Study on Pollution Risk Index Based on ESI and Stochastic Simulation

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Abstract. A calculation method of the risk index of oil spill pollution is presented, and main factors are considered in the method, such as the shoreline environmental sensitivity index $ESI$, the environmental sensitivity index $SI$, the statistical probability of the pollution, and the minimum time to be polluted. After 600 stochastic simulations of oil spill trajectory and fates model, the calculation of the pollution probability is carried out for the probability of the pollution to each segment of the shoreline and the minimum time to be polluted. The $ESI$ and $SI$ indexes, which indicate the shoreline environmental sensitivity, are determined by satellite image analysis, field investigation, data investigation and so on. The calculation method can be applied to the risk assessment of the oil spill accident with environmental conditions not determined, and provide the basis for the emergency preparedness and planning for the oil spill accident. The method was applied in Jiaozhou Bay, and the changes of the risk index along the shoreline was analyzed.

1. Introduction
The ship oil spill accident is one of the major sudden environmental pollution accidents on the sea. In the world, a tanker accident with leakage above ten thousand tons is to occur almost every year \cite{1}. The amount of oil pollutants entering the sea as a result of oil spill accidents is about 390000 tons per year \cite{2}. In the oil spill accident, the leaked oil pollutants drift on the water surface with the action of tide and wind, causing serious ecological and environmental impact on the shoreline and surrounding sensitive resources under adverse environmental conditions, as well as negative social impact. The oil spill fate and pollution consequences are significantly different for various shoreline types, and the shoreline type also determines different decontamination measures. Therefore, the $ESI$ and $SI$ indexes of each segment of shoreline play an important role in the affected degree of sensitive resources and subsequent decontamination in the emergency response of oil spill accidents.

2. Calculation method of pollution risk index
2.1. Oil spill pollution risk index
The risk of oil spill pollution refers to the pollution risk of marine environment caused by sudden oil spill accidents in the course of the ship navigation and operation, represented by risk index $R$. The risk index $R$ is the product of accident probability $P$ and environmental hazard consequence $C$ caused by the accident \cite{3}, that is, $R=P\times C$. The pollution from oil spill accidents to marine environment is
mainly reflected in the pollution degree of shoreline resources. The higher the environmental sensitivity index of shoreline, the greater the harm caused by oil spill accident. The pollution probability of a certain segment of shoreline is predicted by statistics of stochastic simulations with oil spill trajectory and fates model. In addition, the risk degree is closely related to the arrival time of pollutants, and the shorter the arrival time, the higher the pollution risk. Therefore, the calculation method of oil spill pollution risk index is proposed in this study, based on shoreline environmental sensitivity index $ESI$ and $SI$ and pollution probability, shown in (1).

$$R = \frac{P \times (ESI_{10} \times SI_{50}) \times T_{max}}{T_{min}}$$

Where $P$ is pollution probability of a certain segment of shoreline, in %; $ESI$ is shoreline environmental sensitivity index of a certain segment of shoreline, with a value of 1 to 10; $SI$ is environmental sensitivity index of a certain segment of shoreline, with a value of 0 to 50; $T_{min}$ is the minimum time to be polluted, in h; $T_{max}$ is the maximum time of single oil spill drift simulation, in h.

The risk index $R$ of each segment of shoreline potentially polluted, calculated by (1), can be used to rank the pollution risk of objectives, providing decision support for the emergency response of oil spill.

2.2. Probability of pollution

The oil spill trajectory and fates are calculated by the oil spill trajectory and fates model through the input spillage, leakage type, accident location, leakage time and other environmental datum, such as winds and currents. The drift of oil spill pollutants on the water surface is affected by winds and currents at that time. The pollutants drift trajectories under different wind speeds, wind directions, flow velocity and tide fluctuation are quite different. In order to eliminate the randomness of the single simulation results, it is necessary to use the stochastic simulating method to determine the probability of pollution of the environmental sensitive resources around the spill site.

In the stochastic simulation, the oil spill trajectory and fates model simulates the drift fates of hundreds of combined stochastic scenarios at each leakage site. And the occurrence time of each accident scenario is uncertain. The time series of wind direction, wind speed and currents datum in the past years are randomly selected. The arrival time and the amount of oil pollutants in each segment of shoreline are calculated and recorded in each simulation, and then the statistical analysis results are obtained.

For each spill location, no less than 600 stochastic simulations are generally carried out. The pollution probability $P$ is the ratio of the number of scenarios where the segment of shoreline is polluted to the total number of simulated scenarios. The minimum time to be polluted $T_{min}$ is the minimum time for pollutants to drift from the leakage site to the shoreline segment in all simulated scenarios [4].

2.3. Shoreline environmental sensitivity index

Shoreline environmental sensitivity index ($ESI$) is a shoreline sensitivity index developed by NOAA Toxic Substances Response Assessment Office for the making of oil spill emergency response sensitive maps along the coast of the United States and the Great Lakes region. The first environmental sensitivity index map was born a few days before the IXTOC 1 oil well leakage accident in the Gulf of Mexico in 1979 [5]. Since then, the environmental sensitivity index map has become an indispensable part of oil spill emergency planning and emergency response in the United States. The atlas of the environmental sensitivity index map covers most of the shoreline of the United States, including that of Alaska and the Great Lakes. The environmental sensitivity index map includes three types of information: shoreline category, biological resources and human activity resources. In principle, the $ESI$ index used for shoreline environmental sensitivity classification divides the shoreline into 10 classes, that is, $ESI$ sensibility increases gradually from class 1 to class 10. And different $ESI$ classes represent different shoreline categories.
3. Study on the risk of oil spill in Jiaozhou Bay

3.1. General situation of Jiaozhou Bay
The cargo throughput in Qingdao Port, located in Jiaozhou Bay, exceeded 510 million tons in 2017. Qingdao Port is also one of the largest and most advanced oil transit ports in China. In 2017, the comprehensive throughput of oil products exceeded 100 million tons, and has shown a sustained growth momentum. At present, most of the large oil terminals in Qingdao Port are distributed just inside Jiaozhou Bay. Oil transportation ships need to pass through Jiaozhou Bay mouth, and many tankers enter and leave Jiaozhou Bay every year. With the construction of Jiaozhou Bay and its nearby shoreline port wharves, the expansion of navigation capacity of waterway and the increase of tonnage of oil terminals, it is bound to increase the risk of oil spill accident in Jiaozhou Bay and the inshore area outside Jiaozhou Bay mouth [6].

Near the shorelines of Jiaozhou Bay and outside its mouth, there are many nature reserves, wetland reserves and fishery areas which play an important role in balancing the ecological environment of the sea area. Once the oil spill accident occurs, it will cause unrecoverable damage to sensitive resources. Moreover, once tourist resorts, Olympic venues, scenic spots and the Qingdao city shoreline are polluted by a major oil spill, the tourist environment would be seriously damaged in addition to the direct damage to sensitive resources. For example, in 1983, the Panamanian tanker "Oriental Ambassador" ran aground on the Zhongsha Reef in Jiaozhou Bay on its way out of port. After the hull was damaged, the crude oil leaked 3343.6t, polluting the 230 km shoreline, 905000 m² of beach and reef, 66000 m² of bathing beach, 15000 mu of kelp, mussel, mixed color clam and other aquaculture areas. And 190 million kelp seedlings were destroyed. The pollution loss reached more than 28 million yuan in that time.

3.2. Establishment of ESI Index of Jiaozhou Bay shoreline
In this study, the shoreline of Jiaozhou Bay was investigated by means of field investigation and data collection, and the shoreline was divided into segments with WorldView satellite image with resolution 0.5m. On the basis of segmentation, the attribute parameters of each segment of shoreline are filled in, including ID, name, position, length, water function, shore function, sediment quality, slope, shape and structure, energy, value, sensitive time, $ESI$, $SI$, $PI$, contact, telephone and remarks, etc. After data analysis and collation, 265.5km shoreline of Jiaozhou Bay and its surrounding is divided into 343 segments and assigned attribute parameters [7], shown in Figure 1.

![Figure 1. Segment map of Jiaozhou Bay shoreline](image)

In this study, $ESI$ and $SI$ parameters of each segment of shoreline are used in the calculation of pollution risk index.
3.3. Prediction of oil spill pollution probability in Jiaozhou Bay

In this study, it was assumed that there was an oil spill accident in the front waters of the oil wharf inside Jiaozhou Bay mouth. 600 stochastic simulations were carried out by using the oil spill trajectory and fates model. The leakage of a single simulation was assumed as 500t and the simulation time was 72h. The pollution probability statistics and the minimum time to be polluted of each segment of shoreline were obtained through stochastic simulations. The probability contours of sea area pollution is shown in Figure 2. According to the pollution probability of the sea area, the pollution probability of the northern shoreline was about 10%, and that of the eastern and western shorelines of the accident location were about 50%. The minimum time to be polluted for each segment of the shoreline was less than 16 hours.

![Figure 2. Distribution map of pollution probability](image)

3.4. Analysis of oil spill pollution risk index in Jiaozhou Bay

It can be seen from the stochastic simulation that the affected shoreline was mainly concentrated near both sides inside and outside the mouth after the pollution accident occurs in the Jiaozhou Bay mouth. The calculation results from the pollution risk index (formula 1) are shown in Table 1.

| No | Risk index range | Number of shoreline segments | Total length of shoreline (km) | Proportion of the total length of the shoreline (%) |
|----|------------------|------------------------------|-------------------------------|-----------------------------------------------|
| 1  | 2.0<R≤2.3        | 5                            | 5.29                          | 1.99%                                         |
| 2  | 1.5<R≤2.0        | 4                            | 1.26                          | 0.47%                                         |
| 3  | 1.0<R≤1.5        | 8                            | 2.84                          | 1.07%                                         |
| 4  | 0.5<R≤1.0        | 34                           | 31.06                         | 11.70%                                        |
| 5  | 0.1<R≤0.5        | 118                          | 91.25                         | 34.36%                                        |
| 6  | 0<R≤0.1          | 137                          | 110.63                        | 41.66%                                        |
| 7  | R=0              | 37                           | 23.21                         | 8.74%                                         |

From the calculation results, it can be seen that because it was assumed that the oil spill accident occurs within the mouth of Jiaozhou Bay, the southern shoreline of Jiaozhou Bay mouth was almost unaffected, and the most affected area was the shoreline on both sides of the accident location, followed by the northwest shoreline in Jiaozhou Bay mouth. According to the statistical results of pollution risk $R$ value, the shoreline with $R$ value above 0.5 is 40.5 km long, accounting for 15.23% of the total shoreline length; the shoreline with $R$ value between 0.1 and 0.5 is 91.25km long, accounting for 34.36% of the total shoreline length; and the shoreline with $R$ value between 0 and 0.1 is 110.63 km long, accounting for 41.66% of the total shoreline length. The risk index $R$ value distribution map of segments of shoreline is shown in Figure 3.
4. Conclusions and prospects
In the risk assessment of oil spill emergency pollution, the typical scene simulation method is usually used to predict and evaluate the consequences of oil spill accident. Because of the complexity of the environmental conditions of the accident site, the typical scene simulation method is only suitable for the oil spill accident scene with determined environmental conditions, and the evaluation results are often uncertain. In this paper, a calculation method for analyzing the risk index of oil spill pollution is put forward, and the possibility of oil spill pollution on the shoreline, the characteristics of the shoreline, the environmental sensitivity of the shoreline and the minimum time for the shoreline to be polluted are comprehensively considered. The calculation method can be applied to the scene of oil spill accident with irregular environmental conditions.

In the practical application, several possible oil spill accident locations should be randomly simulated by means of the calculation method of oil spill pollution risk index in this paper. The calculation results of probability and the minimum time to be polluted should be added and the pollution risk index of each segment of shoreline should be calculated. The calculation method of oil spill risk index can be applied to the assessment of oil spill accident, and used to make the oil spill preparedness contingency plan more feasible.

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