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Risk analysis of maritime accidents in an estuary: a case study of Shenzhen Waters

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Key words: maritime accident, risk analysis, Bayesian network, fault tree analysis, estuarine waters, maritime safety

Abstract

Due to the unique geographic location, complex navigation environment and intense vessel traffic, a considerable number of maritime accidents occurred in estuarine waters during recent years which caused serious loss of life, property and environmental contamination. Based on the historical data of maritime accidents from 2003 to 2012, which is collected from Shenzhen Maritime Safety Administration, this paper conducted a risk analysis of maritime accidents by applying Bayesian network and fault tree analysis. First a Bayesian network model was introduced to describe the consequence of accidents based on the accident investigation report. Then fault tree analysis was applied to estimate the probability on the basis of accident statistics and ship traffic flow. Finally the risk of maritime accidents in Shenzhen Waters was depicted through the consequence multiplied by the probability of an accident.

Introduction

With the rapid development of the Chinese economy, the shipping industry has witnessed an era of prosperity in recent years. As the largest river in southern China, Pearl River provides a great navigation environment for shipping because of its plentiful tributaries and flow. The estuarine waters however, due to the unique geographic location and intense vessel traffic, etc., yield an increasing danger of accidents involving vessels, such as collision, grounding, sinking, etc. In order to improve the safety of navigation and promote the development of the shipping industry, a large amount of research has been done by scholars around the world.

In the scientific literature there are several aspects in the study of maritime accidents which draw much attention from researchers around the world. One of them is to extract the mechanism of accident from the massive scale of data by applying accident causation analysis or pattern analysis. Based on the historical accident investigation report which contains navigation environment statistics, particulars of the ship involved and detailed description of the accident, the causes, consequences and characteristics of an accident can be discovered which are of great help in providing scientific and comprehensive support for qualitative and quantitative analysis. Mazaheri et al. (2015) extracted knowledge for contributing factors of grounding accidents from 115 grounding accident reports and 163 near-miss grounding reports and discussed the usability of such reports for evidence-based risk modelling. Li (2010) applied petri networks into the causation analysis and structured analytical network of vessel collision, which is of great benefit to studies into the development of vessel collision. Chen et al. (2014) studied the pattern of ship collision accidents in estuarine waters by performing association rule mining on the historical data. Li (2012) applied traffic conflict theory technique and accident-causation theory to recognize the causing factors and accident characteristics in the Chengshantou waters of China. Guo et al. (2007) studied the accident report from the aspect of human, vessel, environment and management respectively. To find out the human failures in vessel accidents, Celik and Cebi (2009) used HFACS (Human Factors Analysis and Classification System) with the help of AHP (Analytic Hierarchy Process) whilst Chauvin (2013) also applied this system to the study of human failure and other factors in accidents. Although studies into the cause of accidents and their patterns can provide profound understanding about accidents, they are still limited in qualitative analysis due to scattered and incomplete accident data.

Risk analysis is an aspect of the study of maritime safety which is drawing increasing attention. Kaplan (1997) defined risk as a triplet of scenario, likelihood and consequence, shown in Eq. 1:

$$R = (S, L, C) \tag{1}$$

The three of these factors answer the questions about risk: what can happen (S)? how likely it is (L)? and what are the consequences (C)? Montewka et al. (2013) used sea collisions involving RoPax vessels as a case study to propose a framework for risk assessment for maritime transportation by using a Bayesian network. Ung Shuen-Tai (2014) built a fuzzy-ruled based maritime risk assessment model. Qu et al. (2011) introduced an index of speed dispersion, degree of acceleration and deceleration and number of fuzzy ship domain overlaps as indices to perform ship collision risk assessments for the Singapore Strait. Hu et al. (2010) applied a method of Formal Safety Assessment and risk matrix to obtain the quantitative characteristic of maritime risk in coastal areas of Fujian Province, China. As for the method of risk analysis, a Bayesian network has been more popular for maritime risk analysis (Hänninen, 2014). A Bayesian network is a probability network which consists of an acyclic directed graph and conditional probability tables of nodes which represent variables. It is suitable for complex system modeling and copes with uncertainty, therefore making it an attractive modeling tool for maritime safety and accident (Hänninen, 2014). Zhang et al. (2013) analyzed the historical accident data for the Yangtze River and applied a Bayesian network to build a navigation risk estimation model incorporated with Formal Safety assessment method. Goerlandt and Montewka (2013) established a probabilistic model by using a Bayesian network to reason under uncertainty for the assessment of accidental cargo oil outflow.

Based on the literature review and advantages of a Bayesian network, this paper conducted a study on risk analysis of maritime accidents in estuarine waters on the basis of historical accident data. During the study, this paper uses the product of accident probability and probability of an accident falling into a certain level of consequence as risk indices. The section *Risk analysis model of maritime accidents* is the model for risk analysis of maritime accidents. In the section *Case study,* a case study of Shenzhen waters is performed and the result of the model is compared with the risk criteria that Mou et al. (2008) proposed. The section *Conclusions and discussion* closes the paper and gives a brief discussion on the model.

Risk analysis model of maritime accidents

In this section the model of risk analysis of maritime accidents was established. This paper applied a Bayesian network to build the consequence model, whilst the fault tree analysis (FTA) method was introduced to calculate the probability of a maritime accident based on the statistics of accident and traffic flow.

The consequence model

A Bayesian network was applied here to calculate the probability of an accident falling into a certain level of consequence via learning from the accident data collected from the Maritime Safety Administration. According to statistical methods for water traffic accidents adopted by the Ministry of Transport of the People's Republic of China on 26th August 2002, the consequence of a maritime accident was classified into four categories which are: minor, major, critical and catastrophic. Therefore the consequence model this paper built utilizes the same standard consistent with the data report. The specific classification standard was shown in Table 1.

Table 1. Classification of maritime accidents

Classification of consequence	Explanation
Catastrophic	3000 GDT and above: more than 3 dead, or direct economic damage 5 million RMB and above; 500–3000 GDT: more than 3 dead, or direct economic damage 3 million RMB and above; 500 GDT and below: more than 3 dead, or direct economic damage 50 k RMB and above
Critical	3000 GDT and above: 1–2 dead, or direct economic damage 3–5 million RMB; 500–3000 GDT: 1–2 dead, or direct economic damage 500 k – 3 million RMB; 500 GDT and below: 1–2 dead, or direct economic damage 500 k RMB and below
Major	3000 GDT and above: serious injury, or direct economic damage 500 k – 3 million RMB; 500–3000 GDT: serious injury, or direct economic damage 200–500 k RMB; 500 GDT and below: serious injury, or direct economic damage 200 k RMB and below
Minor	Excluded from aforementioned above

Table 2. Variables and discretization standard

Variables	States			
Wind	less than 4	between 4 and 7	above 7	
Wave	Calm	Slight	Moderate	Rough
Visibility	less than 500	500 to 2000	2000 to 4000	4000 or above
Time	0000 to 0400 1600 to 2000	0400 to 0800 2000 to 2400	0800 to 1200	1200 to 1600
Ship owner	Private	National fund	International	
Gross tonnage	less than 300 5000 or above	300 to 1000	1000 to 2000	2000 to5000
Accident type	Collision Grounding	Contact damage Sink	Fire Wind damage	Explosion Others
District	Baoan (b1) Shekou (s5)	Dayawan (d2) Tonghangchu (t6)	Mawan (m3) Yantian (y7)	Nanshan (n4) Jidi (j8)
Ship type	Barge Container Passenger ship Dry cargo ship Unknown	Bulk carrier Dredger Sand ship Multifunction ship	Cargo ship Fishing ship Towing ship Public service ship	Chemical cargo ship Oil tanker Working ship General cargo ship
Consequence	Minor	Major	Critical	Catastrophic

Defining the variables

One of the crucial elements of the model is to define the proper variables and the logical relationship between them. Water transportation is a system affected by human, ship, environmental and management factors. Therefore the variables of the consequence model should be defined according to the aspects aforementioned. Based on the maritime accident database that contains structured data of accidents over 10 years, 10 variables with relatively comprehensive data were selected and defined with discretization, which are as follows: wind, wave, visibility, time, ship owner, ship type, gross tonnage, district, accident type, and consequence. The discretization standard of variables are shown in Table 2.

Developing the structure of the model

Since there are missing values in the data set, the current algorithm in the Genie 2.0 software cannot perform structure learning based on them. The structure of the network was then accomplished with the help of expert knowledge in the field. The expert knowledge was obtained via a brief questionnaire which was sent to several researchers in our group. Within the questionnaire there was a network which was built by the author so that researchers could give advice on its modification. Once all the questionnaires were retrieved, the structure of the network was modified according to the advice and the qualitative part of the consequence model is shown in Figure 1.

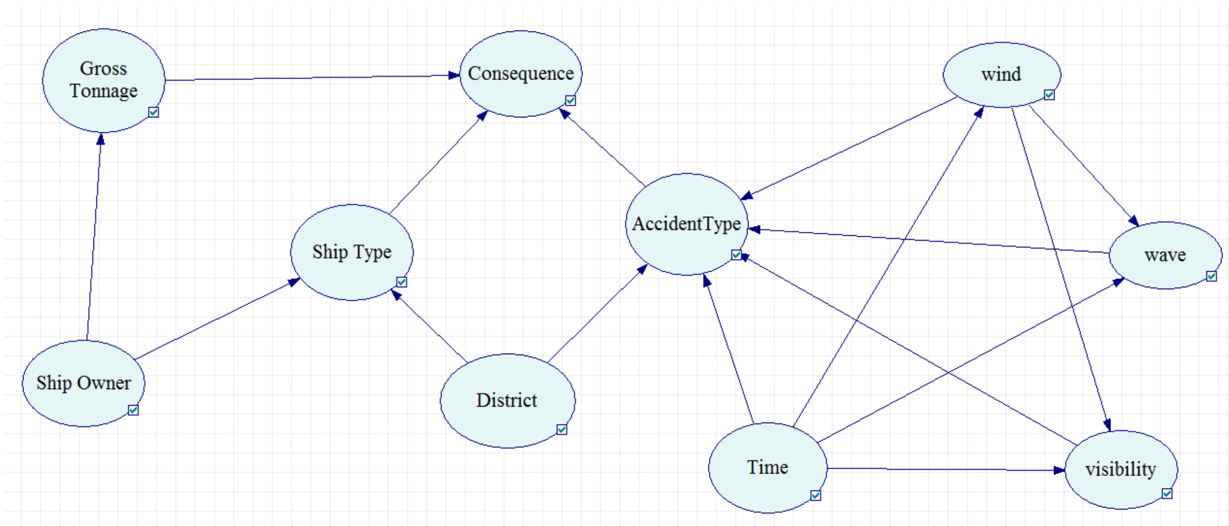

Figure 1. Structure of the consequence model

Developing the parameters of the model

The parameters of the model were obtained via learning from the accident data which contains 185 cases of maritime accident from 2003 to 2012. The accident data was structured and discretized on the basis of the standard mentioned in Table 2. Then, by using parameter learning function of Genie 2.0 software, the probability of the accident falling into a certain level of consequence was obtained.

Accident probability model

The probability of a maritime accident is affected by different parameters, i.e. weather, technical failure and human factors. The FTA model of maritime accident is built to estimate the probability based on the ship accident statistics data and traffic flow. The FTA can be seen as a logical and graphical method highly used to evaluate the probability of one undesirable event or accident occurring as a result of failures. It can be seen as a deductive approach, which starts from an effect and aims at identifying its causes. It starts with the event of interest, the top event, and is developed from the top down.

The maritime accidents this paper analyzes include various categories such as collision, grounding, contact damage, fire and explosion, sinking etc. It is barely possible to use one fault tree to calculate the probability. According to the database, accident due to collision, contact damage and grounding represent more than 70% of the total number of accidents. Therefore this paper performs fault tree analysis on these three categories to calculate the probability of such an accident, whilst the probability of other accidents was replaced by the frequency of them. Finally the probability of maritime accident was calculated from the sum of the probability of each kind of accident.

FTA model of ship collision

Factors affecting ship collision

There are many factors affecting ship collision. This paper selects 13 factors as basic events based on collision accident data analysis. Figure 2 shows the fault tree of ship collision in Shenzhen waters: X0 is negligence in guarding – meaning overconfidence or gross negligence on the voyage; X1 is the wrong assessment collision risk – meaning failure in assessing risk lead to collision; X2 is improper emergency operation – meaning appropriate measures were not taken to avoid collision in an emergency situation; X3 is improper steering control – meaning improper steering control in maneuvering; X4 is improper lookout – meaning the correct lookout was not kept on the voyage; X5 is uncoordinated avoiding – meaning the uncoordinated action of two ships led to collision; X6 is improper avoiding – meaning action taken to avoid a collision was unsuitable; X7 is deviated from channel; X8 is unused safety speed – meaning the speed of the vessel exceeded the safety speed; X9 is poor visibility – meaning fog or rain led to poor visibility; X11 is rough sea; X11 is main engine failed – meaning the main engine could not provide power; X12 is steering failed – meaning rudder failure.

Minimum cut sets of the fault tree

In order to calculate the probability of ship collision, firstly the fault tree is expressed by Boolean algebra, then the Boolean algebra is simplified to acquire minimum cut sets. The ship collision event can be expressed by Eq. 2.

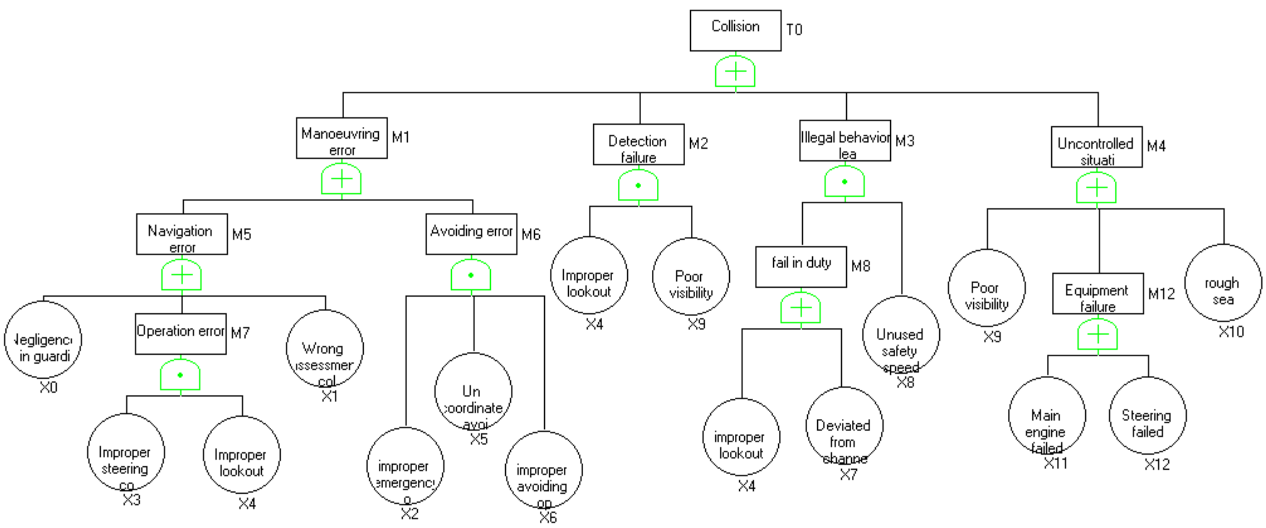

Figure 2. Fault tree of ship collision accident

$$\begin{aligned}
\text{T0} &= (\text{M1}+\text{M2}+\text{M3}+\text{M4}) = \\
&= (\text{M5}+\text{M6})+\text{X4}\cdot\text{X9}+\text{X8}\cdot\text{M8}+\text{X7}+ \\
&\quad +\text{M12}+\text{X10} = \\
&= \text{X0}+\text{M7}+\text{X1}+\text{X2}\cdot\text{X5}\cdot\text{X6}+\text{X4}\cdot\text{X9}+ \\
&\quad +\text{X8}\cdot(\text{X4}+\text{X7})+\text{X9}+(\text{X11}+\text{X12})+\text{X10} = \\
&= \text{X0}+(\text{X3}\cdot\text{X4})+\text{X1}+\text{X2}\cdot\text{X5}\cdot\text{X6}+\text{X4}\cdot\text{X9}+ \\
&\quad +\text{X8}\cdot(\text{X4}+\text{X7})+\text{X9}+\text{X12}+\text{X13}+\text{X10} \\
&= \text{X0}+\text{X3}\cdot\text{X4}+\text{X1}+\text{X2}\cdot\text{X5}\cdot\text{X6}+\text{X4}\cdot\text{X9}+ \\
&\quad +\text{X8}\cdot\text{X4}+\text{X8}\cdot\text{X7}+\text{X9}+\text{X11}+\text{X12}+\text{X10}
\end{aligned} \tag{2}$$

The minimum cut sets of ship collision events can be acquired based on Eq. 2: {X3, X4}, {X4, X8}, {X11}, {X5, X6, X2}, {X9}, {X10}, {X0}, {X1},{X7, X8}, {X12}

Basic event probability

The probability of a basic event means the frequency of a basic event leading to a ship collision accident in this paper. It is calculated by Eq. 3 based on the specific characteristics of ship collision accidents and traffic flow in estuarine waters.

$$q_i = \frac{N_i}{S} \tag{3}$$

where: q_i is the probability of a basic event, N_i is the number of ship collision accidents caused by basic event X_i, S is the annual volume of ship traffic flow in the area.

Ship collision probability

The probability of ship collision can be calculated by Eq. 4 based on Boolean algebra.

$$P_c = 1-(1-q_{\text{M1}})(1-q_{\text{M2}})(1-q_{\text{M3}})(1-q_{\text{M4}}) \tag{4}$$

were: P_c is the probability, q_{M1}, q_{M2}, q_{M3} and q_{M4} is the probability of M1, M2, M3 and M4 respectively.

The q_i is far less than 0.1 in this study because of the intense ship traffic increasing the value of S. Then Eq. 4 can be simplified into Eq. 5.

$$P_c \approx q_{\text{M1}} + q_{\text{M2}} + q_{\text{M3}} + q_{\text{M4}} \tag{5}$$

The probability of ship collision is the sum of the probability of minimum cut sets, and the Eq. 5 can be expressed by Eq. 6 based on Boolean algebra formula of ship collision fault tree.

$$\begin{aligned} P_{\text{collision}} &= P_0 + P_3\cdot P_4 + P_1 + P_2\cdot P_5\cdot P_6 + P_4\cdot P_9 + \\ &\quad + P_8\cdot P_4 + P_8\cdot P_7 + P_9 + P_{11} + P_{12} + P_{10} \end{aligned} \tag{6}$$

FTA model of ship grounding and contact damage

Based on the same principle of the ship collision FTA model, the probability calculation model for ship grounding and contact damage are built as shown in Figures 3 and 4. The definition of each of the fault tree's basic events are listed in Table 3. Since the fault tree for each category of accident is built separately, the code names for the accident cause in each fault tree are the same, which will not affect the calculation result.

As for the remaining categories of maritime accident, this paper utilized the frequency of them as the replacement of the probability. Thus the probability of maritime accident as calculated by Eq. 7.

$$\begin{aligned} P_{\text{Accident}} &= P_{\text{collision}} + P_{\text{grounding}} + P_{\text{contact\_damage}} + \\ &\quad + P_{\text{fire\_and\_explosion}} + P_{\text{sink}} + P_{\text{wind\_damage}} + P_{\text{others}} \end{aligned} \tag{7}$$

where $P_{\text{fire\_and\_explosion}}$ is the probability of fire and explosion, P_{sink} is the probability of sinking, $P_{\text{wind\_damage}}$ is the probability of wind damage, P_{others} is the probability of other accidents.

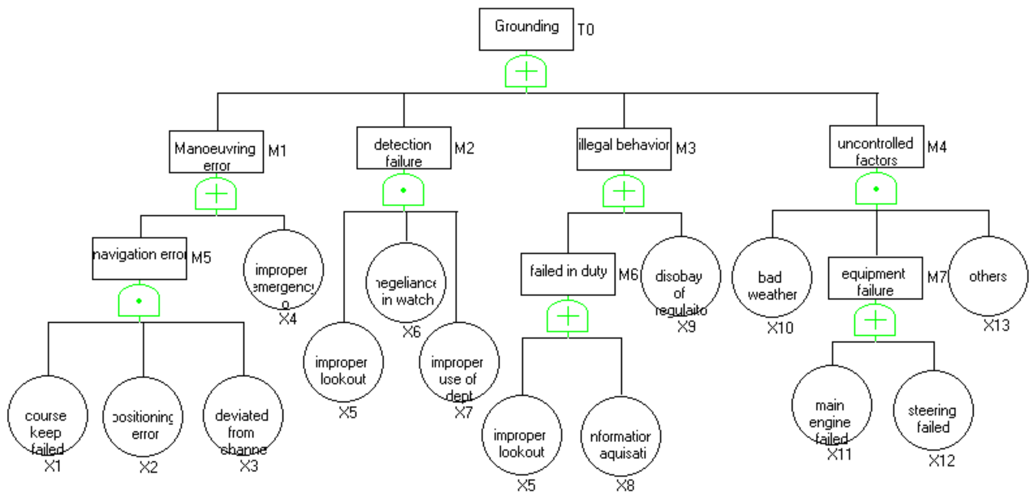

Figure 3. Fault tree of ship grounding accidents

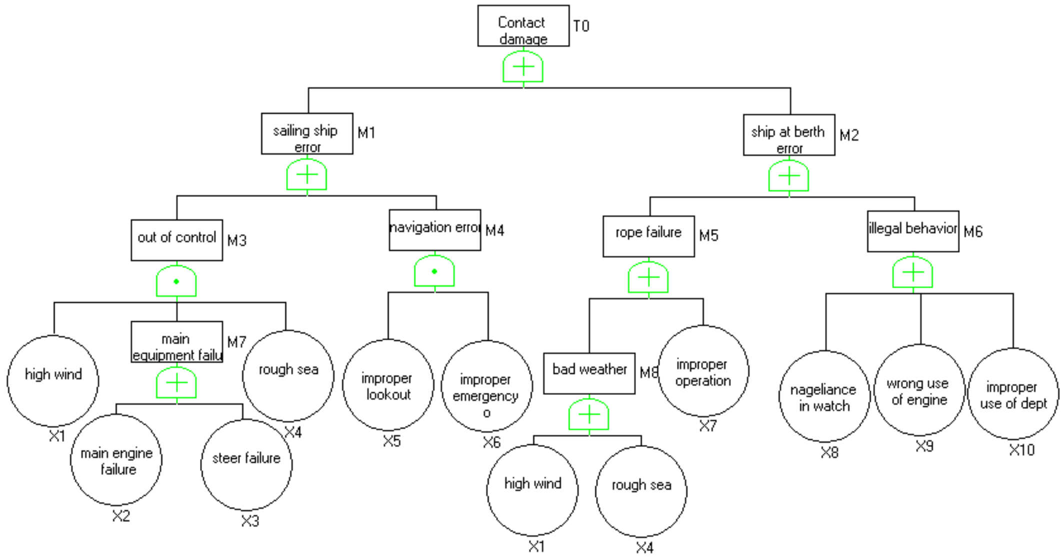

Figure 4. Fault tree of ship contact damage accidents

Table 3. Accident causes of grounding and contact damage

Code	Accident causes of grounding	Accident causes of contact damage
X1	Course keeping failed	High wind
X2	Positioning error	Main engine failure
X3	Deviated from channel	Steer failure
X4	Improper emergency operation	Rough sea
X5	Improper lookout	Improper lookout
X6	Negligence in watch keeping	Improper emergency operation
X7	Improper use of depth gauge	Improper operation
X8	Information acquisition error	Negligence in watch keeping
X9	Contravening regulations	Contravening regulations
X10	Bad weather	Improper use of depth gauge
X11	Main engine failed	
X12	Steering failed	
X13	Others	

Case study

Research area

In this paper, Shenzhen waters were chosen as the study area. Located in the eastern estuary of Pearl River, this area is one of the most developed regions in water transportation and the economy of China. As Figure 5 shows, during 2003 and 2012 the level of ship traffic (number of ships entering and leaving port) witnessed continuous growth. Due to its unique geographic location, complicated environment and intense ship traffic, however, the risk of maritime accident is high for ships that navigate here.

Maritime accident data

The data for maritime accidents this paper analyzed are collected from Shenzhen Maritime Safety Administration (MSA) within which there are 185 cases of maritime accident reported to the MSA, among which ship collision, grounding and contact damage represent the major proportion (42.16%, 11.89% and 18.37% respectively). During the decade, as Figure 6 and 7 indicate, the number of all categories of accident and their consequences witnessed a decline, while the economic loss is still high. This paper also plotted all the locations of the accidents on a chart. According to Figure 8, the number of accidents which happened in the western area of Shenzhen waters is much higher than that

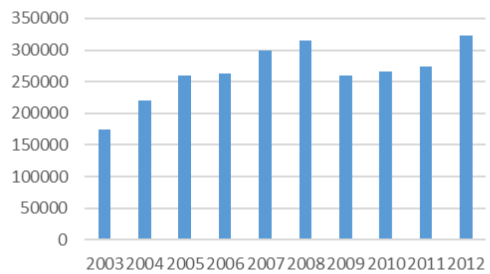

Figure 5. Ship traffic in Shenzhen waters from 2003 to 2012

Figure 6. Accident statistics of Shenzhen waters

in the eastern area. This is mainly related to the volume of ship traffic (83.8% of ship traffic is in the western area of Shenzhen waters).

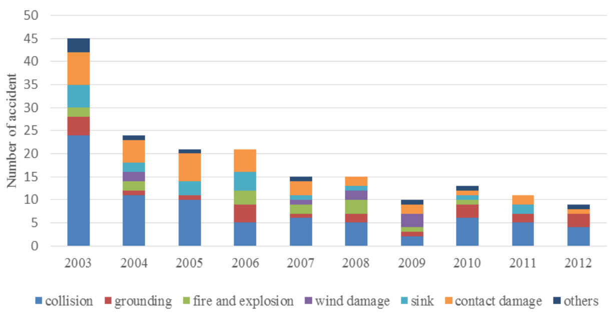

Figure 7. Number of accidents in different categories

Figure 8. Geographical distribution of accidents in Shenzhen waters

Results of consequence model

Data for parameter learning of the Bayesian network was extracted from the accident database and discretized according to the standard proposed in Table 2. Since the information about weather and the sea condition of the area when the accident happened is insufficient in the accident investigation report, historical data from Guangdong Meteorological Observatory was supplemented. Once the data was discretized, the parameter learning of the consequence model was performed using Genie 2.0 software with Expectation Maximization (EM) algorithm. After this step CPTs for each node were obtained and the probability of an accident falling into a certain level of consequence was calculated. As we can see from Figure 9, the probability of an accident falling into minor, major, critical and catastrophic accident are 0.82415, 0.0992, 0.05803, and 0.0186 respectively.

Results of accident probability

As section 2.2 described, this paper utilizes a FTA method to calculate the accident probability of ship collision, grounding and contact damage. The probability of other categories of accident are replaced by their frequency over recent years.

Data from 2003 to 2012 are analyzed to calculate the probability. The accident cause and the number of related collision, grounding and contact damage accidents are obtained by analyzing the accident investigation report, and Table 3 shows the number of collision related accidents as an example. From the table we can see that human error is still the main influencing factor in maritime accidents.

Traffic flow information in this paper is estimated by using the number of ships entering and leaving port, and is shown in Table 4. Based on the

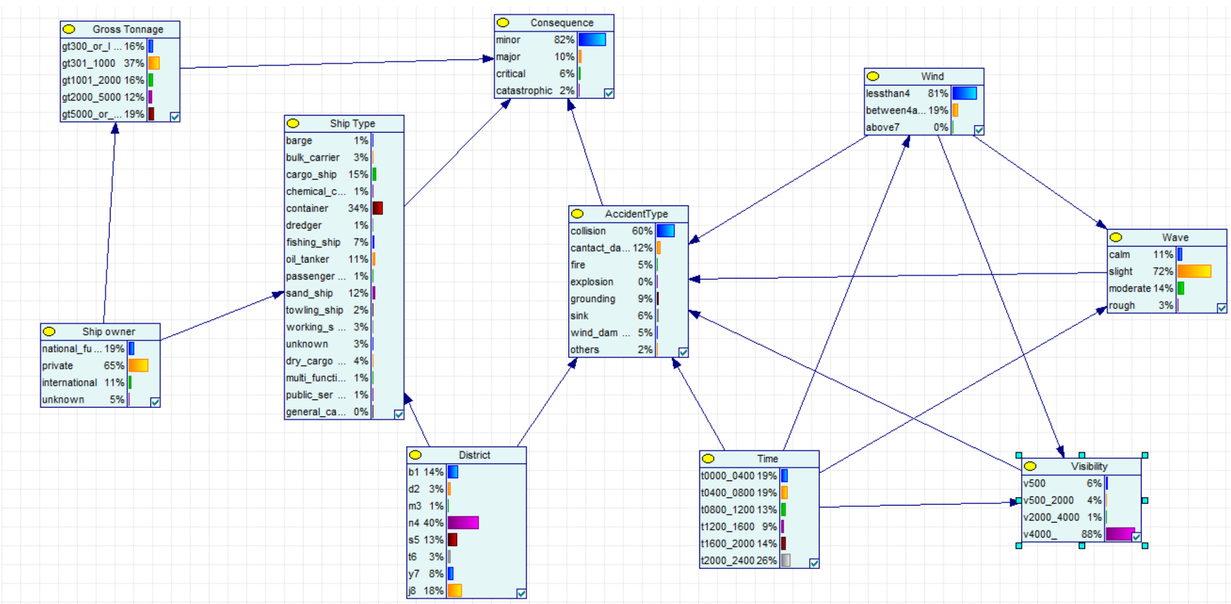

Figure 9. Results of the consequence model

Table 4. Causes and accident incidence from 2003 to 2012

Accident cause	Code	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Negligence in watch keeping	X0	6	5	4	3	2	2	1	4	4	2
Wrong assessment of situation	X1	11	5	2	2	4	3	2	3	2	3
Improper emergency operation	X2	21	4	3	4	4	4	1	2	3	2
Improper steering operation	X3	8	5	1	1	3	2	1	1	0	0
Improper lookout	X4	16	9	5	3	6	5	0	3	5	4
Uncoordinated avoiding operation	X5	10	5	3	1	3	4	1	2	3	2
Improper avoiding operation	X6	12	4	3	0	4	1	1	1	3	2
Deviated from channel	X7	0	0	0	0	0	0	0	0	0	0
Unused safety speed	X8	10	3	4	2	4	2	1	2	2	3
Poor visibility	X9	4	1	2	0	1	0	0	0	3	1
Rough sea	X10	2	1	0	2	1	0	0	0	0	1
Main engine failed	X11	0	0	0	0	0	0	0	0	0	0
Steering failed	X12	1	0	1	0	0	0	0	0	0	0

Table 5. Probability of maritime accidents

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Probability	3.22E–04	1.41E–04	1.08E–04	9.89E–05	7.03E–05	6.35E–05	6.54E–05	7.51E–05	6.88E–05	6.81E–05

statistics of accidents and traffic flow data, the probability of ship collision, contact damage and grounding are calculated by Eq. 3 and Eq 5. The probability of maritime accidents is obtained by using Eq. 6, which is shown in Table 4.

Calculation of maritime accident risk

The risk of maritime accidents in the study area is expressed as the probability of consequences, which is calculated via multiplying the probability of the accident and the probability of the accident falling into certain level of consequence. The result is shown in Table 6 and Figure 10. We can see that the risk level of the study area generally declined during the period, while the probability of catastrophic accident still remains in the same order of magnitude. To verify if the risk level is high enough to take measures to reduce it, this paper compared the result with the risk pre-warning value of Shenzhen waters which Mou et al. (2008) proposed. According to the pre-warning value, the number of minor, major, critical and catastrophic accidents should be controlled to under 20/year, 10/year, 5/year and 1–2/year respectively. Comparing the number of accidents calculated by multiplying the probability of each level of accident and the volume of ship traffic in each year, we can see that all the risk levels are lower than the control value. In the meantime, the number of accidents in each level of consequence from the historical data is also lower than the pre-warning value, which means that the outcome of this model is effective.

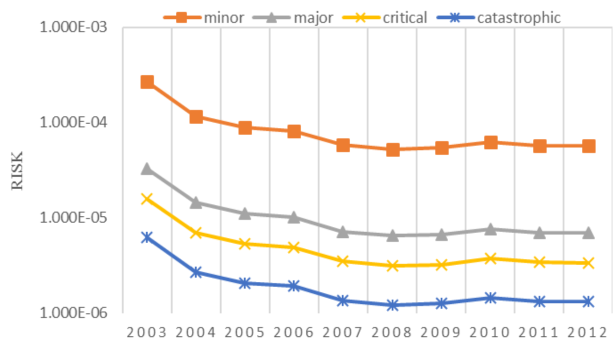

Figure 10. Statistics of maritime risk in Shenzhen waters

Table 6. Risk of maritime accident in Shenzhen waters

Level of consequence	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Minor	2.67E–04	1.17E–04	8.92E–05	8.20E–05	5.83E–05	5.26E–05	5.42E–05	6.23E–05	5.70E–05	5.64E–05
Major	3.29E–05	1.44E–05	1.10E–05	1.01E–05	7.19E–06	650E–06	6.69E–06	7.69E–06	7.04E–06	6.97E–06
Critical	1.59E–05	6.96E–06	5.32E–06	4.89E–06	3.47E–06	3.14E–06	3.23E–06	3.71E–06	3.40E–06	3.36E–06
Catastrophic	6.20E–06	2.72E–06	2.08E–06	1.91E–06	1.36E–06	1.22E–06	1.26E–06	1.45E–06	1.32E–06	1.31E–06

Conclusions and discussion

In this paper, a brief model of maritime accident risk analysis in an estuary was proposed. First a consequence model to calculate the probability of an accident falling into a certain level of consequence was established by using a Bayesian network. The CPTs of the model were obtained by using parameter learning function to extract information from the historical data. Then the probability of an accident was calculated with the application of FTA methodology, and finally the risk of maritime accident was obtained. For the case study, historical accident data over 10 years in Shenzhen waters was collected and analyzed. According to the calculation, the maritime accident risk in Shenzhen waters is lower than the pre-warning value and witnessed a continuous decline during the period.

However, there are still many aspects of this paper which need to be improved. Firstly, validation of the consequence model was not performed. As aforementioned in the paper, the structure of the consequence model was established by the author with the help of some experts in the field. This might cause bias during the procedure. Secondly, due to the small scale of the data set it is difficult to build a proper fault tree to calculate the probability of an accident such as sinking, wind damage, fire and explosion, and this means the probability of accident calculated by the second part of the risk analysis model is higher than the historical data. In the further study the uncertainty and bias of data will be analyzed and the accuracy of the model will be improved with an optimized structure.

Acknowledgments

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