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Research on the safety assessment of navigation situation in the bridge waters

Hao Liu

WORLD MARITIME UNIVERSITY

Dalian, China

RESEARCH ON THE SAFETY ASSESSMENT OF NAVIGATION SITUATION IN THE BRIDGE WATERS

By

LIU HAO

China

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THE DECLARATION

I certify that all the materials in this research paper that are 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.

(Signature): …………………… Liu Hao…. 刘好…..

(Date): …………………… 2014/6/17…………………………………………

Signature:

Date:

Supervised by: Li Wei

Professor

Dalian Maritime University

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ABSTRCT

The research paper is a study on the navigation environment in bridge waters, the safety assessment model and the case analysis on Jingzhou Yangtze River Bridge.

The bridge water is a complex system with the combination of natural environment and human effects. In the first section, kinds of influence factors on navigation environment in bridge waters will be introduced systematically. And the root causes and specific effects of these influence factors will also be shown.

Then, the safety assessment model will be established in the following section which is called Fuzzy Comprehensive Assessment. The key points are the establishment of evaluation index system according to the analysis of influence factors on navigation environment and the establishment of membership function of them.

Next, a case analysis on Jingzhou Yangtze River Bridge will be discussed to verify the practicability of the safety assessment model. And the safety level of this bridge will be obtained which presents its great practical significance.

Finally, some general recommendations and conclusion would be given.

KEYWORDS: Navigation Environment, Fuzzy Comprehensive Assessment, Evaluation Index System, Membership Function

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CHAPTER 1 INTRODUCTION

1.1 The background of the research

Inland river shipping has the advantages like large transport capacity, high energy efficiency and little pollution. It provides characteristics of important support and guarantees of the economic and social development in the inland river basin. In 2008, Pearl River water system has 344 million tons of freight volume, 46 billion ton-kilometers of turnover cargo and 4.32 million TEU in main ports; Yangtze River water system has 1220 million tons of freight volume which is equivalent to the total transport capacity of 18 Beijing-Guangzhou Railways. Yangtze River water system has about 150 thousand transport ships which bear 83% coal transportation for power plants along river and 80% iron ore for steelmakers. (Xiao, 2007) This powerful shipping transportation highly promote the development of steel, petrochemicals and car industry, also the economic and social development of its relevant river basin area.

With the rapid development of national economy, there are more and more bridges build cross rivers. According to incomplete statistics, on nearly 3000 kilometers of Yangtze River from Yibin to estuary, the government has built 28 highway bridges. Plus the bridges under construction and planning in recent years, it is predicted that the number of bridges on Yangtze River will break through 100 in ten years, the average distance between bridges will be less than 30 kilometers. (Li, 2006)

Nevertheless because of overly rapid construction and large numbers of bridges, it may exit some problems in pre construction design and plan. In some situation, because it is lack of sufficient knowledge in bridge water area such as hydrological characteristics and the law of riverbed revolution, it may choose an unsatisfactory bridge location or make unreasonable piers layout. This will make the navigation environment of the bridge water area deterioration which will increase the difficulty of ships sailing and the potential safety hazards. In some serious case, it may cause some major safety accident such as casualty of people, destroy of ships and damages of bridges. For example, the site of Huangshi Yangtze River Bridge is selected in a bend channel and busy waterborne region, leading to 16 ship bridge collision accidents in less than 150 days which cause 9 ships sinking and millions of direct economic losses.

The accidents above show that the increased risk of ship bridge collision in inland water is presented. There are many influence factors: lots of large bridges, bigger ships with large quantity, more high speed ships and dangerous cargo ships etc. So it is a very important work to make comprehensive analysis, research and evaluation on the navigation condition of the proposed bridge water area before the construction.

In recent years, China has launched a series of national standards and industry specifications such as “navigation standard of inland water” (GB50139-2004) and “code of inland waterway and hydrology” (JTJ213-98). These standards have certain constraint functions on the construction of bridge and other hydraulic architecture and regulate requirements of construction in some aspects. But with the development of economy and society, some standards and specifications are not applicable for today’s requirements. Also the contents in these standards which are related to bridge water navigation are relatively scattered, not a perfect system.

Confronted with great reality, we have realized that it is an important work with realistic importance to improve the traffic safety in bridge water area. Based on the consideration above, this research will take navigation situation of the inland bridge waters as object of study, make case study on Jingzhou Yangtze River Bridge and finally establish an effective safety assessment model to analyze and evaluate the navigation situation in bridge waters. On one hand the research will propose an effective method on the assessment of safety navigation near bridge waters; On the other hand it will provide valuable reference for location of new bridges and navigation demonstration.

1.2 The main task in this paper

This paper will research into the following scopes:

First of all, the paper will make systematic analysis on the navigation environment of inland bridge waters. It includes the influence factors on navigation environment such as the natural environment, traffic environment and management environment. The factors of bridge itself like the selection of bridge site and bridge layout will also be discussed. The effects of bridge on navigation and ships will be explained too.

Then, the paper will focus on the establishment of the safety assessment model including includes the principles of this assessment system, basic steps and specific practice. The model I used is called Fuzzy Comprehensive Assessment and the key points of it are establishment of the evaluation index system, weight value and membership function of evaluation indexes.

Thirdly, the paper will give out an example: safety assessment of navigation situation in Jingzhou Yangtze River Bridge waters. All the analysis and assessment are based on the actual information and data from Jingzhou Yangtze River Bridge.

At last, some general recommendations and conclusions would be given and some advices and suggestion would be presented, too.

CHAPTER 2 ANALYSIS ON NAVIGATION ENVIRONMENT IN BRIDGE WATERS

2.1 Influence factors of navigation environment

2.1.1 Natural environment

Natural environment has direct effect on the safety navigations of ships. Every year the hydrological and meteorological factors are both important factors contributing to kinds of accidents, especially when inland waterway is in dry season, accidents happen more frequently. Natural factors that cause accidents can be divided into two types: one is meteorological factors which include strong winds, poor visibility and so on; the other one is channel factors such as the bend of channel, depth limit and effects of obstacles etc. They will be explained in detail in the following.

Visibility is one of the main meteorological factors which effect inland river navigation. When the visibility is poor, it is prone to occur collision and standing accidents. Some scholars have done statistical analysis on the influence of visibility in Yangtze River. (Karen, 2006) They statistically analyze the total number of vessel traffic accidents happened in 1000 hours and draw the following results: there is certain effects not too much on ships when the visibility is less than 4 kilometers; if the visibility reduce into 1000 meters, the safety navigation of ships will be effected seriously, resulting in the soaring amount of accidents.

Wind is also an important influence factor having obvious effects on ships navigation. It can not only make ships in stall situation, but also lead ships drifting towards leeward and deflection. The degree of wind on ships is according to wind scale, wind angel, wind area, wind power center, ship course and speed and other reasons. In the broad lower reaches of Yangtze River, 4 or 5 class wind is sufficient strong to affect the navigation of ships, 6 or higher class wind will increase the complexity and difficult of ship maneuvering sharply so that it becomes a big threaten to both ships and bridges. In addition, because of the inland water ships with shallow draft, they have weak resistance to the strong wind and poor stability, the effect of wind on them are more obvious.

Channel means the course from departure port to destination port and the navigation aids in it. The risk of channel mainly concentrates on reef, shoal, obstacles, narrow and bend places and changeable flows. The damage and shift of navigation aids also have negative effects. In dry season, the depth of channel has big impact on the safety of navigation. When ships is sailing in shallow water, water resistance, the load of host and ship sinkage increase; However, the engine efficiency decreases, thus it is required to trim by stern. In addition, it widely exits the phenomenon of shipping overload in inland water which increase the draft and prone to accidents. Moreover, with the development of large scale ships, the depth of inland waterway is not relatively enough which becomes a hidden danger for the safety navigation.

2.1.2 Traffic environment

Traffic environment includes the flow of ships, operating time of ships, dynamic characteristic and activity mechanism in certain waters.

The flow of ships is also known as traffic density which means the number of ships passing through a point of certain waters in unit time. It is the most basic parameter to show the actual traffic situation in waters. The number of traffic density can directly reflect the busy degree even the dangerous and crowed degree of ships in certain waters.

The traffic order is also an important factor to the safety of navigation. With the increasing traffic density day by day, the probability of ships' meeting and crossing is increasing, besides, it's more likely to cause accidents. Especially in the bridge waters, when different course and different types of ships meet, it is difficult to control all the activities of these ships and may cause collision accidents between ships or bridges. In addition, the bridges of inland water are usually built in economically developed areas with busy water traffic. In these areas, kinds of tributaries and mainstreams intersect and shunt, mounts of anchorage, ports and crossing area gather. The entire complex situations here increase the risk of accidents in bridge waters.

2.1.3 Management environment

Management environment include conditions of artificial facilities, traffic regulations, traffic organizations and ship conditions. If the management environment is good, the complexity of traffic reduces; conversely if the management is in chaos, the complexity increases.

Artificial facilities can be divided into three categories: the first one is monitoring facility, navigation facility and communication network which are used to ensure the safety of ships; second is early warning system for the prevention of accidents; third is emergency equipment for rescue when accidents happen. Nowadays the most widely used monitoring facilities in China are vessel traffic service system (VTS) and automatic identification system (AIS). (Wu, 2004) They monitor the navigation of ships and provide modern traffic service for ships. The communication network using now include traditional media-high frequency communication, mobile phone in nearshore waters and satellite. The main function of warning system is issuing navigational warning and predicting meteorological information.

If the artificial facilities can be called as hardware of management, the traffic regulations and organizations are soft management environment. Traffic regulations should sound a system consist of collision regulation, national laws and local standards. Traffic organizations require improving the construction of pilotage service and maintenance site, cleaning and fire-fighting equipment, support equipment of gas and water, medical and health institution etc. Whether the ships can acquire relative safety service timely and convenience is one of the important factors on the assessment of management environment.

2.2 Influence factors of bridge

2.2.1 The selection of bridge site

The selection of bridge site is one of the key links in the whole construction process. It dose not only affect the safety and economy of bridge, but also have effects on the operation and development of ports. So when we choose bridge site, we need to take many things into account such as the geological condition of the proposed area, flood control safety, navigation effects and planned development of cities. Then make a comprehensive evaluation according to these factors and make sure ships can pass through bridges safety and smoothly. In addition, the bridge location should adapt to the natural conditions and long-term developing plan of the waterway, avoiding higher investment and maintenance costs caused by river regime evolution, and negative impacts on navigation, flood control facilities and ports operation.

The selection of bridge site should be in channel segment which satisfy the requirements such as single straight, enough water depth, favorable flow condition, stable river regime and riverbed. The upstream and downstream flows of the bridge should be smoothly straight and left enough safety distance, avoiding bend channel, inlet, shoal and junction areas. Generally, the distance to upstream shoal should be 4 times longer than the longest fleet at least, the distance to downstream shoal should be 2 times longer.

The river course and riverbed should be stable and the bend degree should be small. According to "navigation standard of inland water", the minimum bend radius of channel should be twice longer than the longest fleet at least; the angle between bridge axis normal and flow should be less than 5 degrees; the axial spacing between two adjacent bridges should larger than distance the fleet sailing 5 minutes.

2.2.2 The bridge layout

The headroom is an important metric to measure the clearance of bridge which means the surplus of ships' headroom plus the height of the peak above ships' light waterline.

The designed maximum navigable stage is used as the starting surface of headroom. The design of headroom requires to fully consider the situation of waterway, operation facility nearby and make comprehensive analysis on the development trend of local economy. At the same time, it needs to consider the traffic demand of other type vessels such as military, engineering and non-transport ships. Generally, it needs to left extra 2 meters of surplus height to ensure the safety of bridges. The main influence factors are: the draft difference in freshwater and seawater, different peak height of ships caused by pitching and heaving, errors between designed draft and real draft and errors after repairing ships. In addition, if the drift angle between the downstream surface of piers and flows is larger than 5 degree, the headroom must be increased.

The design of navigable bridge openings should apply to kinds of vessels' passing and ensure safety of navigation. In busy traffic waterway, the width of bridge opening should consider both technological and economic reasons. According to the statistical analysis on past experience and accidents, it is better to use long-span bridge openings when the economic index is similar. According to the present technology and ability of construction, the span of pre-stressed concrete bridge is 300m, arch bridge is 500m, cable stayed bridge is 1000m, suspension bridge is over 1500m. For the non-navigable bridge openings, it also makes the span as large as possible because it can reduce water area occupied by piers and flow changes caused by construction. (Xu, 2003, p.46) There is a formula to check the minimum width of navigable bridge openings (B_m) :

$$\begin{aligned} B_m &= B_F + \Delta B_m + P_d \\ B_F &= B_S + L \sin \beta \end{aligned} \qquad (2.1)$$

In this formula:

B_m — the navigable clear width of single hole and one-way (m);

B_F — the track belt width of ships or fleet (m);

ΔB_m — the rich width between ships (fleet) and both sides of piers (m);

$\Delta B_m = 0.6 \times B_F$ in Class I~V channel;

P_d — the cross track distance of downstream ships or fleet (m);

B_S — the width of ships or fleet (m);

L — the length of pusher train or freighter (m);

β — the navigable drift angle of ships or fleet (°); $\beta = 6°$ in Class I~V channel;

2.2.3 The design of bridge piers

The position layout and shape design of piers have significant effects on navigation in bridge waters. The setting process of piers should combine the actual characteristics of bridge waterway and kinds of regulation in this area. At the same time, it needs to consider the effects of piers on the riverbed evolution: they should not change the trend of flows and hydrological conditions of the channel. For some reason, the pier hole setting and pier type designing of some bridges are incompatible with the boundary and flow conditions of the channel segment. Furthermore these problems will result in negative effects on navigation, for instance, extra piers and insufficient width will greatly reduce the discharge area of waterway and lead to damming phenomenon in bridge waters.

2.3 Effects of bridge on navigation safety

With the increasing number of bridges across rivers and rapid development of inland water transportation, the traffic density increase year by year and the bridge piers located in the river will have great influence on the normal navigation. Especially in flood period, it may lead to the change of navigation environment and river terrain witch have much more effects on navigation safety.

2.3.1 Effects of bridge on flow environment

The main effects of bridge on inland water course is damming and souring. Because the construction of piers reduces the discharge area and generates some water-blocking effect, this will lead to the phenomenon of damming. When damming happens, the water level of upstream rises, the current velocity slows down, the sediment transport capacity decreases, the beach face of marginal bank and diara increase, the range of sedimentation expand and all these effects above will make the flow and regime of rivers change. In addition, due to the flows around the piers suffer the blocking effects and extrusion, it increases the unit discharge of channel and enlarge the sediment transport capacity. This will result into the souring phenomenon and change the original river regime. So it is necessary to make sufficient scientific demonstration before the construction of bridge to avoid the change of river regime.

The effect of bridge on flows is attributed to the damming phenomenon in upstream will increase the water speed in bridge openings, thus change the flows in channel. In water rising period, the increasing of water speed in bridge openings will strengthen the transverse flow. As a result, when passing through the bridge, ships may appear deflection or drift situation. However the sudden turn caused by the deflection or drift are just the important reasons for collision between ships and bridges.

2.3.2 Effects of bridge on navigation

When ships are sailing in bridge waters, the driver have to strictly control the drift angle of ships and avoid sailing closing to piers which will increase the pressure and fatigue of officers in operation. When ships are sailing in bridge waters at night, the officer may be affected and disturbed by the lights in bridge which have negative effects on safety. Because ships are not permitted overtaking and parallel gonging in navigable bridge openings, so the phenomenon of queue and waiting may occur and it will increase the traffic density here further more. The bridge may have many other effects on the navigation and all of them may increase the danger coefficient when passing through the bridge.

CHAPTER 3 THE ESTABLISHMENT OF THE SAFETY ASSESSMENT MODEL

3.1 The basic principle of the safety assessment

Because the inland river bridge water is a complex system, there are many factors affecting the safety of navigation such as hydrological and meteorological conditions, traffic density, waterway situation, navigation marks and so on. And these factors include many evaluation indexes which are mutual restraint and interacting. Further more, most of these evaluation indexes are fuzzy concepts and difficult to make accurate quantitative analysis. So in this paper, I use fuzzy comprehensive assessment method (FCA) to make safety assessment on bridge waters.

3.1.1 The basic elements of FCA

FCA is the implementation of fuzzy mathematics in actual assessment operation. It is an advanced comprehensive evaluation method with advantages like systematicness, scientificalness and strong maneuverability. The basic ideal of FCA is: first take all risk factors into consideration and set weight of every factor to distinguish their importance; then structure mathematical model to evaluate the risk. To be specific, there are four essential elements in the process of FCA:

• Index set

An event is often caused by a number of factors and the evaluation of it should consider all factors. Index set U is a set of all factors affecting the event and it can be expressed as:

$U = (u_1, \mathrm{u}_2, \mathrm{u}_3, ...u_n)$

Index set U include a lot of influencing factors and the corresponding weight coefficient is w_i (i=1,2,3…n) which reflects the degree of importance of each factors in evaluation process. The weight coefficients w composes the index set W, which is the fuzzy subset of index set U. (Xiao, 2007, p.12) it can be expressed as:

$$W = (w_1, w_2, w_{3,} ...w_n) \quad (\sum_{i=1}^{n} w_i = 1 \quad w_i \geq 0) \qquad (2.2)$$

・Evaluation set

It is a set of possible evaluation results. The purpose of FCA is just to choose a optimum evaluation results from the evaluation set after considering all factors' effects. It can be expressed as:

$V = (v_1, v_2, v_{3,} ... v_n)$

・Single index evaluation

It means making evaluation on one factor in index set U. Then determine the membership grade on evaluation set V according to every factor v_n and obtain single index evaluation vector: $r_i = (r_{i1}, r_{i2}, r_{i3}, ... r_{in})$. Finally output the index evaluation matrix on all factors in U:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

・Fuzzy comprehensive evaluation

It means making multi factor evaluation based on single index evaluation. Using the index set of weight coefficients W multiply single index evaluation matrix R and obtain the final decision evaluation set B: (Wu, 2002, p.37)

$$B = W \square R = (w_1, w_2, ... w_n) \square \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} = (\mathrm{b}_1, b_2, ... b_n) \qquad (2.3)$$

3.1.2 The basic steps of FCA

First, determine the evaluation grade. This paper will divide the navigation environment into five grades: very safe, safe, ordinary, danger and very danger. It can be expressed as: (Wang, 2005)

$V = (v_1, \quad v_2, \quad v_3, \quad v_4, \quad v_5)$

= (2, 1, 0, -1, -2)

= (very safe, safe, ordinary, danger, very danger)

Second, establish the evaluation index system. It is a process that selecting and analyzing all influencing factors on the research object to obtain the index set U. Then establish the standard of assessment about each index according to evaluation set V. It will be done in Chapter 3.2.

Third, determine the weight value of evaluation index. It is a process: reorder all evaluation indexes from high importance to low and obtain the relative weight value. Then calculate out the absolute weight value and obtain the fuzzy subset W. For detail, I will explain them in Chapter 3.3.

Forth, determine the membership function of evaluation indexes. It is a process that establishing the membership function to make quantitative analysis on index set U. This will be elaborated in Chapter 3.4.

Finally, make fuzzy comprehensive evaluation on the research object and reach the final result. This will be induded in Chapter 3.5.

3.2 Establishment of the evaluation index system

Selecting the appropriate evaluation factors and establishing the appropriate evaluation index system are prerequisite to obtain objective and accurate evaluation result. Considering the objective effects of navigation environment and subjective effects of ships sailing, this paper concludes the evaluation index in 9 aspects:

3.2.1 Wind

Although the size of inland waterway is smaller than that of ocean, the effects of wind still exist. Because the inland river ships are generally of shallow draft with poor stability and weak wind résistance ability, they should pay more attention to wind effects when sailing in strong wind condition. Wind will make ship yawing and swaying, especially in bridges waters these situation will cause more danger. According to statistical results, the number of accidents is in linear relationship with the speed of wind. (Liu, 2004, p.21) The equation can be expressed as:

$$k_w = 7.9v_w - 11.6 \qquad k_w \geq 0 \qquad (3.1)$$

v_w — the speed of wind (m/s) k_w — the number of accidents

Consider the wind resistance of ships and meteorological condition of inland waters, as well as some regulation and standards of inland water navigation. This paper use 4 class wind as standard wind. All wind scales are divided into two parts: 4~6 class wind and above 6 class wind. According to equation (3.1), we can deduce that above 6 class wind is 1.5 times than the standard wind. So the number of average annual standard wind is:

Days of average annual standard wind = (4~6) wind days+ 1.5 * (above 6) wind days

According to method of questionnaire and expert surveys, we establish the standard of assessment about wind in table 3.1.

Tab 3.1 the standard of assessment about wind

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger

Days of standard wind (day/year)	＜30	30~60	60~90	90~120	> 120

3.2.2 Visibility

Visibility means the maximum horizontal distance of normal eyesight. When sailing in restricted visibility or poor illumination situation, divers' eyesight will be limited. As a result, the probability of yawing and collision accidents will increase. Visibility has great effects on inland river navigation, especially in bridge waters. (Chen, 2001, p.15) Take Yangtze River as an example, the scholar has made statistical analysis on the number of accidents in 1000 hours in certain visibility and obtained the formula as follow:

$$k = 9.0D^{-0.8} \qquad (3.2)$$

k — the number of accidents under the visibility D (km) in 1000 hours.

The grading standards of Chinese vessel traffic management system (VTS) makes classification on visibility. Poor visibility means the eyesight is within 2000m and it defines that: 12 days of poor visibility annual is 1 class; 22 days is 2 class; 32 days is 3 class; 40 days is 4 class. According to the characteristics of inland water and actual situation, this paper use the average days in visibility 2000m as standard and establish the standard of assessment about visibility in table 3.2.

Tab 3.2 the standard of assessment about visibility

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger

Days of poor visibility (day/year)	＜15	15~30	30~45	45~60	> 60

3.2.3 Water depth

The standard depth means the minimum navigation water depth according to the designed lowest navigable water level. When sailing in shoal waters, water resistance and host load increases, conversely, engine efficiency decrease. It will cause situation like trim by stern and reduce the maneuverability of ships. Generally speaking, the influence degree of water depth on navigation is according to the size of ship, waterway depth and sailing speed.

According to the characteristics of inland water and ships, the draft will increase when ships sail in shallow area. The ship navigation performance will be affected when depth/draft (H/d) is 4; when H/d is 1.2 to 1.5, the ships have the probability of grounding or touching bottom. (Sui, 2006, p.25) Experimental studies show that the formula between water depth and navigation safety is as follow:

$$k = \frac{T\sqrt{\frac{d}{H-d}}}{H+0.3d} \qquad (3.3)$$

k — the number of accidents in unit time and unit length waterway

H — water depth d — ship draft T — fixed coefficient

This paper use water depth/ship draft (H/d) as the evaluation index and establishes the standard of assessment about water depth in table 3.3.

Tab 3.3 the standard of assessment about water depth

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger
water depth/ship draft	> 4	2.0~4.0	1.6~2.0	1.3~1.6	< 1.3

3.2.4 Current

Current has important effects on ship operation in inland waters. The relative speed of the bottom and side of upstream vessels will increase in virtue of the effects of current, ships prone to occur restricted water phenomenon; The stroke on the ground increase when ships are downstream, the stopping and deceleration process are also very slow; Transverse current will make ship transverse drift. In general, the angle between keel-line of ships and flow direction will increase with the speed of flow; the slower ships sail, the bigger flow pressure they suffer and the faster they downstream drift. (Shen, 2004) The effect of current is mainly decided by its velocity and direction. Because the current direction is in accordance with ships in most cases, this paper use the maximum current velocity in bridge waters as the evaluation index. Combined with the relevant regulations in "inland navigation standard", it establishes the standard of assessment about current in table 3.4.

Tab 3.4 the standard of assessment about current

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger
maximum velocity (m/s)	< 1	1~2	2~3	3~4	> 4

3.2.5 Channel curvature

The main difficulty factor in passing through bending waterway is the effects of curvature and sweeping bends. The curvature is usually represented by bending radius and the minimum bending radius is used to ensure the safety passing of ships which depend on the maximum length of ships.

According to regulations in “inland navigation standard”: In I class channel, the minimum channel bending radius should be 4 times longer than length of fleet; If the velocity is more than 3m/s, the minimum radius should be 5 times longer. (MOC, 2004) This paper use accumulative rudder angle as the evaluation index and establishes the standard of assessment about channel curvature in table 3.5.

Tab 3.5 the standard of assessment about channel curvature

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger
accumulative rudder angle (°)	< 5	5~10	10~15	15~20	> 20

3.2.6 Navigation aids

The accuracy and reliability of navigation aids are important guarantee of safety navigation in bridge waters. If there are some limitations for ships, it must set water marks in conspicuous area. The setting of navigation aids should consider the channel condition, traffic density, representative ship types and other factors.

The setting situation of navigation aids is usually expressed by perfect rate. This rate is a ratio of actual navigation aids coverage area to total channel area. The perfect setting of navigation aids should be sufficient quantity, clearly visible and scientific layout. This paper will use perfect rate as the evaluation index and establish the standard of assessment about navigation aids in table 3.6.

Tab 3.6 the standard of assessment about navigation aids

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger
Perfect rate (%) (coverage area/total area)	95~100	90~95	80~90	70~80	＜70

3.2.7 Clearance dimension of navigable bridge opening

Clearance dimension include headroom and clearance width. The numerical value of headroom is the sum of safety clearance height and height of the ships' peak, its starting surface is designed maximum navigable stage. Clearance width is the minimum width for the safety navigation of representative ship types. (Yang, 2007)

The width of bridge opening is the main influence factor to actual navigation. According to the regulation in China, the minimum width of bridge opening is 3 to 7 times longer than the length of fleet in different class channels. This paper use the ratio of bridge opening's width to ships' width as the evaluation index and establishes the standard of assessment about bridge span in table 3.7.

Tab 3.7 the standard of assessment about bridge span

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger
width of bridge opening/ width of ships	＞8	5~8	3~5	2~3	＜2

3.2.8 Traffic density

It means the total number of ships passing through a certain cross section in unit time. Traffic flow reflects the degree of traffic scale and density in certain waters as well as reflects the degree of risk and crowded.

According to the collection and analysis of information on traffic density of many bridges in inland waters, this paper use the ratio of actual ships quantity to designed quantity as the evaluation index. (Zhou, 2005) It establishes the evaluation criteria of traffic flow in table 3.8.

Tab 3.8 the standard of assessment about traffic density

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger
Traffic density (%) (actual /designed quantity)	＜0.4	0.4~0.6	0.6~1.4	1.4~1.6	＞1.6

3.2.9 Complexity of traffic

It includes the layout of ports, anchorage and crossing area around bridge waters, also the effects of intersection between tributary and trunk stream. Along with the effects of fishing boats, traffic chaos is a great threat to safety navigation.

The complexity of traffic is difficult to make quantitative description, so this paper adopts qualitative method using the degree of complexity as the evaluation index and establishes the standard of assessment about traffic complexity in table 3.9. (Liu, 2006)

Tab 3.9 the standard of assessment about traffic complexity

Danger degree / Evaluation index	very safe	safe	ordinary	danger	very danger
degree of complexity	very simple	simple	ordinary	complex	very complex

3.2.10 Result of evaluation index system

According to the analysis in 3.2.1~3.2.9, the index set U is:

$$U = (u_1,\ u_2,\ u_3,\ u_4,\ u_5,\ u_6,\ u_7,\ u_8,\ u_9)$$

= (wind, visibility, water depth, current, channel curvature, navigation aids, bridge span, traffic density, complexity of traffic)

3.3 Determination of weight value of evaluation indexes

Weight value is a kind of metric value to measure the influence degree of each single index on whole assessment. In comprehensive assessment, in order to make evaluation on safety navigation objectively and reasonably, this paper will use method of two elements contrast to make quantitative analysis on the importance of each index and weight of each index approach.

The basic step is: firstly sort all indexes in sequence and compare the weight of adjacent index respectively; then according to the corresponding relationship between relative weight and tone operator, deduce relative weight; finally dispose all relative weight identically and obtain the absolute weight value. (Geng, 2007, p.34)

3.3.1 The order of evaluation indexes by importance

Using method of two elements contrasting to compare two indexes and the value of importance is as follow:

Tab 3.10 the value of the importance by comparison

index	u_{ij}	u_{ji}
u_i is more important than u_j	1	0
u_i is as important as u_j	0.5	0.5
u_i is less important than u_j	0	1

In tab 3.10, u_{ij} is the comparison result between u_i and u_j, so we can deduce the matrix of all indexes:

$$U = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{19} \\ u_{21} & u_{22} & \cdots & u_{29} \\ \cdots & \cdots & \cdots & \cdots \\ u_{91} & u_{92} & \cdots & u_{99} \end{bmatrix} \qquad (3.4)$$

$$T_i = \sum_{j=1}^{9} u_{ij}, \qquad i = 1, 2, 3 \ldots 9.$$

T_i — the ordinal number of each index on importance

Then obtain the reorder of the indexes by importance:

Tab 3.11 the reorder of the indexes by importance

index	wind	visibility	depth	current	curvature	aids	span	Density	complexity	T
wind	0.5	1	1	1	1	1	1	1	1	8.5
visibility	0	0.5	0	0	1	1	0	1	1	4.5
depth	0	1	0.5	1	1	1	1	1	1	7.5
current	0	1	0	0.5	1	1	1	1	1	6.5
curvature	0	0	0	0	0.5	1	0	0	1	2.5
aids	0	0	0	0	0	0.5	0	0	1	1.5
span	0	1	0	0	1	1	0.5	1	1	5.5
density	0	0	0	0	1	1	0	0.5	1	3.5
complexity	0	0	0	0	0	0	0	0	0.5	0.5

According to the value of T, we obtain an order of the indexes by importance. In virtue of this order, we obtain a new index set U from high importance to low importance:

$U = (u_1, \quad u_2, \quad u_3, \quad u_4, \quad u_5, \quad u_6, \quad u_7, \quad u_8, \quad u_9)$

= (wind, depth, current, bridge span, visibility, traffic density, channel curvature, navigation aids, complexity of traffic)

3.3.2 The absolute weight value of evaluation indexes

The evaluation indexes have been reordered in sequence from high importance to low importance. In this section, I will use method of two elements contrasting and tone operator to quantify the importance of evaluation indexes.

Tone operator is a description tool to the result of two elements comparison. It has 11 comparison levels from I to XI and 10 intermediate levels. I level means the two elements have the absolutely same importance and XI level means they have absolutely different importance. (Edward, 2000) Every level has its corresponding relative weight value as follow:

Tab 3.12 the relation between tone operator and relative weight

tone operator	I		II		III		IV		V		VI
relative weight	1.0	0.905	0.818	0.739	0.667	0.60	0.538	0.481	0.429	0.379	0.333
tone operator		VII		VIII		IX		X		XI	
relative weight	0.29	0.25	0.212	0.176	0.143	0.111	0.081	0.053	0.026	0	

Setting relative weight value of u_1 is 1. So w_{12} is the relative weight value of u_2 on u_1; w_{23} is the relative weight value of u_3 on u_2. And $w_{13} = w_{12} \cdot w_{23}$. According to this method, we obtain relative weight of each index:

Tab 3.13 the value of relative weight

relative weight	wind	depth	current	bridge span	visibility	traffic density	channel curvature	navigation aids	complexity of traffic
w_{i-1i}	1	0.818	0.905	0.818	0.818	0.905	0.667	0.905	0.905
w_{1i}	1	0.818	0.740	0.606	0.495	0.448	0.299	0.271	0.245

Using formula (3.5), (Chen, 2001, p.18) it disposes all the relative weight values (w_{1i}) identically and obtain the absolute weight value (w_i):

$$w_i = \frac{w_{1i}}{\sum_{i=1}^{9} w_{1i}} \qquad (3.5)$$

$$W = (w_1,\ w_2,\ w_3,\ w_4,\ w_5,\ w_6,\ w_7,\ w_8,\ w_9)$$
$$= (0.203, 0.166, 0.150, 0.123, 0.101, 0.091, 0.061, 0.055, 0.050)$$

3.4 The membership function of evaluation indexes

We have done detailed analysis on evaluation index system: establish the standard of assessment about each index in Chapter 3.2 and reord them in Chapter 3.3. Now I will establish the membership function of each index which is corresponding to its danger degree. In this way, when we input specific numbers, the membership function will give out the membership grade to each danger degree in specific value.

3.4.1 Wind

According to Tab 3.1 the standard of assessment about wind, the membership function of wind is as follows:

$$r_1^1=\begin{cases}0 & x\geq 40\\ \dfrac{40-x}{20} & 20\leq x\leq 40\\ 1 & x\leq 20\end{cases}$$

$$r_1^2=\begin{cases}0 & x\leq 20或x\geq 70\\ \dfrac{x-20}{20} & 20\leq x\leq 40\\ 1 & 40\leq x\leq 50\\ \dfrac{70-x}{20} & 50\leq x\leq 70\end{cases}$$

$$r_1^3=\begin{cases}0 & x\leq 50或x\geq 100\\ \dfrac{x-50}{20} & 50\leq x\leq 70\\ 1 & 70\leq x\leq 80\\ \dfrac{100-x}{20} & 80\leq x\leq 100\end{cases}$$

$$r_1^4=\begin{cases}0 & x\leq 80或x\geq 140\\ \dfrac{x-80}{20} & 80\leq x\leq 100\\ 1 & 100\leq x\leq 120\\ \dfrac{140-x}{20} & 120\leq x\leq 140\end{cases}$$

$$r_1^5=\begin{cases}0 & x\leq 120\\ \dfrac{x-120}{20} & 120\leq x\leq 140\\ 1 & x\geq 140\end{cases} \qquad (3.6)$$

x — days of standard wind (day/year)

So the single index evaluation vector of wind is: $R_1 = \left(r_1^1,\ \ r_1^2,\ \ r_1^3,\ \ r_1^4,\ \ r_1^5\right)$

3.4.2 Water depth

According to Tab 3.3 the standard of assessment about water depth, the membership function of water depth is as follows:

$$r_2^1 = \begin{cases} 0 & x \le 3.8 \\ \dfrac{x-3.8}{0.4} & 3.8 \le x \le 4.2 \\ 1 & x \ge 4.2 \end{cases}$$

$$r_2^2 = \begin{cases} 0 & x \le 1.8 \text{或} x \ge 4.2 \\ \dfrac{x-1.8}{0.4} & 1.8 \le x \le 2.2 \\ 1 & 2.2 \le x \le 3.8 \\ \dfrac{4.2-x}{0.4} & 3.8 \le x \le 4.2 \end{cases}$$

$$r_2^3 = \begin{cases} 0 & x \le 1.5 \text{或} x \ge 2.2 \\ \dfrac{x-1.5}{0.2} & 1.5 \le x \le 1.7 \\ 1 & 1.7 \le x \le 1.8 \\ \dfrac{2.2-x}{0.4} & 1.8 \le x \le 2.2 \end{cases}$$

$$r_2^4 = \begin{cases} 0 & x \le 1.2 \text{或} x \ge 1.7 \\ \dfrac{x-1.2}{0.2} & 1.2 \le x \le 1.4 \\ 1 & 1.4 \le x \le 1.5 \\ \dfrac{1.7-x}{0.2} & 1.5 \le x \le 2.7 \end{cases}$$

$$r_2^5 = \begin{cases} 0 & x \geq 1.4 \\ \dfrac{1.4 - x}{0.2} & 1.2 \leq x \leq 1.4 \\ 1 & x \leq 1.2 \end{cases} \qquad (3.7)$$

x — water depth/ship draft

So the single index evaluation vector of water depth is: $R_2 = \left(r_2^1,\ \ r_2^2,\ \ r_2^3,\ \ r_2^4,\ \ r_2^5\right)$

3.4.3 Current

According to Tab 3.4 the standard of assessment about current, the membership function of current can be presented as follows:

$$r_3^1 = \begin{cases} 0 & x \geq 1.2 \\ \dfrac{1.2 - x}{0.4} & 0.8 \leq x \leq 1.2 \\ 1 & x \leq 0.8 \end{cases}$$

$$r_3^2 = \begin{cases} 0 & x \leq 0.8 \text{或} x \geq 2.2 \\ \dfrac{x - 0.8}{0.4} & 0.8 \leq x \leq 1.2 \\ 1 & 1.2 \leq x \leq 1.8 \\ \dfrac{2.2 - x}{0.4} & 1.8 \leq x \leq 2.2 \end{cases}$$

$$r_3^3 = \begin{cases} 0 & x \leq 1.8 \text{或} x \geq 3.2 \\ \dfrac{x - 1.8}{0.4} & 1.8 \leq x \leq 1.2 \\ 1 & 2.2 \leq x \leq 2.8 \\ \dfrac{3.2 - x}{0.4} & 2.8 \leq x \leq 3.2 \end{cases}$$

$$r_3^4 = \begin{cases} 0 & x \le 2.8或x \ge 4.2 \\ \dfrac{x-2.8}{0.4} & 2.8 \le x \le 3.2 \\ 1 & 3.2 \le x \le 3.8 \\ \dfrac{4.2-x}{0.4} & 3.8 \le x \le 4.2 \end{cases}$$

$$r_3^5 = \begin{cases} 0 & x \le 3.8 \\ \dfrac{4.2-x}{0.4} & 3.8 \le x \le 4.2 \\ 1 & x \ge 4.2 \end{cases} \qquad (3.8)$$

x — maximum velocity (m/s)

So the single index evaluation vector of current is: $R_3 = \left(r_3^1,\quad r_3^2,\quad r_3^3,\quad r_3^4,\quad r_3^5\right)$

3.4.4 Bridge span

According to Tab 3.7 the standard of assessment about bridge span, the membership function of bridge span is as follows:

$$r_4^1 = \begin{cases} 0 & x \le 6.5 \\ \dfrac{9.5-x}{3} & 6.5 \le x \le 9.5 \\ 1 & x \ge 9.5 \end{cases}$$

$$r_4^2 = \begin{cases} 0 & x \le 4或x \ge 9.5 \\ \dfrac{x-6.5}{3} & 6.5 \le x \le 9.5 \\ 1 & 6 \le x \le 6.5 \\ \dfrac{6-x}{2} & 4 \le x \le 6 \end{cases}$$

$$r_4^3 = \begin{cases} 0 & x \le 2.5 或 x \ge 5 \\ \dfrac{6-x}{2} & 4 \le x \le 6 \\ 1 & 3.5 \le x \le 4 \\ \dfrac{x-2.5}{1} & 2.5 \le x \le 3.5 \end{cases}$$

$$r_4^4 = \begin{cases} 0 & x \le 1.7 或 x \ge 3.5 \\ \dfrac{3.5-x}{2} & 2.5 \le x \le 3.5 \\ 1 & 2.3 \le x \le 2.5 \\ \dfrac{x-1.7}{1} & 1.7 \le x \le 2.5 \end{cases}$$

$$r_4^5 = \begin{cases} 0 & x \ge 2.3 \\ \dfrac{2.3-x}{0.6} & 1.7 \le x \le 2.3 \\ 1 & x \le 1.7 \end{cases} \qquad (3.9)$$

x — width of bridge opening/width of ships

So the single index evaluation vector of bridge span is: $R_4 = \left(r_4^1,\ \ r_4^2,\ \ r_4^3,\ \ r_4^4,\ \ r_4^5\right)$

3.4.5 Visibility

According to Tab 3.2 the standard of assessment about visibility, the membership function of visibility is as follows:

$$r_5^1 = \begin{cases} 0 & x \ge 20 \\ \dfrac{20-x}{10} & 10 \le x \le 20 \\ 1 & x \le 10 \end{cases}$$

$$r_5^2 = \begin{cases} 0 & x \le 10 或 x \ge 35 \\ \dfrac{x-10}{10} & 10 \le x \le 20 \\ 1 & 20 \le x \le 25 \\ \dfrac{35-x}{10} & 25 \le x \le 35 \end{cases}$$

$$r_5^3 = \begin{cases} 0 & x \le 25 或 x \ge 50 \\ \dfrac{x-25}{10} & 25 \le x \le 35 \\ 1 & 35 \le x \le 40 \\ \dfrac{50-x}{10} & 40 \le x \le 50 \end{cases}$$

$$r_5^4 = \begin{cases} 0 & x \le 40 或 x \ge 65 \\ \dfrac{x-40}{10} & 40 \le x \le 50 \\ 1 & 50 \le x \le 55 \\ \dfrac{65-x}{10} & 55 \le x \le 65 \end{cases}$$

$$r_5^5 = \begin{cases} 0 & x \le 55 \\ \dfrac{x-55}{10} & 55 \le x \le 65 \\ 1 & x \ge 65 \end{cases} \qquad (3.10)$$

x — days of poor visibility (day/year)

So the single index evaluation vector of visibility is: $R_5 = \left(r_5^1,\ r_5^2,\ r_5^3,\ r_5^4,\ r_5^5\right)$

3.4.6 Traffic density

According to Tab 3.8 the standard of assessment about traffic density, the membership function of traffic density is as follows:

$$r_6^1 = \begin{cases} 0 & x \geq 0.45 \\ \dfrac{0.45 - x}{0.1} & 0.35 \leq x \leq 0.45 \\ 1 & x \leq 0.35 \end{cases}$$

$$r_6^2 = \begin{cases} 0 & x \leq 0.35 或 x \geq 0.7 \\ \dfrac{x - 0.35}{0.1} & 0.35 \leq x \leq 0.45 \\ 1 & 0.45 \leq x \leq 0.5 \\ \dfrac{0.7 - x}{0.2} & 0.5 \leq x \leq 0.7 \end{cases}$$

$$r_6^3 = \begin{cases} 0 & x \leq 0.5 或 x \geq 1.5 \\ \dfrac{x - 0.5}{0.2} & 0.5 \leq x \leq 0.7 \\ 1 & 0.7 \leq x \leq 1.3 \\ \dfrac{1.5 - x}{0.2} & 1.3 \leq x \leq 1.5 \end{cases}$$

$$r_6^4 = \begin{cases} 0 & x \leq 1.3 或 x \geq 1.65 \\ \dfrac{x - 1.3}{0.2} & 1.3 \leq x \leq 1.5 \\ 1 & 1.5 \leq x \leq 1.55 \\ \dfrac{1.65 - x}{0.1} & 1.55 \leq x \leq 1.65 \end{cases}$$

$$r_6^5 = \begin{cases} 0 & x \leq 1.55 \\ \dfrac{x - 1.55}{0.1} & 1.55 \leq x \leq 1.65 \\ 1 & x \geq 1.65 \end{cases} \quad (3.11)$$

x — actual ship quantity /designed quantity

So the single index evaluation vector of traffic density is:

$$R_6 = \left(r_6^1, \quad r_6^2, \quad r_6^3, \quad r_6^4, \quad r_6^5\right)$$

3.4.7 Channel curvature

According to Tab 3.5 the standard of assessment about channel curvature, the membership function of channel curvature can be displayed as follows:

$$r_7^1=\begin{cases}0 & x\geq 7\\ \dfrac{7-x}{4} & 3\leq x\leq 7\\ 1 & x\leq 3\end{cases}$$

$$r_7^2=\begin{cases}0 & x\leq 3\text{或}x\geq 12\\ \dfrac{x-3}{4} & 3\leq x\leq 7\\ 1 & 7\leq x\leq 8\\ \dfrac{12-x}{4} & 8\leq x\leq 12\end{cases}$$

$$r_7^3=\begin{cases}0 & x\leq 8\text{或}x\geq 17\\ \dfrac{x-8}{4} & 8\leq x\leq 12\\ 1 & 12\leq x\leq 13\\ \dfrac{17-x}{4} & 13\leq x\leq 17\end{cases}$$

$$r_7^4=\begin{cases}0 & x\leq 13\text{或}x\geq 22\\ \dfrac{x-13}{4} & 13\leq x\leq 17\\ 1 & 17\leq x\leq 18\\ \dfrac{22-x}{4} & 18\leq x\leq 88\end{cases}$$

$$r_7^5=\begin{cases}0 & x\leq 18\\ \dfrac{x-18}{4} & 18\leq x\leq 22\\ 1 & x\geq 22\end{cases} \qquad (3.12)$$

x — accumulative rudder angle (°)

So the single index evaluation vector of channel curvature is:

$R_7 = \left(r_7^1,\quad r_7^2,\quad r_7^3,\quad r_7^4,\quad r_7^5\right)$

3.4.8 Navigation aids

Based on Tab 3.6 the standard of assessment about navigation aids, the membership function of navigation aids is as follows:

$$r_8^1 = \begin{cases} 0 & x \le 93 \\ \dfrac{x-93}{4} & 93 \le x \le 97 \\ 1 & x \ge 97 \end{cases}$$

$$r_8^2 = \begin{cases} 0 & x \le 88 或 x \ge 97 \\ \dfrac{97-x}{4} & 93 \le x \le 97 \\ 1 & 92 \le x \le 93 \\ \dfrac{x-88}{4} & 88 \le x \le 92 \end{cases}$$

$$r_8^3 = \begin{cases} 0 & x \le 76 或 x \ge 92 \\ \dfrac{x-88}{4} & 88 \le x \le 92 \\ 1 & 84 \le x \le 88 \\ \dfrac{84-x}{8} & 76 \le x \le 84 \end{cases}$$

$$r_8^4 = \begin{cases} 0 & x \le 66 或 x \ge 84 \\ \dfrac{84-x}{8} & 76 \le x \le 84 \\ 1 & 74 \le x \le 76 \\ \dfrac{x-66}{8} & 66 \le x \le 74 \end{cases}$$

$$r_8^5 = \begin{cases} 0 & x \geq 74 \\ \dfrac{74-x}{8} & 66 \leq x \leq 74 \\ 1 & x \leq 66 \end{cases} \qquad (3.13)$$

x — actual navigation aids coverage area/total channel area

So the single index evaluation vector of navigation aids is:

$R_8 = \left(r_8^1,\ \ r_8^2,\ \ r_8^3,\ \ r_8^4,\ \ r_8^5\right)$

3.4.9 Complexity of traffic

According to Tab 3.9 the standard of assessment about traffic complexity, it is difficult to establish membership function of it. So I decide to use qualitative fuzzy tone operator to describe and membership grade is as follow:

Tab 3.14 the tab of membership grade

	v_1	v_2	v_3	v_4	v_5
very simple	0.8	0.2	0	0	0
simple	0.2	0.6	0.2	0	0
ordinary	0	0.2	0.6	0.2	0
complex	0	0	0.2	0.6	0.2
very complex	0	0	0	0.2	0.8
	r_9^1	r_9^2	r_9^3	r_9^4	r_9^5

3.5 Fuzzy comprehensive assessment

In Chapter 3.2, Chapter 3.3 and Chapter 3.4, we have made sufficient preparation for the final fuzzy comprehensive assessment. We conclude 9 typical evaluation indexes on the safety navigation of bridge waters and establish its membership function on 5 evaluation grades. They are:

Index set of weight coefficients W:

$W = (w_1, \quad w_2, \quad w_3, \quad w_4, \quad w_5, \quad w_6, \quad w_7, \quad w_8, \quad w_9)$

= (wind, depth, current, bridge span, visibility, traffic density, channel curvature, navigation aids, complexity of traffic)

= (0.203, 0.166, 0.150, 0.123, 0.101, 0.091, 0.061, 0.055, 0.050)

Index evaluation matrix R:

$$R = \begin{bmatrix} r_1^1 & r_1^2 & r_1^3 & r_1^4 & r_1^5 \\ r_2^1 & r_2^2 & r_2^3 & r_2^4 & r_2^5 \\ r_3^1 & r_3^2 & r_3^3 & r_3^4 & r_3^5 \\ r_4^1 & r_4^2 & r_4^3 & r_4^4 & r_4^5 \\ r_5^1 & r_5^2 & r_5^3 & r_5^4 & r_5^5 \\ r_6^1 & r_6^2 & r_6^3 & r_6^4 & r_6^5 \\ r_7^1 & r_7^2 & r_7^3 & r_7^4 & r_7^5 \\ r_8^1 & r_8^2 & r_8^3 & r_8^4 & r_8^5 \\ r_9^1 & r_9^2 & r_9^3 & r_9^4 & r_9^5 \end{bmatrix}$$

So we can obtain the final decision evaluation set B:

$B = W \circ R$

$$= (w_1,\quad w_2,\quad w_3,\quad w_4,\quad w_5,\quad w_6,\quad w_7,\quad w_8,\quad w_9) \circ \begin{bmatrix} r_1^1 & r_1^2 & r_1^3 & r_1^4 & r_1^5 \\ r_2^1 & r_2^2 & r_2^3 & r_2^4 & r_2^5 \\ r_3^1 & r_3^2 & r_3^3 & r_3^4 & r_3^5 \\ r_4^1 & r_4^2 & r_4^3 & r_4^4 & r_4^5 \\ r_5^1 & r_5^2 & r_5^3 & r_5^4 & r_5^5 \\ r_6^1 & r_6^2 & r_6^3 & r_6^4 & r_6^5 \\ r_7^1 & r_7^2 & r_7^3 & r_7^4 & r_7^5 \\ r_8^1 & r_8^2 & r_8^3 & r_8^4 & r_8^5 \\ r_9^1 & r_9^2 & r_9^3 & r_9^4 & r_9^5 \end{bmatrix}$$

$$= (b_1,\quad b_2,\quad b_3,\quad b_4,\quad b_5) \qquad (3.14)$$

In formula (3.14), b_j is the final decision evaluation index, and $b_j = \sum_{i=1}^{9} w_i \times r_i^j$.

b_j is a fuzzy vector which reflects the fuzzy distribution status of danger degree on evaluation set V. And this paper will use weighted average method to calculate the final result: (Qiu & Liu, 2003)

$$v = \frac{\sum_{j=1}^{5} b_j \times v_j}{\sum_{j=1}^{5} b_j} \qquad (3.15)$$

At last, using the weighted average value of v to compare with the evaluation set V and find its corresponding value, we can know the safety situation of navigation in inland bridge waters.

CHAPTER 4 THE CASE ANALYSIS ON JINGZHOU YANGTZE RIVER BRIDGE

4.1 Analysis on the navigation environment

4.1.1 Natural environment

Jingzhou Yangtze River Bridge is located in the middle reaches of the Yangtze River in Hubei province (Taiping kou Channel, 481.4km of middle reaches of the Yangtze River). (Li, 2006) The area is in the north of the topic of cancer and belongs to temperate climate. In Jingzhou area, the wind situation is as follow:

Tab 4.1 the statistics about the wind course/speed/frequency

course Speed	N	NNE	NE	ENE	E	ESE	SE	SSE
Maximum value (m/s)	11	12	11	9	12	8	14	7
Average value (m/s)	2.9	2.9	2.3	2.7	2.4	2.3	2.6	2.7
Frequency (%)	16	7	3	4	5	6	9	10
course speed	S	SSE	SW	WSW	W	WNW	NW	NNW
Maximum value (m/s)	10	8	5	5	5	10	7	10

Average value (m/s)	2.7	2.7	2.2	2.3	2.1	2.1	2.3	2.7
Frequency (%)	4	1	2	2	1	1	3	8

According to the tab 4.1, the average wind speed of one year is 2.3 m/s. In chapter 3.2.1, we have defined the days of 4 class wind (5m/s) as the standard wind days, so here we can estimate the standard wind days of Jingzhou area is about 80 days.

Fog is another natural factor with serious effects on safety navigation in Yangtze River. The main foggy season in Jingzhou area is spring and winter. According to statistics in recent years, the average foggy days of one month are 9 days, therefore we can also estimate that the days of poor visibility (less than 2 kilometers) is about 54 days per year.

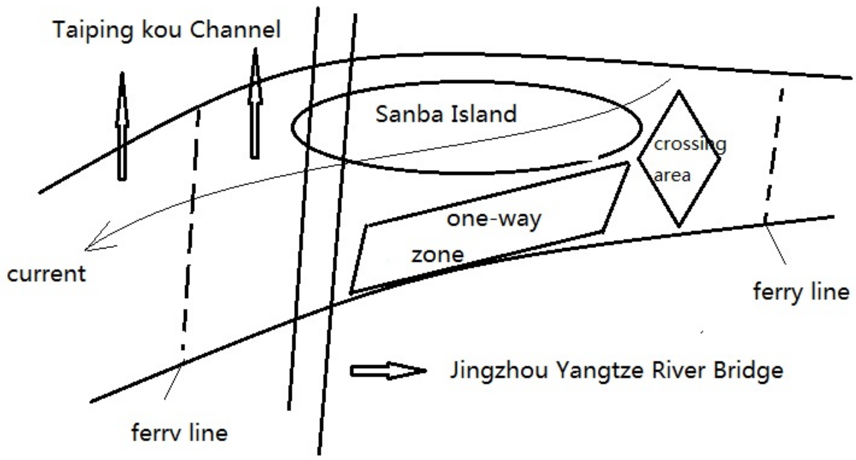
The effect of hydrological condition on navigation is mainly reflected by the speed of current and depth of flow. In Jingzhou basin of Yangtze River, although its waterway is narrow and bending, the current is relative slow. In most areas, the current speed is 1~2 m/s, so we can estimate the maximum current velocity is 2.1 m/s. Because the depth of Jingzhou basin becomes very shallow in dry water season, so the value of water depth/ship draft is relative low accordingly. Generally, the water depth is about 4~5m and ship draft is about 2~3m in Jingzhou basin of Yangtze River, so we can estimate the value at 1.8. (Liu, 2001)

4.1.2 Traffic environment

Taiping kou Channel is in the middle reaches of Yangtze River and there is a middle bar called Sanba Island in the upstream of the bridge. There are also crossing area, one-way navigation zone and ferry lines intersecting in Taiping kou Channel.

Because the Sanba Island has divided the river into two narrow channels, the navigation situation is more serious. According to the data of Jingzhou MSA, the traffic density of Jingzhou Yangtze River Bridge is almost saturation. So we can estimate that the value of traffic density (actual ships quantity/designed ships quantity) is 0.95. To be specific, the situation of the bridge water is shown in Fig 4.1.

Fig 4.1 the schematic diagram about bridge water



The types of ships navigating in the bridge area are complex. For instance, general cargo ships, self-discharging sand boats, fishing ships and ferryboats, etc. And in the downstream, many citizens like to swim in this waters which has negative effects on the navigation. Both these factors increase the complexity of the traffic, so we can estimate the degree of traffic complexity is complex accordingly.

The whole Taiping kou Channel is bending and winding, but the bridge area is relative straight. If ships need to pass through the water, only changing the rudder in upstream to adjust the situation of Sanba Island is available, so we can estimate the channel curvature (accumulative rudder angle) are 10 degree.

Because of the careful maintenance of MSA and channel department, the navigation aids are sufficient and valid. So we can estimate the perfect rate of navigation aids (coverage area/ total channel area) is 90%.

4.1.3 The bridge condition

The basic parameter of Jingzhou Yangtze River Bridge is shown in Tab 4.2.

Tab 4.2 basic parameter of Jingzhou Yangtze River Bridge

Bridge type	Cable-stayed bridge
Total length	4397.6m
Width	24.5m
Maximum height	210m
Maximum span	500m
Under clearance	18m

The bridge has 12 bridge openings and 2 of them are used for navigation. The span of the north navigable opening is 500m which is the largest one in Asia and the second largest in the world (only 30m less than the Belford cross-sea bridge in Norway). It can be called an architectural wonder in inland water bridges and the 500m span can satisfy all kinds of ships in Yangtze River to pass through. The span of the south navigable opening is 300m, and we will calculate the value of bridge span (width of bridge opening/width of ships) based on it.

Now the main types of ships are shown in Tab 4.3.

Tab 4.3 the typical vessels in bridge waters

	Types of ships	Main dimensions

1	1000-ton general cargo ship	58*12.6*2.6
2	1000-ton multi-purpose container ship	49.9*15.6*2.8
3	1000-ton dry cargo ship	49.9*12.8*3.0
4	1000-ton tanker	49.9*13.2*3.2
5	1000-ton self-discharging sand boats	58*12.8*3.2

According to formula 2.1, the width of ships is:

$B_m = B_F + \Delta B_m + P_d \approx 50$ (m)

So the value of bridge span (width of bridge opening/width of ships) is 6.0

4.2 Safety assessment on the navigation situation

According to the analysis on the navigation environment in Chapter 4.1, the evaluation index system and its specific value are as follow:

Tab 4.4 the evaluation index system of Jingzhou Yangtze River Bridge

influencing factors	evaluation indexes	value
Wind (u_1)	days of standard wind (day/year)	80
Depth (u_2)	water depth/ship draft	1.8
Current (u_3)	maximum velocity (m/s)	2.1
Bridge span (u_4)	width of bridge opening/ width of ships	6.0
Visibility (u_5)	days of poor visibility (day/year)	54
Traffic density (u_6)	actual ship quantity /designed quantity	0.95

Channel curvature (u_7)	accumulative rudder angle (°)	10
Navigation aids (u_8)	perfect rate (%)	90
Complexity of traffic (u_9)	degree of complexity	complex

According to Chapter 3.1.2, the navigation environment is divided into five grades: very safe, safe, ordinary, danger and very danger. It can be expressed as:

$V = (v_1, \quad v_2, \quad v_3, \quad v_4, \quad v_5)$

= (very safe, safe, ordinary, danger, very danger)

= (2, 1, 0, -1, -2)

According to Chapter 3.3.2, the weight value of evaluation index is:

$W = (w_1, \quad w_2, \quad w_3, \quad w_4, \quad w_5, \quad w_6, \quad w_7, \quad w_8, \quad w_9)$

= (0.203, 0.166, 0.150, 0.123, 0.101, 0.091, 0.061, 0.055, 0.050)

According to the membership functions in Chapter 3.4, the calculation results of single index evaluation vectors are:

$R_1 = (0 \quad 0 \quad 1 \quad 0 \quad 0)$

$R_2 = (0.5 \quad 0.5 \quad 0 \quad 0 \quad 0)$

$R_3 = (0 \quad 0.5 \quad 0.5 \quad 0 \quad 0)$

$R_4 = (0 \quad 0.1 \quad 0.9 \quad 0 \quad 0)$

$R_5 = (0 \quad 0 \quad 0 \quad 1 \quad 0)$

$R_6 = (0 \quad 0 \quad 1 \quad 0 \quad 0)$

$R_7 = (0 \quad 0.5 \quad 0.5 \quad 0 \quad 0)$

$R_8 = (0 \quad 0.5 \quad 0.5 \quad 0 \quad 0)$

$R_9 = (0 \quad 0.2 \quad 0.6 \quad 0.2 \quad 0)$

So the index evaluation matrix R is:

$$R = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \\ R_6 \\ R_7 \\ R_8 \\ R_9 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0.1 & 0.9 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0.2 & 0.6 & 0.2 & 0 \end{bmatrix} \quad (4.1)$$

According to formula 3.14, we can obtain the final decision evaluation set B:

$$B = W \cdot R = (0.166, 0.2, 0.5, 0.2, 0) \quad (4.2)$$

According to formula 3.15, the weighted average value v is:

$$v = \frac{\sum_{j=1}^{5} b_j \times v_j}{\sum_{j=1}^{5} b_j} = 0.62 \rightarrow 1\ (v_2) \quad (4.3)$$

So we can obtain the conclusion that:

The navigation situation in Jingzhou Yangtze River Bridge waters is **SAFE**.

CHAPTER 5 RECOMMENDATIONS AND CONCLUSION

In order to make safety assessment on navigation situation in bridge waters, this paper has made systematic analysis on the navigation environment and established the evaluation index system. Firstly, when we analyze the effects of navigation environment, we consider as much as possible influencing factors, but there are also some factors we have not considered because of different reality situations. Secondly, we establish the evaluation index system in 9 aspects such as wind, current, depth and so on according to the analysis on the navigation environment. We choose these 9 factors as evaluation index according to document literature and expert advice, so whether they possess representative characteristics and apply to all the inland river bridges, it is necessary to conduct further analysis. Thirdly, in the process of case study, the output of the value of evaluation indexes is according to historical experiences and documentary records, some data may be estimated by them because there are not direct sources, so some errors in numbers may occur.

The recommendation is to make more comprehensive field investigations on inland bridge waters before the theoretical analysis. The selection of data needs to be more cautious and accurate. In actual operation, we can adjust the weight values of evaluation index and the assessment standard about each index appropriately to reduce the error from data.

In conclusion, the method of Fuzzy Comprehensive Assessment is a scientific and effective way to make safety assessment on inland water bridges. The navigation situation in Jingzhou Yangtze River Bridge waters is safe and the facts prove that there are few accidents happened in this bridge water indeed. But because of the vast inland river bridge waters in China and the rapid development of water transportation, the risk of navigation in bridge waters is still a problem of water safety. “Where there is a will, there is a way.” I could say that if we can make scientific safety assessment on bridge waters as much as possible, we can make the occurrence of accidents as few as possible.

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