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Vessel navigation safety analysis and countermeasures in the water of Taizhou Yangtze River Bridge

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VESSEL NAVIGATION SAFETY ANALYSIS AND COUNTERMEASURES IN THE WATER OF TAIZHOU YANGTZE RIVER BRIDGE

By

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DECLARATION

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

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

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ABSTRACT

Title of Research paper: **Vessel Navigation Safety Analysis and Countermeasures in the Water of Taizhou Yangtze River Bridge**

Degree: **MSc**

With the rapid development of economy and the progress of science and technology, more and more bridges have been built over the navigable waters with their length and span increasing, which make the land transportation more convenient. However, the bridges over the navigable waters are in risk of vessel collisions. The navigable width and height restrictions increase vessels' navigation difficulties in the waters. The accident of vessels' collision with bridge is extremely easy to occur when vessels are in distress or emergency circumstances.

Taizhou Yangtze River Bridge is a communication link between the two sides of the river by land transport whose status and role is self-evident. The bridge also faces the risk of vessel collisions. The result of the accident would cause a great loss.

In this paper, firstly, I analyze natural and navigation environment in water area of Taizhou Yangtze River Bridge through data collection and site investigation, and use existing database of accidents of vessels' colliding with the bridge. Secondly, I summarize the characteristics, reasons and regular patterns of the accidents, so as to identify the main risk factors. Thirdly, by constructing fault tree based on accidents of vessel collision with bridge, I calculate the importance of risk factors, combining with the logic relation of basic and top incidents. At last, I propound the risk management measures for navigation safety and reduce the risk in water area of Taizhou Yangtze River Bridge.

KEY WORDS: Vessel, Bridge, Collision, Risk analysis, Fault Tree, Countermeasures

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LIST OF ABBREVIATIONS

AIS	Automatic Identification System
AASHTO	American Association of State Highway and Transportation Officials
FTA	Fault Tree Analysis
FRR	Facility Risk Review
FMEA	Failure Medes & Effects Analysis
HAZOP	Hazard and Operability
MSA	Maritime Safety Administration
MCAPS	Methodology for Comparison of Alternative Production System
PRA	Probabilistic Risk Assessment
PIANC	World Association for Waterborne Transport Infrastructure
QRA	Quantitative Risk Analysis
VTS	Vessel Traffic Service

CHAPTER 1

Introduction

1.1 The background of the research

Vessels as a kind of transport have a long history. Maritime transport has a great role in promoting social progress, economic development and cultural exchanges. Compared with other means of transportation, maritime transport has little pollution to the environment, low cost and large capacity, which is suitable for large-scale transportation. Therefore, inland waterway shipping with its own characteristics and advantages has become one of the important means of transport in the comprehensive transportation system in China (Dai, 2003).

With the rapid development of railways and highways, more and more large bridges over the Yangtze River will be constructed, especially in Jiangsu section. Bridge is a communication link between the two sides of the river by land transport, whose status and role is self-evident. The construction of bridges over Yangtze River will greatly improve the traffic conditions of the land, but at the same time, will also create some contradictions with the maritime transport. The bridge is a fixed building across the waterway and thus will become an obstacle for vessels. Piers of the bridge will also cause the sediment deposition, river bed changes, and the deterioration of channel conditions. With the increasing number and size of vessels, the speed of vessels is faster and the tonnage is bigger and the manoeuvre is more difficult. All these situations increase the risk of vessels' colliding with the bridge.

Therefore, the vessel and the bridge are a pair of contradiction of the main body (Dai, 2003). In the navigable river, along with the construction of the bridge, the accident of vessel colliding with the bridge occurred, causing great damage to life, property, environment and society. Objectively, we can not hope that such events never occur, but in the subjective sense we hope through research to understand the certain regularity, and take certain measures to reduce the rate of occurrence and the negative consequence of the accident. It is of great significance that further research on vessel navigation safety in bridge area could reduce the risk of vessels' collision with bridge.

1. 2 Objectives of Research and Methodology

The main task of this study is to analyze the risk existing in the vessel navigation safety in the water of Taizhou Yangtze River Bridge. I analyze natural and navigation environment in its water area through data collection and site investigation.

I mainly analyze wind, tide, depth and other natural factors and the channel and traffic flow in the area of Taizhou Yangtze River Bridge. Due to the fact that no accidents of vessels' collision with bridge have occurred since its opening less than four years ago, in this paper I use the existing database built by scholars about vessels colliding with bridge in inland rivers in China. Besides, I summarize the characteristics, reasons and regular patterns of the accidents, so as to identify the main risk factors.

I construct fault tree based on accidents of vessels' collision with bridges, combined with the logic relation of basic and top incidents. I will carry on the qualitative analysis (minimum cut sets, the minimum path sets) and quantitative analysis (structure important degree), to determine the importance of risk factors. By comparing the main risk factors and the factors in Taizhou Yangtze River Bridge area, I propound the risk management measures for navigation safety, which will help reduce the risk in water area of Taizhou Yangtze River Bridge.

1.3 Overseas Status

In the late1960s, a handful of countries started the research on vessels' collision with bridges, but the progress was very slow in the first ten years. However, in 1983, International Bridge and Structural Engineering Association held seminars about "Reasonable design and analysis of vessel collision with bridge" in Copenhagen. After this, the problem attracted considerable attention from many countries. As a result, the research on vessels' collision with bridges has entered a new period of development (Li, 2014).

In 1980, the accident of Sunshine Bridge attracted great attention to the bridge safety in navigable waters, which promoted the birth of "Guidelines for the design of Highway Bridges" in 1991 in the United States (Gen, 2007).

The most famous study was carried out by the 19 working group from the

International Shipping Association in 1983, which established a database of 151 cases of collision accidents. The team found that the frequency of very serious collisions was a stable growth trend from 1960-1980. It declined after 1980, but increased slightly in the 1990s. The reasons can be divided into three categories: the first was human error, such as the crew's negligence, improper operation, etc.; the second was mechanical fault, such as main engine failure and steering gear failure; the third category was harsh natural environment, such as stormy weather and poor visibility (Xu, 2010).

In 2001, the Japanese scholars used the fault tree method to establish the risk analysis system of vessels collision. They got the conclusion that human factors are main causes in vessels collision accidents.

1.4 Domestic status

The research on vessels' collision with bridge in China could be traced back to the end of the 1950s. The relevant technical personnel in China had realized that the collisions from vessels were a major threat to the safety of bridges, since the first recorded vessel collision accident in Wuhan Yangtze River Bridge in 1959 (Zhuang, 2008). Huangshi Yangtze River Bridge was constructed in July 1991 and was open to traffic in December 1995. During the period of construction, 20 cases of accidents happened and the direct economic loss was more than tens of millions of dollars, which promoted the deep research on the major bridges across the waterway.

In 2002, Dai Tongyu from Harbin Engineering University established a database of vessels' collision with bridges in China for the first time, developed software for database management, and established general framework of vessel bridge collision risk assessment. In consequence assessment, he put forward the concept of consequences equivalent.

In 2004, China promulgated the "General design of highway bridges and culverts norms", in which the vessels were divided into two types: motor vessels and inland river barges. The design of vessel collision force was listed respectively according to the channel rank.

In 2006, Lin Tieliang added accident records to the database established by Dai Tongyu, and established a new database including 251 accidents from 1959 to 2004. In addition, through the study on accidents of vessels' collision with bridges, he established three different cases of fault tree, namely, canal, river and strait.

M/V Nan Guiji 035 collided with Jiujiang Bridge, which resulted in the collapse of three piers and nearly 200 meters of bridge floor. Four cars fell down into the river. Six persons in cars and two workers on the bridge died after falling into the river. This accident resulted in economic losses of RMB 45 million and caused widespread concern in the community. As a result, the safety of bridge got more extensive attention and more scholars were involved in the research of vessels' collision with bridges.

All the above research focuses on research methods and database established analysis, while for each bridge, it has its own prominent characteristics and the common theory cannot fully account for all circumstances. Therefore, specific research should be carried out according to its unique geographical location and navigation environment to reduce the risk of bridge collided by vessels.

1.5 Structure of Paper

This paper consists of six chapters. Chapter one introduces the background of this research, objectives of research and methodology, overseas and domestic status and the structure of paper. Chapter two introduces the hydrological and meteorological situation, channel settings, traffic flow and other environmental factors in the area of Taizhou Yangtze River Bridge. Chapter three introduces the concept of risk analysis, builds the fault tree about vessels' collision with bridge according to the existing database, and carries out qualitative and quantitative analysis of risk factors and determines the importance of each factor. Chapter four compares risk factors with the specific circumstances in Taizhou Yangtze River Bridge. Chapter five presents practical countermeasures according to the risk analysis results. Finally, the last chapter discourses the overall summaries and conclusions.

CHAPTER 2

Taizhou Yangtze River Bridge and Navigable Environment

2.1 The general situation of Yangtze River and Taizhou Yangtze River Bridge

2.1.1 Yangtze River and the bridges in Jiangsu section of Yangtze River

The Yangtze River is the largest river in China, and its length is 6793km, ranking the third place in the world. The trunk of the Yangtze River flows from west to East, through seven provinces and two cities. There are three shipping centers (i.e., Chongqing, Wuhan and Shanghai) and several large ports alongside the Yangtze River. The cargoes in these centers and ports can be transferred by highway, railway, airlift and pipeline to other places. The amount of cargo travelling on Yangtze River accounts for about 70% of that travelled on all inland rivers in China (Huang, 2015). It is estimated that 85% of the coal and iron ore, 83% of oil, 87% of foreign trade volume of goods in the areas both sides of Yangtze River are travelled on it. Freight volume on Yangtze River exceeded 2.18 billion tons in 2015, ranking the first place in the world, which is four times bigger than that on the Mississippi River and ten times bigger than that on the Rhine.

According to statistics, there will be thirteen bridges in the Jiangsu section of the Yangtze River, including the built, under construction and preliminary planning.

Table 2.1: Bridges in the Jiangsu section of the Yangtze River

No.	The name of bridge	Status
1	Nanjing Dashengguan Yangtze River Bridge	Built
2	Nanjing Third Yangtze River Bridge	Built
3	Nanjing Yangtze River Bridge	Built
4	Nanjing Second Yangtze River Bridge	Built
5	Nanjing Fourth Yangtze River Bridge	Built
6	Runyang Yangtze River Bridge	Built
7	Wufengshan Yangtze River Bridge	Preliminary Planning
8	Taizhou Yangtze River Bridge	Built
9	Jiangyin Yangtze River Bridge	Built
10	Hutong Railway Yangtze River Bridge	Under Construction
11	Sutong Yangtze River Bridge	Built
12	Conghai Yangtze River Bridge	Preliminary Planning
13	Congqi Yangtze River Bridge	Built

2.1.2 Basic facts of Taizhou Yangtze River Bridge

The main body of Taizhou Yangtze River Bridge was constructed on December 26, 2007, and it came into service on November 25, 2012. Taizhou Yangtze River Bridge is divided into two parts: one is the main body and the other is the part over the Jiajiang. The main body is located over Kouan straight waterways and Jiajiang Bridge is located over short cut route of Taiping Island at the right branch of it. The main body of the bridge has two main spans and three tower suspensions. The span is 1080m, ranking the first place in the world (Liu, Hu, Chai, 2013).

Taizhou Yangtze River Bridge is located at the lower reaches of the river in the area of Yangzhong, between Runyang Yangtze River Bridge and Jiangyin Yangtze River Bridge. The bridge lies in the south of Taizhou city and in the north of Zhenjiang city and Changzhou city.

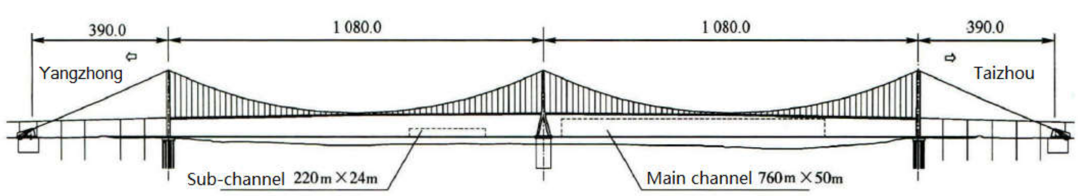

Figure 2.1: Taizhou Yangtze River Bridge

Source: Ji, L., & Han, D. Z. (2008). Technological characteristics and innovation on Taizhou Yangtze River Bridge. *The fourth national highway science and Technology Innovation Forum.* Beijing: China Conference.

2.1.2.1 Navigable dimension

The clear width of main channel: not less than 760m in single channel with two-way traffic;

The height above main channel: not less than 50m above the highest level of navigable water;

Maximum representative vessel type

The representative vessel type within clear width in main river: 406m * 64.8m * 3.5m fleet

The representative vessel type within height in main channel: 50000 tons Panama vessel;

2.1.2.2 Integrated system of anti-collision with the middle tower

As shown in Table 2.2, six parts make up the anti-collision system of the middle tower of Taizhou Bridge. The ability of anti-collision is 15000T, which could bear drift collision of a vessel of 50000 tons.

Table 2.2: The six parts of anti-collision system

No.	The parts of anti-collision system
1	Navigation aid facility
2	Navigation regulations in bridge area
3	Emergency rescue system
4	Independent anti-collision piers
5	Anti-collision sleeve box
6	Base body anti collision

2. 2 Hydrometeorology in the waters area of Taizhou Yangtze River Bridge

2. 2. 1 Basic climate characteristics

Taizhou section of the Yangtze River is located in the north subtropical humid climate, with monsoon climate characterized by abundant rainfall, enough light, mild climate and long period of no frost. Compared with the same latitude adjacent regions, its temperature rises slightly slower in spring and cools slightly later in autumn. Only a few days have high temperature in summer and there are frequent heavy rainfalls during the period of Meiyu. The climate is greatly different in four seasons. Weather alternates with rain and temperature changes rapidly in spring. In summer, weather is hot and rainy because of the influence of the southeast wind from the ocean. Sunny and rainless days are common in autumn. Influenced by northwest wind from northern area in winter, the weather is cold.

2. 2. 1. 1 Rainfall and fog condition

The average annual total rainfall is about 1040mm in Taizhou area. The maximum annual total rainfall is 1600mm, while the minimum annual total rainfall is 600mm. Besides, the maximum daily rainfall is 230mm. The average annual number of rainy days is 117.3.

Winter and spring are foggy seasons in Taizhou area, and the fog occurs in the morning. Visibility is less than or equal to 1km in foggy days which are counted as follows: the maximum number of fog days in a calendar year is 99, and the minimum number of fog days is 28. The average number of fog days is 48 in a calendar year.

2. 2.1.2 Wind condition

According to Figure 2.2 the sixteen wind direction, the dominant wind direction is ESE for summer, and NW for winter, and in spring and autumn it changes to NE~E. Annual maximum wind direction is E~SE, and its frequency is about 10%. While the least wind direction is SW~W, and its frequency is about 3%. The annual average wind speed is about 3.3m/s. The maximum wind speed was 31.0m/s which happened on July 20, 1967. The strong wind direction is NNW and NW and the average wind speed is 17m/s.

According to local meteorological observatory data from 1959 to 1987 in Taizhou, the number of the days with the wind level greater than 5, 6 and 7 is 44.5, 9.1, and 4.5 respectively.

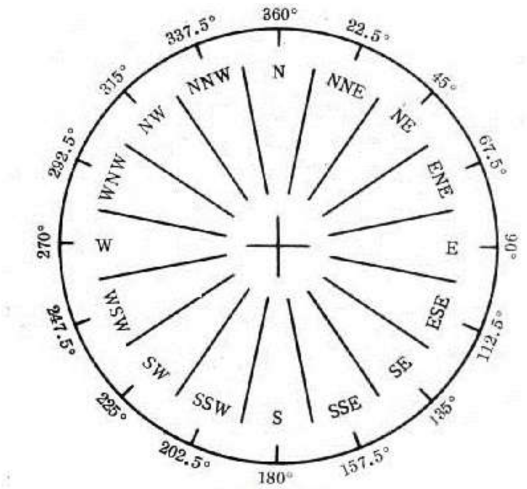

Figure 2.2: The sixteen wind direction

Source:http://baike.baidu.com/pic/4869036/0/207ea60ead51c0ca37d12248?fr=lemma&ct=single#aid=0&pic=207ea60ead51c0ca37d12248

2. 2. 1.3 Tropical cyclone

Taizhou can be easily affected by the typhoon in summer and autumn. According to statistical data on climatic characteristics of gale affecting the lower reaches of the Yangtze River from 1980 to 1999, the typhoon with wind scale greater than 8, first appeared in June (No. 9005) and later appeared in October (No. 9809), and generally arose frequently from July to September. During the 20 years, a total of 54 typhoons affected the lower reaches of the Yangtze River. It was an average of 2~3 times per year, which was up to 7 times in 1990. A total of four typhoons (No. 9711, 9808, 8615 and 9507) seriously impacted the lower reaches of the Yangtze River. The typhoon (No. 9711) most seriously impacted coastal areas of Jiangsu and the wind caused by that was more than 8 wind scales while the wind was up to 9-10 wind scales in coastal areas of Jiangsu.

2.2.2 Hydrological environment

2.2.2.1 Water level

The water level of lower reaches of the Yangtze River changes with rainfall and water regime. Annually the water level of Yangtze River rises in April and May. This is caused by the swollen from tributary of Yangtze River and Dongting Lake and Poyang Lake. As a result, a short-term freshet comes into being. The rainfall increases in the whole area of Yangtze River in June, so the water level rises rapidly and enters the flood season. The water level of Yangtze River is high in the year from July to September because the water level rises in Chuanjiang. Rainfall gradually reduces in late September and October, and water level decreases and the flood season ends. The Yangtze River gradually comes into the dry season in November.

The flood, moderate and dry season are distinguished by water level in the lower reaches of the Yangtze River. Table 2.3 shows the different seasons in different months.

Table 2.3: Water level in flood, moderate and dry season and month

	Flood season	Moderate season	Dry season
The water level in Hankou	more than 10 meters	4-10 meters	less than 4 meters
Month	7, 8, 9	4, 5, 6, 10, 11	1, 2, 3, 12

Source: Taizhou MSA. (2012). Basic information of the area under supervision of Taizhou MSA.

Current velocity in flood period of Yangtze River is generally faster than that in dry season and that in the upstream water area is faster than that in downstream section. It is greater in a narrow region than that in a spacious region and it is greater in the main channel than that in economic channel. And also, ebb current velocity is faster than flood current velocity.

Taizhou is in the lower reaches of the Yangtze River, which has abundant water and large flow. There is two-way flow in dry season and one-way flow in flood season in Taizhou. The maximum drop flow speed is 1.73 m/s in flood season. The speed of flood current is about 0.5~1.0 m/s and the maximum is 1.17 m/s in dry season.

2.2.2.2 Tide

Navigation zone in Taizhou is class B. In this zone, tide difference is small while the water level is greatly different. The neap tide in the lower reaches of the Yangtze River could get to Wuhu and the spring tide could get to Datong in dry season. Tidal range is increasing from top to bottom in tidal area.

There is a non regular semidiurnal superficial tide in Taizhou, which changes daily up and down twice. The ebb and flood are greatly different in length, with ebb being much longer than flood. The average ebb lasts about 8 hours and the average flood only about 3 hours. Tidal level is controlled and influenced by the runoff of Yangtze River and is obviously different in dry season. Annual maximum tidal level appears in August in flood season, while the lowest tide level appears in January or February. Table 2.4 shows the situation of tide in Taizhou.

Table 2.4: The situation of Tide in Taizhou

The highest tidal level over the years	7.61 m
The lowest tidal level over the years	1.13 m
The average high tidal level	4.48 m
The average low tidal level	3.30 m
The highest of tidal range of flood	2.40 m
The highest of tidal range of ebb	2.55 m
The average tidal range	1.19 m

Source: Taizhou MSA. (2012). Basic information of the area under supervision of Taizhou MSA.

2.3 Channel condition and Traffic flow

Since May 16, 2012, maintenance depth in main channel between Nanjing and Jiangyin has changed from 10.5 meters to 10.8 meters from May to October every year. However, this increased to 12.5 meters on July 1, 2016. From that day, trial navigation will go on in main channel with that maintenance depth.

According to the statistics from Taizhou VTS, the traffic flow through Taizhou Yangtze River Bridge is about 2328 vessels daily, 5 of which are vessels of more than 50,000 tons. The peak flow is up to 3143 vessels, which is shown in figure 2.2.

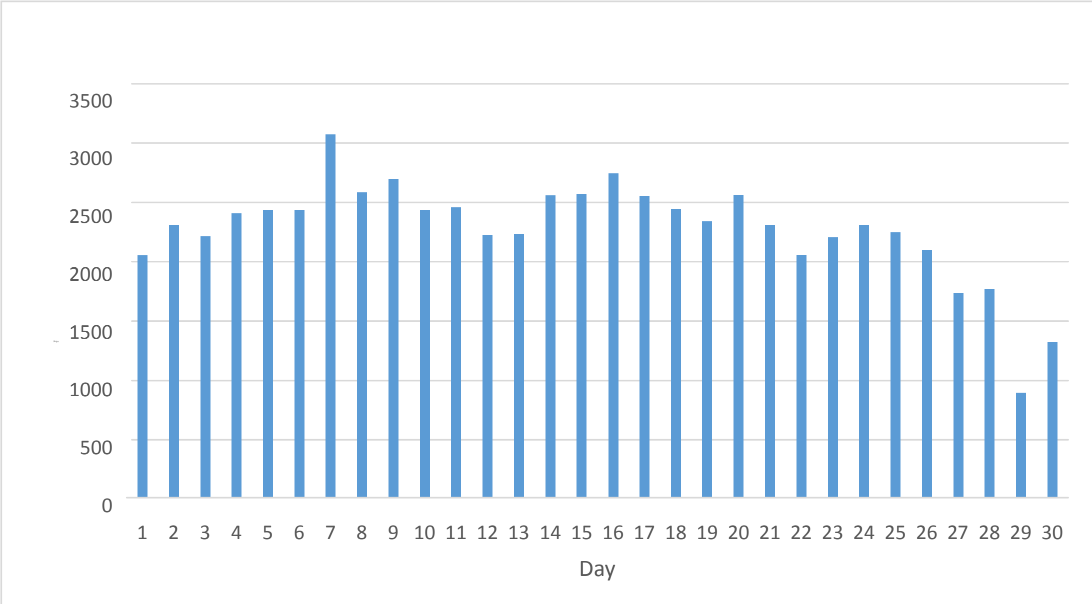

Figure 2.3: The traffic flow at Taizhou Yangtze River Bridge in June 2016
Source: The statistics from Taizhou VTS system

CHAPTER 3

Identify risk factors and fault tree construction and analysis

3.1 Overview of risk analysis methods

3.1.1 Basic concepts of risk and the risk in the research

The risk is closely related to the accident. The accident is an accidental event, involving casualties, property loss, environmental damage and other consequences which we do not wish to happen. Accidents may be caused by human factors, like mistakes, or may also be caused by natural disasters, like earthquakes.

The risk is the combination of the frequency of the accident and the consequence of the accident. This can be expressed with a simple mathematical formula, as:

$R = F \times C$,

R - Risk of accident,

F - Frequency of the accident,

C - Consequence of the accident (Gen, Wang, Wang, Fan, 2007, p. 36).

In this paper, I focus on the risk of vessel collision with bridge. We know that vessel collision with bridge is one kind of accidents and there is a risk in that situation. Whether the accident happens or not, the risk of vessels' collision with the bridge will always exist. No matter what strict measures have been taken, the occurrence of the accident cannot be completely avoided. However, we can take some measures to reduce this risk according to some previous research.

3.1.2 Purpose of risk analysis

The purpose of risk analysis is to provide an analysis of the risk of the object in advance, which involves the content of the object:

1. Forecast various types of risks in the engineering,
2. Estimate the probability of risk and its consequences (economic, personnel, environment, etc.),
3. Analyze the various potential factors leading to the risk and finding the root cause,
4. Make a general assessment of the risk and benefit and provide the basis for decision making,
5. Make safety assessment of alternative designs to select the best plan,
6. Present suggestions on the improvement of system security.

Risk analysis can comprehensively reflect the security of the system, not only to study the probability of accident, but also to study the consequences of the accident. Risk analysis is very helpful to enhance the comprehensive understanding of all aspects and stages of the system, so as to reduce the risk of the system.

3.1.3 Basic methods of risk analysis

Methods of risk analysis can be broadly divided into three categories:

The first category is the qualitative risk analysis, such as HAZOP (Hazard and Operability) analysis, FMEA (Failure Medes & Effects Analysis) method, Fault-tree/Event-tree Analysis and so on.

The second category is the qualitative and quantitative risk analysis, like FRR (Facility Risk Review).

The third category is quantitative risk analysis, such as QRA (Quantitative Risk Analysis), PRA (Probabilistic Risk Assessment), Fault-tree/Event-tree Analysis, MCAPS (Methodology for Comparison of Alternative Production System) and so on.

The methods above are different in the analysis of the depth, breadth and also different in time, manpower, material resources and the amount of information needed. Different methods and techniques should be adopted for different problems, different stages of the same problem and different purposes. QAR or PAR can make the most detailed risk analysis for the system, and it is also the costliest method.

3.2 The method in this paper

In this paper, I use fault trees analysis to find the risk factors of vessel collision with bridge. Fault tree analysis (FTA) is an analysis technique for safety and reliability aspects using a graphical representation to model causal chains leading to failures. The concept is to start with a failure event and to trace its influences back until the basic influence factors are reached. The resulting influence hierarchy is depicted as an upside-down tree with the failure event. Those events whose causes have been further developed are termed 'intermediate events'. The top event of the fault tree is the system failure, which is also an intermediate event (Mo, Liu, Yang, 2007, 124).

Events in the fault tree are combined using logic connectives. ‘AND’ (*) indicates that all influence factors must apply simultaneously and ‘OR’ (+) indicates that at least one of the influence factors must apply to cause the failure. By using the property of the Boolean algebra it is possible to establish the combinations of basic failures which can lead to the top event when occurring simultaneously. These combinations are so called ‘minimal cut sets’ and can be derived from the logical equation represented by the fault tree (Pedro, C, 2006, 108).

3.3 The event analysis by fault tree

3.3.1 Top event and risk

The risk assessment on vessel collision with bridge

1. Acceptable risk criteria

According to European or American Standard (AASHTO), the acceptable frequency of bridge suffering serious impact from vessel is less than or equal to10^{-4} every year (Liu et al., 2013, p. 221).

2. Probability model of vessel collision

AASHTO model in American:

$Pimp = N \times P_A \times P_G$

In this formula:

Pimp - Frequency of bridge suffering impact from vessel every year,

N - Traffic flow in a whole year,

P_A - Yaw probability,

P_G - Geometric probability.

Collision risk of Taizhou Yangtze River Bridge

According to calculation from Liu Xiaoyong et al., using the AASHTO model, damage by vessel collision frequency of Taizhou Yangtze River Bridge is 10^{-4}. So the relevant department should take effective measures as far as possible to avoid the occurrence of accidents, according to risk decision criteria of the U.S. Department of Defense (Liu et al., 2013, p. 222).

3.3.2 Basic event and logical relation

When vessels are navigating, it is possible to collide with Yangtze River Bridge when they yaw from the correct course.

Operation error or force majeure may cause yaw, and the two cases are relation of OR gate. Operation error is caused by influence from subjective and objective factors together. The objective natural environment and situation of buoy in channel belong to objective factors and operating the wrong course is the subjective factor. These three situations are relation of AND gate.

Force majeure is divided into natural and mechanical factors and these two cases are relation of OR gate. Natural factors include sudden natural disasters like tornado and tsunami caused by earthquakes. Mechanical factors include two types of failure, namely, main engine failure and steering gear failure.

Intentional collision with bridge can be divided into two cases, crew or terrorist deliberately set course for collision with bridge. However, the probability is rather low. This paper mainly analyzes the risk factors leading to yaw, and the subjective intention would be outside the focus of this paper.

3.4 Establishment of fault tree

The top event of the fault tree is the accident of vessel collision with the Yangtze River Bridge. According to the data from accident database of Yangtze River Bridge and the possible risk factors in the bridge area, thirteen risk factors have been identified. Figure 3.1 shows the fault tree in Yangtze River Bridge while the terminology and symbols of fault tree is shown in table 3.1.

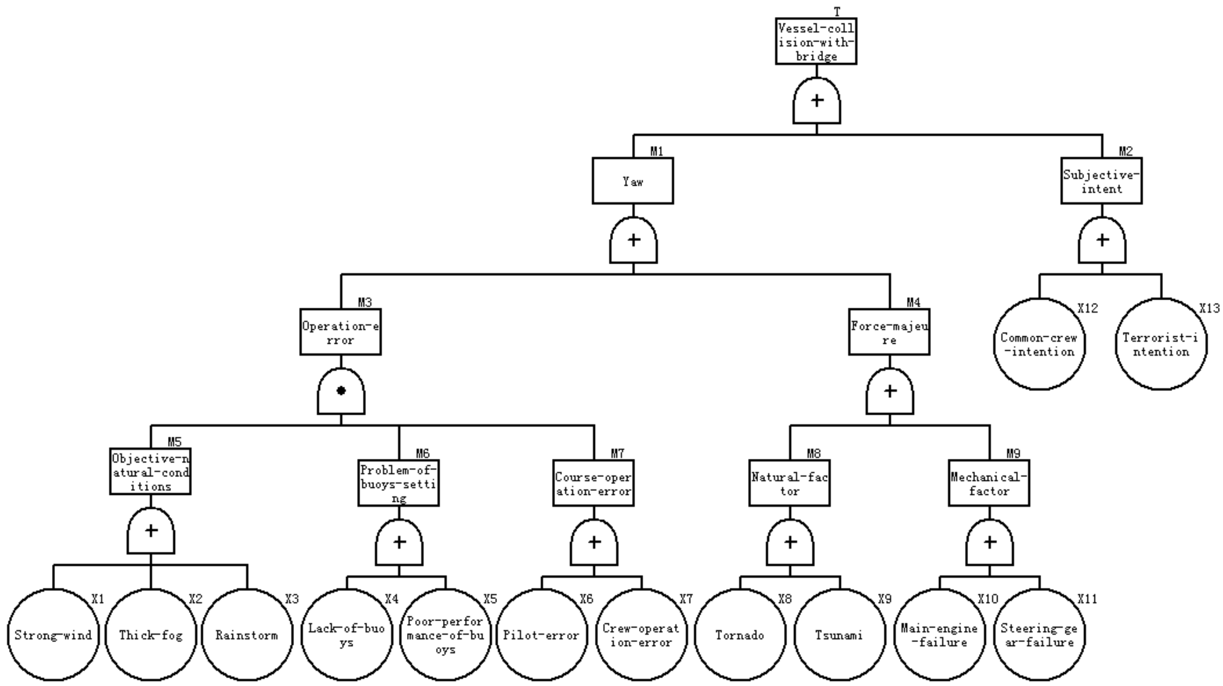

Figure 3.1: The fault tree model of vessel collision with Yangtze River Bridge

Table 3.1: Terminology and symbols of fault tree

Name	Symbol	Illustration
Basic event		No need to ascertain the cause of the occurrence of the bottom event
Result event		Event caused by a combination of other events or events
AND gate		The output event occurs only when all input events occur
OR gate		An output event occurs when the event occurs at least one input event occurs

3.5 Qualitative analysis

3.5.1 Calculation minimum cut sets and minimum path sets

The purpose of qualitative analysis of fault tree is to find out all possible failure modes of the top event. That is, it aims not only to find all the minimal cut sets but also to find the minimal path sets. These can be obtained by calculating the failure of the system.

So, we could get the minimum cut sets:

C1={X1,X4,X7}, C2={X12}, C3={X8}, C4={X10}, C5={X2,X4,X7}, C6={X3,X4,X7}, C7={X1,X5,X7}, C8={X2,X5,X7}, C9={X3,X5,X7}, C10={X1,X4,X6}, C11={X2,X4,X6}, C12={X3,X4,X6}, C13={X1,X5,X6}, C14={X2,X5,X6}, C15={X3,X5,X6}, C16={X9}, C17={X11}, C18={X13}, Minimum path sets is as follow:

{X1,X2,X3,X8,X9,X10,X11,X12,X13},

{X4,X5,X8,X9,X10,X11,X12,X13},

{X6,X7,X8,X9,X10,X11,X12,X13}

Through qualitative analysis, we can know that the main risk factors of vessel collision with bridge are the lack of buoys in the bridge area and the handling errors of vessel course, followed by wind, rain and fog. The less important are the vessel equipment fault, occasional meteorological disaster and intentional collision.

3.5.2 Structure important degree

Structure important degree reflects the importance of each unit in the system. The calculation of important degree is to sort each unit of the system from high to low in a physical sense, which is an important part of system reliability quantitative analysis. The important degree of the structure reflects the elements with time, when the normal state of the system is compared with the fault state, and it also reflects the increasing proportion of the number of normal state in all states of the system. In other words, it reflects the decreasing proportion of the number of fault state when the element corresponding to the basic event is changed from the fault state to the normal state.

The formula of calculation of structure important degree:

$$I_{\varnothing(i)} = \frac{1}{k}\sum_{j=1}^{n}\frac{1}{n_j}\left(j \in k_j\right)$$

In this formula, k – the number of minimum cut sets,

k_j - The jth minimum cut set

n_j - The number of basic events in the jth minimum cut set

Using the theory above to calculate the importance degree of the structure of each basic event in the event of vessel collision with bridge is as follows:

$I_{\varphi(4)} = I_{\varphi(5)} = I_{\varphi(6)} = I_{\varphi(7)} > I_{\varphi(1)} = I_{\varphi(2)} = I_{\varphi(3)} > I_{\varphi(8)} = I_{\varphi(9)} = I_{\varphi(10)} = I_{\varphi(11)} = I_{\varphi(12)} = I_{\varphi(13)}$

From the important degree of each basic event, it is evident that the result is the same with that from the qualitative analysis.

CHAPTER 4

Analysis safety risk factors of vessel navigation in Taizhou Yangtze River Bridge area

According to analysis of the database of accidents by the 19 Working Group, human error counts for 70%, and mechanical failure counts for 20%, and bad natural environment counts for 10% in the cause of the accident. Of the 52 cases of serious accident, 11 cases occurred in the same bridge, and 18 cases occurred in the same bridge twice, and 3 serious cases occurred in 5 bridges. Besides, there are 5 serious cases occurring in one bridge (Dai, 2003).

It is a common research method that scholars tend to adopt on the accident cases and find the regularity in these (Lin, 2006). In accident cases, we can know that there are direct factors and indirect factors in the inland waterways navigable environment of bridge areas, which lead to hazard of traffic (Zhang, 2013). Among them, the direct factor mainly refers to the natural water environment factors, and indirect factors mainly include the factors of human, facilities and management level. These direct or indirect factors are included in the risk factors that affect the traffic safety.

In this chapter, I analyze various risk factors based on the basic event in fault tree of the vessel collision with Yangtze River Bridge, combined with safety management status of the Taizhou Yangtze River Bridge and the feasibility of actual operation.

4.1 Operation error analysis

4.1.1 Problem of buoys setting

4.1.1.1 The setting of buoys and routing scheme in Taizhou Yangtze River Bridge area

Buoy is a navigation mark and could ensure the safety of the vessel, whose main functions include positioning, indicating traffic, avoiding danger and confirming function (Liang, 2011). There were many accidents that happened in bridge area because of the lack of buoys. Table 4.1 shows the light buoys in the waters of Taizhou Yangtze River Bridge.

Table 4.1: The Light Buoys in the Waters of Taizhou Yangtze River Bridge

Light Buoy	Latitude	Longitude	Character of Beacon
#1 Tai Upbound Red	32:13:47.130	119:53:12.590	Red Single Flash
#1 Tai Downbound Black	32:13:54.999	119:53:29.118	Green Single Flash
#2 Tai Upbound Red	32:14:32.886	119:52:54.426	Red Two Flash
#2 Tai Upbound Black	32:14:37.381	119:53:10.235	Green Two Flash
#3 Tai Upbound Red	32:15:19.159	119:52:31.940	Red Single Flash
#3 Tai Upbound Black	32:15:24.497	119:52:46.374	Green Single Flash
Left and Right Navigable	32:15:58.657	119:51:50.085	White Three Flash
#1 Tai Downbound Red	32:13:16.085	119:52:31.802	Red Single Flash
#1 Tai Downbound Black	32:13:22.954	119:52:50.622	Green Single Flash
#2 Tai Downbound Red	32:14:04.059	119:52:22.608	Red Two Flash
#2 Tai Downbound Black	32:14:05.993	119:52:41.818	Green Two Flash

#3 Tai Downbound Red	32:14:58.555	119:51.40.204	Red Single Flash
#3 Tai Downbound Black	32:15:09.633	119:52:18.391	Green Single Flash
#4 Tai Downbound Red	32:15:38.713	119:51:40.143	Red Two Flash
Right Upbound Boundary	32:15:56.616	119:51:24.297	Red Fast Flash
Left Downbound Boundary	32:13:24.631	119:53:52.566	Red Fast Flash
Special Upbound Tower	32:14:55.428	119:52:32.202	Yellow Single Flash
Special Downbound Tower	32:14:41.798	119:52:37.989	Yellow Single Flash

Sources: Channel Situation Bulletin in 2013 from Yangtze Waterway Administration Bureau

As shown in figure 4.1, there is traffic separation scheme in the waters of Taizhou Yangtze River Bridge according to the routing scheme. Upbound vessels should lay Tai Upbound Black buoys from #1 to #3 on their starboard side and go through the bridge by the Upbound traffic lane. While Downbound vessels should lay Tai Downbound Black buoys from #4 to #1 on their starboard side and go through the bridge by the Downbound traffic lane.

Figure 4.1: The channel situation in Taizhou Yangtze River Bridge

Source: Taizhou VTS for user.

In the river where there is routing scheme, the regulation about distance between ipsilateral adjacent buoys is not greater than 0.8-0.9 times of design visual range. On both sides of the channel, buoys should be laid continuously one by one and accurately mark the boundaries of channel (Liang, 2011). The distance between ipsilateral adjacent buoys should be set about 3km in region from Shisiwei and Yanziji (Li, 2010). Taizhou Yangtze River Bridge area is located between the region mentioned above, and the distance is 3km, which satisfies the performance standard and the actual demand.

There are also some abnormal situations in actuality. Buoys may drift, lose, damage or have other abnormal conditions, which lead to poor performance and loss of the original function. The patrol boats of Taizhou MSA would check the status of buoys in their daily patrol. VTS center could also get the abnormal situations from the sailing vessels and then timely notify the competent department of buoys. When the competent department of buoys got into this situation, they should restore it timely. The scheme could make the abnormal buoys recover as soon as possible.

4.1.1.2 Adjustment of Buoys led to accidents

Due to the construction of Taizhou Yangtze River Bridge, the characteristics of waters flow changed in the bridge area, downstream of the moderate tower appeared silt shoal, and navigation environment changed as well. The continuous adjustment of buoys and bend channel itself makes the channel to change, which is shown in figure 4.2. When vessel proceeding after #T5 black buoy, if she does not adjust the course to the right in time, she would directly go out of the channel and proceed to the moderate tower.

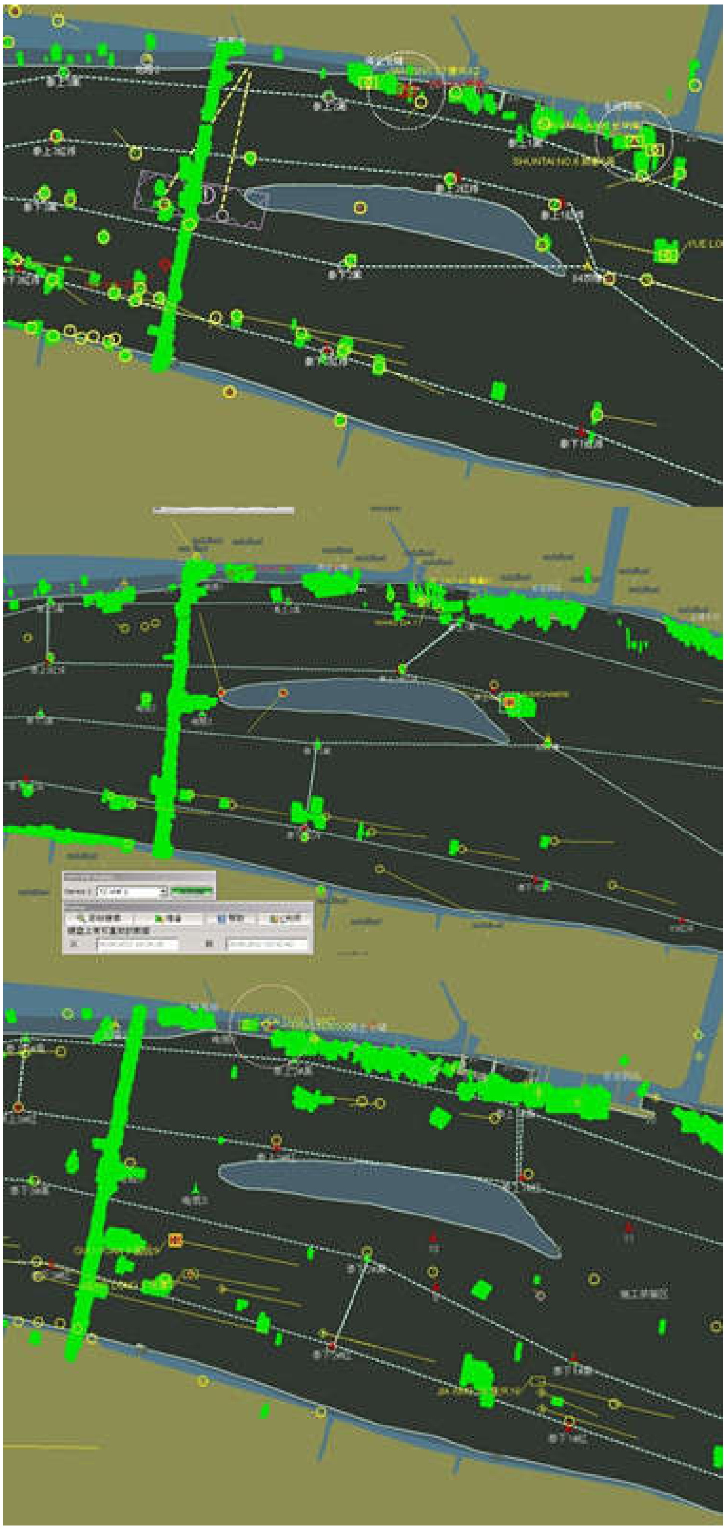

Figure 4.2: The changing of the channel

Source: Taizhou VTS for user

The administration department of buoys should survey the depth changes in channel timely, and adjust the location of buoys and change the traffic lane with the changing of hydrographical conditions and operating of new port. The implementation of adjustment of buoys should have safety assessment. For the operator of bridge, he should entrust the competent department to set buoys and get optimization scheme. While for the competent department he should always optimize the buoys setting in bridge area, and make effort to get the buoys larger, brighter and have electronic display at night (Gao, 2010). Besides, the department should also lay buoy straight in a line and make them flash at the same time as far as possible (Zhang, 2013). Thus the officers on duty on board could find buoys in bridges area by the naked eye or radar more easily, so they can identify and correct the traffic lane and proceed through the bridge area safely and reduce the risk of yaw.

From Figure 4.1, we can know that status of buoys in the area of Taizhou Yangtze River Bridge is proper and straight in a line, which could increase the safety of vessels to go through the bridge.

4.1.2 Course operation error

According to incomplete statistics, the number of yaws in Taizhou Bridge area is shown in figure 4.3.

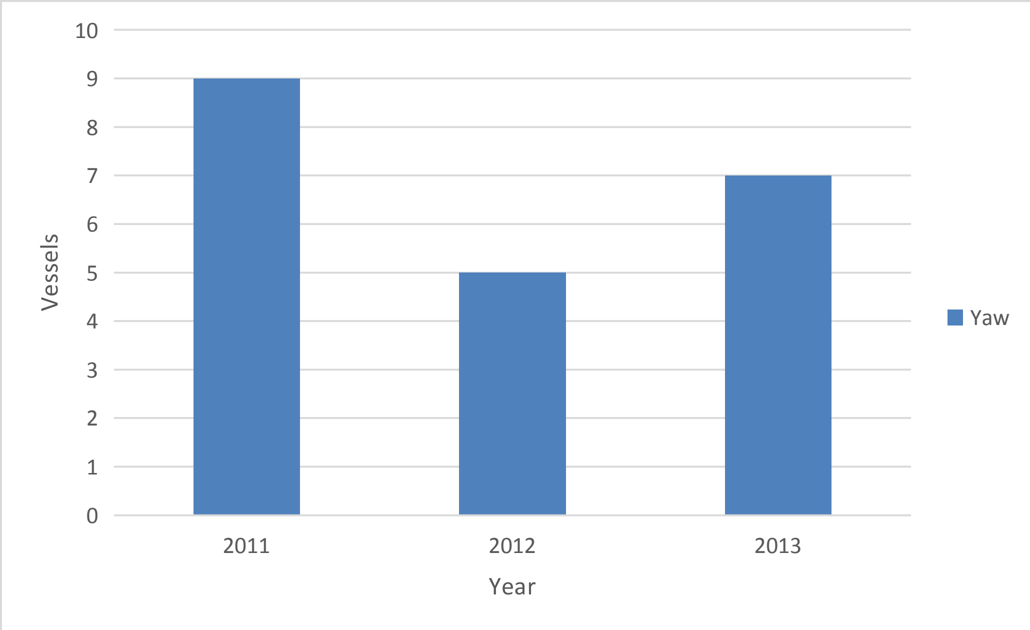

Figure 4.3: The number of yaws in Taizhou Bridge area from 2011 to 2013

Source: The Emergency Statistics of Taizhou MSA in 2013.

According to information of emergency situation in Taizhou, we know that the danger of yaw is caused by crew on board. According to the investigation on the duty officer, the main cause of yaw is that the officers are not familiar with navigable environment in the Taizhou Yangtze River Bridge area. Other causes include the negligence of lookout and the identification of the wrong buoys. The cause that officers are not familiar with navigable environment accounts for a large proportion in the accidents which happened in the bridge area (Gao, 2003).

Lack of nautical publications is the main reason why officers are not familiar with navigable environment. Nautical publications include sailing directions, list of lights, tide tables and other publications, which contains the information about waterway, depth, buoys and other information. This information is necessary for navigation safety. So, supplementing and updating the latest publications is essential for safety at sea. According to statistics, accidents caused by errors of nautical publications accounts for 2%.

As we know, lack of latest nautical publications could lead to the error of vessel course. The only way to check the situation is to embark on board. From chapter 2, we know that the traffic flow through the bridge is about 2328 everyday. We have no idea that which one is lack of latest nautical publications unless we carry out investigation on her. In chapter 3, we know that the error of vessel course is the most important factor contributing to the happening of yaw. By contrasting these situations, we know that this risk also exists in Taizhou.

4.1.3 Objective natural meteorological conditions

Bad weather could affect people's judgment and may cause operation error. Fog and rain affect the visibility. The visibility factor will lead to decrease speed of vessel or make vessel suspend to anchor, which greatly impacts on safety and efficiency of traffic in waters. When the visibility is poor, accidents are prone to occur, like collision and grounding, which would seriously affect transport in waters. Some scholars have done some statistical analysis on influence of visibility on navigation safety in the Yangtze River. They count and analyze on accidents within 1000 hours in specific visibility and get such conclusions as follows. When the visibility is less than 4 km, navigation safety of vessels will be subject to certain influence. When the visibility is less than 1 km, navigation safety of vessels will be significantly affected, and visibility at this time is defined as dangerous visibility (Liang, 2011).

According to chapter 2, the average number of fog days is 48 in a calendar year. The annual average number of rainy days is 117.3. From the statistics of Taizhou VTS, the number of days in which visibility is less than 1 km is up to 110. So, the fog and rain are danger factors that need to be considered when taking measures in Taizhou.

Windy weather also affects the safety and efficiency of traffic in waters. Wind has a significant impact on the sailing vessels. It could make vessels stall or increase their speed. On the one hand, it makes vessels drift to leeward; on the other hand, it makes vessels turn. The extent and feature of impact from wind on vessels are related to several factors, such as wind scale, wind angle, the ratio of freeboard and draught, wind area and wind power center position, speed and course of vessels etc. The greater the wind is, the greater the impact on tilt, drift and deflection of vessels (Wang, 2005). In the broad waters of the downstream of Yangtze River, a force 4-5 wind is enough to impact on safety of sailing fleet. When wind is up to level 6 or more, vessels encounter more complexity and difficulty in maneuvering, and safety of navigation will be affected and the collision vessel with bridge is more likely to occur.

Form chapter 2, we know that the number of days in which wind level is greater than 5 is 44.5, and that greater than 6 is 9.1, and that greater than 7 is 4.5 from 1959 to 1987 in Taizhou. Besides, Taizhou is located at the downstream of Yangtze River. The breadth of Yangtze River is more than 2km in most of Taizhou, which belong to broad waters. Sailing vessels is easy to be affected by wind in this area. So, the wind is the danger factor that needs to be considered in Taizhou.

4.2 Force majeure analysis

Force majeure contains natural and mechanical factors. The occurrence of a very low probability of tornadoes and tsunamis is one of the natural factors which will not be covered in this paper. I mainly focus on the analysis of mechanical factors.

According to incomplete statistics, the number of faults of main engine and steering gear in Taizhou Yangtze Bridge is 12 from the year 2010 to 2012, which is shown in figure 4.4.

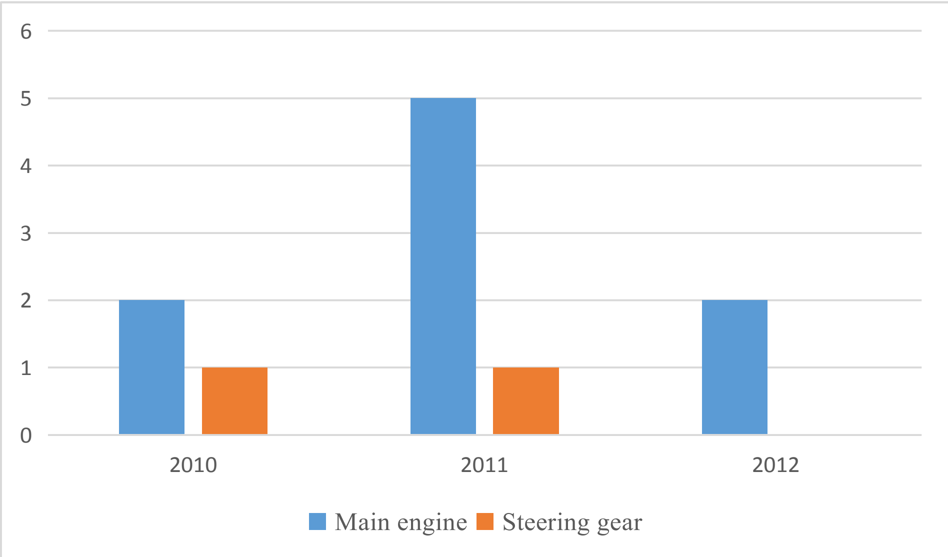

Figure 4.4: The number of faults of main engine and steering gear from 2010 to 2012

Source: The Emergency Statistics of Taizhou MSA in 2012

Because of the disorderly streams in the bridge area, the vessel is affected by the wind, wave and current, and needs to change speed and course frequently, which will probably lead to failure of main engine and steering gear. Major accidents caused by vessel out of control occupy a large proportion in the total number of accidents. According to the PIANC survey, this kind of accident accounted for 21% of the total number of accidents. When vessels get out of control in bridge area, they would have more probability than normal sailing vessels to collide with bridge (Wang, 2010). Vessels get out of control because of failure of main engine or steering gear or both. The occurrence of the failure is not predictable. If the equipment of a vessel is very old and the technical performance is relatively outdated, there would be higher probability of failure. However, the newer equipment and good routine maintenance can effectively reduce the probability of vessel equipment failure.

From chapter 2, we know that the traffic flow that goes through the bridge is about 2328 every day. The vessels sailing in the river are quite different regarding the status in maintenance. The emergency situation in which vessels get out of control may happen at any time, especially for old vessels. The vessels which have record of out of control should also be paid attention to. So, the mechanical factors are also a great danger for Taizhou Yangtze River Bridge and measures should be taken to reduce the risk.

CHAPTER 5

Countermeasures and suggestions for reducing the risk

5.1 Implement the responsibility system for bridge safety management

After the completion of bridge construction, several kinds of buoys should be set in bridge area and maintained regularly in accordance with the relevant regulations and standards. These settings should apply for a special approval by MSA. Safety information should also be announced by MSA. Operators should establish and perfect the enterprise safety management responsibility system according to the provisions of the law of the People's Republic of China. The units who construct, operate, and benefit are responsible for safety management. They should establish long-term regime to prevent vessel from colliding with bridge, speed up research work on preventing collision, and improve the bridge's anti-collision ability.

5.2 VTS system covering bridge area

Taizhou VTS officially started operation on September 1, 2009, including four radar stations. Gaogang radar station is located in Binjiang Economic Development Zone, whose longitude is 119° 50′ 41.43324″ E and latitude is 32° 18′ 13.07029″ N， covering the area between buoys #83 and #91.

VTS is a kind of advanced traffic management system at sea, which should comprise at least an information service and may also include other services,such as a navigational assistance service or a traffic organization service, alli ed service (Zhou, 2010). A large number of facts have proved that the VTS system is an effective means to improve the safety of navigation in the bridge area and reduce the risk of vessel collision with bridge. According to statistics, VTS can reduce illegal and improper operation of accidents by more than 30% in their covering area.

The area of Taizhou Yangtze River Bridge is showed separately on one computer screen in VTS. So, the area would be amplified. When the situation of yaw occurs, VTS officers could easily find this on computer screen and give it timely warnings and thus may prevent collision of vessel with the bridge from happening. According to analysis on tracks of vessels going off course, the difference of course is about 30 degrees when vessels proceeded for 3 minutes after the check point #T5. This situation could be easily found.

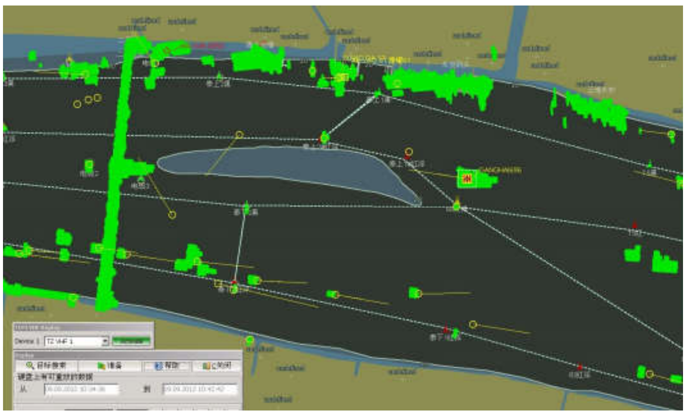

Figure 5.1: M/V Ganghai 696 is going off course

Source: Taizhou VTS for user

VTS should get information from meteorological department timely and give information to vessels especially in the period of bad weather. Besides, VTS should do a good job of warning and take measures when necessary. When the visibility is less than 1km or the wind reaches up to force 7 or more, VTS will prohibit vessels and fleets from proceeding through the waters area of the bridge. In this condition, vessels should anchor and wait until the weather improves.

When the weather gets better, vessels will sail for the port of destination again. As a result, it will cause peak flow in a short time. Vessels would be relatively concentrated in the area of Taizhou Yangtze River Bridge. At that moment, the VTS should give information service and traffic organization service. Besides, the patrol boat of Taizhou MSA should offer help to sailing vessels at scene. The patrol boat should keep pace with VTS to ensure that the peak flow sails through the bridge area safely.

Taizhou MSA has taken traffic control measures over a hundred times because of bad weather in 2015. VTS should be equipped with adequate documented personnel to ensure that its function could full play. The officers should improve their sense of service and render services proper.

5.3 Making provisions on navigation safety in bridge area

In view of the increasing risk in the bridge area, the MSA should study and introduce the regulation of safety navigation management in the bridge area as soon as possible.

Before vessels proceed through bridges, crews on board should check the status of the main engine, auxiliary engine, steering gear, windlasses and other key equipment and make sure that they can be used immediately (Tang, 2009). Vessels should take measures like loading ballast water or cargo, according to bridge clearance, sails safely through bridge. The officers on duty should be familiar with hydrological situation in bridge area, and be skilled, if it is necessary, the captain should be on bridge and give orders himself. Besides, vessels should keep enough rudder safe speed.

5.4 Strengthen the sense of safety responsibility of the crew

Vessels are maneuvered by crews. The performance of crews greatly influences the safety of vessels. According to statistics, 70% of the accidents are caused by human factors. Shipping companies should establish a mechanism of crew training and the system of responsibility, regularly train crews to improve their consciousness of safety and responsibility and their knowledge and skills. Safety awareness is particularly important among them. When the crews realize that their own safety and the vessel’s safety are closely linked, they will learn actively and consciously cultivate their own safety awareness. Crew will consciously obey the rules and they would avoid drinking and have enough rest. In this way, crew could have good spirits and performance (Yang, 2015).

5.5 Set up bridge emergency management system

Bridge operating units should establish a bridge area of emergency plans and emergency rescue mechanism (Chen, 2010). Corresponding emergency rescue facilities should be equipped, such as the rescue tug and anti-pollution facilities. These measures are useful when vessels got out of control in the bridge area, which could control the position of vessels. Drills should be carried out periodically by relevant departments to enhance the comprehensive analysis ability of emergency and rapid response capability and processing capacity if a collision occurs (Lou, 2010).

5.6 Follow the laws and regulations to ensure the safety of navigation

The vessel owners, operators and managers should strictly abide by the maritime traffic safety law of China and inland river traffic safety management regulations of China and other laws and regulations. Firstly, they should equip plenty of competency crews on board. Secondly, they should strengthen the management and training of crew, and improve the crew's ideological quality and operation skills and safety awareness. Thirdly, they should request the crew to strictly comply with the navigation regulations of the bridge area and carefully execute and ensure the safety of navigation through the bridge area. For the vessels that violate the regulations or laws, Taizhou MSA should carry out the investigation, identify the reasons and give the appropriate punishment.

CHAPTER 6

Conclusions

Taizhou Yangtze River Bridge is a main artery of traffic, facilitating the convenience of personnel exchanges between the two sides of the Yangtze River and ensuring the rapid circulation of goods and enhancing the mission of local economic development. At the same time it has an important influence on the sailing vessels in the Yangtze River. However, with the number of the berths on the both sides of the Yangtze River increasing and the water depth of the channel increasing to 12.5 meters, the traffic flow and tonnage of the vessel are rising, and thus the risk of vessels' collision with bridges is also increasing. Influenced by the accident that happened to Guangzhou Jiujiang Bridge in 2007, vessels' collision with bridges has become a sensitive topic and brought much social concern. Due to the importance of the Yangtze River, the traffic safety issue has received unprecedented attention.

By comparing the domestic and overseas research status, I think that the existing research results are mostly based on the common problems, and focus on bridges with small distance between piers, which is not suitable in safety risk analysis in the area of Taizhou Yangtze River Bridge. So, it is necessary to carry out risk analysis in Taizhou Yangtze River Bridge separately. Firstly, the research is carried out by analyzing hydrological and meteorological situation and channel settings, traffic flow and other environmental factors in the area of Taizhou Yangtze River Bridge. Then, based on the establishment of fault tree about vessels collision with bridge in China, the main risk factors are identified. Based on logic relationship between basic and top incidents, qualitative and quantitative analysis of risk factors is carried out, and the degree of the importance of each risk factor is determined, and main risk factors are found. So, we can know that the main risk factors of vessel collision with bridge are the lack of buoys in the bridge area and the handling errors of vessel course, followed by wind, rain and fog. The vessel equipment fault, occasional meteorological disaster and intentional collision are less important. At last, the countermeasures of management of navigation safety risk are presented, according to the main risk factors in Taizhou Yangtze River Bridge.

However, there are some limitations in this paper due to my limited knowledge and research ability, such as, the lack of data in the process of the study and the failure of the risk factors in a comprehensive and in-depth analysis. With the rapid development of Taizhou Port and continuous improvement of waterway in the Jiangsu section of the Yangtze River, the type and tonnage of vessels will also change, which will have a greater impact on navigation safety. I hope that experts and scholars in relevant fields in the future could carry out further research on the risk that exists in Taizhou Yangtze River Bridge and help further reduce the risk.

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