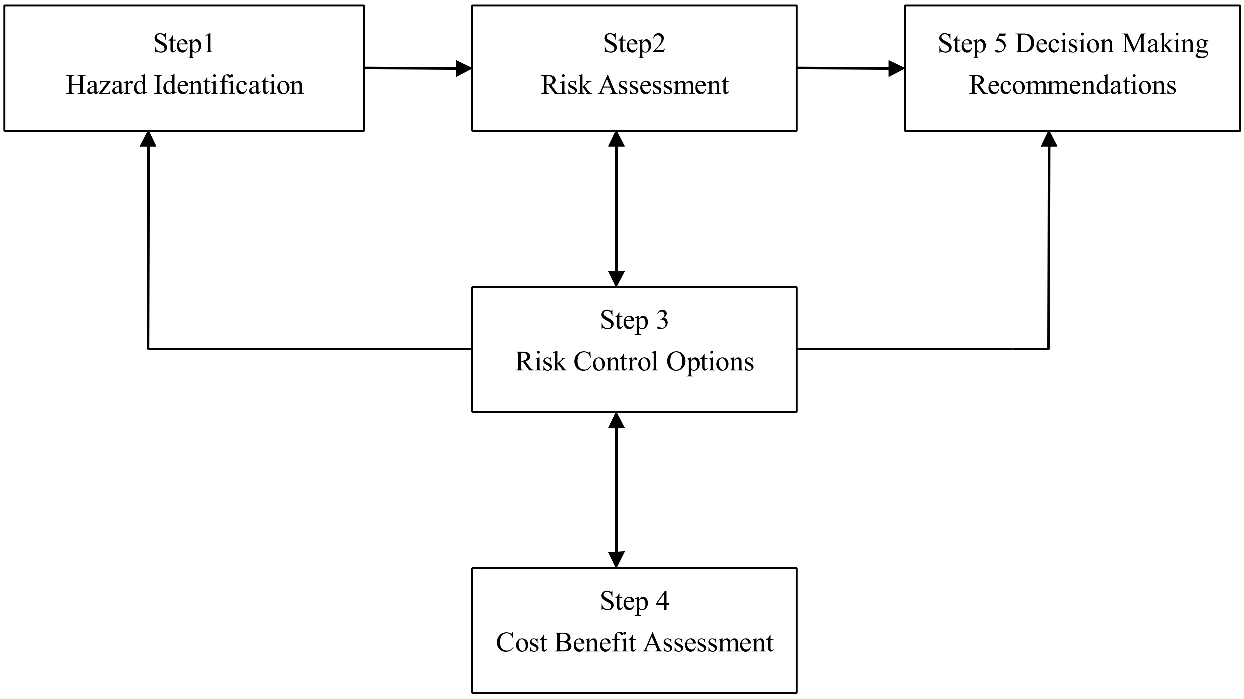


Figure2- Flow Chart of the FSA Methodology

Source: International Maritime Organization. (2007, May, 14). *Consolidated Text of the Guideline for Formal Safety Assessment (FSA) for use in the IMO rule-making process* (MSC/Circ. 1023-MEPC/Circ .392). London: Author.

Figure 2 shows that the FSA method can be divided into five steps: (1) hazard identification; (2) risk assessment; (3) risk control options; (4)costs and benefit assessment; (5)Decision-making and recommendations.

It can be seen from Figure 2 that the process of assessment can be carried out through a variety of approaches, and the use of FSA method in risk assessment is a repeated scrutiny process. In general, three approaches can be found in FSA.

(1) Hazard identification→ Risk assessment risk control options →Costs and benefit assessment →Decision-making and recommendations (Step 1→Step2→Step 3→Step 4→Step 5).

(2)Hazardidentification→Risk assessment→ Risk control options →Decision-making and recommendations (Step1→Step2→Step 3→Step 5).

(3)Hazard identification→Risk assessment→Decision-making and recommendations (Step1→Step2→Step 5)

Generally speaking, the process of costs and benefit assessment is carried out by the professionals in the research field; otherwise it is difficult to calculate. This is why this step is omitted in the application of the FSA methodology. According to the actual situation and relevant characteristics of this thesis, the third option is used in the risk assessment of navigation environment in bridge waters.

2.5.2.3 The Steps of FSA Methodology

(1) Hazard Identification

Hazard Identification is a fundamental step in formal safety assessment with the purpose to identify existing or potential hazards in system. The next step is to rank the risk factors by degree of danger in order to analyze the major risk further.

(2) Risk Assessment

From the first step, the current states and objective distribution of risk factors will be identified. Risk assessment is to analyze the various factors that affect the risk level, high-risk areas and key risk factors will be identified by assorting the primary and secondary risks. By analyzing the relationship between causes and consequences of accident, it is to modify existing regulations or standards, as well as to develop new regulations or standards. In addition, the risk can be controlled as much as possible to arrive at the acceptable criteria. In the process of risk assessment, some of the risk assessment methods recommended in the IMO guidelines can be used , such as Fault Tree Analysis (FTA), event tree analysis (ETA), failure mode and effects analysis (FMEA), hazard and operability study (HAZOP) . Furthermore, systems of engineering methods can also be used to assess the risks of system.

(3) Risk Control Options

After risk identification and risk assessment, according to the situation, risk control options are to develop specific measures to reduce risk, including modifications and formulation of regulations and standards. The implementation of risk control options should be able to prevent accidents or mitigate accident consequences, such as the development of rules, regulations, and operating procedures.

(4) Costs and Benefits Analysis

The purpose of costs and benefits analysis is to estimate and evaluate costs and benefit of risk control options (Duan, 2006). The benefits can reduce the frequency of accidents and the damage to the environment.

(5) Decision Making and Recommendations

In this process, all risk control options should be comparatively analyzed, and the better option should be selected based on the costs and benefits analysis. Considering the reasonable costs and benefits of the better option selected, analyzing its impacts on the party with different interests, taking into account the balance of interests of all parties and the effectiveness of these risk control options, finally, we should make rational decision and suggestions.

2.5.4 Fuzzy Assessment

Fuzzy assessment methodology (Xie&Liu, 2009) is an effective multifactor decision-making method based on fuzzy mathematics, which applies the principle of synthesis fuzzy relationship to quantitatively analyze the fuzzy system, and to make comprehensive assessment of system affected by multiple factors. Fuzzy assessment is a product which combines fuzzy theory with practical application. It takes advantage of the fuzzy transform principle and the maximum membership degree law. Considering the various factors of assessment object, comprehensive evaluation of the object is conducted. The focus of this method is to select various factors.

Fuzzy assessment methodology is widely used in the waters of navigation environment. According to the fuzzy assessment model, the establishment of fuzzy assessment model is divided into four parts. First, the assessment index system should be determined. Second, the weights of each assessment index are to be calculated. Thirdly, membership degree of each assessment index should be determined. Fourthly, the assessment model should be established and applied. The theory is described in following.

Fuzzy set U is a domain of the evaluation factors affecting the determination object, it can be expressed as $U=\{U_1,U_2,U_3,\ldots U_m\}$. Where U_i represents the factor for evaluation, in which i = 1, 2, 3, ..., n.

Evaluation set is a domain of evaluation grade, it can be expressed as $V=\{V_1, V_2, V_3\ldots V_n\}$. Where V_i expresses the evaluation results of the risk degree obtained from every considered factor, in which j = 1, 2, 3, ..., n.

Fuzzy evaluation set of single factor: for a single factor, the fuzzy assessment is to determine the membership degree (r_{ij}) of the element (v_j) of evaluation sets. So that we can get the fuzzy subset is used on the domain of evaluation grade V. $R_i=(r_{i1},r_{i2},r_{i3}\ldots r_{in})$,where r_{in} denotes the evaluation value of the i-th evaluation factor to the membership degree of the n-th evaluation grade. When every factor introduces an evaluation state, the total evaluation matrix R is established as follows.

$$R=\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ . \\ . \\ . \\ R_m \end{bmatrix}=\begin{bmatrix} r_{11} & r_{12} & r_{13} & \ldots & r_{1n} \\ r_{21} & r_{22} & r_{23} & \ldots & r_{2n} \\ r_{31} & r_{32} & r_{33} & \ldots & r_{3n} \\ . & . & . & \ldots & . \\ . & . & . & \ldots & . \\ . & . & . & \ldots & . \\ r_{m1} & r_{m2} & r_{m3} & \ldots & r_{mn} \end{bmatrix} \tag{2-1}$$

The above three elements constitute the basis of the fuzzy synthesis evaluation. In addition, various elements of the factor set U have different degrees of importance in the evaluation, and therefore, for each element U_i, they are given different weights (a_i) according to their degree of importance. The factor weights set (A) is made up of weighting factors. “A” is the fuzzy subset of weighting factor. It can be expressed as A=（$a_1,a_2,a_3\ldots a_m$）. Where a_i indicates the corresponding weight of the i-th factor u_i the value of u_i is the membership degree of the factors U_i to fuzzy set A. It is also reflected the degree of importance of factors in the fuzzy synthesis evaluation, it should meet the normalized and non-negative requirements, $\sum_{i=1}^{m} a_i = 1$， $a_i \geq 0$.

When the weights value A and the evaluation matrix R are given, in accordance with the fuzzy matrix multiplication, the fuzzy synthesis evaluation set B can be set up and calculated as follows.

$$B=A\times R=(a_1,a_2,a_3\ldots a_m)\times\begin{bmatrix} r_{11} & r_{12} & r_{13} & \ldots & r_{1n} \\ r_{21} & r_{22} & r_{23} & \ldots & r_{2n} \\ r_{31} & r_{32} & r_{33} & \ldots & r_{3n} \\ . & . & . & \ldots & . \\ . & . & . & \ldots & . \\ . & . & . & \ldots & . \\ r_{m1} & r_{m2} & r_{m3} & \ldots & r_{mn} \end{bmatrix}=(b_1,b_2,b_3\ldots b_n) \quad (2\text{-}2)$$

Moreover, the fuzzy a synthesis evaluation B can be illuminated to make the evaluation results more intuitive and easier to understand (Gao, 2010).

The fuzzy assessment model is relatively simple, easy to grasp and more convenient to calculate, in evaluation of a complex problem influenced by multi-factors, this method is very helpful.

2.6 Risk Assessment Method Employed in this Paper

According to the descriptions above, we can know that, in theory, all the risk assessment methods can be used in the safety assessment of navigation environment in bridge waters.

The above methods have their own characteristics. The inherent or hidden risk factors of system can be identified directly by FTA. According to the qualitative analysis, the impacts of each event on the accident are easy to determine; it is also can be used for quantitative analysis to calculate the probability of an accident. However, the FTA method becomes complicated, time-consuming and difficult to follow for large and complex systems (DNV, 2002, P.43), as it is complicated to draw up fault tree and calculate the probability, making qualitative analysis and quantitative analysis in the following steps more difficult to carry out.

Fuzzy assessment method is not confined to a single or several hazard factors, but it covers more comprehensive and wide factors. The specific risk value is used to reflect the results of risk assessment, making the process of assessment more direct, easier to be accepted and the assessment results more reasonable and credible.

Although FSA is a risk assessment methodology, it is a systematic and well structured safety assessment method, and it should be further considered to be a scientific idea of risk evaluation. When we carry out the risk assessment of water traffic safety, such as port waters, bridge waters, even risk assessment in other domains, the systematical, well-structured and predictable, comprehensive thought of FSA should always run through the risk assessment process. PRA can be seen as a major component of the risk assessment, it can also be used as a method of quantitative analysis of risk, in particular the frequency of occurrence of the accident identified as the major risk sources can be calculated and estimated, and to some extent it is able to make up for FSA mythology which depends on database of accidents.

For the navigation environment in bridge waters, it is a systematic engineering and the risk factors in this system are extensive and fuzzy. So in this paper, the FSA, fuzzy assessment, PRA method, the three methods are combined to carry out a risk evaluation. The idea of FSA methodology is penetrated into the risk assessment of navigation environment in bridge waters. The risk assessment model of navigation environment in bridge waters is established by using the fuzzy synthesis evaluation methodology to evaluate the risk level. The PRA method is used to calculate risk degree of major risk source.

2.7 Summary

In this chapter, first, the concepts and basic steps of risk assessment are introduced. Then the researches on risk assessment of water traffic safety both home and abroad, waters of navigation environment and navigation environment in bridges waters are presented. Finally, four risk assessment methods are explained and the risk assessment methods adopted in this study are identified.

Chapter 3 Risk Assessment of Navigation Environment in Bridge Waters

Based on the approach of FSA methodology introduced in chapter 2, hazard identification, risk assessment and decision-making and recommendations, from the viewpoint of system theory, transport system of bridge waters will be established and the processes of risk assessment will be carried out.

3.1 The Transport System of Bridge Waters

Analysis and understanding of why accidents occur must be found out in the maritime safety system. Figure 3 shows a general concept of maritime system.

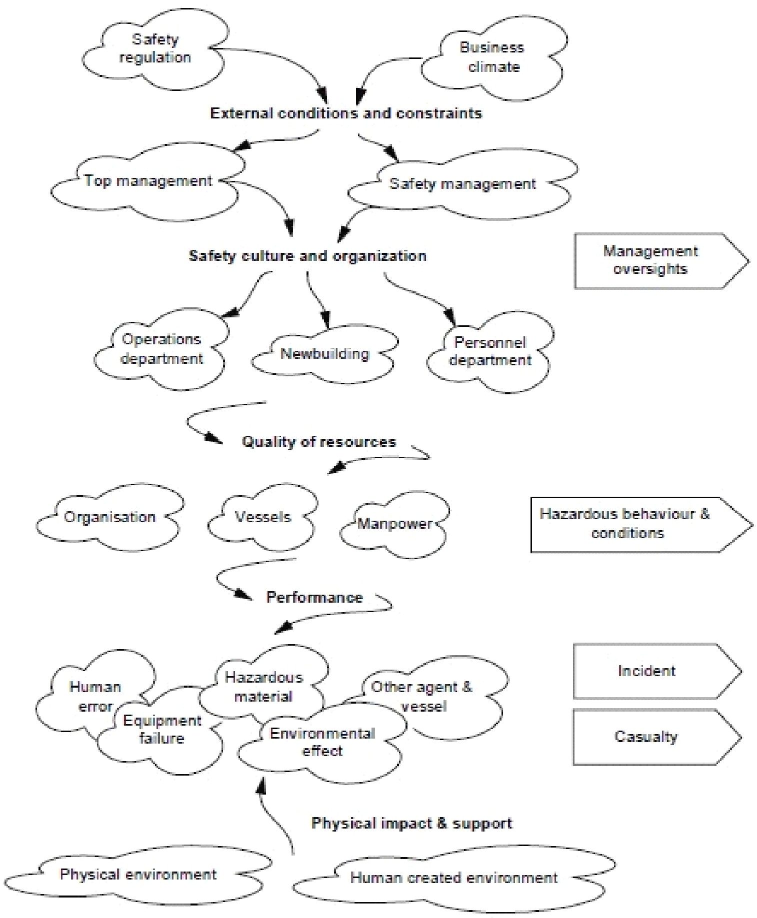


Figure 3-The maritime systems: Actors, effects and deviations

Sources: Norweigian University of Science and Technology (2001, March).WP3, Deliverable D3.1CHIRP, Voyage Recorder &Accident Data state of the Art. Oslo: Author.

The purpose of maritime safety system is to identify hazards, eliminate or control risks and mitigate the residual risks systemically.

3.1.1 The Definition of Bridge Waters

From the angle of the safety navigation, bridge waters are defined as follows. The meaning of bridge waters is where the waters are perpendicular or parallel to the direction of the axis of the bridge, due to ship navigation has an impact on bridge safety, and thus needing to take certain measures to control and guide ship to sail. Taking into account the safety management measures of some bridge waters in China, bridge waters are considered to contain two aspects. Figure 4 shows the scopes of bridge waters. On the one hand, for a ship navigating along bridge channel, the waters that affect ship safety navigation include the channel of bridge and the fore and after stretch of channel waters, which are also called the safe waters in bridge area. On the other hand, for the ship sailing parallel to the axis of bridge or nearby the bridge area, the waters that affected ship navigation safety should be perpendicular to the direction of the axis of bridge before and after the stretch of waters, the waters should contain two regions, the first one is ship navigation control waters, when a ship enters the waters, she should report to the maritime administration. The second one is restricted navigation area, where ships should be prohibited from navigating and operating in the waters.

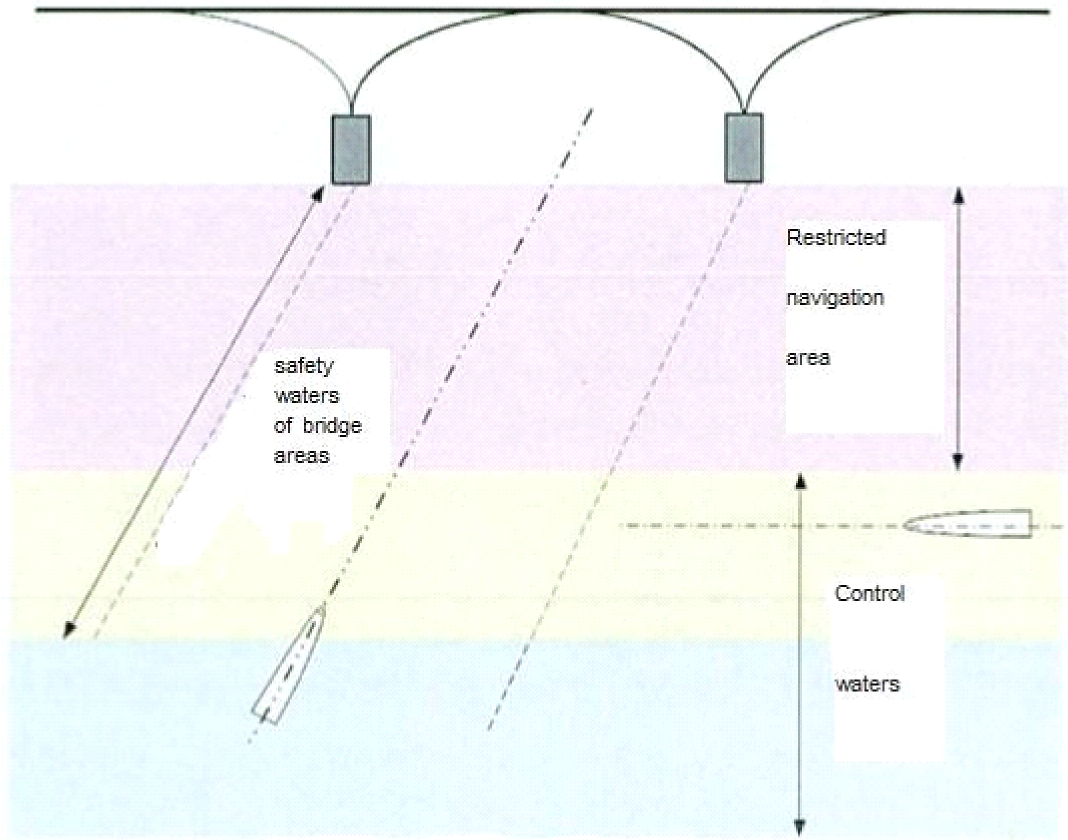


Figure4-The Scope of Bridge Waters
Sources: Y, X. (2012). *A study on the demarcation of bridge water.* Unpublished master's thesis, Wuhan University of Technology, Wuhan , China.

3.1.2 Traffic Safety System of Bridge Waters

With regard to the concept of safety system engineering, the characters of system are determined by the elements of system and their relationships, and it can be expressed as the function S = (E, R). In this formula, where E represents the composition elements set of system, R stands for the relationships between each element (Xiao, 2007). In addition, according to the different functions, the system can be divided into different subsystems, and subsystems can be divided further, until into the smallest elements that can not be divided. As the water traffic safety is a complex system combined with subsystem, therefore, risk assessment of water traffic safety should comply with the principles, viewpoints and theories of safety system engineering. In fact, almost all maritime accidents are under the interaction of man, machine, environment, management. What are worse, disasters and even catastrophic accidents might take place unexpectedly. In order to reduce and avoid the maritime accidents, the elements of safety system, such as man, machine, environment, management must be effectively controlled and their relationships should be coordinated between them. From the viewpoint of man (seafarer), machine (ship), environment (navigation environment in bridges waters), management (maritime administration), water traffic system of bridge waters can be divided into four subsystems, such as man subsystem, machine subsystem, environment subsystem and management subsystems.

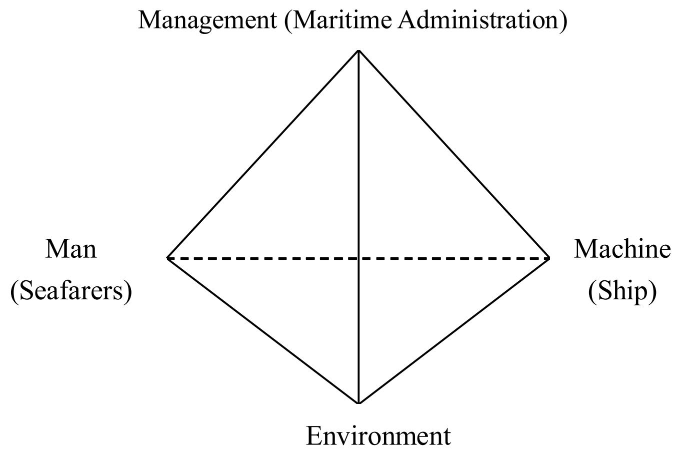


Figure 5-The Fundamental Elements of Water Traffic Safety System in the Bridge Waters

Source: Compiled by the author based on the MMEM theory of Professor Chen Weijiong

Figure 5 shows the basic four elements of the navigation safety system in bridge waters, man(seafarers),machine (ship), environment (navigation environment in bridges waters,) and management (maritime administration). The MMEM system is made up of the four elements

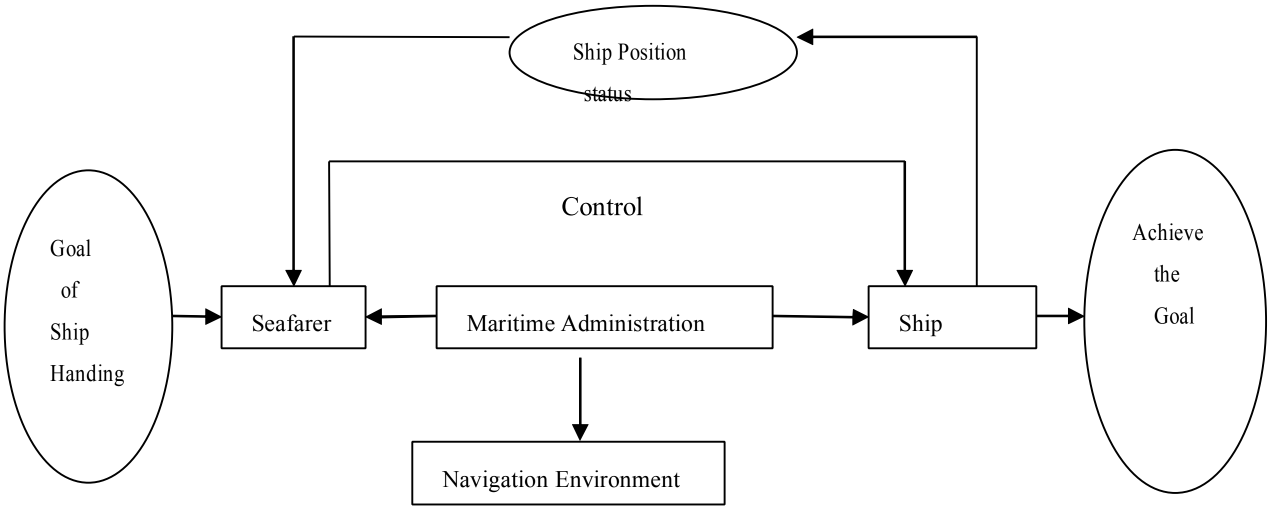


Figure 6-The water traffic safety system composed of the four elements
Source:Xiao,X.L.(2007).*Study on the matters and methods of bridge and nearby waterway navigation assessment.* Unpublished master's thesis, Wuhan University of Technology, Wuhan , China.

Figure 6 shows that water traffic safety system is a multifactorial complex system composed of the four elements. In the system where seafarer is the main body of behavior, ship is the object to handle, environment is key factors impacting ship handling behavior and its results, and maritime administration is referred to the management responsibilities of authority, conducting supervision on the behaviors of seafarers and the conditions of ship, maintaining navigation environment. In this system, given appropriate conditions, seafarers can maneuver a given ship safely and efficiently to a predetermined position. In the transport safety system of bridge waters, navigation environment subsystem imposes psychological impacts on seafarers and further constraints their actions, as well as external physical force imposed on ship affecting safety navigation. In the navigation environment subsystem, many factors have impacts on the seafarer and ship safety, among which these factors are the potential hazards and dangers of navigation environment subsystem. Therefore, research on risk assessment of navigation environment in bridge waters will be carried out in this paper.

3.2 The Process of Formal Safety Assessment

3.2.1 Risk Factors Identification in Navigation Environment in Bridge Waters

3.2.1.1 Characteristics of Ship Flow

(1) Vessel Density

Ship density, also known as traffic density, which means the number of ships (team) passing through a particular place in the waters at per unit time. It is the most basic indictor of traffic conditions in specific waters. Traffic density is a direct reflection the volume and flow rate in some waters and it can represent the degree of traffic congestion and its risk level. More directly, the impacts on ship (team) safe navigation and traffic efficiency can be mirrored.

(2) Ship Size

The main dimensions of ship size are length, width, and depth and draft, and the amount of tonnage is a straight representation of vessel size. The number of ship tonnages has something to do with the water traffic accidents. Experts working on the studies of maritime accidents for a long time find that, under the same conditions, the greater the ship tonnage is, the higher probability of maritime accidents will be. This is because the inertia of the larger ship is greater than the smaller one. It is less flexible in maneuvering, and it is more affected by the wind, tidal stream, depth and other factors, therefore, the frequency of maritime accidents is higher. Maritime Statistics shows that the average marine incidents of incoming vessels increases proportionally to the ship length of 3/2 power. The ship collision rate changes with the average changes in ship tonnage, which can be expressed as: collision rate = 0.0014GT+0.0009, where GT represents gross tonnage (Zhao, 2010). In addition, because the characters of a bridge, if a vessel is planned to navigate through bridges safety, ships size must meet the vertical clearance of the bridge, horizontal width of navigation bridge and other navigation elements.

(3) Ship Speed

Speaking of ship speed, the knowledge of navigation tells us that ship speed is usually expressed in two ways--one is called ship speed, it is the ship speed over water, and the other is called navigation speed, it is the speed over land. On the voyage, ship speed is closely related to ship maneuvering and preventing collisions. According to the requirement of Rule 6 in Convention on the International Regulations for Preventing Collisions at Sea(1972):every ship shall at all times processed at a safe speed, so that she can take proper and effective action to avoid collisions and be stopped within a distance appropriate to the prevailing circumstances and conditions.

However, according to the factors should be taken into account in the rule, the connotation of safe speed should not be limited to ship avoiding collision. When determining a safe speed, it is not confined to avoid collision. According to Rule 8, when taking action to avoid a collision, a succession of small alterations of course and/or speed should be averted. Therefore, safe speed should be determined according to the environmental conditions at relatively stable speed, not including the alternations to take actions to avoid collisions. Since the ship is an important variable factor in ship handling, especially in restricted waters, when determining a safe speed, the speed-related risks should be focused on. For example, safe speed of the ship sailing in large waves should take into account the stability and sway in order to ensure the safety of ship and cargo. Navigation in the bridge waters runs the risk of collision and stranding, which should be considered.

(4) Types of Ship

Most of the ships are classified by its functions. They can be divided into the following types of ships: passenger ship, general cargo ships, container vessel ,RO-RO ships, barge carrier, grain carrier, collier, utility carriers (ore/oil tankers, ore/bulk carrier / tanker), special cargo ships (wooden ship, reefers, car carriers, etc.), oil tankers, liquefied natural gas tankers, liquid petroleum gas tanker. In the bridge waters, the types of ship have much to do with navigation safety in bridge waters, in particular the special ships and the supergage ships navigating through bridge waters, the parameters of bridges should be closely paid attention to ,for example, navigation clearance and clear width of bridge.

3.2.1.2 Hydrological Conditions

Hydrological conditions include current, tide stream and water depth.

(1) Current Conditions

Current conditions include current speed, current direction and current pattern. In the traffic waters where current is swift, current pattern is non-uniform, it is difficult to maneuver the ship and it even affects the safety navigation of ship (fleet). In particular, the impacts of crosscurrent should be looked out in ship maneuvering, if the ship suffers from abeam current, the faster the current rate, the greater the current rudder angle will be and the higher the horizontal drifting speeds will be. The drifting distance of ship sailing in the water affected by current ΔB_w ,it can be calculated as:

$$\Delta B_W = S \cdot \frac{V_S S\text{in}\,\beta + V_W Sin\beta}{V_s Cos\alpha + V_w Cos\beta} \tag{3-1}$$

Where: S represents the calculation of river length (m); V_S represents ship Speed (m/s); Vw represents the current speed (m/s); α represents drift angle of ship (°); β represents the angle between a normal direction of the axis of bridge and the current direction (°).

(2) Water (tidal) Stream

According to their nature, it can be divided into the half-day tidal stream, full-day tidal stream and irregular tidal stream. Inshore sea areas where currents are main tidal stream and currents, the probable maximum sea current speed equals to vector sum of the probable maximum tidal stream speed and wind currents and the maximum wind current(MOC,1999). For the regular semidiurnal sea, it can be calculated as:

$$\overrightarrow{V_{\max}} = 1.295\overrightarrow{W_{M2}} + \overrightarrow{W_{K1}} + \overrightarrow{W_{O1}} + \overrightarrow{W_{M4}} + \overrightarrow{W_{MS4}} \tag{3-2}$$

For the diurnal tide sea, it can be calculated as:

$$\overrightarrow{V_{\max}} = \overrightarrow{W_{M2}} + \overrightarrow{W_{s2}} + 1.6\overrightarrow{W_{k1}} + 1.45\overrightarrow{W_{o1}} \tag{3-3}$$

Where $\overrightarrow{W_{M2}}$、$\overrightarrow{W_{s2}}$、$\overrightarrow{W_{k1}}$、$\overrightarrow{W_{o1}}$、$\overrightarrow{W_{M4}}$、$\overrightarrow{W_{MS4}}$ represents lunar semidiurnal current ,solar semidiurnal current, the declination of the sun and moon semidiurnal current ,the oval semi-major axis vector of lunar semidiurnal current.

The effects of tidal stream should be considered in cross-sea bridge waters; tidal stream is a kind of integrated current, the local tidal stream shall be taken into account in the site selection and layout of bridge.

(3) Water Depth

Generally, the depth of water represents with relative depth, namely depth-draft ratio. For transport ships, the depth of water is divided into four categories, such as deep water port, medium deep water, shallow water, and very shallow water.

When a ship (fleet) navigates from deep water into shallow waters, ship resistance increases, the workload of main engine is increased and the power output is reduced. With an increase of draught, the ship becomes stern trim, the ship maneuverability becomes poor. Impacts of the shallow water on the ship are related to the depth of fairway, ship size and speed. The draught of sailing ship is increased in shallow water, which is known as dynamic draft increases or hull sinkage (Hong&Yang, 2012, p.249). The basic cause of the hull sinkage is that hydrodynamic is reduced in shallow water, which is used to support hull. And the speeds of water and current flowing through the bottom of ship and the bottom of river are increased. The shorter the distance between the ship bottom and the river bottom is, the higher the ship speed and current are, the greater the amount of sinkage will be. The research finds that when the water depth (h)/ship draught (d)≤4, the water depth begins to affect ship navigation performance. If h/d=1.2～1.5, when the ship navigate at the speed $V = \sqrt{gH}$ (g is the free acceleration) ,the ship is likely to be stranded.

3.2.1.3 Meteorological Condition

Meteorological conditions affecting safe navigation of ship, including wind (typhoon), fog (visibility), rain (precipitation) and wave.

(1) Wind (Typhoon)

The analysis of accident shows that many of the accidents occur when the wind scale is 3 or 4 in general and the risk of accident is high when the wind scale is over 7. Wind can render the ship to slope, off course and yawning. Affected by the wind, the water surface will be elevated, affecting ship's safety navigation. Therefore, it should be avoided by constructing bridges in the wind outlet area. In addition, for cross-sea bridge, special attention should be paid to the adverse effects of typhoons and storms.

1) Effect on ship drifting

The ship (fleet) is easy to be dragging and off course in fierce wind, especially in the restricted waters. Due to strong winds, the ship (fleet) swings, and it will affect the seafarer's observation at surrounding environment and the handling ability of ship is restricted. It is found that the wind is an important factor affecting navigation safety, and it affects the ship (fleet) with a higher freeboard and superstructure obviously. Their impacts on ship (fleet) are related to many factors, such as the wind area and the center location of wind force, the ratio of freeboard to draft, the wind scale and the leeway angle, ship heading and speed, and many other factors. The higher the wind force is the degree of sloping, drifting and off course will be higher. The drifting distance of the sailing ship by wind ship ΔB_f can be calculated:

$$\Delta B_f = V_{ap} \cdot S \cdot \frac{|Cos(180° - \alpha)|}{V_s Cos\alpha + V_w Cos\beta} \quad (3\text{-}4)$$

Where: S-calculation of river length (m); Vs –ship speed (m/s); Vw-speed over water (m/s); V_{ap} - drift speed by wind (m/s).

The drift speed by wind can be calculated as

$$V_{ap} = \lambda \cdot K \cdot \sqrt{\frac{B\alpha}{Bw}} \cdot e^{-0.14Vs} \cdot V_\alpha \quad \text{(Liu\&Fang, 2009, p.78)} \quad (3\text{-}5)$$

Where $K=\sqrt{\frac{\rho_\alpha C_\alpha}{\rho_w C_w}}$,the scope of coefficient is 0.038～0.041;

B_α-The wind area of hull above the waterline side. $B_\alpha = c_2 L_{BP}^2$, where c_2 is coefficient;

L_{BP}-The length of ship between perpendiculars, in the estimation it is replaced by design length of ship (m);

B_w - The area of hull waterline side (m), $B_W = L \times d$;

V_S -ship speed (kn);

V_α-The relative wind speed (m/s);

λ - Coefficient amended in shallow water.

2) Effect on Wave Height Increasing

Waves affect the ship safety; waves generated by the wind of scale 4 and 5 could affect the safety navigation of ship (fleet). In a straight stretch of river and at the mouth of wind, the wave is higher than other sections of river or sea, and the high waves appear in the condition that the direction of wind and current are the same. Because the mutual friction between wind and current appears, setting off big waves on the entire river bed. Where the water is deep and current speed is high, there are higher waves. Since waves cause the ship to pitch and roll, how to determine the bridge clearance height in navigation waters, depends on the additional waves caused by wind should be taken into account. The wave height H caused by wind in inland river can be calculated by the following formula:

$$\frac{g\overline{H}}{W^2} = 0.13th\left[0.7\frac{gd}{W^2}\right]\left\{th\frac{0.0018\left(\frac{gD}{W^2}\right)0.45}{0.13th\left[0.7\left(\frac{gd}{W^2}\right)0.7\right]}\right\} \quad \text{(Xiao, 2007)} \qquad (3\text{-}6)$$

Where: W-The average wind speed in ten minutes at designed water level at the height of above l0m,(m / s);

d- Average depth of the calculated waters (m);

D-The length of wind section (m);

g- Acceleration of gravity (m/s^2).

3) Effect on Backwater Generating

Due to the wind power in the bridge waters, backwater is generated, and its height can be calculated as:

$$e = \frac{KW^2 D}{2gd}\cos\beta \quad \text{(MOC, 2000)} \qquad (3\text{-}7)$$

Where: K- Friction coefficient, K=3.6×l0^{-6};

W-The average wind speed in ten minutes at designed water level at the height of above l0m,(m / s);

D-Average depth of the calculated waters (m);

β-The angle between wind direction and normal of shoreline (°).

(2) Fog and Visibility

The so-called visibility is able to tell the difference between object contours. The eyesight is restricted or reduced due to poor visibility and night navigation and visual range is shorter due to illumination errands, causing deterioration in the terms of navigation environment, the ship (fleet) is prone to make wrong waypoints. What is worse, maritime accidents such as off-course, stranding, grounding and collision might occur.

Fog and visibility have great impacts on navigation safety. Chinese scholars have conducted statistical analysis of the impacts of visibility on navigation safety in the Yangtze River. Under a certain visibility, statistical analysis of the number of vessels traffic accidents that occur within 1000 hours, which shows that if the range of visibility is less than 4km, it affects ship navigation safety. When the range of visibility is less than 1km, significant risks increase, which is called dangerous visibility. Fog and poor visibility are more likely to affect the cross-sea bridge waters more apparently.

(3) Wave

The navigation safety of cross-sea bridge waters is greatly affected by waves. The standards of designed wave include the return period of wave and the cumulative frequency of wave. The characteristic statistical values commonly used are wave height, wavelength, and frequency. In practice, the effects of mixed waves formed by storms and swell should receive attention. The wave height H can be approximately calculated as $H=\sqrt{H_1^2+H_2^2}$ (MOC,1999), where H_1 and H_2 represents two series of wave height respectively.

3.2.1.4 Navigation Conditions

(1) Bending in the fairway

The minimum bend radius of fairway is the standard of the minimum bend radius of curve that ship (fleet) can navigate through safely. The length of minimum bend radius mainly depends on the length over all, and secondly, the current speed, current pattern, maneuvering flexibility of ship and other navigation factors should also be considered. According to navigation standards of inland waterway (MOD, 2004), the minimum bending radius for ship navigation is three times of the length of pushing fleet. Theoretically, the calculation of fairway bending radius is a more complex problem, and the value of R is proportional to ship length. In the swift current conditions, the angle between the direction of current and heading is larger, the ratio of ship breadth to fairway breadth, the ratio of ship speed to current speed and steerage, and all of these factors have some impacts on R. The relationship can be expressed as:

$$R=KL(1+\sin\theta)(\frac{av}{V_1})\left(\frac{b}{B}\right)\frac{1}{S} \tag{3-8}$$

θ -The angle between the direction of current and heading;

V-Current speed;

V_1 -Voyage speed;

b-The Breadth of ship;

B-Valid trough width;

S-Rudder area;

K-Coefficient;

av -Coefficient relating to current speed;

L-The length of ship (fleet).

(2) Bridge axial angle

The axis of bridge should be perpendicular to the current direction and designed routes. The angle between water or current direction and the axis of bridge should not be more than 5 ° (MOC, 1997). In this way, the transverse current speed is reduced, which is favorable for handling ship, resulting in the reduction of the track width, shortening of the bridge span and reduction of project cost. However, if the angle is too large, the adverse current will be produced, navigation safety is seriously affected. For example, the angle between the axis of Huangshi Yangtze River Highway Bridge to the main current direction is more than 5 °, the maximum up to 18 °, and the current speed is high, the ship is more difficult to maneuver when navigating across the bridge. If the angle does not meet the requirements, the crossing scale of bridge should be increased to ensure the safe passage of the ship.

For cross-sea bridge, the bridge is often as long as dozens of kilometers, the axis of bridge is bended and varied. In this situation, it can be calculated by the angle between the normal of bridge axis in the main navigation channel and the mainstream direction of the falling and flooding current.

To sum up, the risk factors of navigation environment in bridge waters can be classified into four aspects. First, the characteristics of ship: ship density, ship size, ship speed, ship types. Second, hydrological conditions: tidal steam, tide speed, water depth. Third, meteorological conditions: winds, storm, typhoons, fog. Fourth, navigation conditions: bending in the fairway, bridge axial angle.

3.2.2 Risk Assessment

Risk assessment is the second step of FSA methodology and it is the most important step. At this stage, the appropriate risk assessment model is established to quantify the analysis of navigation environment in bridge waters. In this paper, Fuzzy synthesis evaluation methodology is applied in establishing risk assessment model of navigation environment in bridge waters. The risk assessment model is to be introduced in Chapter Four.

For the major hazardous factors identified in the navigation environment system in bridge waters via utilizing mathematical models and probabilistic risk analysis method, the degree of risk will be assessed further, which is vital for the next step to make decisions and recommendations. Meanwhile, the major risk factors of the system can be reflected, which will be further prevented and controlled.

3.2.3 Decision-making and Recommendations

According to the risk assessment results, appropriate measures and recommendations should be proposed. For the safety of navigation environment in bridge waters, based on the actual risk evaluation results of navigation environment in bridge waters and the risk degree of major risk sources, navigation environment system in bridge waters should be improved in terms of its main factors, such as characteristic of ship flow, hydrological conditions, meteorological conditions and navigation conditions. For the weaknesses of the four main factors in system, starting from traffic safety system in bridge waters, in terms of man, machine, environment and management, countermeasures and recommendations for improvement should be undertaken. The assessment of navigation environment in the Quanzhou Bay Cross-sea Bridge waters is researched as a case, the overall risk level is evaluated and the degree of major risk sources is calculated and estimated, and the corresponding countermeasures should be taken.

3.3 Summary

In this chapter, the water transport system in bridge waters and the processes of FSA methodology are introduced. In the process of FSA, first, risk factors in navigation environment system are identified. Secondly, the risk assessment index system of navigation environment in bridge waters and risk assessment model are established. Finally, for risk assessment results, the corresponding measures and recommendations are provided. This chapter focuses on identifying and analyzing the risk factors in navigation environment system.

Chapter 4 Risk Assessment Model of Navigation Environment in Bridge Waters

In order to carry out risk assessment of navigation environment in bridge waters, the risk factors of navigation environment system identified in Chapter 3 are comprehensively taken into consideration and the risk assessment model will be established in Chapter 4 to evaluate the risk level of navigation environment in bridge waters.

4.1 The Basic Principles of Index System to Be Established

The establishment of scientific and reasonable evaluation index system is one of the key issues of risk assessment (Su, 2005). Whether the index system is scientific and reasonable or not, will be directly related to the final results of the assessment. Therefore, the index system must be objective, reasonable and scientific, as far as possible and practicable to reflect its impacts on system safety (Zhou, 2011). There are many factors related to navigation environment in bridge waters. They have both natural attribute and societal attribute, so it is a little difficult to establish the index system. Therefore, in order to establish a set of scientific and reasonable evaluation index system, the following guiding ideology and basic principles should be followed.

1) Goal-based approach. The establishment of the index system should be centered on the designed evaluation object. The assessment should be carried out objectively. On this ground, the aim of establishing evaluation index system is to achieve the set goal and put forward constructive and effective suggestions to safety management of navigation environment in bridges waters.

2) Scientific principle. The index system should be selected and determined scientifically. Only based on the scientific principles, can the true and objective information be obtained and credible evaluation results will be got.

3) Systematic and hierarchial principle. Navigation environment in bridge waters involves societal attributes (navigation order) and natural attributes (natural environment). The index system can reflect many aspects of the bridge waters systematically and comprehensively, and the index hierarchy at all levels should also be clearly defined.

4) Operable principle. The design of evaluation index system should be defined corrected and cleared. It is convenient to collect data and develop evaluation standards. The indicators should not be too complex or too simple, which would cause unnecessary trouble to the assessment.

5) Effectiveness and prominence. The index system should include a certain controllable factors to ensure that the feedback information of the assessment results can be perfected by improving some factors of navigation environment in bridge waters. The overall system safety condition should be evaluated. At the same time, the key factors of system should be highlighted.

6) Comparability. The indexes in the same layer of assessment index system should be comparable, and the specific factors should also have the characteristics of versatility and comparability. The indexes that are difficult to be compared should adopt relative value or fuzzy value and avoid using absolute value. Not only the actual situation can be reflected, but also the advantages and disadvantages are easy

to be compared with, and finally the safety status of system can be got.

7) The combinations of qualitative and quantitative analysis. That is, on the basis of qualitative analysis, quantitative analysis should be carried out if possible. Because only by quantifying the index, the results of them can be revealed more accurately. Quantitative risk assessment is very useful in decision making when the safety system is complex. For example, it focuses on the uncertainty quantification and can create a vivid picture of the safety condition (Apostolakis, 2004, pp.515-520). For the qualitative indexes are in lack of statistical data, scores, the experts' advice should be followed. In this way, the indexes are approximately quantitative to make it both objective and subjective in risk assessment.

4.2 Determination of Assessment Index

Navigation environment is the exterior environment that all types of ships have to depend on in navigation, berth and operation in bridge waters, including water, underwater and coastal resources (MOC, 2011). Navigation environment in bridge waters has both the natural attributes and societal attributes, involving four major areas, such as seafarers, ship, environment and management. In the study of navigation environment in bridge waters, usually human factors and management factors are not taken into consideration. This article assumes that seafarers on the ship have certificates and they are fit for their jobs, and the maritime management is scientific and efficient. Collecting and reviewing much literature in the related research field, considering the particularities of bridge waters and experts' viewpoints, risk factors of navigation environment system in bridge waters are divided into four parts: characteristics of ship flow, hydrological conditions, meteorological conditions and navigation conditions.

Among them, the characteristics of ship flow include ship density, ship size, ship speed and ship types. Hydrological conditions include tidal stream, current speed and water depth. Meteorological conditions include winds, storm, typhoons and fog. Navigation conditions include bending in the fairway and bridge axial angle.

4.3 The Establishment of Risk Evaluation Model of Navigation Environment in Bridge Waters

The safety system of navigation environment in bridge waters is divided into three layers. The first layer is the goal layer. The second is the code layer, which is also named as main factor layer. The third is program layer, which is also named as evaluation index layer. Based on the synthesis of system theory, the risk assessment model is established.

4.3.1 Construction of Factor Set and Evaluation set

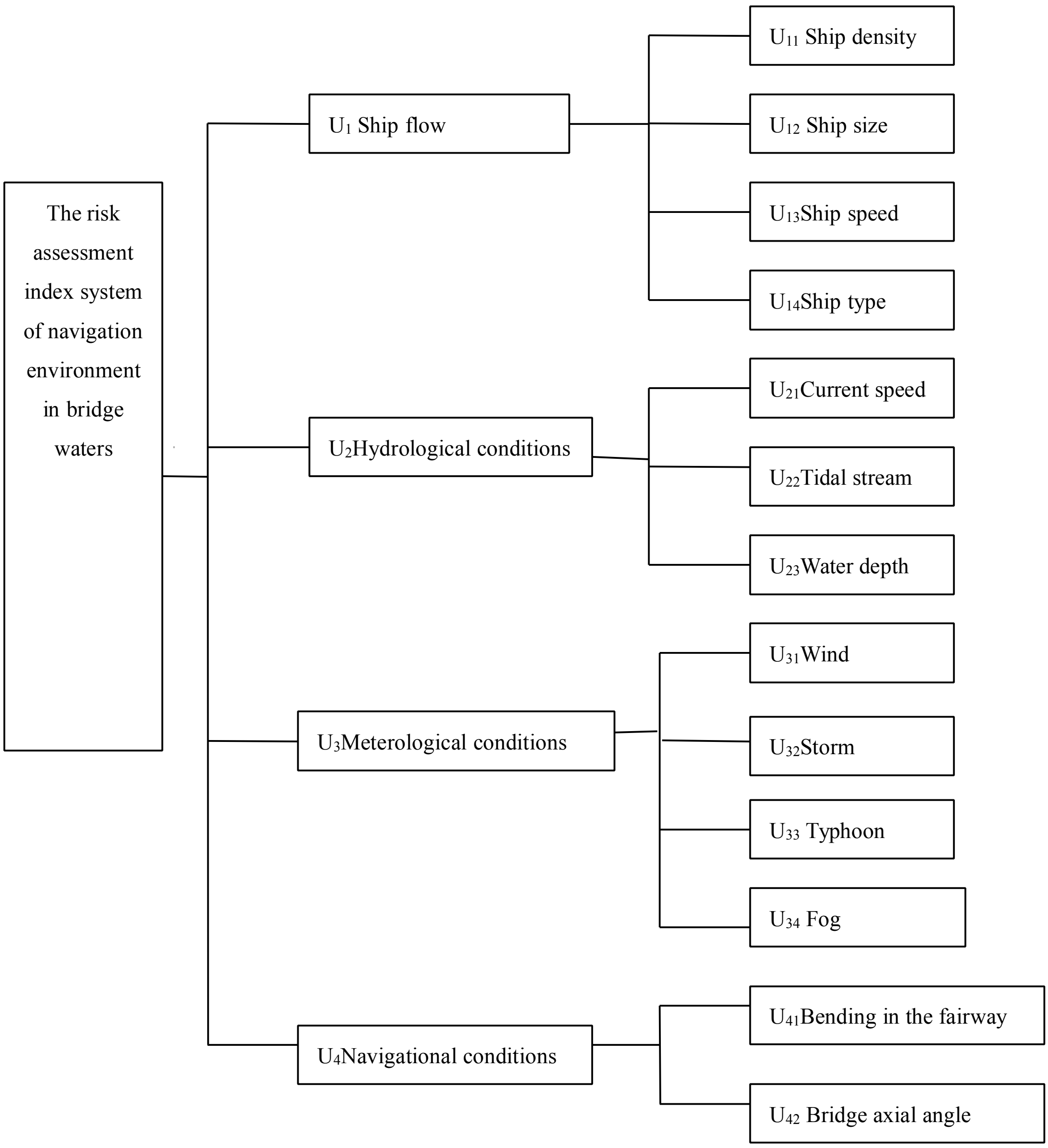


Figure 7-The risk assessment index system of navigation environment in bridge waters

Source: Compiled by the author.

1).The Fuzzy Assessment in First Layer

①Evaluation Factors Set

$U=\{U_1,U_2,U_3,U_4\}$={ characters of ship flow ,hydrological conditions, meteorological condition ,navigation conditions }

②The Characters of Ship Flow

U_1={U_{11},U_{12},U_{13},U_{14}}={ship density, ship size, ship speed ,ship type }

③Hydrological Conditions

U_2= {U_{21},U_{22},U_{23}}={current speed, tidal stream, water depth }

④Meteorological Condition

U_3={U_{31},U_{32},U_{33},U_{34}}={wind, storm, typhoon ,fog }

⑤Navigational Conditions

U_4={U_{41},U_{42} }={bending in the fairway，bridge axial angle }

⑥Evaluation Set

V={V_1, V_2, V_3, V_4, V_5}={very low risk, low risk, moderate risk, high risk ,very high risk }={1,2,3,4,5}

⑦W_i={W_{i1},W_{i2},W_{i3}…,W_{in}} ,where W_{in} indicates the corresponding weight of the i-th factor U_{in}.

⑧ Fuzzy Relation Matrices in the First Layer

$$R_i=\begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ r_{m1} & r_{m2} & r_{m3} & r_{m4} & r_{m5} \end{bmatrix} \quad (4\text{-}1)$$

Where r_{mi} denotes the evaluation value of the m-th evaluation factor to the membership degree of the i -th evaluation grade.

⑨Fuzzy Evaluation Matrix in the First Layer

For the fuzzy synthesis evaluation, assume that the corresponding factor weighting set is W_i, the evaluation matrix of any single factor is R_i, then the evaluation set B_i is

$$B_i=W_i\times R_i=\{b_{i1},b_{i2},b_{i3},b_{i4},b_{i5}\} \quad (4\text{-}2)$$

Where i = 1, 2, 3, ..., k.

⑩Normalizing to standard evaluation matrix

$B_i^*=(b_{i1}^*,b_{i2}^*,b_{i3}^*\ldots,b_{is})$

$$bi^*=\frac{b_i}{\sum_{i=1}^{5} b_i} \quad (4\text{-}3)$$

2).The Fuzzy Assessment in First Layer

①Evaluation Factors Set

$U=\{U_1,U_2,U_3,U_4\}$={ characters of ship flow ,hydrological conditions, meteorological condition ,navigation conditions }

②Evaluation Set

$V=\{V_1, V_2, V_3, V_4, V_5\}$={very low risk, low risk, moderate l risk, high risk ,very high risk }={1,2,3,4,5}

③Weight Values Vector in the Second Layer

$W_i=\{W_{i1},W_{i2},\ldots W_{i5}\}$,where W_{in} indicates the corresponding weight of the i-th factor U_{in}.

④Fuzzy Relation Matrices in the Second Layer

$$R=(B_1^*, B_2^*, B_3^*,B_4^*,B_5^*)^T$$

$$=\begin{bmatrix} b_{11}* & b_{12}* & b_{13}* & b_{14}* & b_{15}* \\ b_{21}* & b_{22}* & b_{23}* & b_{24}* & b_{25}* \\ b_{31}* & b_{32}* & b_{33}* & b_{34}* & b_{35}* \\ b_{41}* & b_{42}* & b_{43}* & b_{44}* & b_{45}* \\ b_{51}* & b_{52}* & b_{53}* & b_{54}* & b_{55}* \end{bmatrix} \quad (4\text{-}4)$$

⑤Fuzzy evaluation matrix in the second layer

$$B=W_i\times R=(b_1,b_2,b_3,b_4,b_5) \quad (4\text{-}5)$$

⑥Normalizing to standard fuzzy evaluation matrix

$B=\{b_1^*,b_2^*,b_3^*,b_4^*,b_5^*\}$

$$b_i^*=\frac{b_i}{\sum_{i=1}^{5} b_i} \tag{4-6}$$

4.3.2 Standards of Evaluation Index

The scientific assessment is closely connected with reasonable assessment standards, the standards are commonly referred to as evaluation criteria. Therefore, in the risk assessment of navigation environment in bridge waters, determining evaluation criteria is one of the important in research. However, there is still not a uniform standard for the risk assessment of navigation environment in bridge waters in the world. Maritime administrations and academics, industry experts in water traffic field have done some research work on risk evaluation standards, but in different periods and regions, the evaluation criteria are different. In this paper, on the basis of the previous studies results, consulting other scholars and experts and refer to the related literature, the assessment index system is divided into five levels: very low risk, low risk, moderate risk, high risk and very high risk, and specific evaluation criteria corresponding to the risk level are developed with fuzzy numbers 1, 2, 3, 4, 5.

Table 1 –The grade table of fuzzy assessment

1	Very Low risk
2	Low risk
3	Moderate risk
4	High risk
5	Very High risk

Source: Compiled by the author.

In order to make the evaluation and its process operative and practicable, based on literature and field research results, the influencing factors of index layer and their evaluation criteria are identified(Hou,2011;Zhao,2010).

Table 2 – The evaluation criteria of influencing factors of index layer

Risk degree Index layer	Influencing factors	Very Low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very High risk 5
Ship density	Vessel traffic volume（ship /day ）	0～30	30 ～ 60	60～100	100～150	≥150
Ship size	Large Vessel traffic volume （ship /day）	≤4	4～10	10～20	20 ～ 30	≥30
Ship speed	Ship speed control	Excellent	Good	Moderate	Poor	Worse
Ship type	Ship carrying dangerous goods/the total Vessel traffic volume（%）	≤10	10 ～ 20	20～30	30 ～ 40	≥40
Current speed	Current speed （kn）	0～0.5	0.5 ～ 2	2～5	5 ～ 7.5	≥7.5
Tidal stream	Maximum tide range（m）	≤2.5	2.5 ～ 5.0	5．0～7.5	7.5 ～ 10	≥10
Water depth	Water depth /draft	≥4	2～4	1.5～2	1.3 ～ 1.5	≤1.3
Wind	Standard wind days（d）/year	≤30	30 ～ 60	60～100	100～150	≥150
Storm rain	Days impacted by storm rain （d）	≤15	15 ～ 25	25～40	40 ～ 50	≥50
Typhoon	The number of typhoon landed and directly influenced	≤2	2～4	4～6	6～8	≥8
Fog	Poor visibility days /year	≤15	15 ～ 25	25～40	40 ～ 50	≥50
Bending in the fairway	Maximum bending in the fairway （°）	0～15	15 ～ 30	30～45	45 ～ 60	≥60
Bridge axial	The angle between the normal of bridge axis in main navigation	≤5	5～8	8～11	11 ～ 14	≥14

angle	channel and the mainstream direction of the falling and flooding current					

Source: Compiled by the author.

4.3.3 The Application of AHP Method to Determining Weight of Factors

Currently, the vast majority of risk assessment is involved in determining weight. Weight is the degree of importance of indexes and their contributions to the assessment system (Su, 2000). The weight plays a role in the assessment process; it is directly related to the results of the evaluation. Because the weights are not only the important weight coefficient of factors in the evaluation model, but also they reflect the subjective will of different evaluators.

With regard to the importance of weights in the evaluation process, the determining method is an important research issue of system assessment theory. According to the determining ways, the method can be divided into two kinds: such as subjective weight method and objective weight method. The subjective weight method is the weight value is defined by the evaluators with expertise or other persons subjectively. The methods are widely used: the expert investigation method, Delphi (Delphi) method, and the Analytic Hierarchy Process (AHP) method. The objective weight method is based on the actual information or historical data of the selected factors with the use of mathematical method, weighting coefficients of index are given directly and objectively, which aims to get rid of the subjective factors. The entropy value method and rough set attributes significance method are generally used. Although there are many methods to determine weights, but the most mature and most widely used is the AHP.

AHP was proposed in the 1970s by T.L.Saaty and his partners, who are experts on Operation Research in the United States (Saaty, 1977, PP. 234-281). With this method, people can make decision on complex issues simply and effectively. It is an evaluation method combined qualitative analysis with quantitative analysis; it is flexible to use and easy to understand in the evaluation of complex systems. Besides, this method is a certain degree of accuracy. According to the overall objective of evaluation and decision-making program, by using the AHP method, the assessment system is divided into three levels: the decision-making goal (G), code layer (C) and programs layer (P), using pairwise comparison method to determine the importance of different programs, then the weighs t of $P_l,P_2 \ldots P_n$ to the goal layer (G) will be got(Saaty,1990,PP. 9-26).

In general, the weights of different evaluation factors are not the same in the formal assessment. Therefore, the AHP method can be used to determine the weight of factors of navigation environment system in bridge waters.

Table 3-Scale of Relative Importance

Intensity of importance	Definition
9	Absolute importance
7	Demonstrate importance
5	Essential or strong Importance
3	Weak importance of one over another
1	Equal importance
2、4、6、8	Intermediate values between the two adjacent judgment
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j,then j has the reciprocal value when compared with i.

Source :Saaty, T. L. (1980), *The Analytical Hierarchy Process*, Mc Graw Hill, New York.

1) Evaluation matrix

The result of the pairwise comparison of criteria can be summarized in an evaluation matrix A in which every element a_{ij} (i,j = 1,2, . . . ,n) is the quotient of weights of the criteria, as shown

$$
\begin{array}{cccccc}
 & x_1 & x_2 & \dots & x_n \\
x_1 & a_{11} & a_{12} & \dots & a_{1n} \\
x_2 & a_{21} & a_{22} & \dots & a_{2n} \\
\dots & \dots & \dots & \dots & \dots \\
\dots & \dots & \dots & \dots & \dots \\
\dots & \dots & \dots & \dots & \dots \\
x_n & a_{n1} & a_{n2} & \dots & a_{nn}
\end{array}
\qquad (4\text{-}7)
$$

Assume $A=[a_{ij}]m\times n$, and A is called comparison matrix, the properties of comparison matrix are $a_{ij}>0;a_{ij}=1,a_{ij}=1/a_{ji}$.

2) The mathematical process commences to normalize and find the relative weights for each matrix.

Calculate the normalized decision matrix. The normalized value r_{ij} is calculated as:

$$W_i=\sum_{i=1}^{n}\overline{a_{ij}} \quad i,j=1,2,\dots,n \qquad (4\text{-}8)$$

$$W_i=\frac{W_i}{\sum_{i=1}^{n}\overline{W_i}} \qquad (4\text{-}9)$$

3) Generally, comparison matrix require consistency test, the following are test methods

First, calculate the largest matrix eigenvalues: $\lambda\max=\frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i}$ (4-10)

Second, calculate the consistency index: $CI=\frac{\lambda_{\max}-n}{n-1}$ (4-11)

Third, calculate the final consistency Ratio: $CR=\frac{CI}{RI}$ (4-12)

The value of RI is determined by the table 4.

Table 4-The value table of RI (Random Index)

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Source: Gao,Q. (2010).*The study on risk assessment of water traffic safety over multi-bridge river.* Unpublished master's thesis, Wuhan University of Technology, Wuhan , China.

4) The number 0.1 is the accepted upper limit for CR. If CR <O.1, the evaluation matrix and weighting coefficients can be accepted. Otherwise, the evaluation procedure should be repeated to improve consistency.

5) The coefficient weight of each factor can be obtained by the above analysis. Weight coefficient is also the evaluation index of the code layer to the goal layer:W= $[w_1,w_2,\ldots,w_n]$. The internal weight coefficient of factors subset in program layer $W_i=[w_{i1},w_{i2},\ldots,w_{in}]$ i=1,2…,n

4.3.4 The Determination of Membership Degree

The degree of membership can be defined as: For any element x in universe U, if there is a function value A(x)∈[0,l] correspondingly to it, then A is fuzzy set on universe U, A (x) is referred to as membership X to A (Xie&Liu,2009). When X changes in U, A (x) is a membership function, and it is called membership function of A. If A(x) is closer to 0, it is indicated that the degree of membership of X to A is low. On the contrary, if A (x) is closer to 1, which means that the degree of membership of X to A is high.

Essentially, the process of determining membership function is objective, but for different persons, the cognition and understanding of the same fuzzy concept is different. Therefore, the membership functions established are often not the same, but as long as they can reflect the same fuzzy concept, they will have the similar effect in solving the actual fuzzy problems. So far, the establishment of the membership function mostly relies on experience and experiment. The commonly used methods to establish membership function are expert experience, case method, fuzzy statistics and bivariate comparing and sorting.

In the process of establishing fuzzy assessment model, the commonly used method is conducting experts' questionnaires to construct a single factor evaluation matrix. The application of expert investigation is as follows. Based on years of experience and viewpoints of experts, the experts give their assessment and score of each factor in the questionnaire. Then the evaluator who conducts investigation should collect the scoring of experts, corresponding to the assessment level and their probabilities of risk factors are calculated. After the normalization of these values again, the degree of membership of each factor corresponding to its evaluation level will be gained. And finally the single factor evaluation matrix can be got. Degree of membership of single risk factor questionnaire and degree of membership of experts' questionnaire can be designed as the Table 4 and Table 5.

Table 5-Degree of membership of single risk factor questionnaire

Risk factor Ui	L_1	L_2	L_3	L_4	L_5
Evaluation standard 1					
Evaluation standard 2					
……					
Evaluation standard N					

Source: Compiled by the author.

Table 6- Degree of membership of experts' questionnaire

Risk factor	L_1	L_2	L_3	L_4	L_5
Factor R_1	（0.8）	(0.2)			
Factor R_2	（0.1）	（0.1）	（0.3）	（0.2）	（0.3）
…	…	…	…	…	…
Factor R_N			（0.3）	（0.3）	（0.4）

Source: Compiled by the author.

4.3.5 Evaluation Model

According to the evaluation results of the single factor, the weights of the indexes can be calculated on corresponding risk level, then the evaluation matrix R will be established.

$$R=\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ . \\ . \\ . \\ R_m \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & \dots & r_{1n} \\ r_{21} & r_{22} & r_{23} & \dots & r_{2n} \\ r_{31} & r_{32} & r_{33} & \dots & r_{3n} \\ . & . & . & \dots & . \\ . & . & . & \dots & . \\ . & . & . & \dots & . \\ r_{m1} & r_{m2} & r_{m3} & \dots & r_{mn} \end{bmatrix} \quad (4\text{-}13)$$

Where $\sum_{j=1}^{n} r_{ij}=1$ （i=1,2,3…m）

When the weights set of risk factors A and evaluation matrix R are identified, according to the weighted average fuzzy operator, implementing matrix multiple, the Fuzzy comprehensive evaluation set B can be achieved.

$$B=A\times R=(a_1,a_2,a_3\ldots a_m)\times\begin{bmatrix} r_{11} & r_{12} & r_{13} & \ldots & r_{1n} \\ r_{21} & r_{22} & r_{23} & \ldots & r_{2n} \\ r_{31} & r_{32} & r_{33} & \ldots & r_{3n} \\ . & . & . & \ldots & . \\ . & . & . & \ldots & . \\ . & . & . & \ldots & . \\ r_{m1} & r_{m2} & r_{m3} & \ldots & r_{mn} \end{bmatrix}=(b_1,b_2,b_3\ldots b_n) \quad (4\text{-}14)$$

As the weight coefficient of risk factors on the previous layer is known, and the evaluation results above can be regarded as degree of membership of the factors in the previous layer, so the evaluation results of the previous layer can be obtained and calculated. Sequentially, the final evaluation results can be obtained.

First, the risk factors in the second layer are evaluated, followed by the factors in the first layer, and finally, the evaluation vector B will be got.

4.3.6 Illumination of Evaluation Vector

Comprehensive evaluation set B is a fuzzy vector. The membership vector is the degree of membership of evaluation object to the evaluation grade. When determining the risk level of evaluation object, the fuzzy vector needs to be anti-fuzzy, which is also known as illumination (Xie&Liu, 2009).

In this paper, the weighted average method is applied to complete the illumination process of evaluation vector. In order to get a clear evaluation results, rank vector G = (1, 2, 3, 4, 5) is set in this paper, a quantization value M of comprehensive evaluation will be obtained by defuzzification process (M=B×G). According to the value M, referring to fuzzy evaluation grade table, the appropriate risk level of assessment will be found out, eventually, this risk level and its definition showing the final evaluation results of the risk assessment of navigation environment in bridge waters and the safety condition are identified.

4.4 Summary

The establishment of risk assessment model is important in the process of risk assessment, and it is also the necessary part of the risk assessment of navigation environment in bridge waters.

In this chapter, first, the index system of navigation environment in bridge waters is introduced, and then the evaluation indexes are determined. Finally, the risk evaluation model of navigation environment in bridge waters is established.

Chapter 5 Case Study - Risk Assessment of Navigation Environment in the Quanzhou Bay Cross -Sea Bridge Waters

Based on the risk evaluation model established in Chapter 4, the Quanzhou Bay Cross-Sea Bridge waters is taken as a case for research on the risk level of its navigation environment in Chapter 5. Besides, in view of the main risk sources identified in the process of risk assessment, the risk degrees of them are evaluated and calculated with the use of queuing model and PRA method.

5.1 The Navigation Environment in the Quanzhou Bay Cross-sea Bridge Waters

5.1.1 Navigation Environment in Bridge Waters

5.1.1.1 Hydrological Conditions

(1) Tide

The bridge is being established in Quanzhou Bay port, according to the data observed from February 12 to March 14 2009 in the three temporary tide-gauge stations: Xiangzhi, Shihu, and Xunpu, the discriminant values in tide gauge stations were 0.285, 0.279, 0.269 respectively, all of them were less than 0.5, so the tides in harbor are regular semidiurnal tides.

1) The tidal datum plane relationship

About 30km ENE direction of the bridge site is the Chongwu ocean station of State Oceanography Bureau, the station and the tidal datum plane relationship is shown in

Figure 8.

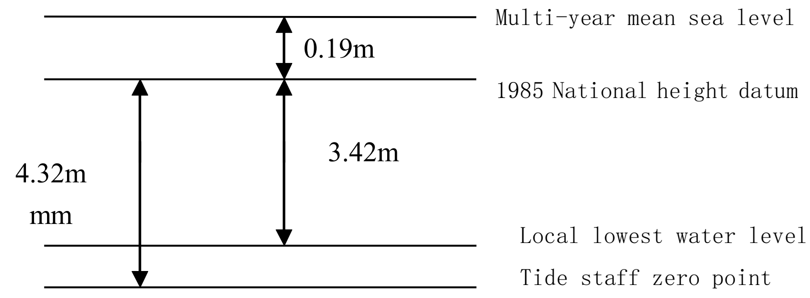


Figure 8-Yellow Sea 56, the height datum is 0.029m below 1985 National height datum

Source: Compiled by the author based on the historical data from Quanzhou MSA

2) Tide

According to the observed data in the three temporary tide-gauge stations: Xiangzhi, Shihu, and Xunpu tide, the statistical Eigenvalue can be analyzed. The tidal Eigenvalue of the three stations are shown in Table 7.

Table 7- The table for tidal Eigenvalue of the stations

Item	Tide station		
	Xiangzhi	Shihu	Xunpu
Mean water level(cm)	14	22	33
Highest water level (cm)	315	336	357
Lowest water level (cm)	-308	-285	-264
Mean high water level (cm)	237	252	264
Mean low water level (cm)	-199	-190	-178
Mean tight range (cm)	435	441	442
Maximum tide range (cm)	589	578	563
Minimum tide range (cm)	180	186	189
Mean duration of rise (hour/minute)	6：08	5：58	5：45
Mean duration of fall (hour/minute)	6：15	6：26	6：39
Tide datum	1985 National height datum		

The year of materials	February 12～march 14,2009

Source: Compiled by the author based on the historical data from Quanzhou MSA

(2) Tidal Stream

The third Institute of State Oceanography Bureau State carried out hydrology and sediment observations for Quanzhou Bay Cross-sea Bridge waters, and the tidal stream is as follows (Tang, J.J, CH, C.H, &Wen, S.H., 2011):

1) Current Speed and Direction

During the spring tide period, in the bridge waters, the observed results are as flows, the maximum current speed of flooding tide is 105cm /s, current direction is 278 º (W) (3 # station, 0.2H layer).

The maximum current speed of falling tide is 109cm /s, current direction is 137 º (SW) (2# station, surface, and 0.2H layer).

In the intermediate tide duration, the maximum current speed of flooding tide is 88cm/s, current direction is 268 º (W) (3# station, 0.2H layer). The maximum current speed of falling tide is 74cm/s, current direction is 160～115º (surface of 2# station and 3# station).

In the low tide duration, the maximum current speed of flooding tide is 56cm/s, current direction is 313 º (W) (2# station, surface). The maximum current speed of falling tide is 46cm/s, current direction is 135º (2# station, 0.2H layer).

Vertical distribution of the current speed is that the general current speed decreases with increasing of water depth. During the spring tide period in bridge waters, the average current speed is higher in the perpendicular of flooding and falling tide. The current speed of the maximum perpendicular of flooding tide is 93cm/s, current direction is 278 º (W) (3 # stations).

The current speed of the maximum perpendicular of falling tide is 93cm/s, current direction is 131 º (W) (2 # stations).

The average current speed of the perpendicular of flooding and falling tide is 46cm/s～51cm/s in 1 # stations of bridge waters.

2) The Nature and Field of Tidal Stream

The tidal stream in bridge waters is regular semidiurnal tide stream and reciprocating current. The maximum current speed in flooding and falling tide appears in the duration of half tide, the flooding and falling slack water appear near the turning of tidal stream period.

(3) Waves

The Quanzhou Bay is located to the west side of the Chongwu Island, where the northeast wind is prevailed, and the bay is mainly affected by the wind and waves from east. Outside of the bay, throughout the year, the wind and wave directions are main NNE and NE. The directions of wind and waves change with the season, in autumn and winter, the main waves direction is NNE, its direction is NE in spring and SW in summer.

The annual average wave height of Chongwu Island is 0.9m, the maximum annual average wave height 1.1m (1974) and the minimum is 0.7m (1962). In recent years, the maximum wave height is 4 to 5m, appearing in typhoon period from June to October.

5.1.2 Meteorological Conditions in Bridge Waters

Quanzhou is located in the southeast Fujian Province and the west side of the Taiwan Strait. Located at the mouth of the Jinjiang River and the Luoyang River, which is at the edge of land and tidal water mouth, Quanzhou Bay's climate belongs to subtropical oceanic monsoons. The annual average temperature is 20.4 °C, the hottest month is July, and the coldest ones are January or February.

5.1.2.1 Temperature

The average temperature in Quanzhou is about 19.5°C to 21.0 °C, that in the hottest month is 26°C to 29 °C and in coldest month is 9 °C. The extreme maximum temperature was 38.7 ° C on August 16, 1966. The lowest temperature was 0.1 °C on January 27, 1963. And the annual and daily temperature range in Quanzhou is relative small, the average daily range in 5.3 ° C.

5.1.2. Rainstorm

The Annual rainfall is about 1291 mm and the number of rainy days is about 120.7. The most rainy month is June. From February to April is spring rainy period, May and June are rainy period, from July to September is typhoon period, and from October to January is dry winter season. The distributional percentages of rainfall are about 33%, 33%, 23%, 10% respectively in the rainy period, typhoon period, spring rain period and winter dry season. Annual rainfall changes too much, the precipitation is 1750 mm in the years 1959 and 1961 and the minimum is only 750 mm in year 1967. Generally speaking, the longest consecutive rainfall days every year are more than 10 days. In May 1975, the longest consecutive days are 21 and the rainfall is 234 mm. Daily maximum precipitation was 300 mm.

5.1.2.3 Fog

The average annual number of foggy days is 29.4 days, and in most years, the largest number of foggy days is 46 days. Foggy days appear from February to May, turning to be rare in October and November and none in September.

5.1.2.4 Wind

Quanzhou is subject to typical monsoon. For many years, the average wind speed is 6.9m /s in bridge waters. Strong wind direction is N and EN, maximum wind speed is 24m/s, the extreme wind speed is 32.6 m/s, the most frequent wind direction is NNE and its frequency is 28%. SSW wind is prevailed in summer, EN and NNE winds are dominated in other months, and the maximum frequency is 45%, the average wind days with wind scale of 6 and above is about 91 every year. The maximum wind speed of every direction, average wind speed, and frequency are shown in Table 8 and Figure 9.

Table 8- The statistical chart of maximum wind speed, mean wind speed and frequency from every direction

Item	N	NNE	EN	ENE	E	ESE	SE	SSE
Maximum wind speed	24	24	24	17	14	18	20	14

(m/s)								
Mean wind speed (m/s)	4.1	8.2	8.4	6.5	4.1	3.6	3.9	4.1
Item	S	SSW	SW	WSW	W	WNW	NW	NNW
Maximum wind speed (m/s)	18	21	18	18	9	12	10	18
Mean wind speed (m/s)	4.6	5.8	4.7	3.5	2.7	3.2	2.5	3.4
Frequency (%)	4	8	8	2	1	0	0	1
The year of material	Maximum wind speed:1956～1980 Mean wind speed:1971～1980 Frequency:1956～1980							

Source: Compiled by the author based on the data from Quanzhou MSA.

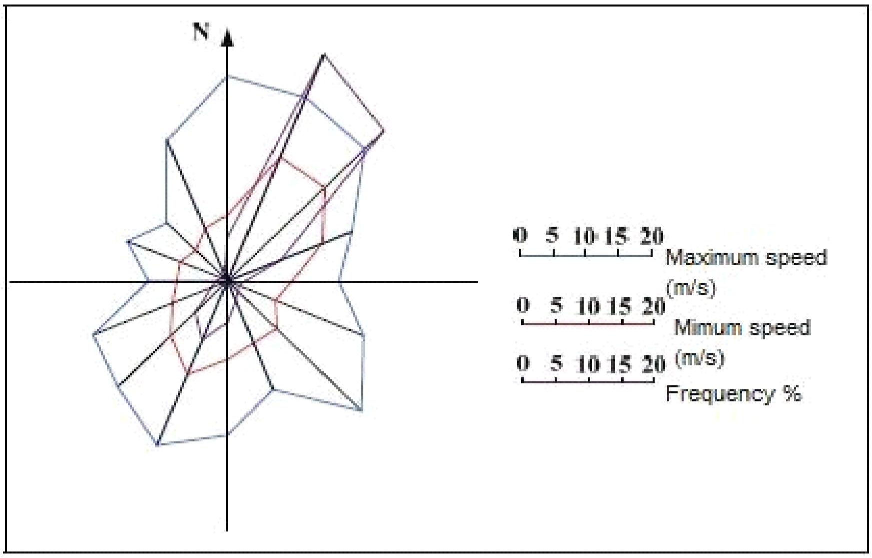


Figure 9-Breeze rose diagram
Source: Compiled by the author based on the data from Quanzhou MSA.

5.1.2.5 Typhoon

The coastal areas of Fujian Province are frequently affected by typhoon and tropical storm, the Quanzhou Bay is located in the middle part of the Fujian coastal area, and it is frequent typhoon zone. From 1949 to 1997, the statistics show that a total of 248 tropical cyclone made landfall in and attacked at Fujian Province with an average number of 5.06 every year. And the maximum number is 13 and the minimum is 1. Among the tropical cyclones, typhoon accounts for 70.6%. The earliest time for typhoon landing is in mid-May, and the latest time is in early October. Most of typhoons last from June to September, accounting for 94.3%. The earliest time that typhoon affects coast water began in early April and the latest influence was terminated in early December, the frequently influences period is from June to September, accounting for 84.3%, especially August. When the typhoon approaches, storm rain and storm surges are usually accompanied. In the Quanzhou Bay harbor, sometimes, the wind scale is above 8, the observed wind speed is more than 40 m/s, the maximum wind speed is up to 60 m /s.

According to the decryption of century typhoon file by Quanzhou Meteorological Bureau, during the 121 years from1884 to 2005 (the data of 1943 was missing), a total of 3063 tropical cyclone were generated in the western North Pacific and the South China Sea with an average of 25.3 per year, and a total of 40 tropical cyclones made landfall in Quanzhou, every three years there is one tropical cyclone made landfall in Quanzhou. Table 9 shows the number of typhoon made landfall Quanzhou monthly from 1884 to 2005

Table 9 –The number of typhoon made landfall Quanzhou monthly from 1884 to 2005

Month	June	July	August	September	October	Total
Numbers of typhoon made landfall	1	10	14	13	2	40

Source: Compiled by the author based on the data from Quanzhou Meteorological Bureau.

During the 121 years, the total number of tropical cyclones affecting Quanzhou is 596 and about 5 annually. Among the tropical cyclones made landfall in Quanzhou, 71% of them are made the second landfall after landing on Taiwan.

5.1.2.6 Storm Surge

Storm surge is prone to occur in Fujian coastal areas. During the 45 years from year 1956 to year 2000, in Fujian coastal area, it was for more than 197 times that water level was increased by 50cm as a result of typhoon and it is an average of occurrence for 4.4 times annually. In the past 10 years, the storm surge disaster in the Fujian coastal area has been more frequent, and it is about 24 times when the water level of the province or part of the coast areas is higher than the local warning level.

In 1996, the Typhoon Herb made landfall in Fuqing, bringing the most serious storm surge in history. Quanzhou suffered a lot, the seawall was broken down, and for the three of seven tide gauge stations, the water levels of them are higher than maximum level in history, water levels of the other four are close to the historical maximum level. The maximum sea level is 30 cm higher than the historical maximum water level, in this case storm surge ,about 21 people died in the city, with a total loss of 4.1 billion RMB.

The sea area is affected by typhoons in summer and autumn every year, storm surge is often generated. According to the storm surge statistics for many years from Chongwu sea station, the maximum sea level increased and reduced by typhoon is about 1.37m and -1.06m respectively. Usually, water level changes in the range from -1.10 m to 1.50 m by the typhoon.

5.1.3 Navigation Conditions in Bridge Waters

5.1.3.1 Fairway Conditions

Currently, there are four fairways in the Quanzhou Bay, such as Quanzhou Bay

Deepwater Channel,the Houzhu Sea Channel,Quanzhou Inner Harbor SeaLanes and Da Zhuimen Fairway.

According to the planning of fairways and anchorages in the Quanzhou Port (Shihu, Xiutu operation area), there are four planning fairways such as Quanzhou Bay Deepwater Channel, Dazhuidao Fairway,The Shi Hu–Houzhu Channel and Xiutu fairway .

5.1.3.2 The Relationships among the Normal of the Axis of Bridge, the Waterways in Bridge Area and Current Direction

As the bridge is being established, according to its recommended bridge position, the direction of axis of main bridge is approximately 037.6°-217.6° and the bearing of normal of its axis is approximately of 127.6 ° -307.6 °. The bearing of fairways is about 143.3 ° -323.3 °. The maximum current speed of flooding tide is 0.92m/s, and the current direction is 314 °. The maximum current speed of falling tide is 1.09m/s, the current direction is 137 °. The angle between the normal of the axis of bridge and the waterway bearing is about 15.7°. The angle between the normal of the axis of bridge and the current direction of maximum flooding tide is about 6.4 °, and the angle between the normal of the axis of bridge and the current direction of maximum falling tide is about 9.4 °. Therefore, both of them are larger than 5 °. According to the bridge navigation standard for seagoing vessel (MOC, 1997), the width of navigation clearance should be increased.

5.1.4 Traffic Management Status in Bridge Waters

At present, in the vicinity of the bridge waters, the state of water traffic safety management is good. The administration that implements supervision and management of the waters is Quanzhou MSA. In terms of safety navigation, prevention and combating marine pollution, and maritime casualty investigation, the administration has developed a complete legal system. For example, Provision of Ship Pilotage and Management in the Quanzhou Port is formulated and implemented.

The ship reporting system (Trial) in Quanzhou Port was implemented on July, 9, 2007. VHF channels 10 and 16 in Coast Radio Station are made use of to give warnings, recommendations safety information services and receive the ship dynamic information. Besides, together with Automatic Identification System (AIS), visualization platform, Closed-Circuit Television (CCTV) and other monitoring equipment, the ships arriving at and leaving Quanzhou Port are statically and dynamically monitored. And dangerous waters, high-risk ships and peak periods of accidents are monitored.

However, the Vessel Traffic System (VTS) has not been set up in the Quanzhou Bay yet, in order to monitor dynamic status of ship and protect the safety construction and operation of bridge; it is recommended the VTS should be established earlier in Quanzhou Bay Port.

5.1.5 Impacts of the Bridge Being Established on Navigation Environment

5.1.5.1 The Analysis of Bridge Waters and Evolution of Seabed

Figure10 shows the comparison of the water depth chart of the Quanzhou Bay Cross-Sea Bridge waters, the sea waters on the north side of the bridge site was washed, as well as the fairway that bridge going across was at substantially steady state from 1998 to 2009. 5 m isobaths are on both sides of fairway, which lies in northwest of the axis of bridge. The range of them in 2009 was slightly narrower than that in 1998, but there was little change in water depth. In the area during the 11 years from 1998 to 2009, the water depth was increased by 0.29m and the average scour rate of water depth is 2.6 cm/a . Therefore, the channel was in a steady state, the washing was caused by widening and excavating fairway from 1995 to 1998. The water depth in south side of tidal areas in bridge waters is becoming slightly deeper, which may be caused by the mining sand activities in this area. The tidal area near the Hanjiang river side is deposited and the average deposited rate is 19.89cm / a.

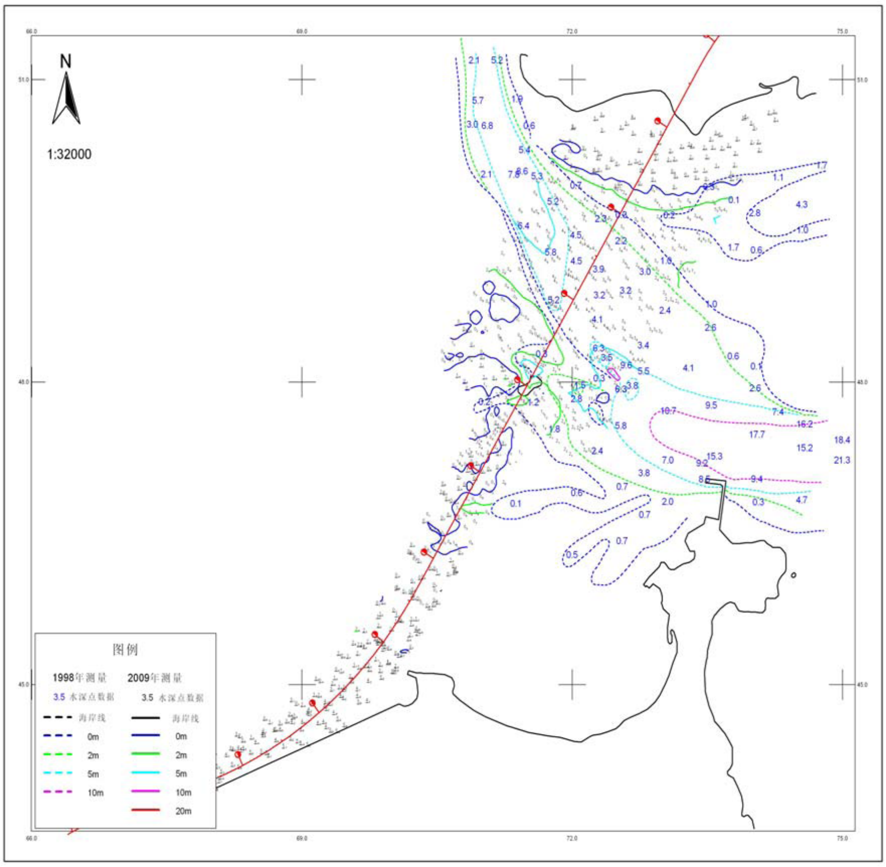


Figure 10 - Comparison of water depth chart of the Quanzhou Bay Cross-sea Bridge waters

Source: Third Institute of Oceanography of State Oceanic Administration (2010). Environmental Impacting Report of Quanzhou Bay Bridge Tunnel Project. Xiamen: Author

5.1.5.2 The Impacts of Bridge on Current

Caps built on pile foundation and piers of the Quanzhou Bay Cross-sea Bridge occupy the project waters, impacting hydrodynamic of nearby bridge waters. According to the results of tidal current and sediment numerical simulation of the Quanzhou Bay Cross-sea Bridge, at the time when the bridge is completed, when the current is flooding and falling, it will flow around the bridge piers and be blocked by piers, the tidal stream pattern will change. Slow current areas are formed in front, SE (low tide) and NW (high tide) of the pier. The current pattern changes little in the waters which are far away from the axis of bridge position. The current speed between the piers increases by 0.03m /s to 0.08m /s.

5.1.5.3 The Impacts of Wind and Current around Bridge Waters on Ship's Safety Navigation

(1) Characteristics of Current around Bridge Waters

When a ship navigates at the hydrostatic speed V_0, α is the angle between ship heading and the current speed vector, according to the law of vector addition, the voyage speed V is equal to the sum of ship Speed V_0 and current speed vector u.

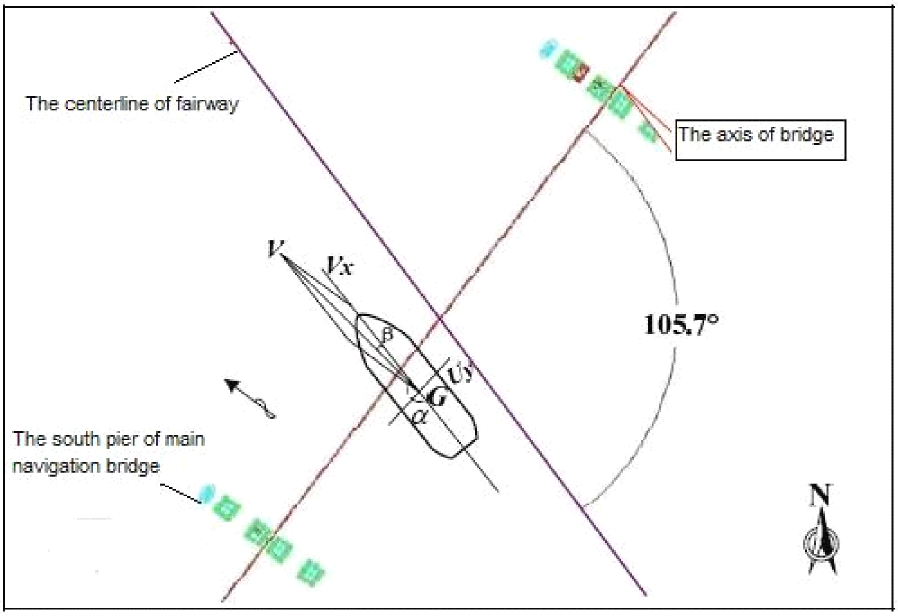


Figure 11 – The impacts of current on ship navigation
Source: Wuhan University of Technology (2010). Navigation Safety Assessment Report of Quanzhou Bay Bridge Tunnel Project. Wuhan: Author.

From figure 11, when there is a certain angle between ship course and current, the ship's speed and voyage track are subject to current, resulting in drifting by current and the voyage track is becoming wider. Therefore, the general requirement of the current direction in bridge waters is parallel to the normal direction of the axis of bridge. According to the bridge navigation standard for seagoing vessel (MOC, 1997), the angle between the normal of the axis of bridge and the current direction of flooding and falling tide should be no larger than 5°. If the angle is larger than 5°, the width of navigation channel should be increased. Generally, it is not allowed to construct bridge in the bending sector, or the sector where the bending degree is small but current speed is fast. However, in the Quanzhou Bay Cross-sea Bridge, it is found that the angle between the normal of the axis of bridge and the main flooding current direction of maximum tide is 6°, the angle between the normal of the axis of bridge and the main falling current direction of maximum tide is 9°, and they doe not meet the standards.

From the viewpoint of bridge constructing, there is a need to increase the width of navigation channel. From the perspective of vessel pilotage and ship safety navigation through the bridge water, current characteristics need to be considered, and navigation course should be corrected for current and wind.

(2) The Impacts on the Passing Ship by Wind and Current

1) The Drifting of Ship by Wind

In order to analyze the impacts of wind on navigation environment, take the designed ship for research object, in poor weather conditions, the drifting of ship by wind can be calculated as follows:

$$\Delta B_\alpha = K(B_\alpha/B_w)^{1/2} e^{-0.14V_s} V_a T \quad (5\text{-}1)$$

Where: K- Coefficient, generally it is from 0.038 to 0.041;

Ba -The wind area upside of the hull waterline (m^2);

B_W- The downside area of the hull waterline (m^2), $Bw = L \times d$ where L is length of ship, d is draft;

Vs - Vessel speed in port (kn);

Va - Relative wind speed (m/s);

T- Drifting time (s), $T=S/V_s$;

S- The distance of ship's straight-line sailing in the fairway, take the multiples of length of ship.

Table 10-The designed ship's drifting distance caused by wind Unit: m

Ship type	Beaufort Wind Scale	Descriptive Terms	L	2L	3L	4L	5L	6L
5000Tonner General Cargo Ship	4	Moderate Breeze	2.39	4.77	7.16	9.55	11.93	14.32
	5	Fresh Breeze	3.23	6.46	9.70	12.93	16.16	19.39
	6	Strong Breeze	4.17	8.34	12.51	16.67	20.84	25.01
	7	Moderate Gale	5.17	10.33	15.50	20.66	25.83	30.99
	8	Fresh Gale	6.25	12.51	18.76	25.01	31.26	37.52
5000Tonner General Cargo Ship	4	Moderate Breeze	3.10	6.20	9.30	12.40	15.50	18.60
	5	Fresh Breeze	4.20	8.40	12.60	16.80	20.99	25.17
	6	Strong Breeze	5.42	10.83	16.25	21.66	27.08	32.49
	7	Moderate Gale	6.71	13.42	20.13	26.84	35.55	40.26
	8	Fresh Gale	8.12	16.25	24.37	32.49	40.62	48.14

Source: Wuhan University of Technology (2010). Navigation Safety Assessment Report of the Quanzhou Bay Bridge Tunnel Project. Wuhan: Author.

2) The Drifting of Ship by Current

When the ship is navigating in the waterway in bridge waters, under the effect of current ,the drifting of ship by current can be calculated as the following formula: $\Delta B_w = V_c T \sin\alpha$ (5-2)

Wherein: V_C-Current speed

α-Current pressure angle;

T -drifting time (s), T = S/V;

S-The distance of ship's straight-line sailing in the fairway, take the multiples of length of ship.

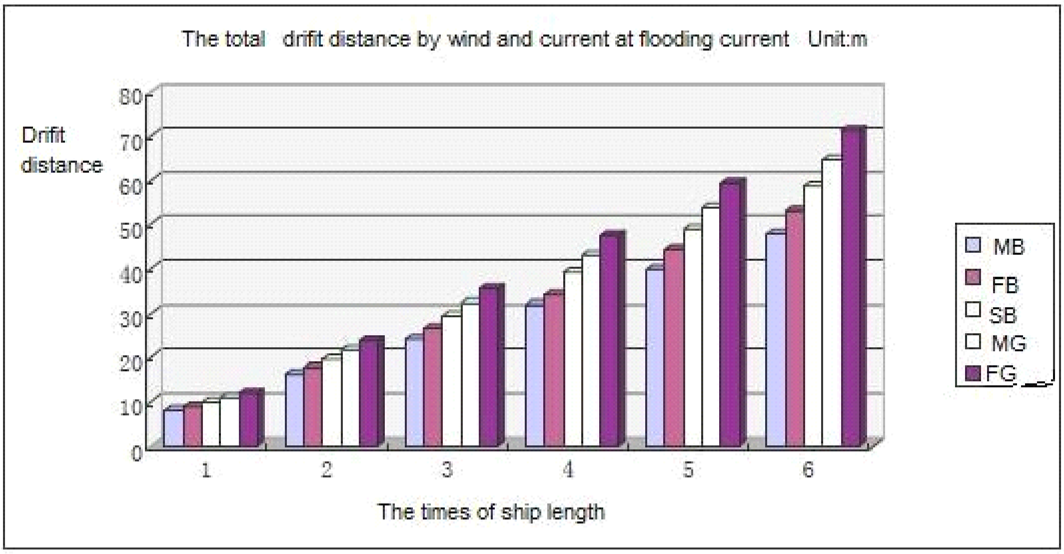
Table 11-The drifting distance of designed ship type by current Unit: m

Ship type	Tidal stream	L	2 L	3L	4L	5L	6L
5000 Tonner General cargo ship	Flood current	5.61	11.22	16.83	22.44	28.05	33.66
	Falling current	4.70	9.40	14.09	18.79	23.49	28.19
10000 Tonner General cargo ship	Flood current	6.73	13.46	20.20	26.93	33.66	40.39
	Falling current	5.64	11.28	16.91	22.55	28.19	33.83

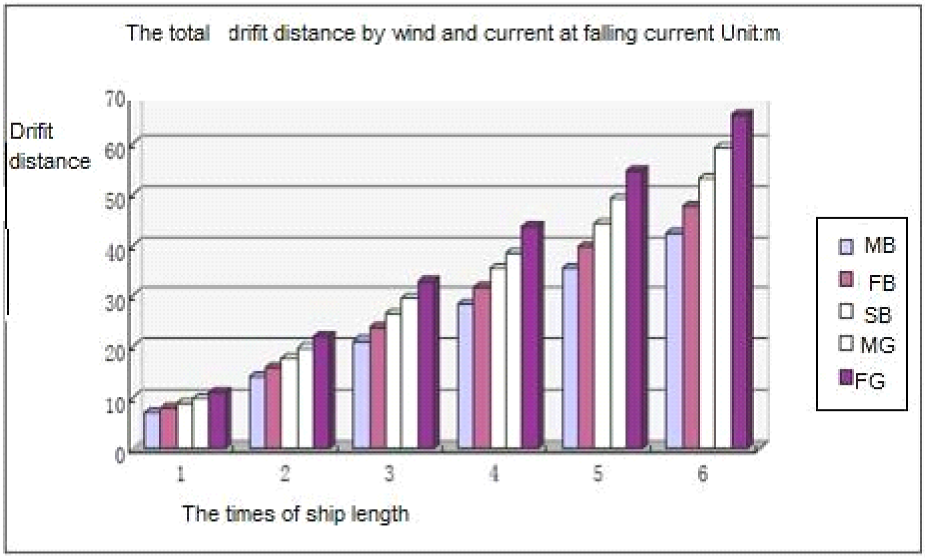
Source: Wuhan University of Technology (2010). Navigation Safety Assessment Report of the Quanzhou Bay Bridge Tunnel Project. Wuhan: Author.

3) The Drifting of Ship by Wind and Current

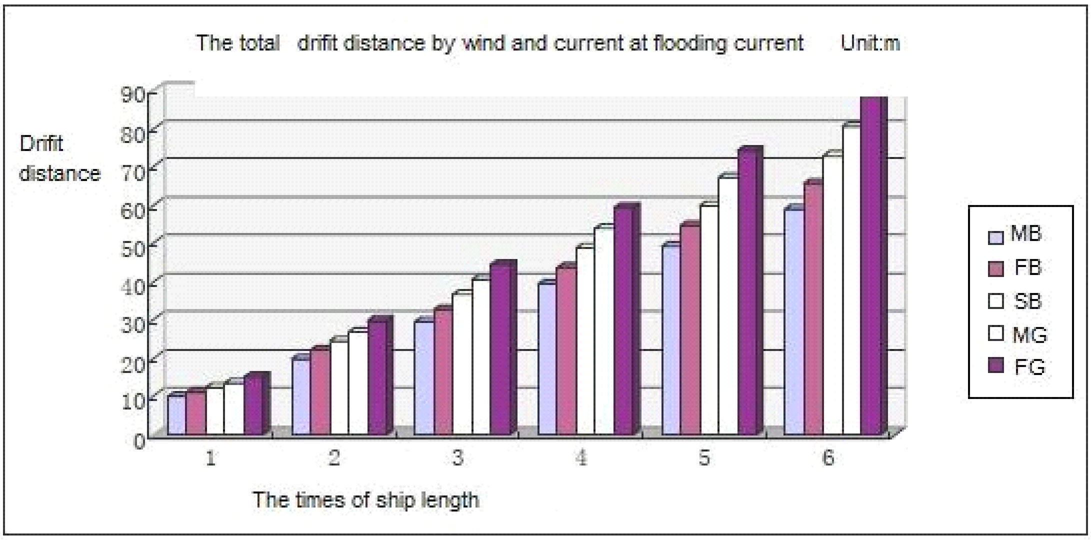
Under the influence of wind abeam and current abeam, the drifting distance of ship can be shown in Figure 12 to Figure15.



Note: MB: moderate breeze. FB: fresh breeze. SB: strong breeze.
MG: moderate gale. FG: fresh gale.
Figure12-The 5000 Tonner ship's total drifting distance by wind and current at flooding current
Source: Wuhan University of Technology (2010). Navigation Safety Assessment Report of Quanzhou Bay Bridge Tunnel Project. Wuhan: Author.



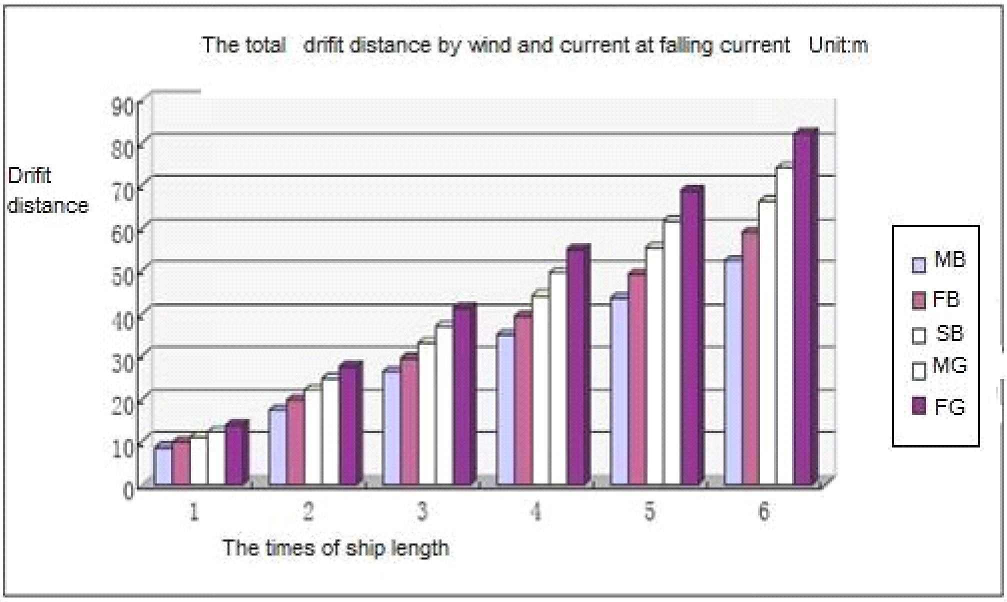
Note: MB: moderate breeze. FB: fresh breeze. SB: strong breeze.
MG: moderate gale. FG: fresh gale.
Figure13-The 5000 Tonner ship's total drifting distance by wind and current at falling current
Source: Wuhan University of Technology (2010). Navigation Safety Assessment Report of the Quanzhou Bay Bridge Tunnel Project. Wuhan: Author.



Note: MB: moderate breeze. FB: fresh breeze. SB: strong breeze.
MG: moderate gale. FG: fresh gale.
Figure14-The 10000 Tonner ship's total drifting distance by wind and current at

flooding current

Source: Wuhan University of Technology (2010). Navigation Safety Assessment Report of the Quanzhou Bay Bridge Tunnel Project. Wuhan: Author.



Note: MB: moderate breeze. FB: fresh breeze. SB: strong breeze.
MG: moderate gale. FG: fresh gale.

Figure 15-The 10000 Tonner ship's total drifting distance by wind and current at falling current

Source: Wuhan University of Technology (2010). Navigation Safety Assessment Report of the Quanzhou Bay Bridge Tunnel Project. Wuhan: Author.

For the 5,000Tonner general cargo ship, six times of the length of ship is about 750m. For the 10000Tonner general cargo ship, five times of the length of ship is about 750m. When the ships navigate close to the cross-sea bridge waters, within the distance of 750m, the wind scale is fresh gale. Figure 12 shows that the total drifting distance of 5000 DWT ship by wind and current at flooding current is 71.18m, and Figure 13 shows that the total drifting distance of 5000 DWT ship by wind and current at falling current is 65.71m. Figure 14 shows that the total drifting distance of 10000 DWT ship's by wind and current at flooding current is 88.53m, Figure 15 shows that the total drifting distance of 10000 DWT ship by wind and current at falling current is 81.97m. As the drifting distance is long, the ship should be cautious in passing the bridge waters.

5.1.5.4 The Analysis of Ship Traffic Density in Bridge Waters

With the rapid growth of throughput of Quanzhou port, the vessel traffic density of ships arriving at port and leaving port in Quanzhou Bay has increased significantly. The ship types of the Quanzhou Bay are container ship, bulk cargo ship and small and medium-sized vessels carrying dangerous cargo, the ship density of this bridge waters ranked first in Quanzhou harbors.

According to the statistics of Quanzhou MSA, in 2007, the number of ships arriving at and leaving the Quanzhou Bay was 11,391 and it was about 31ships every day. In 2008, the ships entering and leaving Shihu Port developing area is 3094 trips, domestic ships accounted for 95%, the total gross tonnage of them was 13,115,000 and the total deadweight of them was 14,955,000. The ships entering Houzhu developing area were 2281 trips, 98% of them were domestic ships, the total gross tonnage of them is 6,063,000 and the total deadweights of them is 8,893,000.

According to the statistical data, the characteristics of ship traffic flow in the Quanzhou Bay can be analyzed as follows:

Figure 16 shows that ships entering and leaving port are ones with the 1000 GT to 9999GT, accounting for 61.8%. The statistical data from Quanzhou MSA shows that 86.6% of the ships 10000 GT and above are container ship.

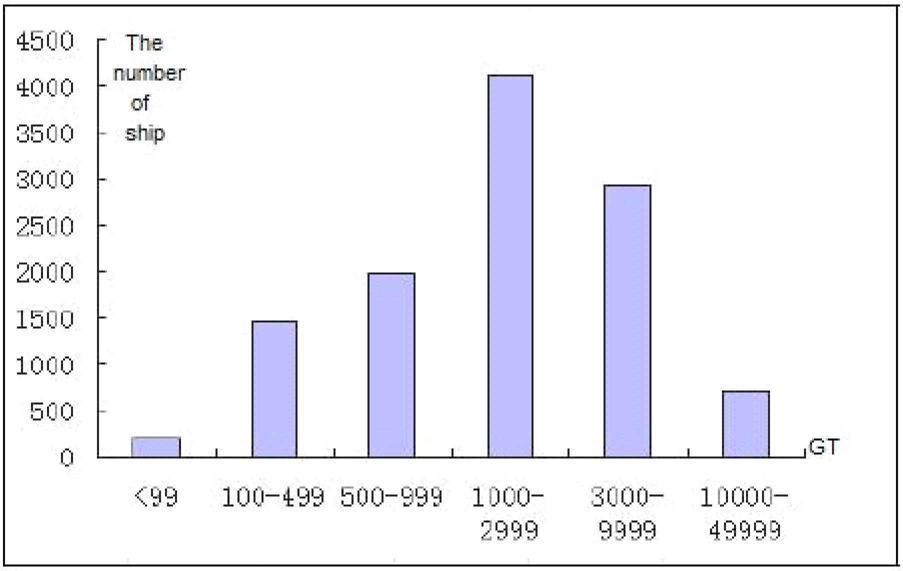


Figure 16 - The ship GT distribution in the Quanzhou Bay from 2006 to 2008
Source: Compiled by the author based on the data from Quanzhou MSA

Figure 17 shows that the main types of ships are cargo ships in the Quanzhou Bay, with a percentage of 89.3%, and container ship accounts for 29.4% of the total cargo ship, leaving vessels carrying dangerous goods with 13%. Statistics data shows that the 68.1% of vessels carrying dangerous goods ships are mainly from 500 to 2999 DWT.

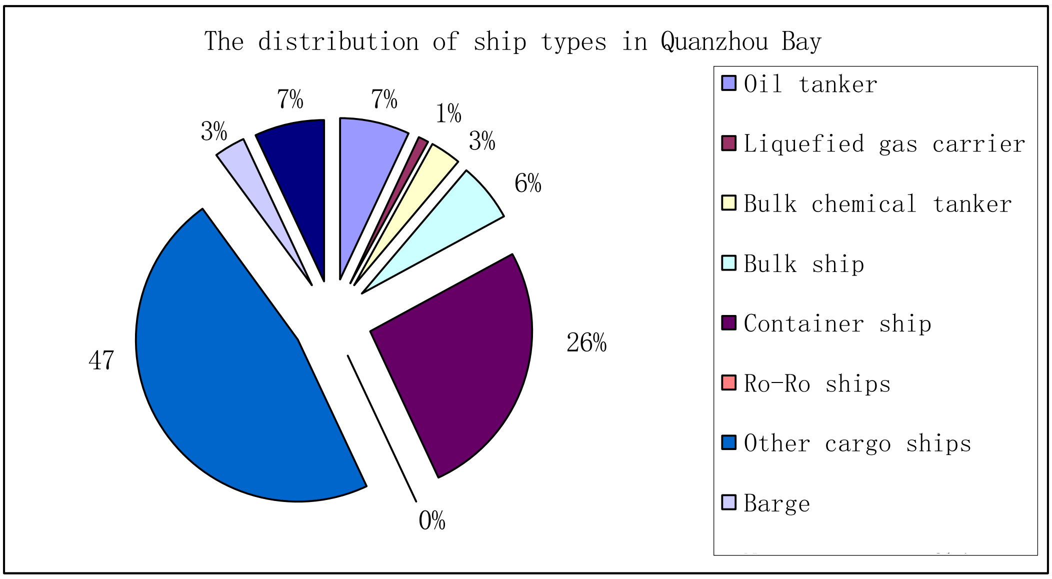


Figure 17 – The types of ship distribution in the Quanzhou Bay from 2006 to 2008
Source: Compiled by the author based on the data from Quanzhou MSA.

Statistics data show that there are about 1695 and 509 fishing boats under the jurisdiction of Shishi branch and Fengze branch of Quanzhou MSA. The sizes of fishing boats are relatively small. Besides, other types of ship are frequently navigating in Quanzhou Bay, mining sand ships are one typical example.

Considering the current situation of Houzhu port operating area and Inner Harbor pier operating point, in the constructional and operational period of bridge, the ships that passing through the bridge waters are bulk cargo ships, oil tankers and fishing boats, Table 12 shows the ship types and tonnage entering and leaving Quanzhou Houzhu harbour from 2006 to 2008, most of the ships are below 5000 Tonner with a percentage of 89.7%.

Table 12- The types of ship and tonnage that enters and leaves the Quanzhou Houzhu harbour from 2006 to 2008

Ship type	Below 3000 tonner	3000～5000 tonner	5000～10000 tonner	10000～20000 tonner
General cargo ship	1311	1600	0	0
Bulk ship	1190	1587	310	303
Container ship	3511	3600	594	491
Liquid cargo ship	1816	108	0	0
Passenger ship	0	0	0	0
Total	7828	6895	904	794

Source: Compiled by the author based on the data from Quanzhou MSA

5.1.5.5 Statistical Analysis of Maritime Accidents in Bridge Waters

Figure 18 shows the maritime accidents and nearmisses data of Quanzhou MSA from 2007 to 2009, the number of accidents and nearmisses occurring in the Quanzhou Bay was 76 with more than 100 vessels involved. Among the types of accidents and near misses, others are main types of accidents, such as seafarer's sickness, but most of them don't pose much threat to ship safety. Besides, the frequency of collision and grounding accidents are relatively higher. Figure 19 demonstrates the location of some types of accidents in the Quanzhou Bay from 2008 to 2009, such as grounding, collision, contact and others. It indicates that the collision accidents often occur in the bridge waters where the Quanzhou bay Cross-Sea Bridge is being established. Therefore, the analysis of the probability of ship-bridge collision has far-reaching significance for the sake of ship and bridge safety.

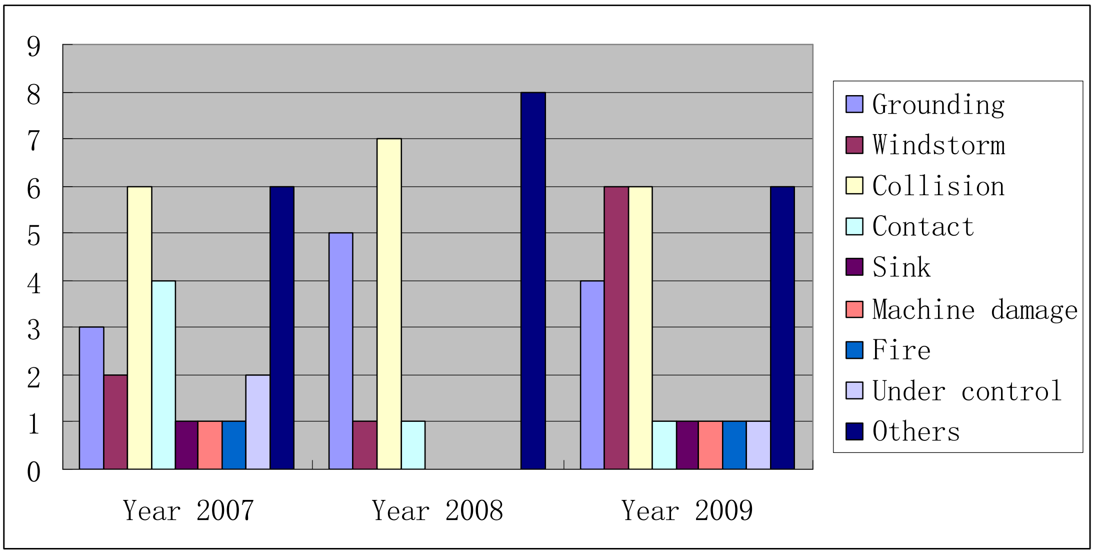


Figure18- The total number of accidents and near misses from 2007 to 2009
Source: Compiled by the author based on the data from Quanzhou MSA

Figure 19–The location of some accidents in the Quanzhou Bay from 2008 to 2009
Source: Compiled by the author based on the data from Quanzhou MSA

From the analysis of dangers and accidents data, the characteristics of them can be found out. Firstly, the main types of accident in the Quanzhou Bay waters are collision and grounding. But there are many windstorm accidents in July 2009. Secondly, seasonal accidents and dangers are obvious, most of the dangers and accidents occurred in January and July. Thirdly, the general cargo ships are always the main type of vessels that have accidents and dangers in the waters.

In recent years, collisions accidents have occurred in the bridge waters. They are mainly caused by improper operation. Therefore, the ship passing the waters should strictly follow the Conventions on the International Regulations for Preventing Collisions at Sea 1972(1972) and or provisions related to safety navigation in Quanzhou MSA to avoid collision and general average accidents. Furthermore, seafarers should be fully familiar with the waterway condition, for example, aids to navigation should be identified and applied correctly. And good seamanship should be employed to prevent stranded accidents.

5.1.5.6 Analysis of Ship- Bridge Collision Accidents

Vessel-bridge collision is one of the outstanding problems in construction and operation of bridge. This paper will analyze two vessel-bridge collision accidents occurring in Fujian Province and other Provinces.

On the early morning of February 14, 2009, a cargo ship Jin 68 carrying nearly 2,000 tons of cement collided at the bridge pier when passing through the Wulongjiang high-speed bridge, the hull was damaged. Finally, half of ship hull sank and submerged in the water. The cause of this accident was that the seafarers were not familiar with the conditions of Fuzhou fairway or hydrological environment

On the afternoon of November 16, 2009, the ship *MV/M.KIMITSU* was not anchored in the permitted anchorage waters, and due to the strong wind and high waves, the ship's anchor was dragging, and finally, the ship collided at two piers of non-navigation channel of Jintang Bridge.

At 4:20 on May 12 in 2013,a seagoing vessel *Xin chuan 8* collided at the pier between the sixth and seventh channel of Nanjing Yantze River Bridge, finally ,the ship sank at 3.5 km downstream of the bridge at the north shore shallow waters and then 18 seafarers on ships were rescued ,but the bridge was temporarily undamaged.

The analysis of the collision accidents indicates that vessel-bridge accidents are mainly caused by the following factors.

(1) Seafarers are not familiar with the waterway in bridge waters.

(2) The ship is under command due to the impacts of bad weather and complex current conditions.

(3) The position of ship anchorage near the bridge waters does not conform to the regulations. The ship may be dragging anchor during the anchoring period.

(4) The aids to navigation are not timely set and updated in the bridge waters.

(5)Most of cross-sea and cross-river bridge piers are not installed with anti-collision equipment.

It is noteworthy that some of the vessel-bridge collision accidents occur in bridges waters when bridges are being established. For example, on March 5 in 2012, an operational vessel *Qi shun bo* collided at the piers of north construction trestle of the Quanzhou Bay Cross-Sea bridge. During the period of bridge construction, safety navigation management of bridge waters does not keep up with practical needs. Seafarers are not familiar with navigation provisions in bridge waters. What is more, the navigation environment is complex when the bridge is being built up.

5.2 The Risk Assessment of Navigation Environment in the Quanzhou Bay Cross-Sea Bridge Waters

According to fuzzy comprehensive evaluation model set up in Chapter 4, the risk assessment of navigation environment in the Quanzhou Bay Cross-Sea Bridge waters, which is also the second step of the FSA methodology in risk assessment. The navigation environment in the Quanzhou Bay Cross-Sea Bridge waters will be evaluated and its risk level will be depicted.

5.2.1 Calculating Weights of Risk Factors in Every Layer

Pairwise comparison matrix results are obtained by the expert investigation, the weights of each factor can be calculated one by one.

Table 13-Weights of goal layer

Primary index	U_1	U_2	U_3	U_4	Normalized weights
U_1	1	5	3	5	0.557864618
U_2	1/5	1	1/3	1	0.09632537
U_3	1/3	3	1	3	0.249484642
U_4	1/5	1	1/3	1	0.09632537
λmax =4.043 CI=0.0144 CR=0.016					1

Source: Compiled by the author.

Table 14- Weights of ship flow factors

Secondary index	U_{11}	U_{12}	U_{13}	U_{14}	Normalized weights
U_{11}	1	1/5	1	1/7	0.077555612
U_{12}	5	1	3	1/3	0.282080291
U_{13}	1	1/3	1	1/3	0.108910465
U_{14}	7	3	3	1	0.531453631
λmax =4.1756 CI=0.0585 CR=0.065					1

Source: Compiled by the author.

Table 15-Weights of hydrology condition factors

Secondary index	U_{21}	U_{22}	U_{23}	Normalized weights
U_{21}	1	1/5	1/7	0.07192743
U_{22}	5	1	1/3	0.278954565
U_{23}	7	3	1	0.649118005
λmax =3.0649 CI=0.0324 CR=0.0559				1

Source: Compiled by the author.

Table 16-Weights of meteorological condition factors

Secondary index	U_{31}	U_{32}	U_{33}	U_{34}	Normalized weights
U_{31}	1	1/5	1/3	1	0.104546774
U_{32}	5	1	1/3	3	0.307663483
U_{33}	1	3	1	3	0.469001673
U_{34}	1	1/3	1/3	1	0.118788069
λmax =4.260 CI=0.0868 CR=0.096					1

Source: Compiled by the author.

Table 17-Weights of navigation conditions factors

Secondary index	U_{41}	U_{42}	Normalized weights
U_{41}	1	1/3	0.25
U_{42}	3	1	0.75
λmax =3.0649 CI=0.0324 CR=0.0559			1

Source: Compiled by the author.

Table18 –The index weight table from APH method

Primary index	Secondary index	Primary weight	Secondary weight	Goal weight
Characteristics of ship flow U_1	Ship density U_{11}	0.557864618	0.077555612	0.043265532
	Ship size U_{12}		0.282080291	0.157362614
	Ship speed U_{13}		0.108910465	0.060757295
	Ship type U_{14}		0.531453631	0.296479177
Hydrological condition U_2	Current speed U_{21}	0.09632537	0.07192743	0.006928436
	Tidal stream U_{22}		0.278954565	0.026870402
	Water depth U_{23}		0.649118005	0.062526532
Meteorological condition U_3	Wind U_{31}	0.249484642	0.104546774	0.026082814
	Storm rain U_{32}		0.307663483	0.076757314
	Typhoon U_{33}		0.469001673	0.117008714
	Fog U_{34}		0.118788069	0.029635799
Navigation condition U_4	The bending in the fairway U_{41}	0.09632537	0.25	0.024081343
	Bridge axial angle U_{42}		0.75	0.072244028

Source: Compiled by the author.

5.2.2 The Determination of Index Value of Risk Evaluation of Navigation Environment

A large number of investigations and researches are carried out on navigation environment information of Quanzhou Bay Cross-sea Bridge waters, the evaluation criteria of influencing factors in index layer introduced earlier in chapter 4 was referred to. Finally, the influencing factors index values of navigation environment in the Quanzhou Bay Cross-sea Bridge waters are determined.

Table 19-The index values of influencing factors of the navigation environment in the Quanzhou Bay Cross-sea Bridge Waters

Index signs	Influencing factors	Values
Ship density	Vessel traffic volume （ship /day）	14
Ship size	Large Vessel traffic volume（ship /day）	4.6
Ship speed	Ship speed control	Moderate
Ship type	Ship carrying dangerous goods/the total Vessel traffic volume（%）	13
Current speed	Current speed（kn）	2.18
Tidal stream	Maximum tide range（m）	5.89
Water depth	Water depth /draft	1.48
Wind	Standard wind days（d）annually	91
Storm rain	Days impacted by storm rain (d) annually	120.7
Typhoon	The number of typhoon landed and directly influenced	5
Fog	Poor visibility days /year	29.4
Bending in the fairway	Maximum bending in the fairway （°）	38
Bridge axial angle	The angle between the normal of bridge axis in main navigation channel and the mainstream direction of the falling and flooding current	9.4

Source: Compiled by the author.

5.2.3 Qualitative Evaluation of Influencing Factors of Navigation Environment in the Quanzhou Bay Cross-Sea Bridge Waters

According to the evaluation criteria of influencing factors of index layer set up in Chapter 4, based on the index values of influencing factors of the navigation environment in the Quanzhou Bay Cross-Sea Bridge waters, qualitative evaluation results can be achieved.

Table 20–The qualitative risk evaluation results of navigation environment in the Quanzhou Bay Cross-sea Bridge Waters

Risk degree Index layer	Influencing factors	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Ship density	Vessel traffic volume （ship /day ）					
Ship size	Large Vessel traffic volume （ship /day）					
Ship speed	Ship speed control					
Ship type	Ship carrying dangerous goods/the total Vessel traffic volume（%）					
Current speed	Current speed （kn）					
Tidal stream	Maximum tide range （m）					
Water depth	Water depth /draft					
Wind	Standard wind days （d）annually					
Storm rain	Days impacted by storm rain （ d ） annually					
Typhoon	The number of typhoon landed and					

	directly influenced					
Fog	Poor visibility days /year					
Bending in the fairway	Maximum bending in the fairway （°）					
Bridge axial angle	The angle between the normal of bridge axis in main navigation channel and the mainstream direction of the falling and flooding current					

Note: The risk level 1, 2, 3, 4 and 5 can be expressed with the color green, blue, yellow, orange and red respectively.

Source: Compiled by the author.

5.2.4 The Establishment of the Risk Matrix and Calculation of Evaluation Vector

In carrying out risk assessment of navigation environment in bridge waters with fuzzy evaluation assessment model, the risk assessment starts from the calculation of risk factors in the second layer. First, degree of membership of risk factors in the second hierarchy is calculated, and based on the weights value calculated in section 5.2.1, and then the evaluation results of risk factors in the second hierarchy can be achieved. And the evaluation results can be regarded as the degree of membership of risk factors in the first layer, calculation should be made similar to the above, thereby the final evaluation results will be obtained.

In determination of the degree of membership of each evaluation factors, the expert investigation method was used, about 30 questionnaires were handed out to the duty officer in Quanzhou MSA command center who were in charge of search and rescue job, on-site law enforcement officers, pilots, seafarers, all of the questionnaires were submitted and collected, the final degree of specialist memberships was calculated. Considering the actual navigation environment in Quanzhou Bay Cross-Sea Bridge waters, the actual degree of membership and the evaluation matrix are established.

Degree of membership of the single influencing factor and evaluation degree are collected in Appendix 2.

Table 21-The factual degree of membership of the influencing factors and evaluation grade

Primary index	Secondary index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Characteristics of ship flow U_1	Ship density U_{11}	0.3	0.3	0.2	0.1	0.1
	Ship size U_{12}	0.3	0.2	0.3	0.1	0.1
	Ship speed U_{13}	0.1	0.3	0.3	0.2	0.1
	Ship type U_{14}	0.2	0.3	0.3	0.1	0.1
Hydrological condition U_2	Current speed U_{21}	0.1	0.2	0.3	0.3	0.1
	Tidal stream U_{22}	0.3	0.1	0.3	0.2	0.1
	Water depth U_{23}	0.1	0.4	0.4	0.1	0
Meteorological condition U_3	Wind U_{31}	0.1	0.1	0.4	0.3	0.1
	Storm rain U_{32}	0.3	0.2	0.2	0.2	0.1
	Typhoon U_{33}	0.3	0.2	0.2	0.2	0.1
	Fog U_{34}	0.1	0.3	0.3	0.2	0.1
Navigation condition U_4	The bending in the fairway U_{41}	0.5	0.2	0.1	0.1	0.1
	Bridge axial angle U_{42}	0.5	0.2	0.1	0.1	0.1

Source: Compiled by the author.

Risk matrix can be achieved as following:

$$R_{U1}=\begin{bmatrix}0.3 & 0.3 & 0.2 & 0.1 & 0.1\\0.3 & 0.2 & 0.3 & 0.1 & 0.1\\0.1 & 0.3 & 0.3 & 0.2 & 0.1\\0.2 & 0.3 & 0.3 & 0.1 & 0.1\end{bmatrix}$$

$$R_{U2}=\begin{bmatrix}0.1 & 0.2 & 0.3 & 0.2 & 0.1\\0.3 & 0.1 & 0.3 & 0.2 & 0.1\\0.1 & 0.4 & 0.4 & 0.1 & 0.0\end{bmatrix}$$

$$R_{U3}=\begin{bmatrix}0.1 & 0.1 & 0.4 & 0.3 & 0.1\\0.3 & 0.2 & 0.2 & 0.2 & 0.1\\0.3 & 0.2 & 0.2 & 0.2 & 0.1\\0.1 & 0.3 & 0.3 & 0.2 & 0.1\end{bmatrix}$$

$$R_{U4}=\begin{bmatrix}0.5 & 0.2 & 0.1 & 0.1 & 0.1\\0.5 & 0.2 & 0.1 & 0.1 & 0.1\end{bmatrix}$$

Therefore the risk matrix in first level U_1, U_2,U_3,U_4 can be calculated as the flowing :

$$U_1=\begin{bmatrix}0.077555612 & 0.282080291 & 0.108910465 & 0.531453631\end{bmatrix}\times$$

$$\begin{bmatrix}0.3 & 0.3 & 0.2 & 0.1 & 0.1\\0.3 & 0.2 & 0.3 & 0.1 & 0.1\\0.1 & 0.3 & 0.3 & 0.2 & 0.1\\0.2 & 0.3 & 0.3 & 0.1 & 0.1\end{bmatrix}=\begin{bmatrix}0.2251 & 0.2718 & 0.2922 & 0.11109 & 0.1000\end{bmatrix}$$

$$U_2=\begin{bmatrix}0.1558 & 0.3019 & 0.3649 & 0.1351 & 0.0351\end{bmatrix}$$

$$U_3=\begin{bmatrix}0.2553 & 0.1076 & 0.2328 & 0.2105 & 0.1000\end{bmatrix}$$

$$U_4=\begin{bmatrix}0.5000 & 0.2000 & 0.1000 & 0.1000 & 0.1000\end{bmatrix}$$

The fuzzy comprehensive evaluatation matrix in the second layer can be calculated as follows:

$$U=\begin{bmatrix}0.557864618 & 0.09632537 & 0.249484642 & 0.09632537\end{bmatrix}\times$$

$$\begin{bmatrix} 0.2251 & 0.2718 & 0.2922 & 0.1109 & 0.1000 \\ 0.1558 & 0.3019 & 0.3649 & 0.1351 & 0.0351 \\ 0.2553 & 0.1076 & 0.2328 & 0.2105 & 0.1000 \\ 0.500 & 0.2000 & 0.1000 & 0.1000 & 0.1000 \end{bmatrix} = \begin{bmatrix} 0.2524 & 0.2268 & 0.2658 & 0.1370 & 0.0937 \end{bmatrix}$$

5.2.5 The Illumination of the Final Evaluation Vector

Based on the risk vector G set in Chapter 4, the final risk evaluation vector of the navigation environment in Quanzhou Bay Cros-Sea Bridge waters will be illuminated, and risk level of navigation environment in Quanzhou Bay Cross-sea Bridge Waters will be obtained. The process of illumination can be calculated as follows:

$M=U\times G=\begin{bmatrix} 0.2524 & 0.2268 & 0.2658 & 0.1370 & 0.0937 \end{bmatrix} \times \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} =2.5199$， according to the illuminated result, we can conclude that the present navigation environment in the Quanzhou Bay Cross–Sea Bridge waters is between low risk and moderate risk .

5.3 Analysis on Vessel Traffic Capacity of Bridge

In chapter 5.2.4, the risk matrix vectors calculated are as follows:

$U_1=\begin{bmatrix} 0.2251 & 0.2718 & 0.2922 & 0.11109 & 0.1000 \end{bmatrix}$

$U_2=\begin{bmatrix} 0.1558 & 0.3019 & 0.3649 & 0.1351 & 0.0351 \end{bmatrix}$

$U_3=\begin{bmatrix} 0.2553 & 0.1076 & 0.2328 & 0.2105 & 0.1000 \end{bmatrix}$

$U_4 = [0.5000\ 0.2000\ 0.1000\ \ 0.1000\ \ 0.1000]$

According to the maximum degree of member law, the risk levels of the four main factors are moderate risk, moderate risk, very low risk and very low risk respectively. Therefore, the ship flow (U_1) and hydrological conditions (U_2) are identified as the first and second major risk sources separately. In 5.3, queuing model is used to predict and analyze vessel traffic capacity in bridge waters. In 5.4, the probability of vessel-bridge collision will be calculated.

From the relative scale of navigation channels of bridge and the bridge fairways, when Quanzhou Bay Cross-Sea Bridge is completed, the bridge does not affect the passage of ships in this waters, but considering the fact that the vessels shall be prohibited from overtaking and going hand in hand in bridge waters, navigable channel will probably restrict the ship passage to Houzhu developing area to some extent, whether the vessel traffic capacity of bridge is able to meet the needs of ships entering and leaving Houzhu developing area will be analyzed.

According to the maritime traffic engineering theory, if we assume the time pattern of traffic flow follows Poisson distribution, the time to pass through the bridge is deterministic distribution, then the queue is an M/G/1 model(Wang,2010,p.145). Therefore, according to queuing theory, M/G/1 model can be applied in the process of ship passing through the bridge.

5.3.1 Queuing Model of Ship Passing through Bridge

The system has only one service window, the time interval for customer arrival at system follows Poisson distribution with parameter λ, for the service time for customer is deterministic distribution G, this queuing system is an M/G/1 model.

For the Quanzhou Bay Cross-Sea Bridge, the ship are only allowed to pass through the navigation channel of bridge, and the ship is prohibited overtaking in the process of crossing bridge, the time interval of ship arrival at the bridge waters approximately follows Poisson distribution, the time of ship passage through bridge is deterministic distribution, M/G/1 queuing model can be established for studying the ship going through bridge (Liu&Yu, 2011, pp.253-254). The various parameters of Queuing model are as follows.

5.3.1.1 Service Rate μ

The service rate refers to the numbers of vessels to pass through bridge and leave the bridge waters per unit time. The service rate is reciprocal of service time. Considering the service rate of a variety of ship types, it can be calculated with the following formula:

$$\mu = 1852 \cdot \sum_{i=1}^{m} \frac{V_i \cdot P_i}{D_i} \tag{5-3}$$

Where: m-The number of ship types in ship flow;

V_i- Ship speed of the ith -type;

P_i-The probability of occurrence of ith-type ship;

D_i -Under the time interval between ith-type ship entering the bridge waters and the next ship can enter the bridge waters, the sailing distance (m) of ith-type ship. It can be calculated as follows:

$D=L+A_U$

Where: L-Length of ship (m);

A_U-The longitudinal safe distance of ship (m).

The longitudinal safety distance of ship A_U can be determined by ship domain model developed by Japanese scholar Fuji. The ship domain is an ellipse shape, taking the give-way vessel as the center, and semi-major axis of ellipse is the same direction as the fore and aft and the semi-minor axis of ellipse is along the direction of ships abeam. The specific scale of Ship domain is related with ship speed, ship density, current and other factors. Under normal conditions, the scale of overtaken vessel is 8L and 3.2L. When ship navigates in the port and narrow waters where the speed needs to be slow down, scale of ship domain can be reduced to 6L and 1.6L. Ship domain is shown in Figure 20.

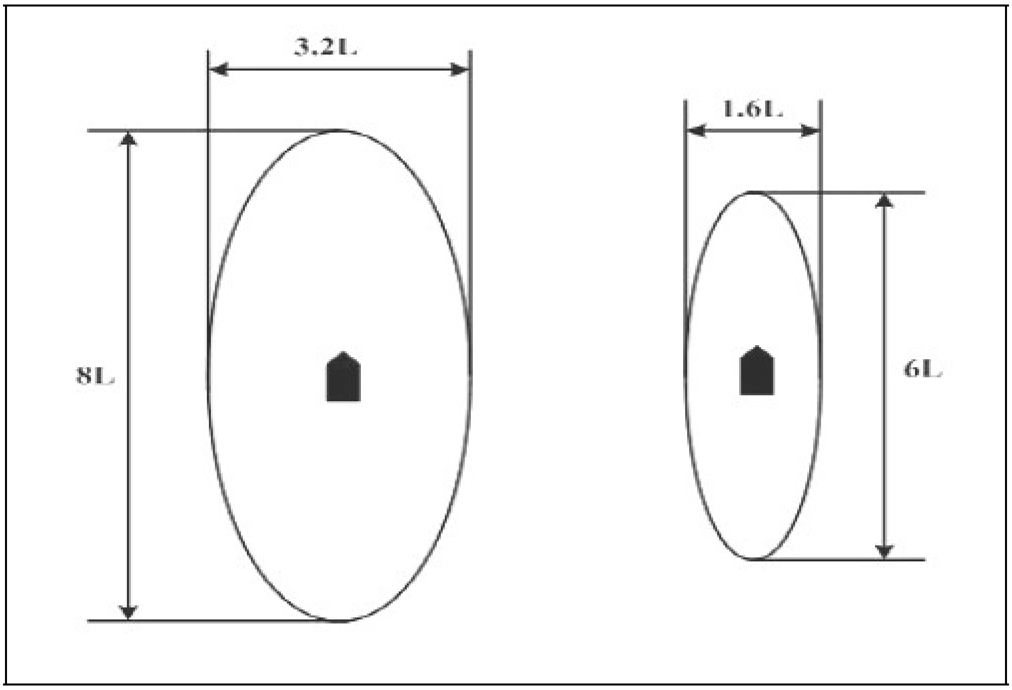


Figure20-The diagram of ship domain

Source:Wu,Z.L,&Zhu,J. (2004).Sea traffic engineering. *Ship domain* (p.120).Dalian: Dalian Maritime University Press.

In the calculation of this bridge waters, the longitudinal safe distance of ship A_U can be valued with 6L and 1.6L.

5.3.1.2 Arrival Rate λ

The arrival rate means that the numbers of ship arrives at the bridge waters ship per unit time, the data can be obtained by observations, statistics and collection of ship flow. The arrival rate of Ship approximately follows Poisson distribution. The arrival rate λ is taken the mean time for a ship arriving at bridge waters.

5.3.1.3 Average length of queue Lq

The average length of queue index Lq in the M/G/1 queuing model provides an important reference for the design of the waiting anchorage for ship passing through bridge. It can be calculated with the following formula:

$$L_Q = \frac{\rho^{2?} + \lambda\ \sigma}{2(1-\rho)} \tag{5-4}$$

where ρ -service intensity of system; λ -arrival rate; σ -service time.

The average waiting time index in the M/G/1 queuing model, reflects the degree of ship free passage, which is the basis to establish navigation order for ship passing through bridge, it can be calculated as follows:

$$W_Q = \frac{L_Q}{\lambda} = \frac{\rho^{2?} + \lambda\ \sigma}{2\lambda(1-\rho)} \tag{5-5}$$

Service intensity of system $\rho = \frac{\lambda}{\mu}$ (5-6)

Where the condition of system equilibrium is ρ＜1, the index indicts whether vessel traffic capacity of channel can meet the requirements of ship flow. The variance of service time σ^2 can be calculated as follows:

$$\sigma^2 = nD\overline{T} = nD\left(\frac{1}{n}\sum_{i=1}^{n} T_i\right) = \frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{Ti} - \mathrm{E}(\mathrm{T})\right)^2$$

$$= \frac{1}{n}\left(\sum_{i=1}^{n1}\left(\mathrm{Ti} - \mathrm{E}(\mathrm{T})\right)^2 + \sum_{i=1}^{n2}\left(\mathrm{Ti} - \mathrm{E}(\mathrm{T})\right)^2 + \ldots \sum_{i=1}^{nk}\left(\mathrm{Ti} - \mathrm{E}(\mathrm{T})\right)^2\right)$$

$$=\frac{1}{n}\left(\left(n_1\left(T_1-E(T)\right)^2+n_2\left(T_2-E(T)\right)^2+\dots n_k\left(T_k-E(T)\right)^2\right)\right) \quad (5\text{-}7)$$

Where n_1、n_2、n_k represents the number of various types of ship, $\sum_{i=1}^{k} n_i$=n; $\frac{n_1}{n}$=p_1, $\frac{n_2}{n}$=p_2, $\frac{n_k}{n}$=p_k, as $E(T)=\frac{1}{\mu}$,therefore the variance of service time calculation formula can be simplified to:

$$\sigma^2=\sum_{i=1}^{k} p_i\left(\frac{1}{\mu}-T_i\right)^2=\sum_{i=1}^{k} p_i\left(\frac{1}{\mu}-\frac{D_i}{1852\cdot V_i}\right)^2 \quad (5\text{-}8)$$

5.3.2 Data Calculation and Results Analysis

The Houzhu developing area lies in the upper part of the Quanzhou Bay Cross-Sea Bridge. According to the overall planning of Quanzhou Port, New berths will not be built in Houzhu developing area and the berths basically maintain the status quo, so it is feasible to use the numbers and types of ships calling at Houzhu operation area to analyze the vessel traffic capacity of the Quanzhou Bay Cross-Sea Bridge. According to the demonstration and research report on navigational clearance scale of Cross-sea Bridge and its technical requirements – channel project of the Quanzhou Bay, the 5000 tonner cargo ship is selected as standard type of ship. For the non-standard ships, they should be converted into a standard ship. The coefficient is the ratio of the length of non-standard ship to the length of standard ship. Table 20 shows the length of various types of ships entering and leaving port and their conversion coefficient.

Table 22-The length of ships arriving and leaving port and their conversion coefficient

Ship type	Below 3000 tonner		3000～5000 tonner		5000～10000 tonner		10000～20000tonner	
	Length(L)	Coefficient (C)	L	C	L	C	L	C
General cargo ship	108	0.87	124	1				
Bulk cargo ship	96	0.77	115	0.93	135	1.09	150	1.21
Container ship	106	0.85	121	0.98	141	1.14	183	1.48
Liquid gas carrier	97	0.78	125	1.01				

Source: Wuhan University of Technology (2010). Navigation Safety Assessment Report of the Quanzhou Bay Bridge Tunnel Project. Wuhan: Author

From the calculation and analysis of table 20, the number of standard ships entering and leaving Houzhu developing area is 15,255 trips from 2006 to 2008. The navigation speed of ship coming across the bridge waters is 8 kn, according to the formula 5-2,the calculated results of service rate $\mu=(1852\times 8)/(125\times 6+125)=16.933$, arrival rate $\lambda=0.5805$, system service intensity $\rho=\lambda/\mu=0.034$, the variance of service time $\sigma^2=0$, the average waiting time $\sigma^2=0$, the average waiting time W_Q=6s. Basically, there is no need for ship to wait to pass through the Quanzhou Bay Cross-Sea Bridge, and it is not necessary to establish waiting anchorage to pass through bridge.

The theoretical vessel traffic capacity of fairway in the Quanzhou Bay Cross-sea Bridge Waters can be calculated as follows:

$$Q=\frac{24\times 3600}{A_U/V} \quad (5\text{-}9)$$

Where: Q- Daily vessel traffic capacity of fairway (trips / day);

A_U-Ship domain (m);

V-Speed in bridge waters (m/s).

5000-tonner cargo ship is selected as the standard ship to calculate the daily vessel traffic capacity of fairways in the Quanzhou Bay Cross-sea Bridge waters, ship speed in bridge waters is 8kn (4.12m/s), *Au*= 6×125=750m. Under the 24-hour navigation conditions, you can calculate the standard vessel traffic capacity of bridge fairways is 474 trips per day. But considering the fairway conditions, the time for the 5,000-tonner ship waiting for tide lasted 2 hours, and the success rate of navigation is 90%, therefore, the daily vessel traffic capacity of bridge fairway is 36 trips. From 2006 to 2008, the number of standard ships entering and leaving Houzhu operation area is 15255; it is about 14 trips every day, and therefore, the vessel traffic capacity of bridge fairway can meet the demand of navigation.

5.4 Ship- bridge Collision Risk Analysis

When a ship navigates through bridge waters, she is subject to hydrological and meteorological conditions. If the maneuverability of ship is not good or the seafarers are not familiar with navigation environment, the ship might collide with the bridge. Based on PRA method, from the aspects of the probability of vessel-bridge collision ship collision force and other aspects, the risk analysis of vessel-bridge collision is carried out.

5.4.1 Risk Analysis of Vessel-bridge Collision

5.4.1.1 Risk Criteria of Vessel-bridge Collision

In general, the risk of the vessel-bridge collision should meet the following two criteria.

The first one is safety criterion. The general practice is to control the probability of bridge collapse if the collision accident happens, which is adopted and implemented as mandatory standards in many countries of the world, and the objective is to reduce the loss of disaster and accident. For example, in AASHTO *Guide Specification* (1991), according to the impacts on economic and society, the bridges are divided into critical and regular ones and the risk probability of designed goal is specified in guidelines. Corresponding to the two kinds of bridges, designed annual goal of probability of failure are as follows: P_f = 0.0001 (critical bridges), P_f = 0.001 (regular bridge).

The second one is risk control criterion. Throughout the whole lifespan of bridge, the total risk expectations of vessel-bridge collision should be the lowest. The probability of annual failure of bridge collapse design in the safety criterion is just the minimum requirements. Taking into account the fact that the loss of vessel-bridge Collision accidents with low risk level is little, but the probability of its occurrence is high, and the total loss will be relatively large.

It is very difficult to carry out deterministic design of ship–bridge collision events. In terms of risk criteria of vessel-bridge collision, the present study is mainly concentrated on the allowable probability of bridge damage, and some focus on the allowable probability of death and the research on the criterion of minimum cost.

The Quanzhou Bay Cross-Sea Bridge is an important bridge. Therefore, it is recommended that the probability of designed annual failure is 0.0001.

5.4.1.2 Causal Analysis of Vessel-bridge Collision

Henrik Gluver and Dan Olsen made research on the causes of ship–bridge collision accidents (Henrik& Gluver, 1998). From the analysis of 152 vessel-bridge collision accidents, there were 107 accidents caused by human error, accounting for 70.4%. 34 accidents caused by natural environment, accounting for 22.4%. Another 11 accidents are caused by mechanical failure with the percentage of 7.2 %. The causes of vessel-bridge collision researched by the 19th Working Group of PINAC are that the proportion of the accident cause of the main 3 categories (human error, natural environment and mechanical failure) is 70%, 10% and 20% respectively (Dai, 2003).

The main factors of bridge–ship collision are human error, equipment failure and environmental impact. From the statistical analysis of vessel-bridge accident, human factor is the main factor for the accidents, but the human error can be reduced by management. It is also important to improve navigation environment in bridge waters to bring the potential hazards under control. Further, it is necessary to improve the technical condition of equipment and its operation in harsh situations.

So we can see that perfecting aids to navigation in bridge waters and the establishment of monitoring facilities, for example, VTS, the establishment and implementation navigation management rules of bridge waters, all of them are effective measures to improve safety navigation in bridge waters.

5.4.1.3 Calculation Model of the Probability of Bridge Collapse in Vessel-bridge Collision Accident

In order to assess the risk of vessel-bridge collision, this paper will analyze vessels not under command and the probability of bridge failure as a result of ship collision. According to the AASHTO *Guide specificatio*n (1991), the probability of bridge failure because of the vessel-bridge collision shall be within 0.0001, the frequency of annual damage caused by collision at bridge pier can be calculated as follows:

$$AF = N \times PA \times PG \times PC \tag{5-10}$$

Where: AF-The annual frequency of collapse (number expected collapses per year);

N-Vessel trip frequency and dead weight tonnage (DWT) data for traffic on a given waterway may be determined from various factors.

PA - The probability of vessel aberrancy;

PG-The geometric probability;

PC-The probability of collapse.

(1) The Probability of Vessel Aberrancy

PA is the statistical probability of ship collision at bridge due to the vessel aberrancy from the normal routes, which may be caused by operational errors, mechanical failure, poor environmental conditions and other reasons.

PA can be obtained with statistical method or calculated method, taking into account the bridge location, current, and vessel traffic density and other influencing factors, it can be calculated as:

$$PA=BR\times R_B\times R_C\times R_{XC}\times R_D \tag{5-11}$$

Where, PA-The probability of aberrancy;

BR -The aberrancy base rate derived from historical accident data from several

U.S.waterways ; for ship , $BR = 0.6\times10^{-4}$ and for barges, $BR = 1.2\times10^{-4}$;

R_B -The correction factor for bridge location; if the bridge area is straight waterway, R_B=1.0.If the bridge waterway waypoint is within 910m from the bridge, $R_B = 1 + \frac{\theta}{45^\circ}$,θ represents the bending in the fairway. If the bridge waterway waypoint is between 910 m and 1920 m from the bridge, $R_B = 1 + \frac{\theta}{90^\circ}$.

R_C -The correction factor for current acting parallel to vessel transit path; $R_c = 1 + \frac{V_c}{19}$;

Vc-The current speed parallel to the direction of the routes

R_{XC}-The correction factor for crosscurrents acting parallel and perpendicular to vessel transit path; $R_{XC} = 1 + 0.54V_{XC}$;

Vxc- The current speed perpendicular to routes direction;

R_D-The correction factor for vessel traffic density. If the traffic density is low ,R_D = 1.0. If the traffic density is moderate, R_D = 1.3. If the traffic density is high, R_D = 1.6.

(2) The Geometric Probability

The geometric probability is conditional probability and it represents the probability of aberrancy when ship not under command is close to the bridge. The geometric probability is defined in AASHTO *Guide Specifications* (1991; 2009) as the shaded area under the curve of normal distribution density function; its boundaries are the sum of width of the pier and half of ship breadth on each side of the pier.

Two statistics are involved in normal distribution function, one is a mean value μ, and the other is the standard deviation σ. If there are enough observational data and they can be obtained by statistics. In the absence of observational data, the sample mean μ is generally on the routes, which is most likely to be selected in navigating through the bridge, but the standard deviation value is more difficult to determine, AASHTO *guide specifications* (2009) take the length of all as the standard deviation of ship or tugs.

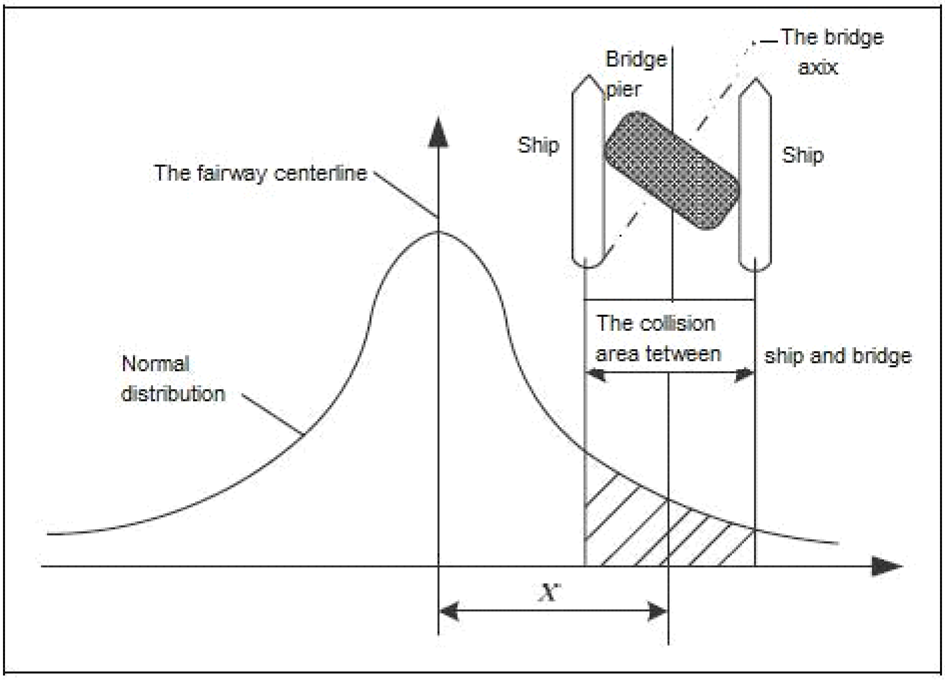


Figure 21– The geometric probability distribution

Source: AASHTO.(2009). *Guide specification and commentary for vessel collision design of highway bridges*, Washington D.C.

(3) The Probability of Collapse

PC is a function of many variables, such as ship size, type, speed, collision direction; the PC also depends on the pier resistance of itself. The probability of collapse curve can be shown in the Figure 22.

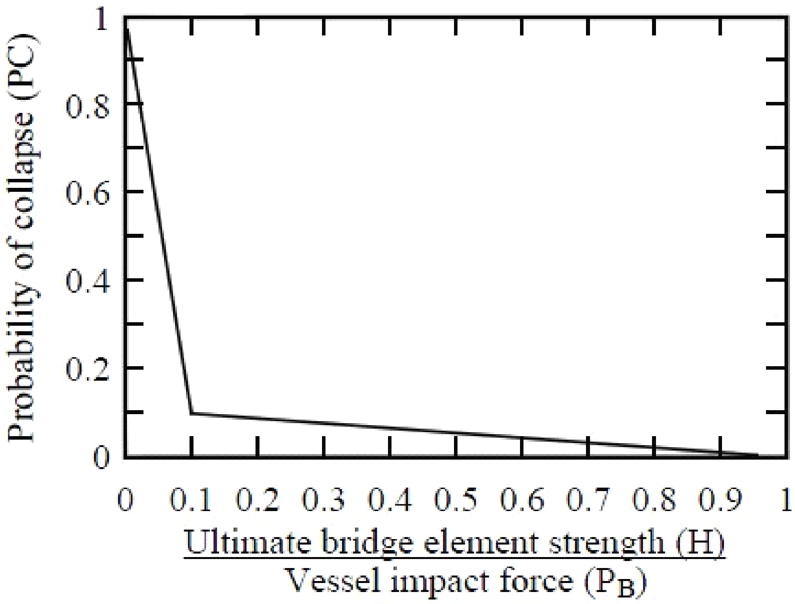


Figure22- Probability of collapse for vessel-bridge collisions (AASHTO, 2009)

Source :AASHTO. (2009). *Guide specification and commentary for vessel collision design of highway bridges*, Washington D.C.

The value of PC depends on the following situations:

1) If $0 \le \frac{H}{P} \langle 0.1$，PC=0.1+9(0.1-$\frac{H}{P}$);

2）If $0.1 \le \frac{H}{P} \langle 1.0$，PC=$\frac{1}{9}\left(0.1-\frac{H}{P}\right)$;

3) If $\frac{H}{P} \rangle 1.0$，PC=0。

Where H is bridge resistance, P is vessel impact force.

Ship collision force can be calculated with the following formula: P=$1.2\times10^{5}V\sqrt{DWT}$. Where V represents ship collision speed (m/s), the maximum speed is ship speed, and the minimum speed is the average current speed; DWT represents displacement of ship.

(4) Risk Acceptance Criteria

According to the AASHTO *guide specifications* (1991), for a regular bridge, the probability of collapse should be less than 10^{-3}. For a critical bridge, the probability of collapse should be less than 10^{-4}.

5.4.1.4 Probability of Bridge Collapse of Quanzhou Bay Cross-Sea Bridge

In bridge waters area, turning point of waterway is 1200 meters far from the bridge, waterway steering angle (bending in the fairway) is 45 °, R_B =1+45°/90°=1.5. Maximum current speed is 1.09m /s ,current direction is 137 °, the direction of fairway is from 143.3 ° to 323.3 ° , R_c = 1.0568 , R_{xc} =1.0594. The correction coefficient of vessel traffic density is taken the correction coefficient of moderate density 1.3.PA can be calculated as follows:
PA=BR×RB×RC×RXC×RD = (0.6×10^{-4}) ×1.5×1.0568×1.0594×1.3=1.3099 × 10^{-4}.

The length of piers along the direction of bridge is 22.5m, the transverse direction is 77.1m, the angle between the axis of bridge and waterway is 15.7 °, and the width of piers along the direction of waterway is 43.4m. Geometric probability (PG) of the 10,000-tonner ship is 0.0909. Geometric probability (PG) of the 5,000-tonner ship is 0.0729.

According to the planning Houzhu sea lanes, the anti-collision design is 5,000-tonner ship, the main pier is recommend to use force dissipation facilities to avoid collision, ship collision force is reduced by 30%, so for the 5000-tonner ship PC = 0. For the 10000-tonner general cargo ship, PC= 0.009.

Statistical data from 2006 to 2008 show that the annual average number of 5000-tonner ships going through the bridge was 566, for the convenience of calculation, all of them are treated as 10,000 tonner ships, and the annual frequency of collapse AF can be calculated as follows:

$AF = N \times PA \times PG \times PC = 566 \times 1.3099 \times 10^{-4}. \times 0.0909 \times 0.009 = 0.61 \times 10^{-4}$

Therefore, the annual frequency of collapse for bridge piers is 0.61×10^{-4}; it is less than the risk acceptance criteria 10^{-4}, and the risk of ship-bridge collision is acceptable.

5.4.2 The Calculation of Ship Impact Force at the Bridge Pier

5.4.2.1 Vessel Impact Speed at the Bridge Pier

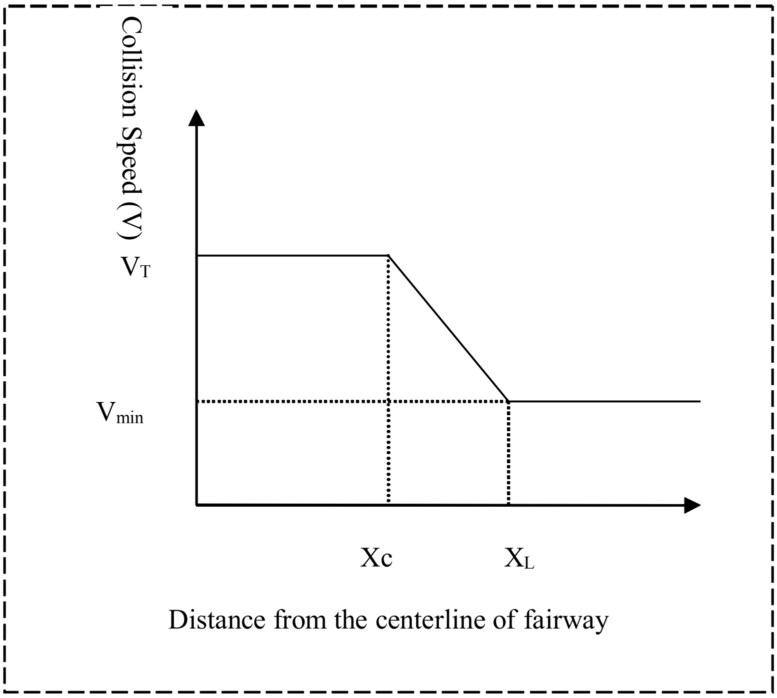


Figure23-The designed vessel impact speed curve at bridge

Source: AASHTO. (2009). *Guide specification and commentary for vessel collision design of highway bridges*, Washington D.C.

The determination of the designed ship collision speed is specified in *Guide specification and commentary for vessel collision design of highway bridges*. In the waterway, the ship is navigating at normal speed. The distance from the centerline the waterway is more than three times of ship length, the ship is drifting at current speed, and the current speed is determined by the average speed of current for years. In the area between them the designed speed is determined by linear interpolation.

Figure 23 shows the designed speed curve of ship collides at bridge, where
V-Designed impact speed;
V_T- The normal speed navigating in the fairway;
V_{min}-The minimum designed collision speed ;
X - Distance from the centerline of piers to the centerline of waterway;
X_C-The distance from the centerline of waterway to the edge of fairway;
X_L-The distance from the centerline of waterway to 3 times of ship length.

With the purpose of safety, in calculating the bridge collision force, the maximum current speed is taken as 1 m/s. The vessel impacting speed at the bridge pier when navigating at the speed of 8 knots is shown in table 23. Figure 24 shows the general location and layout of bridge piers.

Table 23-The vessel impact speeds on the bridge pier when ship navigating at the speed of 8 knots

Ship speed	Bridge pier	Ship type	Navigation Course	Impact Speed (m/s)
8	Z003	10000DWT	East ,West	3.44
		5000DWT	East	3.46
		5000DWT	West	2.06
	Z004	10000DWT	East ,West	3.44
		5000DWT	East	2.06
		5000DWT	West	3.46

knots	Z001	10000DWT	East ,West	1.49
		5000DWT	East	1.45
	Z002	10000DWT	East ,West	2.17
		5000DWT	East	2.16
	Z005	10000DWT	East ,West	2.17
		5000DWT	West	2.16
	Z006	10000DWT	East ,West	1.49
		5000DWT	West	1.45

Source:Wuhan University of Technology (2010). Navigation Safety Assessment Report of Quanzhou Bay Bridge Tunnel Project. Wuhan: Author

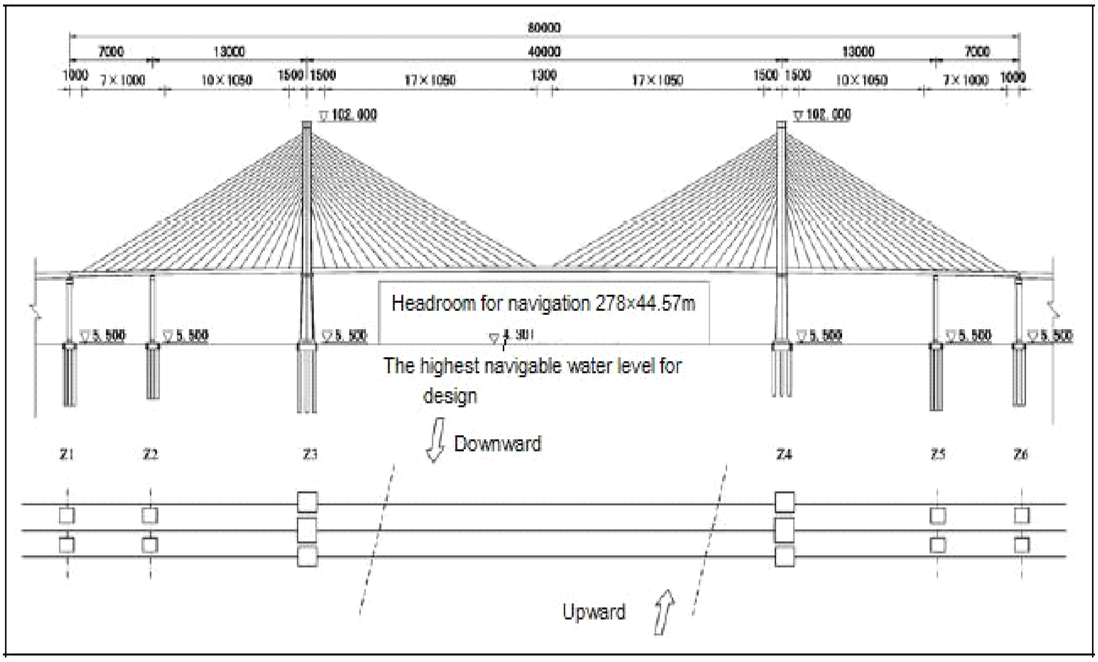


Figure24- Layout of main navigation bridge type of the Quanzhou Bay Cross-sea Bridge

Source: Fujian Provincial Communications Planning and Design Institute(2009).The Feasibility report of the Quanzhou Bay Tunnel Project.Fuzhou,Author..

Figure 25 – Fashion drawing of the Quanzhou Bay Cross-sea Bridge

Source:Fujian Provincial Communications Planning and Design Institute(2009).The Feasibility report of the Quanzhou Bay Tunnel Project.Fuzhou,Author.

5.4.2.2 Specified Formula of Ship Collision Speed

(1) General Code for the Design of Highway Bridges and Culverts (DHBC Code)

The ship collision force in DHBC code is calculated as follows (MOC, 2004):

$$P_m = \frac{W \cdot V}{g \cdot T} \quad (5\text{-}12)$$

Where: P_m - Average impact force (KN);

W –ship weight (KN);

V – Ship Speed (m/s);

T - The time of impact, if there is no information 1 second is taken;

g - Acceleration gravity, 9.81m/s^2.

(2) Fundamental Code for Design on Railway Bridge and Culvert (Railway bridge Code) (MOR, 2005)

$$P=\gamma \times V \times \sin\alpha \sqrt{W/(C_1+C_2)} \quad (5\text{-}13)$$

Where: γ- reduction factor of kinetic force（$m/s^{1/2}$）, when it is positive impact, γ=0.3. When it is oblique impact, γ=0.2.

V - Vessel impact speed (m/s);

α-The angle between vessels approaching direction and the tangent the point impact at pier, it should be determined depending on the circumstances. If there are any difficulties, it can be regarded to be 20 °;

C_1, C_2-Elastic and deformation coefficient of vessels and the pier, if there is no information, given that $C_1 + C_2 = 0.0005$ m/KN;

W – Ship weight (KN).

(3) Woisin Formula amended

$$P_{max}=0.88(DWT)^{1/2}(V/8)^{2/3} \quad (5\text{-}14)$$

Where: P_{max} - Maximum impact force (MN);

DWT-Deadweight of ship (t);

V–Navigation speed (m/s)

(4) Specifications Formula of AASHTO

Guidelines for the design specifications of ship-bridge collision are developed by AASHTO, considering the research results of Woisin, Dormberg and other persons, the designed impact force formula of ship bow positive impact at the pier (AASHTO, 1991). Woisin experiments (woisin, 1979) lead to empirical formula with speed of ships consideration

$$P = 0.98(DWT)^{1/2}(V/8) \quad (5\text{-}15)$$

Where: P - Equivalent static impact force (MN);

DWT– Dead weight of Ship (t);

V-The vessel impact speed (m/s).

5.4.2.3 Calculating results of Ship Impact Force

The ship impact forces calculated by the various formulas are shown from Table 24 to Table 26.

Table 24 -The vessel impact forces (MN) at the bridge pier (Z003, Z004)

Bridge Pier	Ship Type	Navigation Course	DHBC Code	Railway Code	Woisin Formula amended	AASHTO Formula
Z003	10000DWT	East ,West	56.37	6.39	50.19	42.14
	5000DWT	East	34.04	4.98	35.59	29.97
		West	20.27	2.97	25.19	17.84
Z004	10000DWT	East ,West	56.37	6.39	50.19	42.14
	5000DWT	East	20.27	2.97	25.19	17.84
		West	34.04	4.98	35.59	29.97

Note: General Code for the Design of Highway Bridges and Culverts (DHBC Code)
Source: Compiled by the author.

Table 25 -The vessel impact forces (MN) at the bridge pier (Z001, Z002)

Bridge Pier	Ship Type	Navigation Course	DHBC Code	Railway Code	Woisin Formula amended	AASHTO Formula
Z001	10000DWT	East ,West	24.42	2.77	28.70	18.25
	5000DWT	East	14.27	1.66	19.93	12.56
Z002	10000DWT	East ,West	35.56	4.03	36.87	26.58
	5000DWT	East	21.25	3.11	25.99	18.71

Note: General Code for the Design of Highway Bridges and Culverts (DHBC Code)
Source: Compiled by the author.

Table 26 –The impact forces (MN) at the bridge pier (Z005, Z006)

Bridge Pier	Ship Type	Navigation Course	DHBC Code	Railway Code	Woisin Formula amended	AASHTO Formula
Z005	10000DWT	East ,West	35.56	4.03	36.87	26.58
	5000DWT	West	21.25	3.11	25.99	18.71
Z006	10000DWT	East ,West	24.42	2.77	28.70	18.25
	5000DWT	West	14.27	1.66	19.93	12.56

Note: General Code for the Design of Highway Bridges and Culverts (DHBC Code)
Source: Compiled by the author.

It can be seen from the tables (Table 24, Table 25 and Table 26), the calculating results of the vessel impact force are different with use of different calculation model, but they are all associated with the vessel impact speed and the deadweight of ship, and the impact force increases with the increase of ship impact speed and vessel's DWT.

5.4.3 Risk Analysis of Ship-bridge Collision When the Vessel Is Not under Command

When a ship is not under command, the main causes are the failure of steering gear and main engine. Before the ship navigates across a bridge, the steering gear and main engine are required to be inspected and tested to ensure the reliability and controllability to navigate across the bridge. Onboard, the emergency procedures responding to the conditions that the vessel not under command are established, for example, if the main engine is out of power, the initiative emergency measures are to strand the ship voluntarily or drop anchor actively. In case of the failure of steering gear, measures that should be taken are starting emergency steering procedures, stopping the engine, dropping anchor or running aground. But owing to the differences in emergency response ability, operational errors and other restricted objective conditions. When a ship is out of control, there is a hidden risk of ship-bridge collision.

When a ship lose power or engine stops, it will continue sailing some distance by inertia. Meanwhile, because the ship is affected by wind, current and other factors, she may deviate from the intended course. Therefore, the navigation state of ship not under command is impacted by inertia, wind and current.

Figure 26 shows the coordinate axis of analysis ship drifting and its collision at bridge, which takes the bridge toward as the X-axis and the normal direction of it as the Y-axis. Then the coordinate system is established to analyze ship drifting and its collision at bridge.

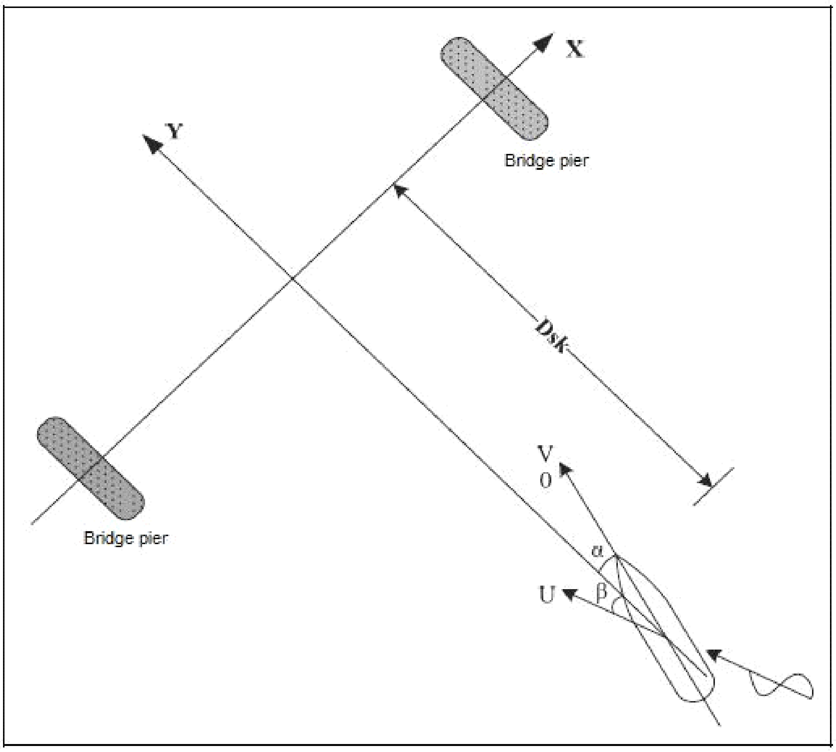


Figure 26-The coordinate axis of analysis of ship drifting and its collision at bridge

Source: compiled by the author.

5.4.3.1 Calculation of Speed of ship Not under Command

The speed of ship not under command is related to the ship's hydrostatic speed and current speed when it is not under command waters, it can be calculated as follows:

V= $\sqrt{(V_0\cos\alpha + U\cos\beta)^2 + (V_0\sin\alpha + U\sin\beta)^2}$ (Liu&Fang, 2009,p.74) (5-16)

Where: V - Speed of ship not under command;

U -Current speed;

V_0 - hydrostatic speed of ship not under command;

α- The angle between bow and the normal of the axis of bridge;

β- The angle between current direction and the normal of the axis of bridge.

The proposed normal direction of the axis of Bridge is from 127.6° to 307.6 °, waterway direction is from 143.3° to 323.3 °, and the angle between bow and normal of axis of bridge α is 15.7 °. The maximum current speed in flooding tidal stream is 0.92m/s, the current direction is 314 °. The angle between current direction and the normal of the axis of bridge β is 6.4 ° in flooding tidal stream. The angle between current direction and the waterway in flooding tidal stream is 9.3 °.

The maximum current speed in falling tidal stream is 1.09m/s, and the current direction is 137 °. The angle between current direction and the normal of the axis of bridge β is 9.4 ° in falling tidal stream. The angle between current direction and the waterway in falling tidal stream is 6.4 °.

The ship speed in navigating through the bridge waters is taken as 8 Kn, for the speed of ship not under command, it is 9.77 Kn in the flooding tidal stream condition and it is 10.11kn in the falling tidal stream condition.

5.4.3.2 Calculations of Stopping Distance and Stopping time

(1) Stopping time

Stopping time (T) is refers to the time period from the time point when the ship is out of control to the time point when the motion state of ship and water is relatively static. In general, the ship movement speed over water speed is regarded as the minimum speed to maintain steerage effects. For the 10000 tonner ship, it can be 2kn. In this paper, the ship's relatively static speed of 5,000-tonner cargo ship and 10000-tonner cargo ship to water speed are all taken as 2kn. The stopping time can be calculated as follows:

$$T = \ln\left(\frac{v}{v_0}\right) \cdot \left(-T_{st}\right) \qquad (5\text{-}17)$$

Where: v - Ship Speed in the process of stopping distance at any time (m /s);

v_0 - The initial ship speed (m / s);

T_{st} -Time constant of ship deceleration, T_{st}=C/ln2, the parameter C can be obtained by looking up the table with the ship's displacement.

Table 27-The constant time parameter C when ship's speed is reduced by half

Displacement(t)	C(min)	Displacement(t)	C(min)	Displacement(t)	C(min)
1000	1	～36000	8	～120000	15
～3000	2	～45000	9	～136000	16
～6000	3	～55000	10	～152000	17
～10000	4	～66000	11	～171000	18
～15000	5	～78000	12	～190000	19
～21000	6	～91000	13	～210000	20
～28000	7	～105000	14		

Source:Liu,M.J,&Fang,J.H.(2009).Pre-control vessel collision technology research on Sutong bridge. *Study on the navigable ships on bridge* (p.77,).Wuhan: Wuhan University of Technology Press.

Table 27 shows the parameters of navigation ship type, for example, the displacement of 5,000-tonner cargo ship is 6,961 tons, by looking up the table , the constant time parameter C=4 and T_{st}=4/ln2.

The displacement of 10000 tonner cargo ship is 13,836 tons, by looking up the table, the constant time parameter C=4 and T_{st}=5/ln2. The initial ship speed is taken as 8kn, by calculating, the stopping time of 5000-tonner cargo ship and 10,000-tonner cargo ship are 8 minutes and 10 minutes respectively.

(2) Stopping distance

1) Stopping distance in hydrostatic water. It means in the period of stopping time, the moving distance of ship in ship speed direction. It can be estimated with the following formula: $S = v_o T_{st}\left(1 - e^{-T/T_{st}}\right)$ (Liu&Fang, 2009, p.77)

(5-18)

2) Stopping distance in hydrodynamic water. In calculating hydrodynamic distance, within the stopping time, the drifting distance caused by current should be taken into consideration. Therefore, the stopping distance in hydrodynamic water can be expressed with the following formula: S = S= $v_o T_{st}\left(1 - e^{-T/T_{st}}\right) + UT$ (Liu&Fang, 2009, p.77) (5-19)

3) Dashing distance (advance). The projection of stopping distance in hydrodynamic water in the Y-axis Sc is dashing distance. It can be calculated as follows:

$S = v_0 T_{st}\left(1 - e^{-T/T_{st}}\right)\cos\alpha + UT\cos\beta$ (Liu&Fang, 2009, p.77) (5-20)

Calculated by the above formula, the stopping time and stopping distance of 5000-tonner and 10000-tonner cargo ship are shown in Table 28.

Table 28-The data sheet of the ship's stopping time and stopping distance

Ship type	Tidal stream		Stopping time (min)	Stopping distance in Clam water (m)	Stopping distance in Hydrodynamic water (m)	Dashing Distance (advance) (m)
5000 Tonner General cargo ship	Flood current	With the current	8	1068	1510	1443
		Against the current			627	566
	Falling current	With the current			1592	1520
		Against the current			546	489
10000 Tonner General cargo	Flood current	With the current	10	1336	1888	1799
		Against the current			784	712
	Falling current	With the current			1990	1899
		Against the current			682	611

Source: Compiled by the author.

4) Drifting distance (transfer). When the inertia disappears, if the ship has not arrived at the bridge yet, under the effects of current, the ship continues to drift along the

direction of Y-axis, and the drifting distance can be calculated as follows:

$S_p=Ut_p\cos\beta$ (Liu&Fang, 2009, p.77) (5-21)

$t_p=S_p/(U\cos\beta)=(D_{sk}-S_c)/(U\cos\beta)$ (Liu&Fang, 2009, p.77) (5-22)

Where t_p – The drifting time by stream(s), the time period is calculated from inertial vanishing point to bridge;

D_{SK} – It is the distance from the point where ship is out of control to the bridge.

It can be concluded from the formula that the distance from the point where ship is out of control to the bridge is the sum of the drifting distance and dashing distance.

5.4.3.3 Calculation of the Drifting Distance

(1) Drifting Distance by Current during the Stopping Time Period

Drifting distance by current during the stopping time (B_1) means the ship's drifting distance along the X-axis under the impacts of current during the entire stopping time period. It can be calculated with the following formula:

$B_1= v_o T_{st}\left(1-e^{-T/T_{st}}\right)\sin\alpha + UT\sin\beta$ (Liu&Fang, 2009, p.78) (5-23)

(2) Drifting Distance by Stream

Drifting distance by stream (B_2) can be defined as follows: when the ship inertia disappears, if the ship has not yet arrived at the bridge, under the impacts of stream, the ship will move on in direction of the X-axis before it arrives at the bridge. It can be calculated as:

$B_2=Ut\sin\beta=S_p\tan\beta$(Liu&Fang, 2009, p.78) (5-24)

(3) Drifting Distance before Bridge by Current during the Stopping Time

When ship's dashing distance is longer than the distance from the point where ship is out of control to the bridge, that is, $S_c > D_{sk}$,in the process of ship dashing from the point where ship is under command to bridge, the moving distance along the direction of X axis. It can be calculated with the following formula:

$B_3 = v_0 T_{st}\left(1-e^{-T/T_{st}}\right)\sin\alpha + UT\sin\beta$ (Liu&Fang, 2009, p.78) (5-25)

Where: t –The time range from the point when ship is out of control to arrive at the bridge, min.

(4) Drifting Distance by Wind during the Stopping Time

During the stopping time, under the effect of wind, the drifting distance in the direction of X-axis. It can be calculated with the following formula:

$B_4 = \lambda \cdot K \cdot \sqrt{\frac{B\alpha}{Bw}} \cdot e^{-0.14Vs} \cdot V_\alpha$ (Liu&Fang, 2009, p.78) (5-26)

Where $K=\sqrt{\frac{\rho_\alpha C_\alpha}{\rho_w C_w}}$,the scope of coefficient is 0.038～0.041;

B_α -The wind area of hull above the water line side .$B_\alpha = c_2 L_{BP}^2$,where c_2 is coefficient, L_{BP} represents the length of ship between perpendiculars, in the estimation it is replaced by design length of ship(m)

B_w- Area the hull waterline side (m), $B_W = L \times d$;

V_S -Ship speed in winds (Kn), it is taken the mean speed of ship not under command and the speed to maintain the minimum steering effect (5kn);

V_α-The relative wind speed in stopping time (m / s);

λ - Coefficient amended in shallow water, Table 29 shows the amended coefficient of shallow water.

Table 29 –The amended coefficient of shallow water

Ship type	H/d		
	1.1	1.5	2.1
General ship form	0.6	0.7	0.8
Very large ship form	0.5	0.6	0.7

Source: Liu,M.J,&Fang,J.H.(2009).Pre-control vessel collision technology research on Sutong bridge. *Study on the navigable ships on bridge* (p.78).Wuhan: Wuhan University of Technology Press.

(5) The Drifting Distance by Wind during the Period of Stream Flow

When the inertia disappears, the ship has not arrived at the bridge yet, under the impacts of wind, when the ship arrived at the bridge, the moving distance in the direction of X-axis. Its can be calculated as follows:

$B_5 = \lambda \cdot K\sqrt{B_a / B_w}\, v_{a3} t_p$ (Liu&Fang, 2009, p.79) (5-27)

Where V_{a3} represents the relative wind speed in the period of stream flow (m/s).

(6) Drifting Distance before Bridge by Wind during the Stopping Time

When ship's dashing distance is longer than the distance from the point where ship is out of control to the bridge, that is, $S_c > D_{sk}$,in the process of ship dashing from the point where ship is under command to bridge, under the influence of wind ,the ship's moving distance along the direction of X axis. It can be calculated with the following formula:

$B_6 = \lambda \cdot K\sqrt{B_a / B_w}\, e^{-0.14 v_{a4}} v_{a5} t$ (Liu&Fang, 2009, p.79) (5-28)

Where: V_{a4} -The ship Speed in winds the before bridge, kn;

V_{a5}-The relative wind speed before the bridge (m /s);

t -The time calculated from point not under command to the bridge.

(7) The Total Drifting Distance

The total drifting distance B can be defined as follows: from the time point when ship is out of control to the time of arrival at bridge, under the combined impacts of ship deviation, wind and current, the ship's drifting distance in the direction of X-axis. The total drifting distance is one of the important indexes to judge whether the ship not under command will collide at bridge pier.

1) If $D_{sk} > S_c$,the inertia of ship disappears before reaching the bridge, under the effects of wind and current , the ship will flow for some distance to reach the bridge. In this case, the total drifting distance can be calculated as follows:

$B = B_1 + B_2 + B_4 + B_5$ (Liu&Fang, 2009, p.79) (5-29)

The required time: $T_Z=T+t_p$ (Liu&Fang, 2009, p.79) (5-30)

2) If $D_{sk}<S_c$, the inertia of ship has not yet disappeared before arriving at the bridge, the ship continues to move on some distance under the impacts of inertia, the total drifting distance in this case can be calculated as follows:

$B=B_3+B_6$. (Liu&Fang, 2009, p.79) (5-31)

5.4.3.4 Analysis of Ship Drifting Collision at Bridge

When a ship is out of control, it will drift some distance under the impacts of wind and current. Its drifting distance in the direction of the axis of bridge is related to the direction of wind and current, the distance from under command point to bridge.

10,000tonner cargo ship entering Houzhu work port is taken for an example to analyze ship drifting distance under the impact of wind and current.

The length of straight waterway is 1000m and it lies in downstream direction of Quanzhou Bay Bridge. Assuming the moment a ship transfers to the straight waterway, it is out of control, therefore, D_{SK}= 1000m. Given that wind scale is 7 and wind abeam, the flooding and falling tidal stream speed is the maximum current speed, and the current direction is the same with the direction of maximum current.

(1) Analysis of Ship Drifting Collision at Bridge in Flooding Tide Stream

In this case, the dashing distance of ship under command is 1799m, which is greater than the distance from the out of control point to bridge D_{sk}=1000m, so the total drifting distance $B = B_3 + B_6$.

When the ship is out of control, it begins to decrease speed. Taking the ship speed at out of control point as 8kn, the ship speed that is relatively static to water speed as much as 2 kn ,stopping time is 10minutes, then the ship acceleration of ship under command is -0.0051m/s^2,. It can be calculated that if the distance from the out of out of control point to bridge is 1000m, the time for ship dashing to the bridge is 298s, the drifting distance before the bridge by wind during the stopping time B_6=39m , the drifting distance before the bridge by current during the stopping time B_3=278 m .

If the ship is affected by northeastern wind, the drifting direction of flooding tidal stream and wind impact are the same, so the total drifting distance of ship B=278 +39 = 317m. If the ship is influenced by southwestern wind, the drifting direction of flooding tidal stream and wind impact are opposite, so the total drifting distance of ship B=278-39 =239m.. As the navigation span clearance of the bridge is 400m, when the ship navigates along the centerline of waterway, as a result, the ship will collide at the bridge. In practice, whether the ship under command collides at the bridge depends on ship's draft and tide height. When the tide is low, and the water depth in the bridge pier waters is less than ship's draft, the ship will run aground before contacting the pier.

(2) Analysis of Ship Drifting Collision at Bridge in Flooding Tide Stream

In this case, the dashing distance of ship under command is 611m, which is less than the distance from the out of control point to bridge D_{sk}=1000m, so the total drifting distance $B=B_1+B_2+B_4+B_5$.

The drifting distance by current during the stopping time period B_1=255m, the drifting distance by wind during the period of stream flow B_5=131m, and the time from out of control point to the bridge is about 16min.

If the ship is influenced by northeastern wind, the drifting direction of falling tidal stream and wind impact are opposite, so the total drifting distance of ship B=255+69-120-131=73m. The drifting direction is the same as the current direction. As the span of the bridge is 400m, the total drifting distance is less than the half of the navigation breadth clearance of bridge, in theory, in this case, the ship can drift safely across the bridge, but in practice, when the ship is out of control, she can not navigate in the centerline of fairway. If the course is near one side, the ship might collide at the bridge.

If the ship is influenced by southwestern wind, the drifting direction of falling tidal stream and wind impact are the same, so the total drifting distance of ship

255+69+120+131=575m. When the navigation span clearance of the bridge is 400m, as a result, the ship will collide at the bridge. In practice, whether the ship under command collides at the bridge or not depends on ship's draft and tide height. When the tide is low, if water depth in the bridge pier waters is less than ship's draft, the ship will run aground before contacting the pier.

(3) The Deflection of Ship by the Impact of Wind

The above analysis is based on the ship drifting caused by wind and current, the actual movement of ship is also impacted by wind factors. Generally, the deflection of ship under command is related with the ship’s movement state and its loading state.

In view of the complexity of wind-induced deflection, to assess the risk of the ship under command colliding at bridge, it is not enough to consider the impact of current and wind, therefore, wind-induced deflection should also be taken into account, as it will change ship direction and track.

(4) Emergency Measures for the Ship Not under Command

From the above analysis we can see that with the current, there is shorter time left for the ship to respond to emergency. While the countercurrent left relatively long time for the ship to react to emergency. The drifting distance for the ship under command is affected by wind and current. Whether the ship not under command collides at the bridge or not depends on the distance from its out-of-control point to the bridge, the hydrological and meteorological conditions in bridge waters, the ships position in the fairway, the ship's speed, ship heading and deflection factors.

Ships navigating through Quanzhou Bay Cross-Sea Bridge should be familiar with the navigation environment in bridge waters, wind and current. For example, the seafarers should check and test steering gear and main engine. Once the ship is out of control in bridge waters, emergency measures should be taken immediately to avoid the damage to bridge pier and superstructure.

1) Failure of the main engine. After the failure of the main engine, considering the properties of ship's position, speed, heading, deflection and inertia, the steering gear and anchor should be taken to advantage of and the appropriate measures should be taken, for example dropping anchor. If the situation is very urgent, double anchor brake should be thrown immediately. If necessary, ship can take the initiative to run aground, where ship can be grounded at the sand beach on both sides of the fairway.

2) The failure of steering gear. After the failure of steering gear, emergency steering procedures should be started immediately if necessary, anchor brake should be used. If the situation is very urgent, ship should be turned backwards immediately and the anchor should be dropped.

3) Emergency tugs. It should be noticed that if the out of control point is about 1000m from the bridge, with the current, it takes about 10 minutes to arrive at the bridge. The distance from the out of control point to planning Xiutu Artificial Island Pier, Shihu Liquid Cargo Terminal and Shihu Container Terminal is approximately 1300m , 1500 m and 2000m respectively, given that the average speed of tugboat is 6 kn, it takes about 7 to 10 minutes for the tugboat from the mooring position to arrive at the bridge. Therefore, the location of emergency tug is vital in preventing from the ship colliding at the bridge.

5.5 Countermeasures and Suggestions

The risk assessment result of navigation environment in the Quanzhou Bay Cross-Sea Bridge waters is between low risk and moderate risk. Considering the various kinds of factors, for the safety protection of bridge and ship and promoting the development of local economy and society, the following countermeasures and suggestions are put forward.

5.5.1 Maritime Administrations Should Establish the Management Mechanism of Bridge Waters

5.5.1.1 Setting up Organizations and Functional Division in Bridge Waters

Organizations and functional division in bridge waters should be set up to implement the obligations to maintain navigation safety in bridge waters, to deal with safety and emergency affairs in bridge waters. Cooperating with the fishery superintendency agencies, the navigation behaviors of fishing vessels in the bridge fairway waters should be standardized. Strengthening publicity, education, training and supervision of fisheries practitioners are also efficient measures to prohibit fishing boats from affecting the safety of bridge and ship, in this way, good navigation order and safety conditions in bridge waters will come true.

5.5.1.2 Developing Navigation Regulations in Bridge Waters

It is suggested that safety navigation regulations on the Quanzhou Bay Cross-Sea Bridge should be formulated during the constructional and operational period by

Quanzhou MSA. The safety waters of bridge, restricted navigation waters and control waters should be defined and specified. Besides, seaworthiness of ship, safety navigation plans for ships passing through bridge and navigation behaviors should be formulated and standardized. The regulations on operational period in bridge waters should be covered and smoothly transited to the regulations in constructional period.

5.5.1.3 Focusing on Safety Supervision and Management of the Constructional Period

Quanzhou Bay Cross-Sea Bridge project involves a wide range of waters, the navigation environment is complex, and density of vessel traffic flow is big. The construction of bridge affects traffic order and traffic capacity significantly. Especially in constructional period, there are many temporary facilities, engineering ships, haul vessels, supply vessels, transport vessels, and all of them affect navigation environment in bridge waters. Safety supervision in construction period is directly related to construction safety and navigation safety of passing ships. During the constructional period, Maritime Administrations should adopt measures such as the administrative audit and approval, supervision of operational jobs, maintaining and configuring aids to navigation, emergency management and other effective supervision methods.

5.5.1.4 Taking Effective Measures to prevent Ships Transiting through the Non-navigable Bridge Channel

Spans between the non-navigation channels of main bridge are as following, the spans between Z_2 and Z_3, between Z_4 and Z_5 are 130m. The spans between Z_1 and

Z_2, between Z_5 and Z_6 are 70m. Spans of some channels of the approaching bridge in deep waters are 70m, the illegal behaviors to cross bridge may occur. Therefore, there is a need to take effective measures to prevent ships passing through the non-navigable bridge channel.

First, navigation regulations should be developed in bridge waters, in which should be explicitly specified that all types of ships are forbidden to enter the non-navigable bridge channel. Secondly, the non-navigable channel waters should be designed to be restricted waters where vessels shall be prohibited from entering. Thirdly, warning signs should be set in the restricted waters to warn the transiting ships to avoid the restricted waters bridge area. Finally, if possible, combining with the anti-collision facilities of piers, the non-navigable channels should be enclosed in order to prevent ships from entering.

5.5.1.5 Establishing the Quanzhou Bay Port VTS

It is recommended that the Quanzhou Bay Port VTS should be established as soon as possible. The Quanzhou Bay Cross-Sea Bridge should be the monitored scopes to observe the ship density, ship size, ship speed and other characters of ship flow in bridge waters. When the radar stations and other monitoring equipments are set up, the impacts of bridge building on radar echo should be taken fully into account. Further, CCTV equipment should be set up in the bridge waters to monitor the navigation environment in port waters and bridge waters, to monitor the real-time dynamic status of ship and vessel traffic flow.

5.5.1.6 Observing Hydrological in Bridge Waters and Collecting on-site Meteorological Information

When the bridge is established, due to the presence of piers, the current pattern will be changed to some extent in bridge waters, the erosion and deposition may be changed. Therefore in bridge navigation waters, the current patterns changes in the flooding and falling tidal stream should be noticed. The sizes and changes of turbulent current area around the piers within navigable channel should be watched out. Therefore, it is recommended that the hydrological observations should be carried out in the navigation waters upstream and downstream and waters near piers. The bridge waters should be made soundings regularly. In particular the water depth of navigation waters in the bridge area should be measured and the layout of fairway should be adjusted according to the changes of water depth. If necessary, water depth of navigation waters in the bridge area should be maintained.

Except collecting the meteorological information from professional meteorological stations, Maritime Administration should make full use of the maritime patrolling ship to gather timely meteorological safety information and collect the on-site winds, visibility and other weather information and safety information in bridge waters. According to the circumstances, the navigational warnings and notices information should be broadcasted and vessel traffic control should be implemented.

5.5.1.7 Updating Navigational Information and the Notice to Navigation Should Be Published Relating to Bridge Waters

During the constructional and operational period of bridge, navigation safety and warning information of operations in bridge waters, changes of waterways, aids to navigation, navigation controls, and other restricted conditions should be updated, broadcasted and published immediately.

5.5.1.8 Maintaining and Protecting Navigation Environment in Bridge Waters in Special Circumstances

(1) Maintaining Navigation Environment during Typhoons Period

During the typhoon period, a large number of fishing boats and small vessels come back to Houzhu Port for shelter from the wind, and ships berthing at the piers are required to leave port for the sheltered anchorage. Therefore, in this duration, the traffic density is very high in bridge waters, together with the impacts of fierce wind and swift current, the maneuverability of ship becomes poor. Consequently, vessel traffic accidents at sea and ship-bridge collision accidents are prone to occur.

In case of a large number of fishing boats and other vessels to return to port for sheltering winds, when they pass through the bridge waters, considering the actual circumstances of bridge waters, vessels control measures should be implemented . For example, one-way traffic navigation is enforced in bridge waters. For ships leaving piers, the leaving berth plan and crossing bridge plan should be made carefully and in advance to avoid a large number of ships meeting or encountering at the bridge waters.

(5) Maintaining Navigation Environment during the Fishing Season

During the fishing season, traffic flow of fishing vessels leaving and entering port is intensive; it will affect the inbound and outbound ship by tide, and it is recommended that as far as possible the peak time of ship flow should be shifted between fishing vessels and merchant ships. Communicating with the fishery superintendency agencies, making it that the time of fishing boats entering and leaving port is not the by tide period. If a large number of fishing vessels navigate close to the bridge waters, it will affect the normal navigation for commercial ships. On the one hand, the Maritime Administration should consider the situation of the other ships nearby of that is ready to go across the bridge waters, leaving the ship to make proper preparations. If necessary, the plan of arrival and departure should be adjusted. On the other hand, marine patrolling ships should be sent to command the on-site water transport in bridge waters to maintain traffic order.

5.5.2 Bridge Owners Should Fulfill Their Safety Management Responsibilities

5.5.2.1 Configuring and Maintaining Buoy System in the Bridge Navigation Waters

In the design and demonstration period of bridge, in accordance with the relevant regulations and standards, together with the installment of bridge collision–avoidance systems and the scopes of bridge waters, the bridge owners should entrust the relative parties to develop the buoy system during the constructional and operational period.

In the period of bridge construction, in accordance with the plan of configuring the temporary aids to navigation in constructional period, along with the constructional progress of the bridge and the new circumstances, the temporary buoys should be timely removed, changed or added. Also the embedded conditions should be considered for the placement of bridges and culverts buoys in operational period of bridge, providing convenience to configure buoys. In the operational period, the transition from temporary buoys to the operational buoys should be completed earlier.

5.5.2.2 Commissioning the Specialized Agencies to Develop Program of Bridge Collision -Avoidance System

In design and demonstration period of bridge, in accordance with the requirements, bridge owners should commission the specialized agencies to develop program of bridge collision-avoidance system. In this way, the design of bridge collision-avoidance system and its treatment project in the process of bridge design and construction will be more convenient.

5.5.3 Bridge Construction and Management Parties Should Further Implement the Safety Management Responsibility

First, the bridge construction parties should incorporate the navigation vessel traffic capacity of bridge into the design of bridge, and the shipping development of the Quanzhou Houzhu Port should be fully given into consideration.

Secondly, the navigation safety acceptance of bridge should be applied to Maritime Administrations, and safety information should be made public.

Thirdly, navigation channels constructed should meet the requirements of navigation conditions. In accordance with the requirements and standards, the lighting sign in bridge waters, signs of aids to navigation and forbidden navigation should be maintained. If necessary, a display screen should be set above the navigation bridge channel to display the allowable maximum navigation height and width of the bridge. Fourth, the anti-collision facilities should be constructed. Based on the early warning theories, warning device or warning alarm devices of ship- bridge collision should be set up. The management systems of anti-collision and emergency response plans should be established and improved, and the emergency facilities should be provided with necessary equipment. What is more, emergency drills should be carried out regularly. Fifth, the duty system should be established and the monitoring equipment should be provided in the bridge waters. For example, CCTV systems can be installed on the bridge, which can play an important role in monitoring the navigation environment and navigation order in bridge waters at night and poor visibility.

5.5.4 Officers and Pilots Should Be Cautious to Steer the Ship in Bridge Waters

The angle between the normal of the axis of the Quanzhou Bay Cross-Sea Bridge and the direction of fairway is approximately 15.7 °. The angle between the current direction of the maximum flooding tidal stream and the direction of fairway is about 6 °, and the angle between the current direction of maximum falling tidal stream and the direction of fairway is approximately 9 °. The ship passing through the Quanzhou Bay Cross-Sea Bridge should pay attention to the impacts of winds and current to adjust ship positions so as not to collide at bridge. Ship owners, operators, managers should strictly abide by relevant laws and regulations, and the ship should be manned with adequate seafarers. Seafarers should be trained to improve their moral and operational skills as well as safety awareness, and seafarers should strictly comply with rules and provisions of navigation safety management in bridge waters. In addition, compared with other waters, the bridge fairway waters is relatively narrow, so there is less room for maneuvering, which requires the ship to navigate with caution in the bridge waters. First, according to the navigational clearance of the bridge, the passing ships should be left with sufficient safety factors. Second, before crossing the bridge, the key equipment of ship should be strictly inspected to maintain in good technical condition and good maneuverability, such as the steering equipment, anchorage equipment, main engine and auxiliary engine. Before navigating to the bridge, when the engine is ready, manipulate and control test of main engine should be carried out. Thirdly, seafarers who navigate the ship to pass the bridge should be familiar with navigation environment in the bridge waters, and the ship should be navigated at safe speed with adequate steerage. Finally, the ship should comply with the provisions of navigation, in poor visibility, high winds and other hard weather conditions, the ship should not pass through the bridge. Furthermore, the ship should not be handled with the U-turn when going through the non-navigable bridge channel in the bridge waters.

5.6 Summary

In this chapter, the navigation environment in the Quanzhou Bay Cross-Sea Bridge is taken as a case. Firstly, the navigation environment in Quanzhou Bay Cross-Sea Bridge waters is introduced. Secondly, based on the risk assessment model of navigation environment in bridge waters established in Chapter 4, the risk assessment of navigation environment in the Quanzhou Bay Cross-Sea Bridge waters is carried out and the risk degree has been obtained. Thirdly, for the characteristics of ship flow acting as major risk source, taking advantage of queuing model, the vessel traffic capability of bridge waters is analyzed and predicted. Fourthly, ship-bridge collision risks are quantitatively calculated with use of the PRA method. Finally, in terms of Maritime Administrations, bridge owners, bridge construction parties and ships passing through bridge, countermeasures and suggestions are put forward to improve the safety navigation environment in bridge waters. It is noteworthy that before the establishment of the risk matrix, the evaluation criteria of influencing factors of index layer established in Chapter 4 is used to determine the safety indexes of the navigation environment in Quanzhou Bay Cross-Sea Bridge waters and qualitative analysis of the influencing factors.

Chapter 6 Conclusion

In this paper, the FSA method is applied in the process of risk assessment of navigation environment in bridge waters. Based on the man-machine-environment -management theory, the traffic safety system structure of bridge waters, the so-called MMEM system of bridge waters is proposed. By reviewing related literature, the risk factors of navigation environment in bridge waters are identified. With the use of fuzzy comprehensive evaluation model, the risk assessment model of navigation environment in bridge waters is established. In addition, navigation environment in Quanzhou Bay Cross-Sea Bridge Waters is taken for an example, based on field research and data survey, experts investigation and other research methods, together with the risk assessment model, the comprehensive evaluation of navigation environment Quanzhou Bay Cross-Sea Bridge waters is carried out, and the specific evaluation score and its corresponding risk level are obtained, so that we can have more rational understanding of the risk condition of navigation environment in bridge waters. Then degree of major risk are evaluated and calculated. In more specific terms, the queuing model is used to assess the capability for ships passing through bridge. With the use of PRA method, the risk of ship-bridge collision is calculated. Also the vessel impact speed at bridge and vessel impact force at bridge is quantitative calculated. According to the overall risk assessment level and the risk evaluation results of major sources, recommendations and countermeasures are made to evade and reduce risks. On the whole, the research on risk assessment of navigation environment in bridge waters achieves the intended goal of the paper. The following conclusions can be obtained:

(1) FSA is a new risk assessment methodology, and it is reasonable and feasible to

apply in the risk assessment of navigation environment in bridge waters.

(2) The safety navigation systems in bridges waters is an open MMEM system, it is the combined effects of man - machine - environment –management. In this paper, for the particularity of the navigation environment, the risk assessment of navigation environment system in bridge waters is carried out.

(3) In establishing the risk assessment matrix, the primary and secondary fuzzy matrix is established by pairwise comparison method. Weights of risk factors are calculated and determined with the use of Analytic Hierarchy Process (APH) method. Expert questionnaire method is used to determine the degree of membership of influencing factors. So in the model-building process, it is influenced by subjective factors.

(4) It is an inevitable trend to introduce the FSA method into comprehensive evaluation of water traffic safety. However, scopes of the applications of FSA methodology are not very extensive. The application of specific technical methods to FSA method needs to be developed and improved in the future. In practice, there are still some problems in the application of FSA method, for example, the collection of data in risk assessment, the establishment of risk assessment model. It is believed that with the gradual improvement of the FSA method and the development of some new risk assessment method, the prospects of the application of FSA will be broader.

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Appendix 1

Dear experts:

In order to carry out risk assessment of navigation environment in bridge waters, by consulting to specialists, looking up literature materials and statistic data, field research, the index signs systems of navigation environment in bridge waters are established. Now, your kindness cooperation and help is very useful for me to carry out research. Please according your professional knowledge and working experience, based on the requirement of the scale of relative importance table, the degree of importance between different factors and fill in the tables of questionnaires, thank you for your time and efforts.

The relative factors are set out in column in the following table, they are requires to be compared Pairwisely, fill the results in the corresponding column in the table. With regards to the standards, you can refer to the following table.

For example, comparing the importance of two factors, if they are equally important, the column should be filled with number 1.If the factor in horizontal column is more important than factor in the vertical column; please fill the column with number 3.

Scale of Relative Importance

Intensity of importance	Definition
9	Absolute importance
7	Demonstrate importance
5	Essential or strong Importance
3	Weak importance of one over another
1	Equal importance
2、4、6、8	Intermediate values between the two adjacent judgment
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j,then j has the reciprocal value when compared with i.

For example ,the characteristic of ship flow lies in the goal layer， its index signs factors are ship density ,ship size ,ship speed ,ship type，if you think the ship size is essentially or strongly important than the ship density ,the ratio of ship size to ship density is 5,and the ratio of ship density to ship size is 1/5.

Factor Xi/Xj	Ship density U_{11}	Ship size U_{12}
Ship density U_{11}	1	1/5
Ship size U_{12}	5	1

Table1- Relative importance of risk factors in goal layer

Primary index	Characteristics of ship flow U_1	Hydrological condition U_2	Meteorological condition U_3	Navigation condition U_4
Characteristics of ship flow U_1				
Hydrological condition U_2				
Meteorological condition U_3				
Navigation condition U_4				

Table 2- Relative importance of risk factors in index layer- Characteristics of ship flow

Characteristics of ship flow U_1	Secondary index	Ship density U_{11}	Ship size U_{12}	Ship speed U_{13}	Ship type U_{14}
	Ship density U_{11}				
	Ship size U_{12}				
	Ship speed U_{13}				
	Ship type U_{14}				

Table 3- Relative importance of risk factors in index sign layer- Hydrological condition

Hydrological condition U_2	Secondary index	Current speed U_{21}	Tidal stream U_{22}	Water depth U_{23}
	Current speed U_{21}			
	Tidal stream U_{22}			
	Water depth U_{23}			

Table 4- Relative importance of risk factors in index layer- Meteorological condition

Meteorological condition	Secondary index	Wind U_{31}	Storm rain U_{32}	Typhoon U_{33}	Fog U_{34}
	Wind U_{31}				
	Storm rain U_{32}				
	Typhoon U_{33}				
	Fog U_{34}				

Table 5- Relative importance of risk factors in index layer- Navigation condition

Navigation condition U_4	Secondary index	The bending in the fairway U_{41}	Bridge axial angle U_{42}
	The bending in the fairway U_{41}		
	Bridge axial angle U_{42}		

Appendix 2

Table 1-Degree of membership of Ship density and evaluation grade- Characteristics of ship flow

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Vessel traffic volume (ship /day)	0～30	0.3	0.3	0.2	0.1	0.1
	30～60	0.2	0.2	0.3	0.1	0.2
	60～100	0	0.0667	0.2	0.5333	0.3
	10～150	0	0.0333	0.1	0.4333	0.4333
	⩾150	0	0	0	0	1

Table 2-Degree of membership of Ship size and evaluation grade- Characteristics of ship flow

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Large Vessel traffic volume（ship /day）	⩽4	0.4667	0.3333	0.13333	0.0667	0
	4～10	0.3	0.2	0.3	0.1	0.1
	10～20	0	0.2667	0.3333	0.3	0.1
	20～30	0	0.2	0.2333	0.3333	0.2333
	⩾30	0	0.0333	0.2333	0.2333	0.5

Table 3-Degree of membership of Ship speed and evaluation grade- Characteristics of ship flow

Risk degree / Index layer	Fuzzy Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Ship speed control	Excellent	0.4667	0.5333	0	0	0
	Good	0.3	0.3	0.4	0	0
	Moderate	0.1	0.3	0.3	0.2	0.1
	Poor	0	0.0333	0.4	0.4	0.1667
	Very poor	0	0	0.0333	0.4667	0.5333

Table 4-Degree of membership of Ship type and evaluation grade- Characteristics of ship flow

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Ship carrying dangerous goods/the total Vessel traffic volume（%）	≤10	0.5333	0.3	0.0667	0.1	0
	10～20	0.2	0.3	0.3	0.1	0.1
	20～30	0	0.2333	0.3667	0.3	0.1
	30～40	0	0.0667	0.3667	0.3333	0.2333
	≥40	0	0	0.1	0.4	0.5

Table 5-Degree of membership of current speed and evaluation grade- Hydrological condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Current speed（kn）)	0～0.5	0.4	0.4667	0.1333	0	0
	0.5～2	0.1333	0.4	0.3667	0.1	0
	2～5	0.1	0.2	0.3	0.3	0.1
	5～7.5	0	0.0333	0.2667	0.5	0.2
	≥7.5	0	0	0.1333	0.1333	0.7333

Table 6-Degree of membership of tidal stream and evaluation grade- Hydrological condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Maximum tide range （m）	≤2.5	0.4667	0.3667	0.1667	0	0
	2.5～5.0	0.4	0.2333	0.2333	0.1333	0
	5.0～7.5	0.3	0.1	0.3	0.2	0.1
	7.5～10	0	0.3	0.1	0.4	0.2
	≥10	0	0	0.3	0.1333	0.5666

Table 7-Degree of membership of water depth and evaluation grade- Hydrological condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Water depth /draft	≥4	0.7333	0.2333	0.0333	0	0
	2～4	0.5	0.3333	0.1667	0	0
	1.5～2	0.1667	0.5	0.2667	0.0667	0
	1.3～1.5	0.1	0.4	0.4	0.1	0
	≤1.3	0	0.0667	0.3	0.5	0.1333

Table 8-Degree of membership of winds and evaluation grade- Meteorological condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Standard wind days（d）annually	≤30	0.4	0.2667	0.3333	0	0
	30～60	0.1	0.4333	0.3	0.1667	0
	60～100	0.1	0.1	0.4	0.3	0.1
	100～150	0	0.0667	0.1667	0.4667	0.3
	≥150	0	0	0.1333	0.2333	0.6333

Table 9-Degree of membership of storm rain and evaluation grade- Meteorological condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Days impacted by storm rain （d） annually	≤15	0.8667	0.1333	0	0	0
	15～25	0.7	0.2	0.1	0	0
	25～40	0.5	0.2333	0.2	0.0667	0
	40～50	0.3	0.3667	0.2333	0.1	0
	≥50	0.3	0.2	0.2	0.2	0.1

Table 10-Degree of membership of typhoon and evaluation grade- Meteorological condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
The number of typhoon landed and directly influenced	≤2	0.6667	0.2667	0.0667	0	0
	2～4	0.4667	0.1667	0.2667	0.1	0
	4～6	0.3	0.2	0.2	0.2	0.1
	6～8	0	0.2	0.3	0.2667	0.2333
	≥8	0	0	0.2667	0.3667	0.3667

Table 11-Degree of membership of fog and evaluation grade- Meteorological condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Poor visibility days /year	≤15	0.5	0.3667	0.1333	0	0
	15～25	0.1333	0.5333	0.2333	0.1	0
	25～40	0.1	0.3	0.3	0.2	0.1
	40～50	0	0.0667	0.4333	0.3667	0.1333
	≥50	0	0	0.2333	0.3667	0.4

Table 12-Degree of membership of the bending in the fairway and evaluation grade- Navigation condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
Maximum bending in the fairway （°）	0～15	0.7333	0.1667	0.1	0	0
	15～30	0.6333	0.1667	0.1	0.1	0
	30～45	0.5	0.2	0.1	0.1	0.1
	45～60	0	0.4333	0.2667	0.1667	0.1333
	≥60	0	0.1	0.3667	0.2333	0.3

Table 13-Degree of membership of bridge axial angle and evaluation grade- Navigation condition

Risk degree / Index layer	Quantitative Index	Very low risk 1	Low risk 2	Moderate risk 3	High risk 4	Very high risk 5
The angle between the normal of bridge axis in main navigation channel and the mainstream direction of the falling and flooding（°） current	≤5	0.8	0.1333	0.0667	0	0
	5～8	0.6333	0.1667	0.1333	0.0667	0
	8～11	0.5	0.2	0.1	0.1	0.1
	11～14	0	0.3	0.3667	0.1667	0.1667
	≥14	0	0.1	0.2667	0.3667	0.2667