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Dynamic risk assessment model of Tianjin VTS Water Area and its application

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DYNAMIC RISK ASSESSMENT MODEL OF TIANJIN VTS WATER AREA AND ITS APPLICATION

By

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DECLARATION

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

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

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ABSTRACT

As one department of Tianjin MSA, Tianjin VTS(short for Vessel Traffic Services) plays an essential role in marine traffic management. With the intelligent development in marine industry, the management technology and intelligent innovation are integrated into routine work of Tianjin VTS. Before finding effective risk control options, dynamic risk assessment in port water area is necessary for decision-makers to adopt traffic management measures. In order to realize the fundamental function of the risk assessment system in VTS, various methodologies are introduced in the research and experimental phase. Such as FSA tool, fuzzy math theoretical demonstration of fuzzy mathematical model and Analytic Hierarchy Process(AHP).

This dissertation researches on how to establish traffic dynamic risk assessment model and its application in VTS waters through fuzzy mathematics and comprehensive assessment methods. The main body is divided into 6 parts.

Firstly, Chapter 1 gives a brief introduction of the background of Tianjin Port marine traffic environment and current situations of risk assessment in port waters at domestic and abroad. Different risk assessment methods, principles and algorithms of the evaluation method used in this paper is discussed in Chapter 2.

The newest traffic statistics data and risk evaluation indices of Tianjin Port are discussed in Chapter 3. Chapter 4 provides details about establishing dynamic risk assessment model and the model is verified by experimental application in Chapter 5. Lastly a short conclusion and an expectation of the model’s application is given in Chapter 6.

Keywords: Dynamic risk; Fuzzy mathematics; Comprehensive assessment; APH

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
AIS	Automatic Identify System
ALARP	As Low as Reasonably Practicable
ANFIS	Adaptive Network-based Fuzzy Inference System
ETA	Event Tree Analysis
FSA	Formal Safety Assessment
IMO	International Maritime Organization
MCA	Maritime and Coastguard Agency
MTC	Ministry of Transport of China
PAM	Process Analysis Method
QRA	Quantitative Risk Assessment
STMC	Ship Traffic Management Code
VTS	Vessel Traffic Services
VTSO	Vessel Traffic Services Officer
ULCS	Ultra-Large Container Ships

CHAPTER 1

INTRODUCTION

1.1 Research Background

Tianjin Port is located in the west coast of Bohai Sea of China. The port is comprised by several port regions. The main port area refers to Xingang harbor and the Da gugou Anchorage water areas. Tianjin Port is the biggest integrated open port, essential logistics centre in Northern provinces and the biggest artificial harbor in China. It trades with many ports in many countries and regions of the world and plays a role of comprehensive international trade hub port in China, mainly for the transportation of general cargo and containers.

Tianjin Port embraces 200 km^2 water areas and 47 km^2 land. As to the end of 2017, there are 132 berths totally in the harbor, among which 87 berths (including 23 container berths) belong to Tianjin Port Corporation that ordinates 20,115 meters quayside directly. The cargo throughput of Tianjin Port reached 502.84 billion tons in 2017, and it is predicted to reach 600 million tons in 2020. According to the statistics of Tianjin MSA, the traffic volume of Tianjin Port counted by entry and exit is 269,787 pass-through times in 2017, and the average daily traffic flow in and out of the port is 458 times. The high density of navigation within the harbor poses challenges to the navigation safety of the region's waterways.

As one department of Tianjin MSA, Tianjin VTS is authorized to enhance maritime traffic security, improve traffic efficiency and protect the environment. Within the VTS area, this service should be able to interact with ships and react to the traffic situation change. Tianjin VTS is responsible for improving marine traffic safety, the traffic efficiency and protecting the water environment and the service range is from simple information service to port and waterway traffic management.

As a kind of aids to navigation, VTS not only plays the role of maintaining the water traffic order, but also plays the role of reducing the risk of heavy traffic and wharf areas. To implement the management of ship traffic in the port and coastal navigation intensive areas, it is necessary to consider the rationality and effectiveness of safety management measures. Therefore, Tianjin VTS needs a systematic analysis and evaluation over the covering waters, and explores the potential risk factors affecting the safety of navigation system before taking corresponding vessel traffic safety management countermeasures (SUN S.J., 2011).

At present, Tianjin VTS crew have to face potential risks in maritime traffic every day. Timely awareness of the existence and magnitude of risks and then providing human intervention are the main function of VTS. The term *risk* refers to a comprehensive status of the frequency and consequences of an accident or incident which has adverse effect on human and objects compared to marine safety（ZHOU Z.F.,2006）. IMO FSA guidelines, adopted at the MSC74 meeting, define *risk* as a combination of frequency and severity of consequences (WANG J.H., et al.,2013).Dynamic risk refers to the traffic risk that ships are forced to bear during navigation or anchoring. It changes with geographical position, weather and traffic environment at any time, mainly referring to the potential threat that the surrounding environment forces ships to have a traffic accident.

How to evaluate the navigation environment safety of Tianjin VTS water area is an urgent problem. The purpose of this study is to analyze the level and distribution of dynamic risk in Tianjin VTS waters using appropriate risk assessment methods, so as to provide regional risk alert for VTSO. Furthermore, it may provide references for updating traffic management rules.

1.2 Literature Review

Although the maritime business has a long history of maritime accidents and loss of life, the marked increase in research publications only occurred in the past two decades. This phenomenon may be due to the increasing number of maritime accidents, the greater consequences of accidents in terms of the higher values of the ships and cargoes affected, and the resulting effects on the environment(LUO M.F.& SHIN,2018). Japanese scholars Toyota and Fujii referred to that marine traffic engineering is applied to investigate marine traffic conditions and to seek a better arrangement in 1971. The application of these research results is aimed at improving the facilities of ports, fairways, and their traffic regulations. The navigational risk in Tianjin port have recently been studied by (Zhang et al. 2016) using a Bayesian belief network (BBN) model. The objective was to estimate the consequences of all types of accidents and, further, to identify the indicators that have the greatest influence on consequences. A framework of safety indexes to evaluate the risk level in busy waterways according to accident severity, fatality rate and special indicators of maritime transportation was formed based on the historical traffic accidents data reported in the Western Shenzhen Port(MOU J.M., et al.,2016). FSA approach was applied to the Istanbul Strait to evaluate risks and establish safety system (Omer Faruk Gorcun& Selmin Z. Burak,2015).

With the consideration of present traffic management model of Tianjin VTS, the potential risks in dense traffic waters are coordinated and governed by VTS crew who are responsible for maintaining safe traffic waters where vessels voluntarily navigate and arrive. The precaution to risks mainly depends on the subjective judgments of personnel and mandatory regulations towards ships. The Radar, E-chart and AIS data collection terminals only supply personnel direct dynamic pictures which lacks optimized data and information contributed to risk control and prevention.

1.3 Methodology

It is necessary to carry out a preliminary analysis of the port water risk status before assessing the integrated risk in port waters. Thus the maritime accident data of Tianjin Port during 2008-2013 is analyzed in Chapter 3 through using quantitative risk assessment method in the FSA aiming to understand the outline of risk level of Tianjin VTS waters.

After that, the Delphi method was used to establish the water dynamic risk evaluation index system in Chapter 3. Combined with the actual data of Tianjin Port, the membership function of evaluation index of secondary level is established by using fuzzy mathematical algorithm in Chapter 4, which provides the basis for establishing risk assessment model. In Chapter 4, analytic hierarchy process (AHP) is used to establish the weights of risk evaluation indices of two layers.
Finally, a comprehensive dynamic risk assessment model of Tianjin VTS water area is formed by fuzzy and comprehensive assessment method.

CHAPTER 2

Basic knowledge of risk assessment

2.1 Overview of risk assessment methods

There are many methods used in risk assessment, such as FSA, event tree method, Bayesian network method, Grey system theory method, Fuzzy assessment method, BP neural network method, etc. This part briefly introduces the basic theories and application characteristics of the above methods, and finally determines the theories and methods suitable for dynamic risk assessment of Tianjin VTS waters.

2.1.1 FSA

Risk assessment was applied early in the field of Marine engineering and then introduced into the field of Marine transportation. FSA has been recognized as a structured and systematic framework for risk assessment and control in maritime transportation-related industries. In 2002, a FSA framework proposed by the UK Maritime and Coastguard Agency (MCA) was approved by the IMO as a formal policy making tool. It allows for the use of all possible data sources to conduct risk assessment in a qualitative or quantitative manner or a combination of the two. Although being widely utilized, some studies have shown that FSA still has some drawbacks, such as not being able to give an overall picture of risk and not being able to measure the risk precisely(Merrick& Van Drop,2006).

2.1.2 Event tree analysis method

Event Tree Analysis（ETA) method is a top-down logical deduction method from cause to effect，i.e. this method starts with an initial event and analyze the results of the sequence of events that it can cause. Each possible event needs to consider both the possibility of success or failure. The analysis is then continued with this possible new initial event until the final result. Since many event chains form a tree structure can track the development path of events, this method can evaluate the loss of human life, property and economy qualitatively and quantitatively.

From the existing literature, the event tree is structured according to the sequence of events. During the process, it does not consider factors affecting the occurrence of intermediate events, including human factors and organizational factors. Therefore, the ability is insufficient in the analysis of sequential event correlation degree,i.e. conditional probability.

2.1.3 Bayesian network theory

Bayesian network theory is based on probability theory to express the uncertainty of variables. Random variables are represented as nodes, and the causal relationship between variables is represented by connecting nodes. The network structure of Bayesian theory is formed by the relation graph connecting the reason nodes and the result nodes. The degree of correlation between variables is described by a conditional probability that represents the degree of dependence between parent and child nodes.

Bayesian network theory often involves conditional probability, multiplication formula, chain rule, full probability formula and Bayesian formula, in which the functional meaning of Bayesian formula is especially important.

｛B_1,B_2,…, B_n｝is set as a complete set of complementary and compatible events of E, and p(B_i) > 0.A is any event of E, and there is

$$p(B_i|A)=\frac{p(B_i)p(A|B_i)}{\sum_{j=1}^{n}p(B_j)p(A|B_j)}$$

2.1.4 Grey system theory

In recent years, scholars studying maritime traffic safety have gradually introduced the grey system theory into the evaluation of Marine traffic environment, and achieved good results. ZHENG Z.Y. analyzed eight selected environmental factors affecting the safety of port navigation of ships with grey system theory, and the risk of navigation environment of ships in ten coastal ports of China was evaluated. MA H.&WU Z.L.(1998) makes a quantitative evaluation on the danger degree of the ship operating environment of the port channel and the influence degree of each evaluation index on the navigation safety of ships by applying Grey clustering and grey statistical evaluation method.

2.1.5 Neural network theory

BP (Back Propagation)neural network proposed by Rumelhart and McCelland in 1986 is one multi-layer feedforward network trained by error back-propagation algorithm and is widely used in neural network models. Chinese scholars SHAO Z.P. proposed the adaptive neural network and fuzzy reasoning model and established the Adaptive Network-based Fuzzy Inference System which includes visibility, wind and natural environment that influences the maritime traffic environment. The model was used to evaluate the environmental risk of ship operation. The neural network theory has strong adaptive ability and good fault tolerance, but it also has the defects of low accuracy, which requires a certain number of training samples(ZHU J.J.,2016).

2.1.6 Expert knowledge base method

Expert knowledge base method (short for EKBM) is a method used in the phase of risk identification. It only estimates the risk consequences and does not involve quantitative calculation. The purpose of applying this method is to identify potential risks. EKBM is mainly suitable for certain circumstances in which the risks are difficult to identify in a short period of time by using statistics and causality reasoning method. For instance, when a ship sailing on the sea waters where related navigation information lacks, experienced captain and other experts must be consulted. At present, Brainstorming and Delphi method are used extensively in this field. Brainstorming is a kind of group decision making method to improve the quality of decision-making, and its main purpose is to generate new ideas or to stimulate creative thinking. Delphi method (ZHANG Y.Y., 2012) is to use methods such as questionnaire to collect opinions of relevant experts. Through statistics and repeated consultation, the questionnaire results tend to be unified and the expected survey objective is achieved. According to systematic procedures, surveyors design the questionnaire and consult with different experts by means of questionnaires or inquiry letters, different experts express their opinions anonymously. After repeated consultation and feedback for many times, experts gradually concentrate their opinions and finally get the collective judgment result with high accuracy.

2.1.7 Fuzzy comprehensive assessment method

Firstly, the fuzzy comprehensive assessment method uses the fuzzy mathematics theory. Fuzzy mathematics is a mathematical concept proposed by Professor L.A.Zadeh in1965 to deal with fuzzy phenomena, in which "fuzzy subset" and "membership function" quantitative description methods are introduced(ZHANG D.H.,2007) (DAI J.F.,2003). This theory changes the traditional mathematical view "not right is wrong", and it is used to build a mathematical model to make the fuzzy information quantitative and formal. There are many uncertain factors in the objective environment, which cannot be analyzed and judged in the traditional way. However, fuzzy mathematics theory can deal with fuzzy information quantitatively.

Secondly, comprehensive evaluation is the evaluation of the object affected by various factors. The idea is to treat the evaluated object as a fuzzy set composed of multiple factors -- factor set. By setting the evaluation level of these factors, the evaluation set is formed. After that, according to the membership function, the membership degree of each single factor to each evaluation level is calculated to construct the fuzzy matrix. Finally, the weight of each factor in the evaluation index system is combined with the fuzzy matrix to obtain the quantitative value of the evaluated object .

2.2 Selecting suitable dynamic risk assessment method for Tianjin VTS

In this paper, the fuzzy comprehensive evaluation is taken as the main method to carry out the research based on the fuzzy mathematics theory, which mainly considers the following reasons.

2.2.1 Dynamic risk assessment involves many factors

Port traffic environment risk assessment process involves many factors, including the hydro-meteorological factor, geographic factor and traffic condition factor ,and these three factors also include many sub-factors. Since there are many kinds of factors influencing each other, it is one-sided to conduct research from a single aspect that the actual situation is not illustrated correctly.

2.2.2 The related factors are highly ambiguous

The factors related to the evaluated objects are ambiguous, which are difficult to analyze and evaluate quantitatively. When assessing risk values, there are many transitional standards. Vague information such as "safety, general danger, relatively dangerous and extremely dangerous" often appears in risk assessment（LI H.X.,1993）（ZHU J.,1995）. Researchers need to find effective mathematical tools to analyze and quantify these fuzziness.

2.2.3 The advantage of fuzzy mathematics in risk research

Fuzzy mathematics is good at dealing with fuzzy information which is difficult to be processed by other methods. Fuzzy comprehensive evaluation based on fuzzy mathematics theory can concretize the fuzzy problem, which can be used for subjective and objective comprehensive evaluation. Furthermore, the membership function introduced can be used to quantify the fuzzy information in the evaluation of risks. In addition, the fuzzy mathematics theory combined with multi-factor and multi-level system analysis, can build a multi-level fuzzy comprehensive evaluation model， which facilitates to evaluate complex objectives. Therefore, according to the needs of actual research work, this paper selects the theory of fuzzy comprehensive evaluation to conduct dynamic risk assessment of Tianjin VTS waters.

2.3 Principles of fuzzy comprehensive assessment method

Fuzzy comprehensive evaluation method refers to the use of multiple indices to consider the possibility of risk and conduct quantitative calculation to get the risk values that describes the risk level. In the process of risk assessment, the importance of evaluation index is weighed and the score is used to represent the comprehensive risk status of evaluated objects. The following is a comprehensive evaluation procedure for practical research.

2.3.1 Determining the set of factors for assessed objects

The set of factors U=(u_1,u_2,... u_i) is a number of factors that influence the research object and u_i (i=1,2,3, ……n) in this set represents several evaluation indices that affect the comprehensive assessment.

2.3.2 Determining the set of comment

The set of comments is defined as V=(v_1,v_2,⋯⋯v_i). Where v_i(i=1,2,3,⋯⋯ n) is sub-set of comments which is also called set of judgment corresponding to u_i(i=1,2,3,⋯⋯ n).

2.3.3 Establishing the weight set of influencing factors

The weight set A=(a_1,a_2……a_i) indicates the importance of each influencing factor to the research object, and it can reflect the importance of each factor in the comprehensive assessment. In general, the weight set should satisfy the two principles of non-negative and normalization, i.e.

$$\sum_{i=1}^{m} a_i = 1, \qquad a_i \geq 0$$

2.3.4 Determining the membership function of a single evaluation index

The so-called single factor fuzzy evaluation refers to the evaluation of a single factor u_i (i=1,2,3,……n). A fuzzy set (r_{i1},r_{i2},r_{i3}……,r_{im})on the comment set V is obtained by a fuzzy mapping from U to V. The evaluation matrix of fuzzy relationship can be obtained by fuzzy evaluating, each factor in factor set:

$$R=\begin{bmatrix} r_{11} & r_{12} \cdots & r_{1m} \\ r_{21} & r_{22} \cdots & r_{2m} \\ & \vdots \cdots & \vdots \\ r_{n1} & r_{n2} & r_{nm} \end{bmatrix}$$

2.3.5 Establishment of fuzzy comprehensive assessment model

When the weight vector $A=(a_1,a_2\ldots\ldots a_{im})$and the fuzzy evaluation matrix R are known, the membership vector of fuzzy comprehensive evaluation index can be determined by fuzzy transformation:

$$B=A\circ R=(a_1,a_2,\cdots a_m)\circ\begin{bmatrix} \mathbf{r_{11}}\mathbf{r_{12}} & \cdots & \mathbf{r_{1n}} \\ \mathbf{r_{21}}\mathbf{r_{22}} & \cdots & \mathbf{r_{2n}} \\ \cdots\cdots\cdots & \cdots & \cdots \\ \mathbf{r_{m1}}\mathbf{r_{m2}} & \cdots & \mathbf{r_{mn}} \end{bmatrix}=(b_1,b_2,\cdots,b_n)$$

where, $b_j=\sum_{i=1}^{n}a_i\times r_{ij}$, j=1,2, $\cdots$;m.

The result of fuzzy comprehensive assessment is a fuzzy vector, i.e., the membership vector b_j (j=1,2,……,m)presents the extent that evaluated object belongs to each rating level of each evaluation index. The final assessment result can be determined by anti-fuzzification.

CHAPTER 3

Dynamic risk assessment index system of Tianjin VTS water area

3.1 Dynamic risk characteristics of Tianjin VTS waters

Risk characteristic analysis is the starting point of risk assessment and defines the essential characteristics of risks. In order to carry out risk characteristic analysis, it is necessary to have a comprehensive cognition of the assessed system according to relevant data and information.

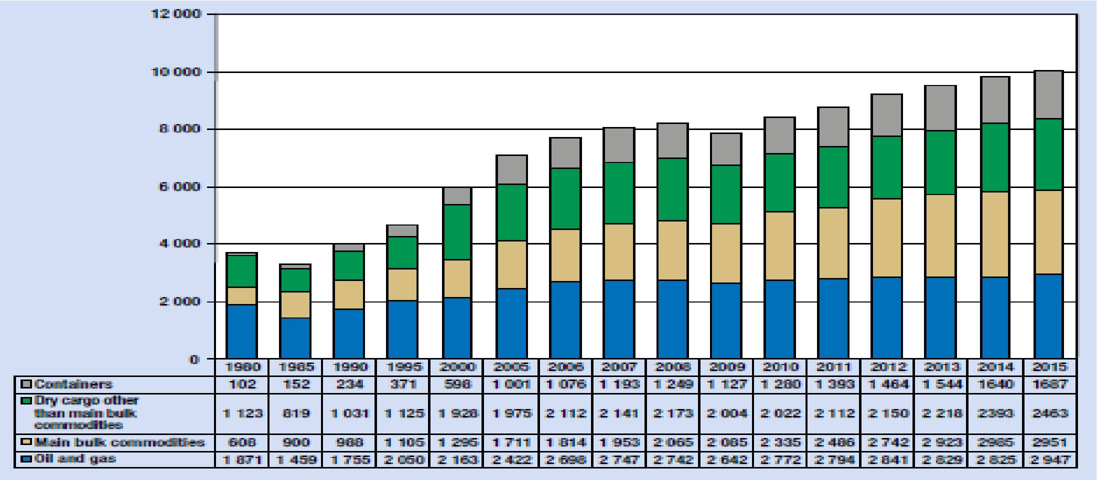
The analysis of risk characteristics of specific water areas can help to identify risk assessment indices and identify uncertainty factors that affect system losses. Quantitative Risk assessment method (QRA) has received increased interest in maritime transportation risk assessment. It is generally accepted that quantitative measures of the probability and consequences are critically significant for risk managers, particularly to identify cost-effective risk control options focusing on different aspects of safety management. QRA is used to analyze risk characteristics in Tianjin VTS water areas based on historical data of marine accidents and events in harbor areas. For the convenience of explanation, the frequency and severity of marine accidents in Tianjin VTS waters were analyzed and discussed respectively.

3.1.1 Frequency of marine accidents in Tianjin VTS waters

In order to determine whether Tianjin VTS water area is with frequent maritime accidents, historical data should be processed firstly, i.e., calculating the proportion of Tianjin Port's historical throughput to global ports (Table3-1) and the proportion of accidents occurring in Tianjin VTS waters to global maritime accidents (Table3-2). Then, by comparing the two ratios, the preliminary evaluation results of risk level of

Tianjin VTS water area can be obtained.

Figure3-1 and Figure3-2 are the historical throughput of the world and Tianjin Port respectively. Accident locations in Figure3-3 comprise rivers, ports/terminals, inland waterways, offshore, restricted waters, and the open sea, which is some different with the data form Tianjin Port Area. But it does not influence the rough judgment on the risk level of Tianjin VTS water area. Through the comparison, the risk level of Tianjin VTS water area is relatively lower than the mean level of global marine transportation risk level.



	1980	1985	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
▨ Containers	102	152	234	371	598	1 001	1 076	1 193	1 249	1 127	1 280	1 393	1 464	1 544	1640	1687
🟩 Dry cargo other than main bulk commodities	1 123	819	1 031	1 125	1 928	1 975	2 112	2 141	2 173	2 004	2 022	2 112	2 150	2 218	2393	2463
🟨 Main bulk commodities	608	900	988	1 105	1 295	1 711	1 814	1 953	2 065	2 085	2 335	2 486	2 742	2 923	2965	2951
🟦 Oil and gas	1 871	1 459	1 755	2 050	2 163	2 422	2 698	2 747	2 742	2 642	2 772	2 794	2 841	2 829	2 825	2 947

Fig.3-1 Historical throughput of the world. Source: UNCTAD 2016

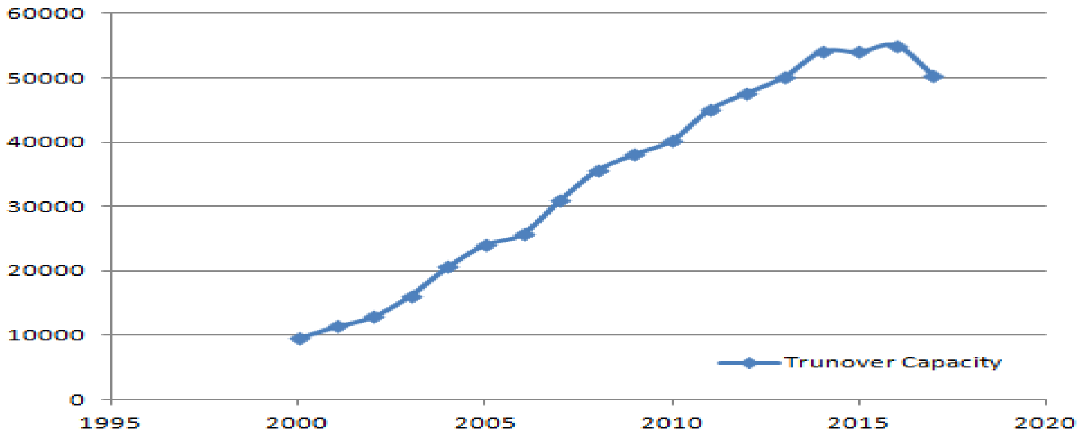


Fig.3-2 Historical throughout capacity of Tianjin Port. Source: State Statistical Bureau, http://www.mot.gov.cn/shuju/

Table3-1 Comparison of throughout of global and Tianjin Port.

Year Turnover	2005	2006	2007	2008	2009	2010	2011	2012	2013
Tianjin(M tons)	240.69	257.60	309.46	355.93	381.11	402.47	450.00	476.00	501.00
Global(M tons)	7109	7700	8034	8219	7858	8409	8785	9197	9514
Ratio（‰）	33.76	33.45	38.52	43.30	48.50	47.86	51.22	51.76	52.66

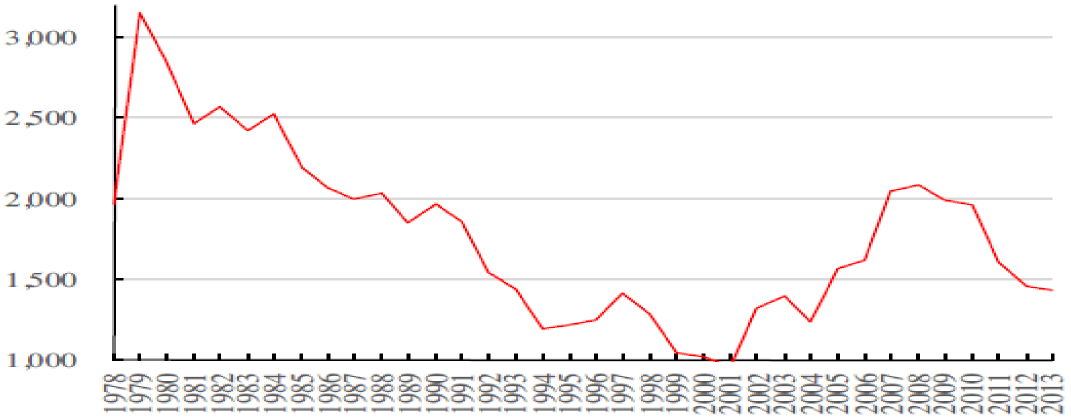


Fig.3-3The number of maritime accidents from 1978 to 2013. Data source: Lloyd’s List

Table3-2 Comparison of accident number of global and Tianjin Port.

Year Accident	2005	2006	2007	2008	2009	2010	2011	2012	2013
Tianjin Port	42	42	44	26	21	21	20	21	23
Global	1550	1600	2050	2080	2000	1970	1575	1450	1425
Ratio（‰）	27.09	26.25	21.46	12.50	10.50	10.65	12.70	14.48	16.14

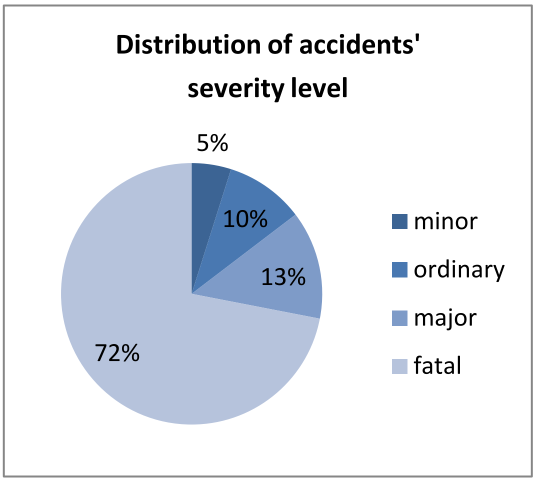
Through the comparison between Table3-1 and Table3-2, it shows that the water traffic risk of Tianjin Port is at an acceptable level. However, the above calculations only take into account the number of accidents, not the severity of the accident, i.e., the human life, property and environmental losses caused by accidents are not included. For instance, on June20,2009, a 100,000-ton Cambodian-registered general cargo ship collided with a 150,000-ton Panamanian-registered bulk carrier near the deep-water channel of Tianjin Port. The collision caused serious damage to the bulk carrier, and the bow was flooded, resulting in the sinking of the ship. Another serious collision accident occurred on July7, 2011, when an oil tanker collided with a general cargo ship outside Tianjin Port（ZHANG J.F., 2018）.Therefore, port risk assessment also needs to consider the severity of the accident.

3.1.2 Severity of marine accidents in Tianjin VTS waters

To understand water accident severity, it needs statistical data of historical fatalities and property losses caused by accidents to estimate that whether the risk level of Tianjin VTS waters is in ALARP range. According to the statistics of Tianjin MSA from 2008 to 2013, the severity of traffic accidents in Tianjin VTS water is as follows:

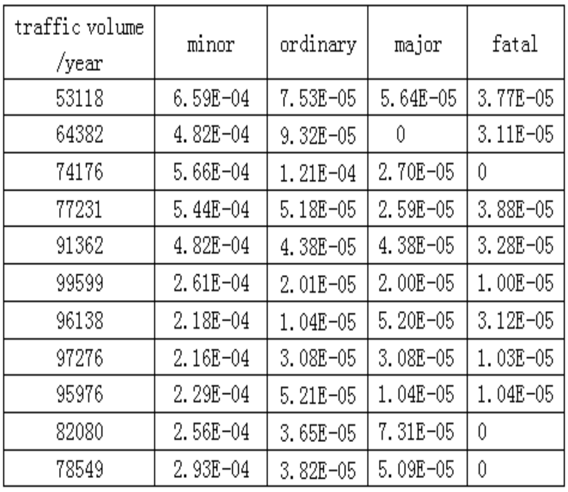
Table3-3 Distribution of traffic accident severity in Tianjin VTS waters

year	times	minor	ordinary	major	fatal
2003	35	26	4	3	2
2004	31	23	6	0	2
2005	42	31	9	2	0
2006	42	33	4	2	3
2007	44	33	4	4	3
2008	26	21	2	2	1
2009	21	12	1	5	3
2010	21	14	3	3	1
2011	22	15	5	1	1
2012	21	12	3	6	0
2013	23	16	3	4	0
total No.	328	236	44	32	16



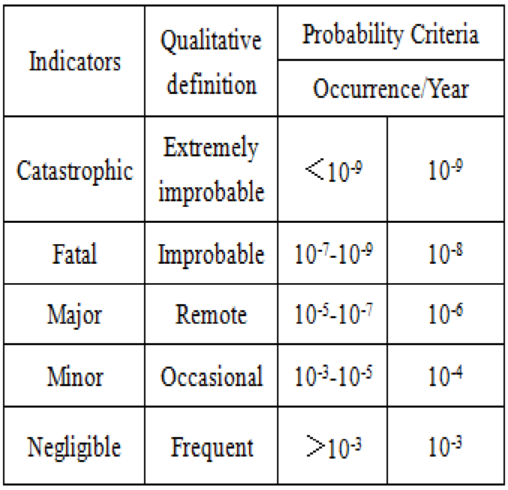
As an undesired event, the severity of accident and the exposure to death are two key subjects deserving the attention in risk assessment for modern societies. The framework of risk criteria commonly can be established on the frequencies of accident severity and fatality. The International Maritime Organization (IMO, 2002, 2007)promoted Formal Safety Assessment (FSA) as a framework for risk assessment and management. Moreover, all risk is advised to be controlled under ALARP (As Low as Reasonably Practicable) principle. In China, maritime transportation shares the same rule to categorize accidents according to the severity(Ministry of Transport of China, 2015). FSA approach is to find the region of tolerable risk based on the typical probabilities of occurrence and reduce the risk to a level ALARP. Trough comparing Table3-4 and Table3-5, the marine risk of Tianjin VTS water area is in the level ALARP.

Table3-4 Statistics of probability of accidents



traffic volume /year	minor	ordinary	major	fatal
53118	6.59E-04	7.53E-05	5.64E-05	3.77E-05
64382	4.82E-04	9.32E-05	0	3.11E-05
74176	5.66E-04	1.21E-04	2.70E-05	0
77231	5.44E-04	5.18E-05	2.59E-05	3.88E-05
91362	4.82E-04	4.38E-05	4.38E-05	3.28E-05
99599	2.61E-04	2.01E-05	2.00E-05	1.00E-05
96138	2.18E-04	1.04E-05	5.20E-05	3.12E-05
97276	2.16E-04	3.08E-05	3.08E-05	1.03E-05
95976	2.29E-04	5.21E-05	1.04E-05	1.04E-05
82080	2.56E-04	3.65E-05	7.31E-05	0
78549	2.93E-04	3.82E-05	5.09E-05	0

Table3-5Practicable risk criteria for vessel traffic in China.



Indicators	Qualitative definition	Probability Criteria	
		Occurrence/Year	
Catastrophic	Extremely improbable	$<10^{-9}$	10^{-9}
Fatal	Improbable	10^{-7}-10^{-9}	10^{-8}
Major	Remote	10^{-5}-10^{-7}	10^{-6}
Minor	Occasional	10^{-3}-10^{-5}	10^{-4}
Negligible	Frequent	$>10^{-3}$	10^{-3}

3.1.3 Distribution of historical traffic accidents by category

According to the types of accident statistics, accident ratio of Tianjin VTS waters: 62.3% collision accident, touching accidents by 18.7%, 8.4% grounding accident, fire, storm, sunk accident respectively for 2.5%, 0.6% accidents caused by wave damage, 2.5% other accidents(Fig.3-4).

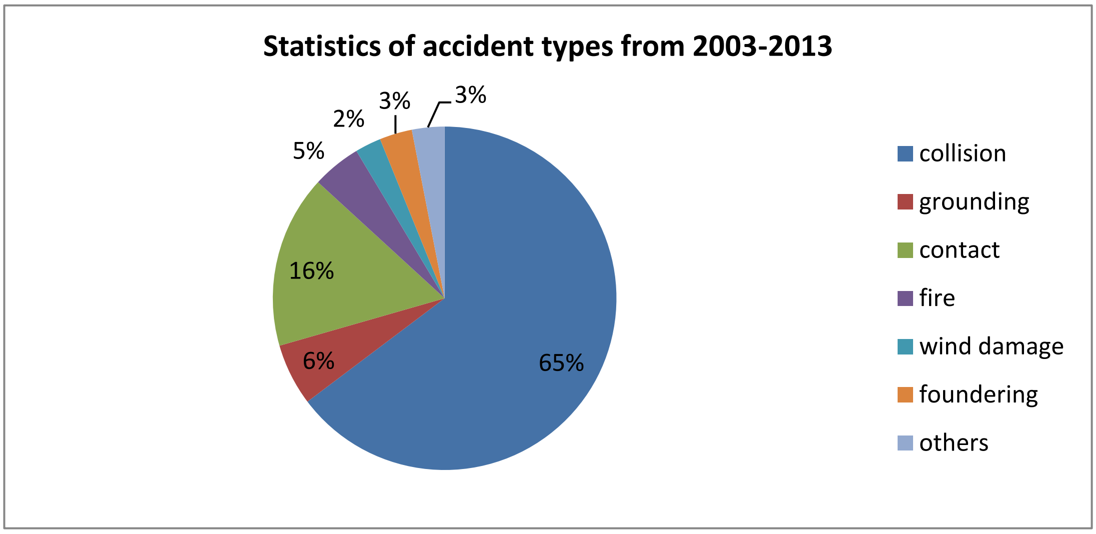


Fig.3-4 Distribution of historical traffic accidents by category

According to the statistics of Tianjin VTS, from 2012 to 2014, there were 31 maritime traffic accidents in Tianjin VTS water area, in which 21 collision accidents, accounting for 67.7% of the total number of accidents, 9 cases of contact damage and one stranding accident, accounting for 29% and 3.2% of the total number of accidents respectively. It can be observed that collisions and contacts are the most common types of accidents from the historical data.

3.2 Evaluation index system

There are many evaluation indices related to dynamic risk assessment of port waters, and the evaluation index system composed of different evaluation indices is prone to be different, which leads different risk assessment results. Therefore, it is important to establish a reasonable evaluation index system in accordance with certain principles for the scientific and accurate assessment results（LIU X.J.,2007）. Since risk assessment indices are difficult to be quantified and qualitative, this paper uses process analysis method (PAM) to decompose the determination process of risk evaluation indices of Tianjin VTS waters. At the same time, the comprehensive and dynamic nature of risk evaluation indices are considered. According to the general process, the determination of risk evaluation indices is divided into three processes: primary selection of indices, initial determination of indices and establishment of indicator system.

3.2.1 Preliminary selection of evaluation indices

When conducting dynamic risk assessment, risk evaluation indices should be preliminarily selected according to the characteristics of evaluated objects, combined with specific principles and special research of scholars. In addition, it needs to design expert questionnaires according to the primary indices. The Delphi method was adopted and "Dynamic risk evaluation index confirmation questionnaire" (Appendix A)was distributed to different experts.

Based on principles of selection of evaluation indices and referring to the special study on the classification of VTS in China's coastal ports by relevant scholars (DAI J.F.,2003), 18 indices were identified as the main influencing elements for the traffic safety in ports in this paper. The importance of indices is divided into five levels: unimportant, slightly important, important, very important and definitely important.

3.2.2 Preliminary determination of evaluation indices

In the process of determining dynamic risk assessment indices for Tianjin VTS waters, a total of 25 navigation and maritime management experts received questionnaires. 23 anonymous questionnaires from pilots, one from ship captain and one from Tianjin VTS crew were collected and counted as Table3-6.

Table3-6 Questionnaire results of evaluation indices confirmation in Tianjin VTS water area

Importance Index	Un-important	Slightly important	Important	Very important	Definitely important
Visibility	0	0	1	10	14
Wind	0	0	1	13	11
Current	0	7	7	5	6
Tide	2	7	9	4	3
Ice	3	4	10	5	3
Wave	0	2	15	3	5
Channel with	0	1	12	3	9
Channel depth	0	3	9	5	8
Channel length	2	5	11	4	3
Channel curvature	0	3	10	8	4
Distance from channel side line	1	3	10	7	4
Traffic flow speed	1	2	9	7	6
Traffic density	1	0	4	14	6
Traffic volume	1	0	7	12	5
Cross traffic flow	1	0	4	11	9
Aids to navigation	0	1	13	4	7
Area of ship maneuvering or turning	0	2	5	10	8
Traffic management	0	2	9	5	9

The expected value $\overline{x_i}$ represents the degree of concentration of experts' opinions on each index, the variance S_i^2 represents the degree of dispersion of each index's importance, and the coefficient of variation represents coordination degree of each index. Three indices are used to determine whether the questionnaire meet the requirements and whether the next round of consultation should be conducted. The main calculation methods of the three indices are as follows:

A total of *k* indices are set up in the primary indicator system, and m experts are invited to evaluate the importance of each index in the process of index confirmation. Where x_{ij} represents the magnitude level j at which the index i is located. In this paper, the significance of index is divided into five levels, j=1-5, and they are respectively expressed as: definitely important, very important, important, slightly important, unimportant，and values for each level are assigned as (1,0.8, 0.6, 0.4, 0.2). m_{ij} represents the number of experts for index i has been rated as level j.By calculating the survey results, the following values of three indices are obtained:

The expected value of each index $\overline{x_i} = \frac{1}{m}\sum_{j=1}^{5} x_{ij} m_{ij}$

The variance of each index $s_i^{\ 2} = \frac{1}{m-1}\sum_{j=1}^{5} m_{ij}(x_j - \overline{x_i})^2$

The coefficient of variation per index $cv_i = \sqrt{s_i^{\ 2}} \big/ \overline{x_i}$

When the standard deviation $\sqrt{s_i^{\ 2}}$ is greater than 0.6, the expert opinion is too scattered and they needs to be consulted again. In this study, through calculating the questionnaire survey results, the expected value, variance and coefficient of variation of 18 indices are obtained respectively through the above formulas(Table3-7).

Table3-7 Statistics of each evaluation index

Statistics / Initial index	$\overline{x_i}$	$s_i^{\ 2}$	$\sqrt{s_i^{\ 2}}$	cv_i
Visibility	0.904	0.013733	0.117189	0.129634
Wind	0.88	0.013333	0.11547	0.131216
Current	0.68	0.053333	0.23094	0.339618
Tide	0.592	0.0516	0.227156	0.38371
Ice	0.608	0.054933	0.234379	0.385491
Wave	0.688	0.0336	0.183303	0.266429
Channel with	0.76	0.04	0.2	0.263158
Channel depth	0.744	0.045067	0.212289	0.285335
Channel length	0.608	0.048267	0.219697	0.361343

Channel curvature	0.704	0.033733	0.183666	0.26089
Distance from channel side line	0.68	0.043333	0.208167	0.306127
Traffic flow speed	0.72	0.046667	0.216025	0.300034
Traffic density	0.792	0.0316	0.177764	0.224449
Traffic volume	0.76	0.033333	0.182574	0.240229
Cross traffic flow	0.816	0.0364	0.190788	0.233809
Aids to navigation	0.736	0.035733	0.189033	0.256838
Area of ship maneuvering or turning	0.792	0.034933	0.186905	0.235991
Traffic management	0.768	0.042267	0.205589	0.267693

3.2.3 Dynamic risk assessment index system of Tianjin VTS waters

Through the analysis of the expectation, variance and coefficient of variation of experts' opinions on 18 indices, the standard deviation of all indices is less than 0.6 and within a reasonable range, so the survey results are valid. In selecting suitable evaluation indices, the following three aspects should be considered in addition to the importance of the indices in the questionnaire survey:

(1) The correlation between the indices---Because of the Bohai bay is half closed harbor, and the average water depth is shallow. Thus the formation of sea waves in Tianjin VTS water area is basically affected by wind and the correlation degree between wave and wind indices is high, the sea wave index is no longer selected as a single index in evaluation system.

(2)The fixed indices are not considered in this study. For example, ground characteristics of anchorage, aids to navigation, fixed obstacles, etc. Traffic management and aids to navigation are static indices, which are not considered in dynamic risk assessment.

(3)This study aims at macroscopic risk assessment. In consideration of the key factors that constitute the dynamic risk of port traffic, the individual operational behaviors of ships is not taken as the focus of the evaluation index. Therefore, this paper does not take human factors, ship factors and environmental factors as the main evaluation indices like most scholars in China. Traffic flow speed and area of ship maneuvering or turning indices are suitable for assessing the dynamic risk of a single ship in particular waters. In the assessment of regional comprehensive risk, however, due to the lack of regularity and universality, they cannot be used as a component of dynamic risk index system.

All in all, according to the above index analysis of important degree， combined with a large number of studies by scholars related to traffic safety risk assessment in port waters, the content and structure of dynamic risk assessment index system in Tianjin VTS water area are finally determined as follows (Table 3-8) and (Fig. 3-5).

Table3-8 Dynamic risk evaluation index system of Tianjin VTS water areas

Evaluation index	Index meaning
Visibility	Fog, haze, rain ,snow, etc.
Wind	Wind force, wind direction
Current	Current speed and direction
Channel width	Ratio of channel width/ship breadth
Channel depth	Ratio of channel depth/ship draft, underkell clearance
Channel curvature	Number of turning points, turning angle of channel
Traffic density	Ratio of the number of ships in a traffic flow or anchorage / water area
Cross traffic flow	The frequency of ships' crossing encounter or number of crossing points of channel
Traffic volume	The number of ships passing through a channel section per unit time

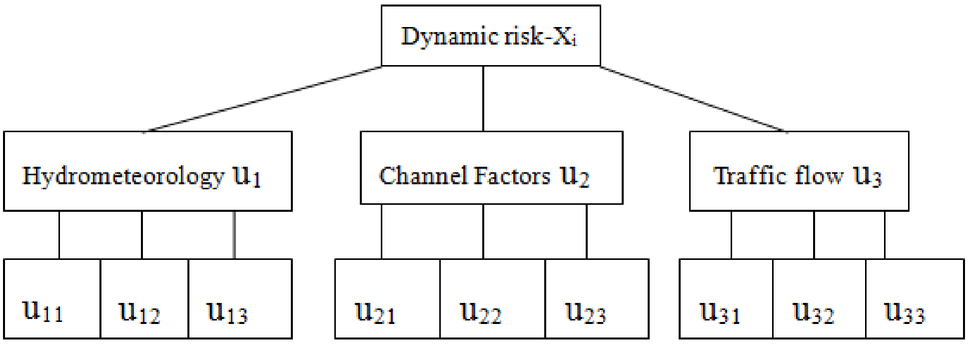


Fig.3-5Hierarchical structure of dynamic risk comprehensive evaluation index for Tianjin VTS water area

CHAPTER 4

Comprehensive assessment model of dynamic risk in Tianjin VTS waters

4.1 Set of dynamic risk assessment objects

In order to achieve the comprehensive assessment of the dynamic risk in Tianjin VTS waters, this water areas are divided into 10 different risk areas according to the geographical characteristics and VTS routine work mode, and each area with dynamic risk is defined as evaluated objects. These 10 water areas are Haihe Channel-Zone1, channel waters from east of lock to 42# buoy-Zone2, North harbor basin waters -Zone3, channel water area from Dongtudi to breakwater gate-Zone4, Dagukou No.1 Anchorage and its adjacent waters-Zone5, channel water area from breakwater gate to No.15#buoy-zone6, Dagukou No. 2 and No. 3 Anchorages and the adjacent waters -Zone7, water area near VTS reporting line-Zone8, and 100, 000 ton Deep Water Anchorage- Zone9(Fig.4-1).

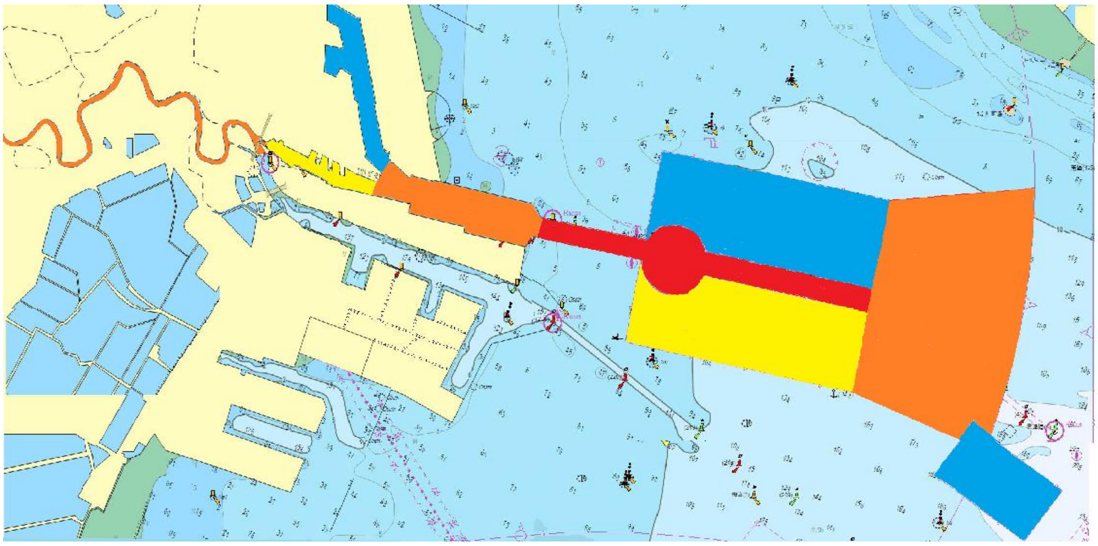


Fig.4-1 Divisions of Tianjin VTS water areas for dynamic risk assessment

4.2 The set of dynamic risk assessment indices

Based on the evaluation index system in Chapter 3, a set of two levels of dynamic risk assessment indices is established as follows:

The set of indices of first class:

U=｛hydro-meteorological factor u_1, channel factor u_2, traffic flow factor u_3｝.

The set of indices of second class:

Hydro-meteorological factor u_1=｛visibility u_{11}, wind u_{12}, current u_{13}｝;

Channel factor u_2=｛channel width u_{21},channel curvature u_{22},channel depth u_{23}｝;

Traffic flow factor u_3=｛traffic volume u_{31}, traffic density u_{32}, crossing traffic flow-u_{33}｝.

4.3 Dynamic risk comment set

The v_i (i=1,2,3……,m) in dynamic risk assessment set V=(v_1,v_2,⋯⋯,v_i) is the comment set corresponding to the evaluation index u_i (i=1,2,3,⋯⋯n),where m represents the dynamic risk rank number. There are four levels of risk assessment in this paper, namely extremely high, high, ordinary and low. Therefore, the risk comment set is V= {extremely high risk, high risk, ordinary risk and low risk}. In order to facilitate mathematical calculation and reflect the evaluation results, this paper marks the comment set as $V= \{v_1,v_2,v_3,v_4\} = \{1,2,3,4\}$.

In the process of establishing the risk membership function of evaluation index, $\underset{\sim}{A}$, $\underset{\sim}{B}$, $\underset{\sim}{C}$, $\underset{\sim}{D}$ stand for different dynamic risk levels of evaluation indices. The risk value set of $\underset{\sim}{A}$, $\underset{\sim}{B}$, $\underset{\sim}{C}$, $\underset{\sim}{D}$ is defined as ｛4,3,2,1｝ .η(u) is the membership value to the risk value set calculated by the membership functions.

4.4 Membership functions of evaluation indices

4.4.1 Hydro-meteorological index

Hydro-meteorological factor is the external natural factor that may cause maritime traffic accidents. It affects the navigation safety of the ship by interfering with the navigation ability of ships and exerting physical force posed on the ships. Three sub-indices included in hydro-meteorological index are analyzed:

(1)Visibility

Visibility is affected by fog, haze, rain and snow, among which the heavy fog poses the most serious threat to ships' safe navigation. Fog in Tianjin Port is mainly concentrated in autumn and winter. From October to December of each year, fog prevails, accounting for 47% of the annual fog days, and the annual fog days in December account for about 30.0% of the annual fog days. The average fog with visibility less than 1000m is 16.60 foggy days per year. According to the actual occurrence time of fog, the average accumulated foggy period is 8.70 days per year. According to the traffic management regulations of the Tianjin MSA, the channel is switched to one-way transportation when the visibility is within 3000m and ship's navigation is forbidden when the visibility is lower than 1000m, of which the visibility (u_{11}) is assumed to be "poor".

Firstly, VTS regulation of traffic management is not considered to affect risk factors, but only to start from initial risk assessment in this study. According to international fog level regulations, visibility is poor if the visible range < 4000m (GUO Y.,1999). Secondly, according to the Visibility rating table (CHENG J.H.,1999), the risk assessment levels associated with visibility are divided into: Visibility less than 1000m is assigned with extreme risk value; Visibility=2000m-high risk; Visibility=4000m ordinary risk; Visibility greater than 10km, low risk. The risk membership function of visibility index is as follows:

$$\eta_{\underline{A}}(x)=\begin{cases}\dfrac{2{,}000-x}{1{,}000}, & 1{,}000<x<2{,}000\\ 1, & 0\le x\le 1{,}000\\ 0, & x\ge 2{,}000\end{cases}$$

$$\eta_{\underline{B}}(x)=\begin{cases}\dfrac{4000-x}{2{,}000}, & 2{,}000<x<4{,}000\\ \dfrac{x-1{,}000}{1{,}000}, & 1{,}000\le x<2{,}000\\ 0, & \text{others}\end{cases}$$

$$\eta_{\underline{C}}(x)=\begin{cases}\dfrac{10{,}000-x}{6{,}000}, & 4{,}000\le x<10{,}000\\ \dfrac{x-2{,}000}{2{,}000}, & 2{,}000\le x<4{,}000\\ 0, & \text{others}\end{cases}$$

$$\eta_D(x)=\begin{cases}\dfrac{x-4,000}{6,000}, & 4,000 < x \leq 10,000\\ 1, & x > 10,000\\ 0, & \text{others}\end{cases}$$

(2)Wind

Because Tianjin Port is located in the west coast of Bohai bay and in the middle latitude zone, the wind has obvious monsoon characteristics. In winter, northwest wind prevails and the wind direction is stable. The wind force is strong and the maximum wind force reaches Beaufort Wind Scale 8 to 9, somtimes10~11. In addition, due to the influence of narrow pipe effect, when the northwest wind prevails, the wind force in the North-branch Channel and the downstream of Haihe Channel will be relatively strong. In summer, Bohai bay is controlled by low air pressure of southeast China and sub-high air pressure of northwest Pacific，south -east wind prevails in Tianjin Port and the wind force is weak. From 1996 to 2005, the actual measured wind condition statistics of Tanggu Ocean Station in Dongtudi showed that: The normal wind direction of Tianjin VTS is south, and the occurrence frequency is 9.89%.The strong wind direction is northeast, and the maximum wind speed measured is 20.7m/s.The annual average anisotropic wind speed was 4.61m/s, of which the maximum average east wind speed was 6.5m/s.The average number of gales above Beaufort Wind Scale 6 (10.8m/s) and above Scale 7 (13.8m/s) was 55 and 13.5 respectively. The wind frequency statistics are shown in Table 4-1.

Table 4-1 Wind frequency statistics. Source: Tanggu Ocean Station,1996-2005.

Speed Direction	0.3~5.4 m/s	5.5~7.9 m/s	8.0~10.7 m/s	10.8~13.8 m/s	13.9~17.1 m/s	≥17.2 m/s	Total
N	3.20	0.68	0.25	0.09	0.01	0	4.23

NNE	18.6	0.44	0.24	0.10	0.03	0	2.67
NE	2.78	0.93	0.37	0.13	0.02	0.01	4.24
ENE	2.22	1.10	0.74	0.32	0.09	0.02	4.49
E	3.74	2.33	1.80	1.01	0.28	0.04	9.2
ESE	2.71	1.44	0.66	0.15	0.02	0	4.98
SE	4.01	2.35	0.96	0.12	0	0	7.44
SSE	3.71	2.25	0.64	0.04	0	0	6.64
S	6.30	2.97	0.55	0.06	0	0	9.91
SSW	5.20	0.98	0.14	0.01	0	0	6.33
SW	7.16	0.90	0.07	0	0	0	8.13
WSW	5.72	0.71	0.07	0.01	0	0	6.51
W	5.96	0.53	0.04	0	0	0	6.53
WNW	2.41	0.28	0.05	0.01	0	0	2.75
NW	4.80	2.23	1.21	0.41	0.05	0	8.7
NNW	3.39	1.48	0.76	0.24	0.05	0	1.33
C	1.33	-	-	-	-	-	1.33
Total	66.53	21.6	8.55	2.7	0.55	0.07	100

Wind(u_{12})is supposed to be “strong” when its speed is higher than 14m/s (Beaufort Wind Scale 7). The channel will be switched to one-way transportation when the wind speed is higher than 50 km/h. Furthermore, ship navigation will be forbidden when the wind speed is higher than 21 m/s(Beaufort wind scale 9) . Combining VTS traffic management rules and officers’ experience in maritime safety management, the classification methods (ZHANG D.H.,2007) are used in establishing membership function of the wind-associated risk levels: Wind speed 17m/s(Beaufort wind scale 8)-extreme risk; Wind speed = 14m /s-high risk; Wind speed =8m/s-ordinary risk;

Wind speed is less than or equal to 5m/s-low risk. The membership function of wind index is as follows:

$$\eta_{\underline{A}}(x)=\begin{cases}\dfrac{x-14}{3}, & 14<x<17\\ 1, & x\geq 17\\ 0, & \text{others}\end{cases}$$

$$\eta_{\underline{B}}(x)=\begin{cases}\dfrac{17-x}{3}, & 14<x<17\\ \dfrac{x-8}{6}, & 8\leq x<14\\ 0, & \text{others}\end{cases}$$

$$\eta_{\underline{C}}(x)=\begin{cases}\dfrac{14-x}{6}, & 8<x<14\\ \dfrac{x-5}{3}, & 5<x\leq 8\\ 0, & \text{others}\end{cases}$$

$$\eta_{\underline{D}}(x)=\begin{cases}\dfrac{8-x}{3}, & 5<x<8\\ 1, & 0\leq x\leq 5\\ 0, & \text{others}\end{cases}$$

(3)Current

According to the data provided by Sailing Directions of Tianjin Port, Tianjin Port is an irregular half-day tidal port, with diurnal tides and significant low tides. The tidal current (u_3) in Tianjin VTS waters is basically reciprocating flow. The rising tide flow direction is 280°~310°, and ebb tidal direction is100°~120°.The average speed of rising tidal current is 0.29kt~0.45kt, and the maximum speed of rising tidal current is 0.93kt. The maximum speed of ebb tidal current is 0.87kt, and the average speed of ebb tidal current is 0.27kt~0.37kt. It is worth noting that, due to the influence of the terrain, there will be a large change in the flow speed at the entrance of the breakwater. When a ship enters or leaves the breakwater, it will have a large turning moment causing a sudden and large turning of the ship, which may cause the ship to break out of the channel or rush towards other ships.

The calculation formula of ship's lateral drift velocity under the influence of current is $u_y=u*sin\alpha$, where u is the current velocity and α is the angle between the ship longitudinal profile and the current velocity vector (LIU M.J.&QI C.X.,1998). Considering the direction of Main Channel in Tianjin Port is 306 ° and 280 °, the maximum value of α is 30 °.Thus the maximum value of u_y is 0.5kt at most. The classification principle of risk level affected by current is as follows: $x=u_y$, when $u_y>$ 0.5kt, high risk level is extremely high; when u_y=0.4kt, risk level is high; when u_y= 0.3kt, risk level is ordinary; when u_y less than 0.2kt, the risk level is low. The dynamic risk membership function of the current is as follows:

$$\eta_{\underline{A}}(x)=\begin{cases}\dfrac{x-0.4}{0.1}, & 0.4<x\leq 0.5\\ 1, & x>0.5\\ 0, & \text{others}\end{cases}$$

$$\eta_{\underline{B}}(x)=\begin{cases}\dfrac{x-0.3}{0.1}, & 0.4<x<0.5\\ \dfrac{x-0.3}{0.1}, & 0.3<x\leq 0.4\\ 0, & \text{others}\end{cases}$$

$$\eta_C(x)=\begin{cases}\dfrac{0.4-x}{0.1}, & 0.3<x<0.4\\ \dfrac{x-0.2}{0.1}, & 0.2<x\leq 0.3\\ 0, & \text{others}\end{cases}$$

$$\eta_D(x)=\begin{cases}\dfrac{0.3-x}{0.1}, & 0.2\leq x<0.3\\ 1, & x<0.2\\ 0, & \text{others}\end{cases}$$

4.4.2 Channel index

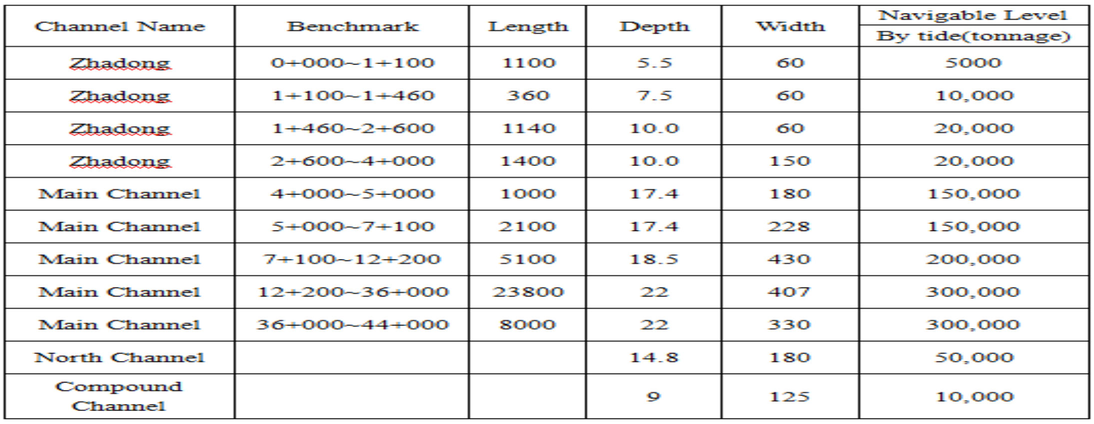
The influence of channel index on dynamic risk is mainly manifested as: the risk is caused by the limitation of ship operation due to the large width or draft of ships in the channel area. The initiative parameters of Tianjin Port waterway are as follows:

------Width and depth of different segments of channels

The waterways covered by Tianjin VTS include Haihe river channel, Zhadong channel, North Branch channel and Main channel (Compound channel is one segment of Main channel). The Zhadong channel starts from the east entrance of Xingang ship lock to the entrance of third quay pool at Beijiang port area and connects with the Main channel, with a length of 2.2n miles. The main channel refers to the artificial dredged channel between No. 1 buoy of Tianjin Port and the third quay pool. At present, the length of the main channel is 23.8n miles, the maximum width of the channel is 430 meters, and the maximum depth is 22.6 meters. of One segment of Main channel have set up narrower channels at two sides for one-directional navigation of 10,000-ton ships, thus forming a complex channel. The Northern Branch channel refers to the channel with a total length of 3km from

Dongtudi to Beigang port pool between the #D3buoy and the D21# buoy. The specific width and depth of the channels are detailed in Table4-2.

Table4-2 Channel Parameters of Tianjin Port. Source: Tianjin Port Sailing Directions



Channel Name	Benchmark	Length	Depth	Width	Navigable Level By tide(tonnage)
Zhadong	0+000~1+100	1100	5.5	60	5000
Zhadong	1+100~1+460	360	7.5	60	10,000
Zhadong	1+460~2+600	1140	10.0	60	20,000
Zhadong	2+600~4+000	1400	10.0	150	20,000
Main Channel	4+000~5+000	1000	17.4	180	150,000
Main Channel	5+000~7+100	2100	17.4	228	150,000
Main Channel	7+100~12+200	5100	18.5	430	200,000
Main Channel	12+200~36+000	23800	22	407	300,000
Main Channel	36+000~44+000	8000	22	330	300,000
North Channel			14.8	180	50,000
Compound Channel			9	125	10,000

---Channel directions

The direction of Zhadong channel is 294°-114°.The direction of the segment of Main channel which ranges from 2,600m to 13,493m(2600m is measured from the east entrance of Xingang ship lock as the base line) 281°-101°.The direction of the segment of Main channel ranges from 13,493m~23,924m is 279.6°-99.6°;The direction of the segment of Main channel ranges from 23,924m~36,000m is 281°-101°;The direction of segment of Main channel ranges from 23,924m~44,000 m is 306°-126°(LI Y.B., 2008).

---Compound channel

The Compound channel of Tianjin Port has been put into operation on December 26, 2014, which not only can meet 300,000 tons and 19000 TEU container ships entering or leaving the port successfully, also can achieve large and small ships sailing in the "double-entering and double-leaving" four-channel traffic model(SUN J.K.,2017). The Compound channel is constituted by adding a 10,000-ton one-way navigation channel on both sides of the original deep-water channel to realize the separation of traffic flows. The channel length is about 8.5km from No.29 buoy to No.39 buoy as shown in Fig.4-2.

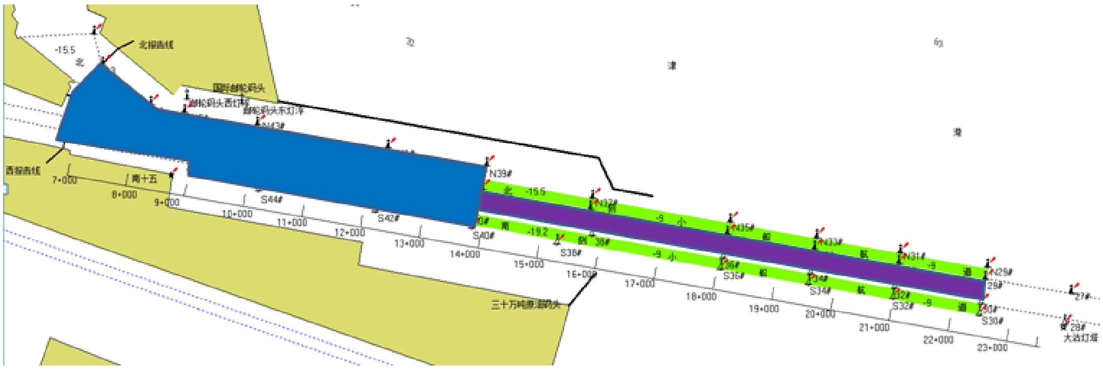


Fig.4-2 Diagram of Compound channel of Tianjin Port. Source: Tianjin VTS

Three sub-indices included in channel index are analyzed:

(1)Channel Width

Channel width(u_{21}) is studied by the ratio of channel width to ship breadth. Because the Small ship channel in Compound channel is one-way passage, the influence on ships' navigation safety induced by channel width can be ignored compared to the size of small vessels (ship length less than or equal to 146m and ship breadth less than or equal to 20 m). Therefore, this evaluation index is mainly aimed at the Main channel that can be navigable in both directions.

According to *Graphic Design Specification of Sea Ports* issued by Ministry of Transport of China, The effective width of the channel consists of three parts, which are the width of the track zone, the rich width between ships and the rich width between ships and the bottom edge of the channel. The formula is: Two-way channel $W=2A+B_{max}+2C$, where W is the channel effective width (m); In Fig.4-3,A is the track width $=L*sin + b*cos\alpha$ (m), where b is the ship width, L is ship length, andα is the ship's heading angle(LI Ye,2017); B_{max} is the distance between ships in the two-way channel, and the value is the maximum ship width (m) designed for the two-way channel（ZHU Q.L.&YU G.L.,2012）.According to *Ship Traffic Management Code* of Tianjin Port, Bmax=52m;*C* is the distance(m) between ship and channel boundary. In order to reduce the bank effect, this distance is determined as *C*=1/4* (*b*+ *L*sin*).

In conclusion, $W/b=(2A+B_{max}+2C)/b$. According to (SHA Bo,2008) ship model experiment, x equals W/b when the main channel is navigable in two directions. When $x>9.5$,the risk is low; When $W/b=8.5$, the risk level introduced by channel width is ordinary; When $W/b=7.5$ the risk level is high , and when $W/b < 6.5$ the risk level is extremely high.

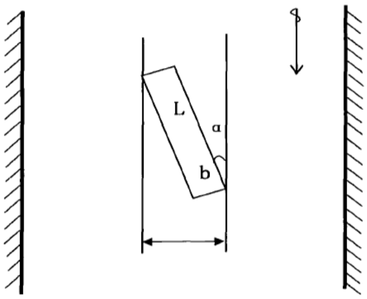


Fig.4.3 Sketch map of waterway's breadth needed for vessel. Source:(SHA Bo,2008)

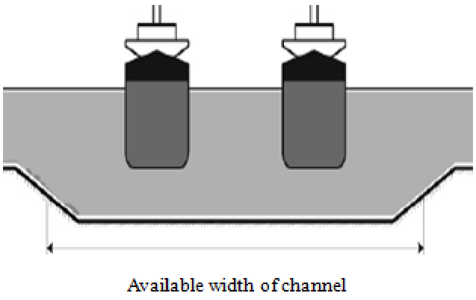


Fig.4.4 Sketch of two-way channel. Source:（ZHU Q.L.&YU G.L.,2012）

The dynamic risk membership function of the channel width is as follows:

$$\eta_A(x)=\begin{cases} 1, & x<6.5 \\ \dfrac{7.5-x}{1.0}, & 6.5\le x<7.5 \\ 0, & x\ge 7.5 \end{cases}$$

$$\eta_{B}(x)=\begin{cases}\dfrac{x-6.5}{1.0}, & 6.5<x<7.5\\ \dfrac{8.5-x}{1.0}, & 7.5\le x<8.5\\ 0, & \text{others}\end{cases}$$

$$\eta_{C}(x)=\begin{cases}\dfrac{x-7.5}{1.0}, & 7.5<x<8.5\\ \dfrac{9.5-x}{1.0}, & 8.5\le x<9.5\\ 0, & \text{others}\end{cases}$$

$$\eta_{D}(x)=\begin{cases}\dfrac{x-8.5}{1.0}, & 8.5<x\le 9.5\\ 1, & x>9.5\\ 0, & \text{others}\end{cases}$$

(2)Channel curvature

The evaluation index of channel curvature mainly analyzes the risks caused by the ship steering and changing course along bending channel where ship operation is prone to be limited due to ship's width or length being too large. Different from the risk measured by channel turning angle alone (FANG X.L., 1989),the larger size of the ship and turning angle of the channel，the larger water area occupied by the ship when changing course and the more likely it is to run aground or collide with buoys on both sides of the channel.

It’s worth noting that considering that the navigable ship in Haihe river is 3,000~5000deadweight tons, the ship length is generally between 95 and 100 meters, while the width of most navigable segments of Haihe channel is between 200 and 400 meters. The channel curvature evaluation index u_{22} is no longer considered in Haihe river.

Fig.4-5 and Fig.4-6 indicate that the u_{22} is not only related to the channel bending angle and width, but also the length and breadth of the vessels.

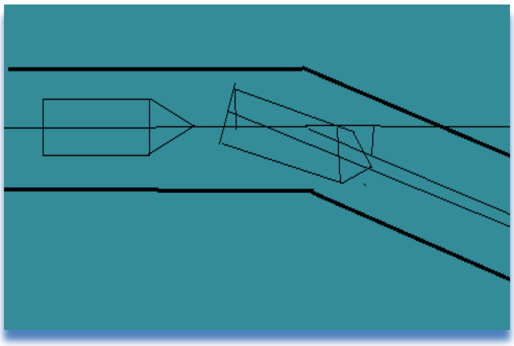


Fig.4-5 theoretical illustration

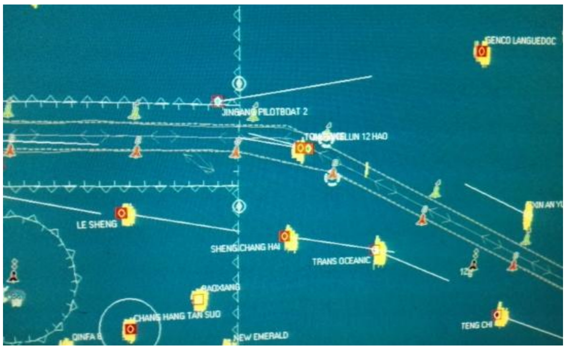


Fig.4-6 real-time image

Where the ship length $L= L_1+L_2$,the channel width occupied by the ship after turning with angle θ is

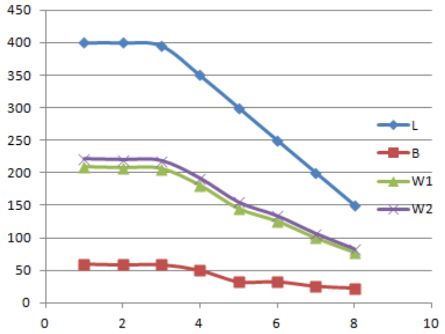
$$x=(L_1*\sin\theta+\frac{B}{2})\cos\theta+(L_2*\sin\theta+\frac{B}{2})\cos\theta=(L*\sin\theta+B)\cos\theta\geq B,\theta\in 0\sim\frac{\pi}{2}. \qquad (4\text{-}1)$$

It can be seen from Formula4-1 that u_{22} is not fixed in this paper. It is the ratio of theoretical track width to channel width and it changes with ship size. The greater the ratio, the greater the dynamic risk level.

Considering that the width of Main channel is unchangeable in short period, the theoretical track width W_θ is taken as the evaluation principle when establishing the risk membership function of channel curvature. For instance: Main channel changes 25 °,i.e., $\theta_1\approx0.14\pi$,at 13#Buoy-No.1Waypoint and changes 29 °,i.e.,$\theta_2\approx0.16\pi$, at D_1# Buoy-No.2Waypoint (CHENG J.K.&CHAI T.,2009）. Then it needs to take the largest container ships CSCL GLOBE (ship length-400m, ship width-58.6m) and MSC OSCAR (ship length-395.4m and ship width-59m) which successfully berthed at Tianjin Port in 2014 and 2016 as examples(Table4-3). These ultra-large container ships（ULCS）need to make two turns in the main channel when sailing to the container berths at Tianjin Port. The values of W_θ for these two vessels at No.2 Waypoint are 219.7m and 218.1m respectively.

Table4-3 Relationship between Container ship size and W_θ

Ship name	Length(m)	Breadth(m)	Waypoint1(m)	Waypoint2(m)
*	400	60	208.432876	220.9492
CSCL GLOBE	400	58.6	207.166223	219.7205
MSC OSCAR	395.4	59	205.755424	218.1362
*	350	50	180.116887	191.1366
*	300	32	144.562885	154.3033
*	250	32	125.294413	133.2665
*	200	25	99.6926795	106.0867
*	150	22	77.7099525	82.41714



Considering the navigability of Main channel (Main channel changes to one-way navigable when the width of one vessel is greater than 52m) and Table4-3, the standards for determining the risk level is: When x >220m, the risk level is extremely high; When x =200m, the risk level is high; When x=150m, the risk level is ordinary and when x < 100m, the risk level is low. The dynamic risk membership function of channel curvature is as follows:

$$\eta_A(x)=\begin{cases}1, & x>220\\ \dfrac{x-200}{20}, & 200<x\leq 220\\ 0, & x<200\end{cases}$$

$$\eta_B(x)=\begin{cases}\dfrac{220-x}{20}, & 200<x\leq 220\\ \dfrac{x-150}{50}, & 150<x\leq 200\\ 0, & \text{others}\end{cases}$$

$$\eta_C(x)=\begin{cases}\dfrac{200-x}{50}, & 150<x<200\\ \dfrac{x-100}{50}, & 100<x\leq 150\\ 0, & \text{others}\end{cases}$$

$$\eta_D(x) = \begin{cases} \frac{150 - x}{50}, & 100 < x < 150 \\ 1, & 0 \le x \le 100 \\ 0, & \text{others} \end{cases}$$

(1) Channel depth

The ratio of channel depth to ship draught is an important factor affecting ship maneuverability. Lloyds' statistics show that an uncorrected course and an excessive speed with respect to the traffic in the sea zone are responsible for about 50% of all the maritime accidents, particularly groundings(P. Trucco, et al.2008). According to the investigation and analysis of four stranding accidents in Haihe waterway from 2003 to 2004, the stranding accidents of Haihe waterway are mainly related to the ratio of water depth/ship draft（LI J.X.,2006）.

The international water depth is generally divided into four grades. If h stands for channel depth, and d stands for ship draught, the water depth is defined as deep when $H=h/d>3.0$;medum deep when $3.0>h/d>1.5$. The above two conditions have little effect on the ship's maneuverability. When $1.5 > h/d > 1.2$,the water depth is shallow and ship's maneuverability will be affected to some extent. When $h/d <1.2$, it becomes ultra shallow water where the ship sails, its maneuverability may be significantly affected. The ratio set $\{a_1,a_2,a_3,...,a_n\}$ is constituted by the ratios of the channel depth/ ship draft of n ships, i.e.,

$a_i=\frac{Depth}{Draft}$,$i=1,2,\ldots,n$. By defining $x=\text{Max}\ \{a_i\},i=1,2...,n$. The risk membership function of channel depth is:

$$\eta_{A}(x)=\begin{cases}1, & x<1.2\\ \dfrac{1.4-x}{0.2}, & 1.2\le x\le 1.4\\ 0, & x>1.4\end{cases}$$

$$\eta_{B}(x)=\begin{cases}\dfrac{x-1.2}{0.2}, & 1.2<x<1.4\\ \dfrac{2.2-x}{0.8}, & 1.4\le x<2.2\\ 0, & \text{others}\end{cases}$$

$$\eta_{C}(x)=\begin{cases}\dfrac{x-1.4}{0.8}, & 1.4<x<2.2\\ \dfrac{3-x}{0.8}, & 2.2\le x<3\\ 0, & \text{others}\end{cases}$$

$$\eta_{D}(x)=\begin{cases}\dfrac{x-2.3}{0.7}, & 2.3<x\le 3\\ 1, & x>3\\ 0, & \text{others}\end{cases}$$

4.4.3 Traffic flow index

The layout of the traffic system, the traffic density, the pattern of the traffic flow and their encounter rates are necessary elements when it comes to having a general view of marine traffic management. Three sub-indices included in traffic flow index are analyzed:

(1)Traffic volume

The traffic flow index u_{31} is related to the number of vessels sailing in the waters, and it refers to the number of vessels passing through the transverse-section of the channel within unit time. The traffic volume is higher, the dynamic risk in this water area is greater. Fig.4-7 shows the traffic volume distribution in Tianjin VTS reporting line area in months, which can be used as a parameter to evaluate the dynamic risk value of the water around the reporting line.

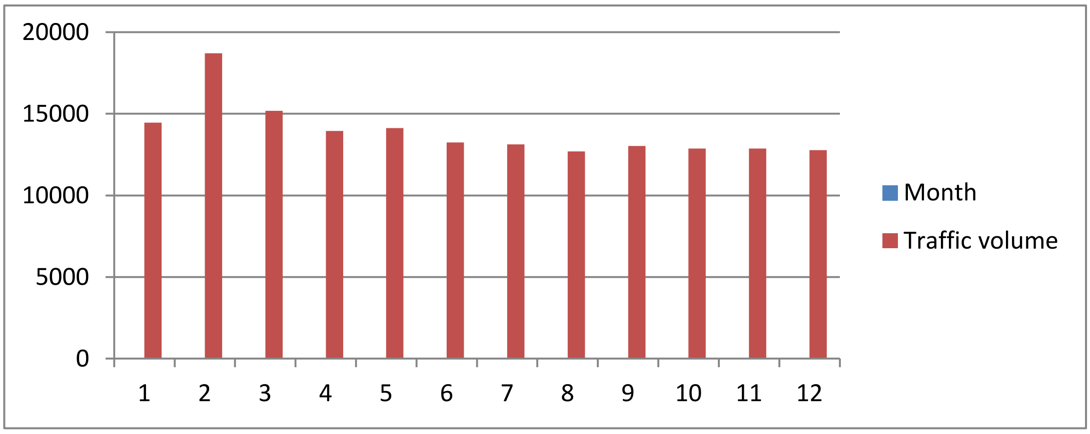


Fig.4-7 Traffic volume of Tianjin Port in 2017. Source: Tianjin MSA

For convenience of calculation, traffic volume evaluation index can be defined as the time interval (in minutes) between each ship passing through any channel transverse-section, i.e., $t=(N_{channel}* L_{channel})*60/(N_{ship}*V_{ship})$.Wherein $N_{channel}$ is the number of navigable channels side by side(SUN J.K., 2017). For instance, $N_{channel}$ equals four in compound channel of Tianjin Port(Fig.4-8). $L_{channel}$ is the length of channel (unit: nm) and N_{ship} is the number of ships in the region, V_{ship} is the average speed of ships in the channel.

In order to keep vessels at a safe queuing distance, the authority in the Port of Kaohsiung provides recommendations for various types of merchant vessels(Hua Zhi HSU,2014) to keep safe distance between two queuing vessels. Combining the recommendations of Kaohsiung Port and traffic flow characteristics of Tianjin VTS waters, the judgment standards of dynamic risk level associated with traffic volume are formed as: When t=4, the risk level is extremely high; when t=6, the risk level is high; when t=8, the risk level is ordinary and the risk level is low when $t>10$.

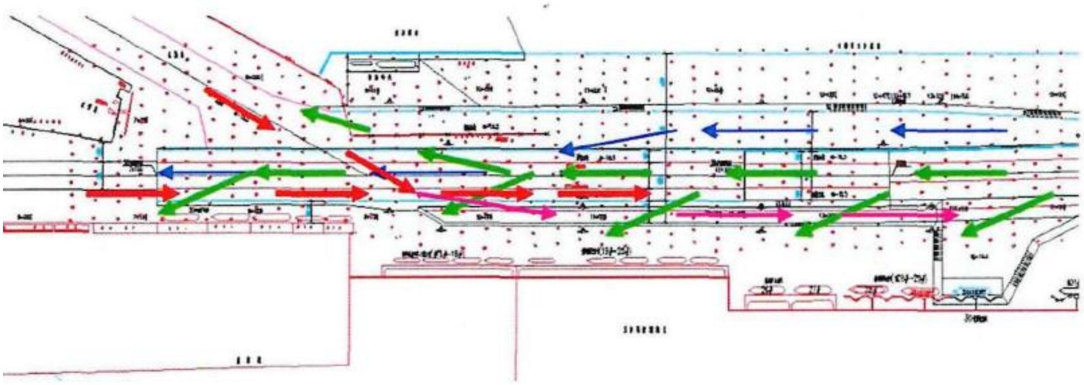


Fig.4-8 The cross situation of traffic flow at compound channel

The dynamic risk membership function associated with traffic volume is as follows:

$$\eta_A(t)=\begin{cases}1, & t\le 4\\ \dfrac{6-t}{2}, & 4<t<6\\ 0, & t\ge 6\end{cases}$$

$$\eta_B(t)=\begin{cases}\dfrac{t-4}{2}, & 4<t\le 6\\ \dfrac{8-t}{2}, & 6<t<8\\ 0, & \text{others}\end{cases}$$

$$\eta_C(t)=\begin{cases}\dfrac{t-6}{2}, & 6<t\le 8\\ \dfrac{10-t}{2}, & 8<t<10\\ 0, & \text{others}\end{cases}$$

$$\eta_D(t)=\begin{cases}\dfrac{t-8}{2}, & 8<t\le 10\\ 1, & t>10\\ 0, & \text{others}\end{cases}$$

（2）Traffic density

Ship safety domain is a term which is widely used in research on collision avoidance and traffic engineering(Rafal Szlapczynski&Joanna Szlapczyn ska,2017).

As a parameter, ship safety domain is introduced into the calculation of ship density in anchorage or fairway. According to different operating states of ships, the ship safety domain is divided into two types: elliptical domain during navigation and circular domain during anchorage. In anchorage, the domain of anchored vessels is a alert circle centered on the ship and with radius R_S(nautical miles). Minimum safe distance should be maintained between anchorage ships: $D_s=L+6h+180$(m),when Beaufort wind scale≤7; $D_s=L+8h+270$(m), when Beaufort wind scale＞7(YANG M.,2002). Wherein the h stands the water depth of anchorage and the maximum water depth of anchorage of Tianjin Port is 28.2m(Sailing Directions of Tianjin Port). In order to maintain data independence, D_s is conservatively identified as $L+500$(m). Formula $x=\sum_{i=0}^{N} S_i \ / \ S_{anchorage}$ is used to calculate the density of anchoring ships, where x is the density of anchoring ships. S_i is the anchoring area of ship i and $S_{anchorage}$ is the area of anchorage. If the density of ships in the anchorage area is too high, VTS officers shall prohibit new arrived ship from entering the anchorage. If a vessel heaves anchor up and leaves the anchorage, x shall be recalculated.

(ZHAI H.L.,2008) demonstrated that under ideal conditions, the No.1anchorage at Tianjin Port could accommodate 127 ships, 32 ships in No.2 anchorage and 34 ships in No.3 anchorage area. Deep Water Anchorage could accommodate 14 ships. According to the theoretical data of anchorage, the dense extent of ships in anchorages can be measured.

The second type of ship safety domain is used to judge the traffic density of waterway. The mathematical model proposed by Japanese scholars Fujii and Matui indicates that the number of ship collisions is proportional to the square of traffic density (ZHANG Di,2008). Japanese scholar Fujii proposed that when vessels are sailing in the harbor and narrow waterways, the ship safety domain is an ellipse of 6L long axis and 1.6L short axis (TIAN X.,2009) where L means the length of the ship. The formula $\sum_{i=0}^{N} S_i \leq L_e * W * \beta$ is used to determine whether the ship density in the channel is saturated. Therein W is the channel width,β is the permutation factor and L_e is the length of the channel(FANG X.L., et al.,2003).

In an ideal state,β equals 1 and the traffic density of this channel is:

$$x=\frac{\sum_{i=0}^{N} S_i}{L_e * W * \beta}=\frac{\sum_{i=0}^{N} \pi \frac{6L_i}{2} \times \frac{1.6L_i}{2}}{L_e * W}=2.4\pi \times \frac{\sum_{i=0}^{N} L_i^{\ 2}}{L_e * W}$$

Considering the width of Compound channel in Tianjin Port, it is not practical to satisfy the 1.6L as the width of ship safety domain. Thus it is more realistic to consider the safe distance of fore and aft ships-6L as the traffic density index rather than the ship safety domain for ships in channels, i.e.,

$x_{\mathrm{j}}=\frac{6\sum_{i=0}^{N} L_i}{L_e}$, j is serial number of channels.

When Compound channel has two-way traffic flow, or the Main channel satisfies two-way navigation, x=Max{x1, x2, x3, x4}(Compound channel), or x=Max{x1, x2} (two-way navigation of Main fairway). If $\sum_{i=0}^{N} S_i > L_e * W * \beta$, the VTS crew shall prohibit new arrived ships from entering the channels. If a ship leaves the channel, $\sum_{i=0}^{N} S_i$ needs to be recalculated.

When $\sum_{i=0}^{N} S_i + S_{ownship} \le L_e * W * \beta$, the VTS crew can allow one new arrived ship-*ownship* whose safety domain is $S_{ownship}$ to enter the channel. If there are too many ships sailing in the channel synchronously, the navigability of the channel will be blocked and the risk level of the traffic will rise.

The risk evaluation criteria of the traffic density evaluation index u_{32} of anchorage or channel water areas are: when x＜30%，the risk level of this water area is low; when x=50%,the risk level is ordinary; when x=70%,the risk level is high and when x=90% , the risk level is extremely high. The dynamic risk membership function associated with traffic density is as follows:

$$\eta_{\underline{A}}(x) = \begin{cases} 1, & x \le 0.3 \\ \frac{0.5-x}{0.2}, & 0.3 < x < 0.5 \\ 0, & x \ge 0.5 \end{cases}$$

$$\eta_{\underline{B}}(x) = \begin{cases} \frac{x-0.3}{0.2}, & 0.3 < x < 0.5 \\ \frac{0.7-x}{0.2}, & 0.5 < x < 0.7 \\ 0, & \text{others} \end{cases}$$

$$\eta_{\underline{C}}(x) = \begin{cases} \frac{x-0.5}{0.2}, & 0.5 < x \le 0.7 \\ \frac{0.9-x}{0.2}, & 0.7 < x < 0.9 \\ 0, & \text{others} \end{cases}$$

$$\eta_{\underline{D}}(x) = \begin{cases} \frac{x-7}{2}, & 7 < x \le 9 \\ 1, & x > 9 \\ 0, & \text{others} \end{cases}$$

(3)Crossing traffic flow

The number of vessels that cross a particular area will also greatly affect the safety of the waters. For example, in Tianjin VTS water area, the intersection of the Northern Branch channel and the Main channel, the breakwater(Fig.4-9) and the reporting line waters are all the waters with high frequency of cross traffic flow occurring (REN J.C.,2013).

In view of the correlation between the cross traffic flow evaluation index u_{33} and the number and times of vessels crossing in the water area x, and combining the actual traffic situation of Tianjin Port, a risk evaluation standard related to cross traffic flow is established: when $x \leqslant 2$, the risk level is low; when x=4, the risk level is ordinary; when x=6,the risk level is high and when $x \geqslant 8$， the risk level is extremely high.

Fig.4-9 VLR recorded data

The dynamic risk membership function associated with traffic density is as follows:

$$\eta_{\underline{A}}(x) = \begin{cases} 1, & x \leq 2 \\ \dfrac{4-x}{2}, & 2 < x < 4 \\ 0, & x \geq 4 \end{cases}$$

$$\eta_{\underline{B}}(x) = \begin{cases} \frac{x-2}{2}, & 2 < x < 4 \\ \frac{6-x}{2}, & 4 < x < 6 \\ 0, & \text{others} \end{cases}$$

$$\eta_{\underline{C}}(x) = \begin{cases} \frac{x-4}{2}, & 4 < x < 6 \\ \frac{8-x}{2}, & 6 < x < 8 \\ 0, & \text{others} \end{cases}$$

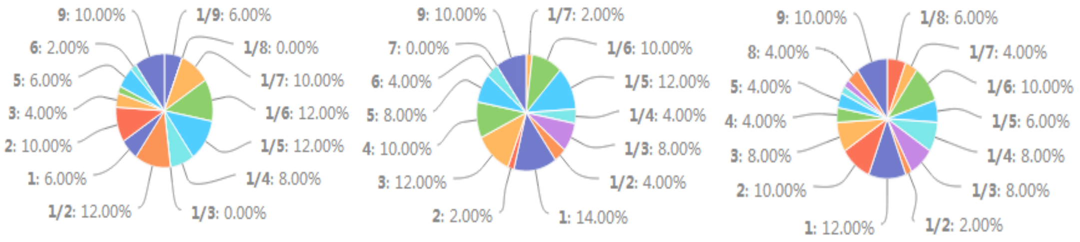
$$\eta_{\underline{D}}(x) = \begin{cases} \frac{x-6}{2}, & 6 < x \leq 8 \\ 1, & x > 8 \\ 0, & \text{others} \end{cases}$$

4.5 Determining the evaluation index weight

In order to avoid losing effect of the evaluated objects due to consideration of excessive elements, the two-level fuzzy comprehensive assessment method is adopted in this paper.

The judgment matrix of the evaluation index weight is determined by using the Delphi method to collect expert questionnaire (Appendix B). The experts are composed of the captain, pilot, ship traffic management personnel and academic staff. A total of 50 valid questionnaires were received. After that, AHP method was used for statistics and analysis. AHP is a decision-making method that decomposes the elements related to the general decision into the target, criterion, scheme and so on, and conducts qualitative and quantitative analysis on this basis. It was created by American scientist P.L.Saaty at the University of Pittsburgh in the 1970s.

After statistics and analysis, the opinions of the expert on the weight distributions of risk evaluation indices are showed in Fig.4-10.



Channel factor/hydro-meteorology　Traffic factor/hydro-meteorology　Traffic factor/channel factor

Fig.4-10 The comparison results of the importance of the evaluation indices of the first layer

The comparison results of the importance of the second level evaluation indices are obtained by the same method.

The importance ratio of channel factor/hydro-meteorology calculated by weighted average method is $1.84 \approx 2$.Same as that, the importance ratio of traffic factor/hydro-meteorology is $2.58 \approx 3$ and the importance ratio of the traffic factor/channel factor is $2.24 \approx 2$. Thus the judgment matrix of index weight in first layer is formed as:

$$A=\begin{pmatrix} u_1/u_1 & u_1/u_2 & u_1/u_3 \\ u_2/u_1 & u_2/u_2 & u_2/u_3 \\ u_3/u_1 & u_3/u_2 & u_3/u_3 \end{pmatrix}=\begin{pmatrix} 1 & 1/2 & 1/3 \\ 2 & 1 & 1/2 \\ 3 & 2 & 1 \end{pmatrix}$$

By the same way, the judgment matrixes of index weight in second layer are obtained too:

$$A_1=\begin{pmatrix} u_{11}/u_{11} & u_{11}/u_{12} & u_{11}/u_{13} \\ u_{12}/u_{11} & u_{12}/u_{12} & u_{12}/u_{13} \\ u_{13}/u_{11} & u_{13}/u_{12} & u_{13}/u_{13} \end{pmatrix}=\begin{pmatrix} 1 & 1 & 2 \\ 1 & 1 & 1 \\ 1/2 & 1 & 1 \end{pmatrix}$$

$$A_2=\begin{pmatrix} u_{21}/u_{21} & u_{21}/u_{22} & u_{21}/u_{23} \\ u_{22}/u_{21} & u_{22}/u_{22} & u_{22}/u_{23} \\ u_{23}/u_{21} & u_{23}/u_{22} & u_{23}/u_{23} \end{pmatrix}=\begin{pmatrix} 1 & 1/2 & 1/2 \\ 2 & 1 & 1 \\ 2 & 1 & 1 \end{pmatrix}$$

$$A_2=\begin{pmatrix} u_{31}/u_{31} & u_{31}/u_{32} & u_{31}/u_{33} \\ u_{32}/u_{31} & u_{32}/u_{32} & u_{32}/u_{33} \\ u_{33}/u_{31} & u_{33}/u_{32} & u_{33}/u_{33} \end{pmatrix}=\begin{pmatrix} 1 & 1/2 & 1/3 \\ 2 & 1 & 1/2 \\ 3 & 2 & 1 \end{pmatrix}$$

Due to the complexity of objective things, the judgment on the importance of indices will be subjective and one-sided, and the deviation of judgment matrix consistency will lead to mistakes in decision-making(LI B.N.,2007).Thus, it is necessary to check the consistency of judgment matrix.

(1)Finding the weight vector by logarithmic least squares method(LLSM)

The principle of LLSM is

$$w_i=\frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)^{\frac{1}{n}}},\quad i=1,2,\cdots\cdots,n$$

The weight vector of A is obtained as

$W=(0.163\quad 0.297\quad 0.540)^{\mathrm{T}}$

(2)Calculating the maximum Eigen value

The maximum Eigen value $\lambda_{\max}=\frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{w_i}=3.010$

(3)The CI(Consistency Index) can be used as a mathematical criterion to measure the degree of inconsistency of the judgment matrix:

$$CI=\frac{\lambda_{\max}-n}{n-1}=\frac{3.010-3}{3-1}=0.005$$

According to the average random consistency index given by professor Saaty(Table4-4),

when $n\geqslant 3$, $CR=\frac{CI}{RI}=\frac{0.005}{058}=0.008<0.1$, the consistency of judgment matrix A is considered acceptable.

In the same way, the index weights of the judgment matrixes of second layer are calculated, and the matrix consistency test is carried out too. The consistency of the judgment matrixes are all found to meet the requirement $CR < 0.1$($CR_1=0.046$,$CR_2=0$, $CR_3=0.009$),and the weight vectors of A_1,A_2,A_3 are as follows:

Weight of the three sub-indices concluded in hydro-meteorology index:

$W_1=(0.411 \quad 0.328 \quad 0.261)^T$

Weight of the three sub-indices concluded in channel index:

$W_2=(0.2 \quad 0.4 \quad 0.4)^T$

Weight of the three sub-indices concluded in channel index:

$W_3=(0.164 \quad 0.297 \quad 0.539)^T$

4.6 Establishing a dynamic risk assessment model

4.6.1 Establish membership matrix of different risk levels for evaluation indices

$B_i=[\gamma_{i1} \ldots \gamma_{ij} \ldots \gamma_{in}]$, $i=1,2, \ldots,9$. $1 \le j \le n=4$.

4.6.2 Integrated risk assessment vector

(1)Calculating the risk assessment vector of sub-layer firstly

$$K_1= W_1 \bullet \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix}, \quad K_2= W_2 \bullet \begin{bmatrix} B_4 \\ B_5 \\ B_6 \end{bmatrix}, \quad K_3= W_3 \bullet \begin{bmatrix} B_7 \\ B_8 \\ B_9 \end{bmatrix}$$

(2)Calculating the integrated risk assessment vector

$$K=W \bullet \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix}$$

4.6.3 Integrated dynamic risk value

The integrated risk assessment vector is multiplied by the risk assessment set *v*=(4,3,2,1) to obtain the integrated dynamic risk value of the specific water area:

$$v = \frac{\sum_{j=1}^{4} k_j * v_j}{\sum_{j=1}^{4} k_j}$$

The dynamic risk level of the water area is obtained by anti-fuzzy treatment of the dynamic risk value（4-extremely high,3-high,2-ordinary,1-low）.If the dynamic risk level is high, the model can remind VTS personnel of the need to take measures to relieve traffic pressure.

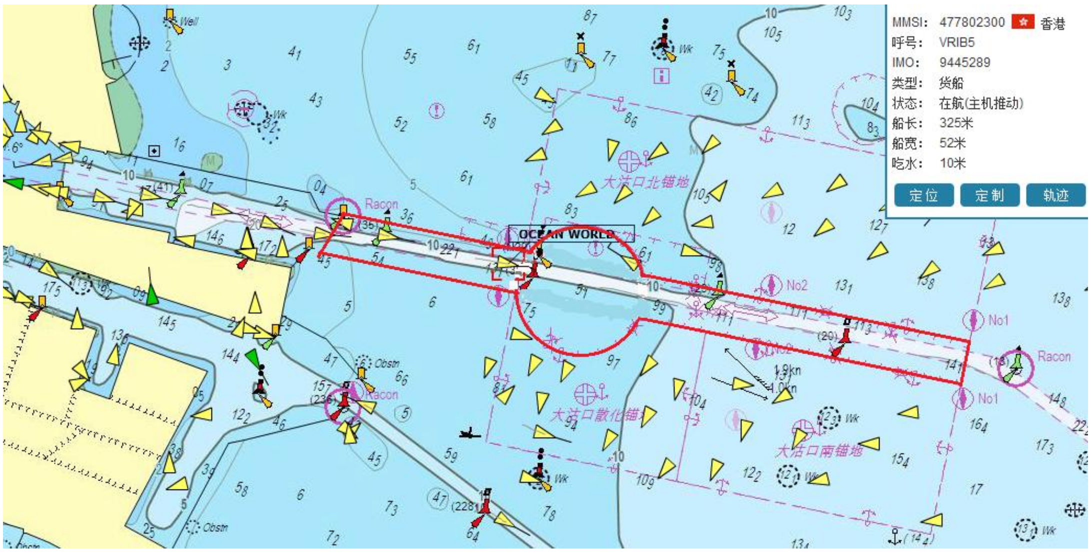
CHAPTER 5

Application of dynamic risk assessment model

5.1 Real-time data acquisition

Zone5 was selected as the experimental sample for the application of this risk assessment model. The real-time data of evaluation indices in zone 5 were collected at 1600 hours on May 25, 2018, and the data of evaluation indices were :

The visibility in Zone5 is 12 km , wind force is Beaufort Wind Scale4~5 (8 m/s), the velocity of current is 0.3 knots and the total number of ships is 3. The draft of the largest ship is 10m,its length is 325m and ship width is 52m. The dynamic data of the largest is as: ship speed-12.6knots, heading-101°.The channel width is 407m, W/b=7.8 (Fig.5-1).



MMSI： 477802300 香港
呼号： VRIB5
IMO： 9445289
类型： 货船
状态： 在航(主机推动)
船长： 325米
船宽： 52米
吃水： 10米

Fig.5-1 Real-time image of AIS data

The index value is introduced into the membership function of each index in Section4 of Chapter 4 and the risk membership vector of a single evaluated object is obtained:

B_1=（0　0　0　1）
B_2=（0　0　1　0）
B_3=（0　0.5　0.5　0）
B_4=（0　0.7　0.3　0）
B_5=（0　0　0　1）
B_6=（0　0　1　0）
B_7=（0　0　0　1）
B_8=（0　0　0　1）
B_9=（0　0　0　1）

5.2 Calculating integrated risk assessment vectors for specific water area

Risk assessment vector of hydro-meteorological indices：

$$K_1=(0.411\quad 0.328\quad 0.261)\bullet\begin{bmatrix}B_1\\B_2\\B_3\end{bmatrix}=(0\quad 0.131\quad 0.458\quad 0.411)$$

Risk assessment vector of channel indices：

$$K_2=(0.2\quad 0.4\quad 0.4)\bullet\begin{bmatrix}B_4\\B_5\\B_6\end{bmatrix}=(0\quad 0.14\quad 0.46\quad 0.40)$$

Risk assessment vector of traffic flow indices：

$$K_3=(0.164\quad 0.297\quad 0.539)\bullet\begin{bmatrix}B_7\\B_8\\B_9\end{bmatrix}=(0\quad 0\quad 0\quad 1)$$

Then, integrated risk evaluation vector of Zone5 is obtained:

$$K=(0.163\quad 0.297\quad 0.540)\bullet\begin{bmatrix}K_1\\K_2\\K_3\end{bmatrix}=(0\quad 0.063\quad 0.211\quad 0.726)$$

5.3 Calculating the integrated dynamic risk value of the specific water area

According to Formula 4-5, the integrated dynamic risk value of Zone5 is calculated :

$$v = .\frac{\sum_{j=1}^{4} k_j * v_j}{\sum_{j=1}^{4} k_j} = 0.189 + 0.422 + 0.726 = 1.337$$

Therefore, according to the calculation result, the dynamic risk of Zone5 is of low risk（Fig.5-2）.

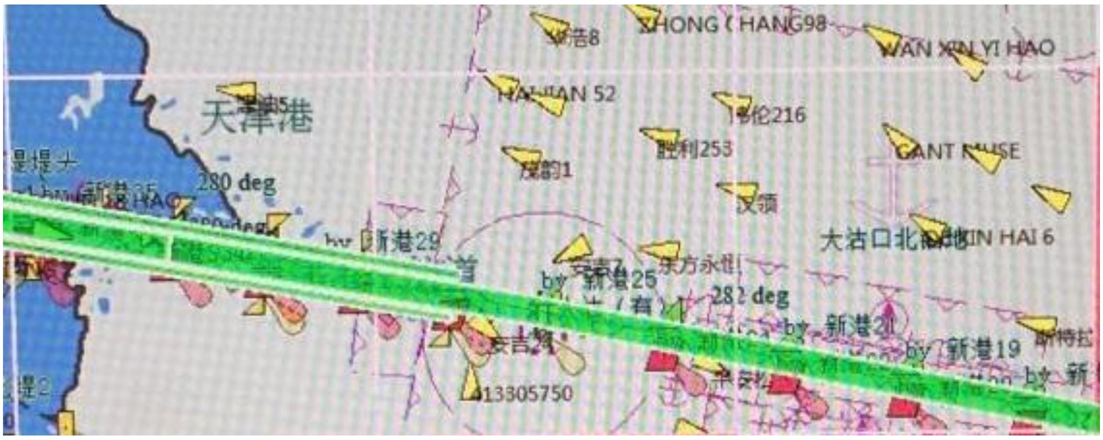


Fig.5-2 Real-time dynamic risk assessment result of Zone5 in Tianjin VTS waters

CHAPTER 6

CONCLUSION and EXPECTATION

6.1 Conclusion

In this paper, the geography, hydro-meteorology, traffic flow and traffic management model of Tianjin Port are analyzed systematically according to the actual situations, which provides the bases for the research work. Then through data collection, questionnaire survey and consulting experts, the dynamic risk evaluation index system of Tianjin VTS waters is identified to constitute the main body of the risk assessment model. After that, through applying fuzzy mathematics and integrated assessment methods, the dynamic risk assessment model is constructed. The real-time risk assessment of traffic environment of Tianjin VTS water area has carried on at last and has got the expected result.

However, there are still some shortcomings in this paper. For example, some data obtained on the basis of expert investigation are subjective and deviate from the actual situation to some extent. Due to the lack of experience and data, the establishment of index system is not comprehensive enough and this risk assessment model needs further check.

6.2 Expectation

In the initial stage of the evaluation model application, the dynamic risk assessment system can be simulated many times with the help of VTS simulator to summarize experience and deficiencies. If the application of the evaluation model is mature enough, it will continue to explore its functions. E.g., in the period when traffic accidents occur frequently, the risk evaluation thresholds in membership functions of evaluation indices can be adjusted, which will change the sensitivity of the model on risk assessment. If the dynamic risk value of a specific region is frequently higher than that of other waters, it can be suggested to modify the traffic management rules of this region. Moreover, risk assessment model established in this paper aims to provide assistance to VTS crew initially. If the model in practice is good, also can propagate to the shipborne terminals to provide dynamic risk warning service for ships operating in Tianjin Port for a long time.

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APPENDIX: A

Table (1): Questionnaire on dynamic risk evaluation indices of Tianjin VTS area

Please fill the mark“√”within the corresponding space of the table based on your professional knowledge.

Importance Index	unimportant	Slightly important	Important	Very important	Definitely important
Visibility					
Wind					
Current					
Tide					
Ice					
Wave					
Channel with					
Channel depth					
Channel length					
Channel curvature					
Distance from channel side line					
Traffic flow speed					
Traffic density					
Traffic volume					
Cross traffic flow					
Aids to navigation					
The area of ship maneuvering or turning					
Traffic management					

APPENDIX: B

Table(2): Expert questionnaire

Please use your professional knowledge and maritime management experience to assign values in the blank of the form. The value is the ratio of two different factors to the importance of ship traffic safety. E.g., Current/Wind，value for 1/9,　1/7，1/5, 1/3，1，3, 5, 7, 9.You can also use the middle value，such as1/8，　1/6，1/4,　1/2，1, 2，4，6，8.

Index Index	Hydro-meteorology	Channel parameters	Traffic Flow	Index Index	Visibility	Wind	Current
Hydro-meteorology	1			Visibility	1		
Channel parameters		1		Wind		1	
Traffic flow			1	Current			1

Index Index	Channel width	Channel curvature	Channel depth
Channel width	1		
Channel curvature		1	
Channel depth			1

Index Index	Traffic volume	Traffic density	Cross traffic
Traffic volume	1		
Traffic density		1	
Cross traffic			1