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Research on the risk-based model for regional emergency resource allocation for ship-source oil spill

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Abstract
The key point for rational allocation of emergency resources is to match the oil spill response capacity with the risk of oil spill. This paper proposes an innovative risk-based model for quantitative regional emergency resource allocation, which comprehensively analyzes the factors such as oil spill probability, hazard consequences, oil properties, weathering process and operation efficiency, etc. The model calculates three major resources, i.e., mechanical recovery, dispersion and absorption, according to the results of risk assessment. In a field application in Xiaohu Port, Guangzhou, China, and the model achieved scientific and rational allocation of emergency resources by matching the assessed risk with the regional capacity, and allocating emergency resources according to capability target. The model is considered to be beneficial to enhancing the resource efficiency and may contribute to the planning of capacity-building programs in high-risk areas.

Key words: oil spill risk, oil spill quantity, probability, emergency capability

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1 Introduction

Rapid development of China's maritime transportation is witnessed by the continuous increase of ships navigating in China's coastal waters, and is accompanied by the increasing risk of ship-source oil spill accidents. From 1973 to 2017, 157 ship-source oil spill accidents (spillage over 10 tons) occurred along China's coasts, and the majority of the spills occurred in the waters near ports. To address the increasing risk, matters with regard to the overall oil spill response capacity, the balance of capacity among different areas, and scientific allocation of emergency resources, have drawn increasing concern of competent authorities and the public.

To achieve scientific response to ship-source oil spill accidents, it is essential to conduct risk assessment and to allocate emergency resources accordingly, as highly valued by experts around the world. For the assessment of risk of ship-source oil spill accidents, tools including stochastic theory, fuzzy mathematics, probability theory, statistics, oil spill dynamics, event trees, etc., were applied (Devanney, 1974; DNV, 2000, 2011; Frate et al., 2000; Udoh and Ekanem, 2011; Lee and Jung, 2013; Akhtar et al., 2012; Montewka et al., 2010a; Pedersen, 2010; Van Dorp and Merrick, 2011; Goerlandt and Montewka, 2015, Xiao, 2001; Li, 2000; Jin, 2006; Xu and Li, 2005; Xi, 2009; Ren et al., 2000; Deng et al., 2011; Lan et al., 2014; Jiang, 2015; Gao, 2015; Wang et al., 2016; Wu, 2017; Sun and Cao, 2018), qualitative, semi-quantitative and quantitative assessment models were established (Curtis, 1986; Tan and Otay, 1999; Fowler and Sørgard, 2000; Trucco et al., 2008; Gucma and Przywarty, 2008; Geng et al., 2009; Montewka et al., 2010b; Li et al., 2012; Xu, 2017). There are also related computer software systems (TRB, 2001; Friis-Hansen and Simonsen, 2002; An et al., 2010) for risk assessment by analyzing the probability of oil spill accidents and their hazardous consequences. With regard to the allocation of oil spill response resources, current research is mainly based on the scenario analysis method, i.e., allocating emergency resources for oil recovery, containment, adsorption, dispersion, etc., according to the oil spill accident with certain spillage quantity (Verma et al., 2013; Ha, 2018; Zhang, 2013). However, there are few researches focusing on regional emergency resource allocation (Wei and Geng, 2013; Ding, 2015). At present, the allocation of emergency resource allocation mainly refers to the standard promulgated in 2009 the Requirements on Emergency Response Equipment/Facilities for Oil Spill in Wharfs in Ports (hereinafter referred to as "the Standard").

The regional ship-source oil spill response capability is the overall capacity of the units within the region, in terms of responding to oil spill accidents with their resources. Although it is a principle for the allocation of emergency resources to match the capability of each unit in the region with their respective risk, current study fails to provide solution to this issue, as: (1) quantitative relationship is only established between the quantity of oil spill and the capacity of preparedness, while the probability of oil spill accidents and the hazardous consequences are not taken into account; (2) current requirement on oil spill response capacity of ports does not take into account the joint response capacity of wharfs, and may cause over-equipping of emergency resources; (3) sea condition, equipment efficiency, oil characteristics are not

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reasonably considered in terms of the response methods including mechanical recovery, absorption, dispersion. Based on risk assessment of ship-source oil spill accident, this paper provided a risk index based on the probability of oil spill and its hazard consequences, set up a preparedness target allocation method for each wharf in the port area based on the risk index, and proposed a method on allocating oil spill response resources that should be equipped by each wharf, establishing a regional emergency resource allocation model based on the risk of ship-source oil spill. This method can be applied to the emergency resource allocation for individual wharf in the port, for individual port in an area, and for individual areas in a country.

2 Modeling

2.1 *The oil spill risk index model*

The oil spill risk assessment based on the probability and hazardous consequences of accidents is a semi-quantitative method. During the assessment process, the calculated risk value is compared with the pre-established criteria to determine the risk level, i.e., high, medium or low risks. The calculation formula (HSC, 1991) is

$$R = P \times C, \tag{1}$$

where R is the risk value; P is the probability of accidents; C is the hazardous consequences of accidents.

This paper establishes a quantitative oil spill risk index method that comprehensively considers key factors such as probability of accident, oil spill quantity, sensitivity coefficient of sensitive resources, and probability of oil spill impact. The calculation formula is as follows:

$$R = Pc \times \frac{Cc}{a}, \tag{2}$$

where R is oil spill risk index; Pc is oil spill accident probability index; Cc is oil spill hazardous consequence index; a is risk grading constant. The value of the risk grading constant for oil spill of ships is 5 (IMO, 2002, 2008; Ministry of Communications and Transportation of People's Republic of China, 2017).

$$Pc = \lg P + 5, \tag{3}$$

where P is oil spill accident probability, obtained through statistical analysis; Pc is a value greater than 0. That is, the probability of accident P should not be less than 10^{-5}. If the return period of accident is 100 000 years, the risk would be considered negligible.

$$Cc = \lg A + \frac{\left[\max(Pi \times Si) + \left(\sum Pi \times Si\right)/n\right]}{2}, \tag{4}$$

where Cc is comprehensive hazardous consequence index; A is the oil spill quantity of the largest oil spill accident in the area (ton) (IMO, 2002); Pi is the probability that sensitive target (i) would be affected, predicted through the stochastic simulation statistics method; Si is sensitive coefficient of sensitive protection target (i) (IMO, 2002); n is the number of sensitive resources affected; max is the maximum value.

2.2 *The oil spill response capacity target allocation model of each unit*

The response capacity target is allocated according to the results of regional oil spill risk assessment and the proportion of risk preparedness responsibilities. The calculation formula is

$$Wi = W \times \frac{Ri}{\sum_{i=1}^{n} Ri}, \tag{5}$$

where Wi is the response capability target of unit i (t); W is regional emergency response target (t), the maximum value of the possibly largest oil spill accident of each unit in the area; Ri is oil spill risk index of unit i; $\sum$ means summation.

2.3 *The oil spill response resources allocation model of each unit*

The oil spill response capability mainly refers to the mechanical recovery capacity of oil skimmers, the dispersion capacity of dispersants, and the adsorption capacity of sorbent materials. As the response capability target of each unit in the area is determined, the quantity of response resources needs to be determined.

The emergency resource allocation calculation model of recovery, dispersion and adsorption is established by comprehensively considering the types and characteristics of emergency resources, on-site operating environment, operation time, features and weathering process of oil, etc.

The calculation formula of the recovery capacity is

$$R_e = \frac{W \times (1 - r_v - r_s) \times E \times P_1}{\rho \times \alpha \times t}, \tag{6}$$

where R_e is the recovery rate of oil skimmers (m^3/h), which refers to the quantity of oil and water recovered by oil skimmers per hour; W is the oil spill quantity according to the emergency response target (t); r_v is the evaporation rate of spilled oil on the water surface (%); r_s is the dissolution rate of spilled oil in water (%); E is the emulsification rate of spilled oil in water (%); P_1 is the proportion of oil recovered by machinery in the process of oil spill removal (%); ρ is the density of oil and water mixture recovered (t/m^3); α is the efficiency of oil skimmers (%), which refers to the proportion of the actual oil recovery rate to the labeled oil recovery rate; t is the time of response operation (h), which is subject to the emergency plan and can be adjusted according to the scale of accidents.

The calculation formula of the dispersion capacity is

$$G = W \times (1 - r_v - r_s) \times 10^3 \times P_2 \times \gamma, \tag{7}$$

where G is the quantity of oil dispersants (kg); W is the oil spill quantity identified according to the emergency response target (t); r_v is the evaporation rate of spilled oil on the water surface (%); r_s is the dissolution rate of spilled oil in water (%); P_2 is the proportion oil dispersed with chemical dispersant (%); γ is the ratio of dispersants and oil.

The calculation formula of the adsorption capacity is

$$I = \frac{W \times (1 - r_v - r_s) \times P_3}{J \times K \times \varphi}, \tag{8}$$

where I is the quantity of absorption materials (t); W is the quantity of oil spilled determined according to the regional emergency capacity target (t); r_v is the evaporation rate of spilled oil on the water surface (%); r_s is the dissolution rate of spilled oil in water (%); P_3 is the proportion of oil absorbed by adsorption materials (%); J is the adsorption multiple; K is the oil retention rate (%); φ

is the adsorption efficiency (%).

As the length of oil booms is mainly determined by the size of ships and berths, it is not necessary for this paper to provide a specific calculation formula.

3 Model application and discussion

3.1 *Calculation results*

Xiaohu Port area in Nansha Port, Guangzhou has 5 adjacent petrochemical wharfs, i.e., Guangzhou Xiaohu Petrochemical, Sinopec Xiaohu, Guangdong Petrochemical, Gangfa Petrochemical and Kingboard Petrochemical, as shown in Fig. 1. The port is visited by over 3 000 ships per year and the annual throughput of oil and chemical is about 9 million tons. Adjacent to several environmental sensitive areas, the port has a high risk of ship-source oil spill accidents.

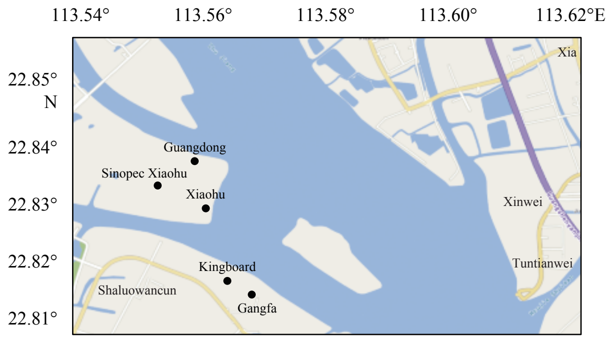

Fig. 1. Location of petrochemical wharfs in Xiaohu Port area, Guangzhou Port.

The probability of oil spill accidents at the wharfs is calculated by the number of accidents and the number of ships entering and leaving the port. The maximum possible oil spill quantity is calculated based on the scenario where a wing cargo tank of oil tanker (1 000–3 000 DWT, common tanker in the port) completely spilled. And the probability of affecting adjacent sensitive area is predicted according to the random scenario numerical simulation method. The oil spill risk of each wharf is calculated according to Eqs (2)–(4) and shown in Table 1. The data of accident probability, possible maximum oil spill quantity, and sensitive coefficient are all from *The Report on Environmental Risk Assessment of Ship-source Pollution in Joint Defense of Xiaohu, Guangzhou*. And the response capacity target and resource allocation results of each wharf are calculated according to Eqs (5)–(8) and shown in Table 2.

3.2 *Discussion*

3.2.1 *Comparison of risk index assessment results*

The purpose of regional oil spill risk assessment is to determine the relative risk of each risk source and take preventive measures based on the risk of different areas. The results of oil spill risk assessment for wharfs in Xiaohu Port area is achieved with the risk matrix method as shown in Fig. 2. It can be seen that all wharfs fall into the medium risk area using the accident probability and oil spill quantity as indicators (Fig. 2a) and there is almost no difference among them. 4 wharfs fall into the high risk area and 1 wharf the medium risk area using the accident probability and hazardous consequence index as indicators (Fig. 2b). There is also no obvious difference among the 5 wharfs. If the oil spill risk index (Table 1) is chosen as an assessment indicator, the risk index of wharfs in Xiaohu Port area is greater than 4, indicating high risk. And the risk index of three wharfs - Sinopec Xiaohu, Guangdong and Gangfa Petrochemical, ranges from 3 to 4, indicating medium risk, with obvious difference among them. Kingboard's risk index is less than 3, indicating low risk.

According to the oil spill risk index of each wharf, the risk ranking (high to low) is Xiaohu Petrochemical, Sinopec Xiaohu, Guangdong, Gangfa and Kingboard. Therefore, the oil spill risk index method is more suitable for regional oil spill risk assessment.

3.2.2 *Selection of model parameter*

A number of parameters are involved in the oil spill response resource allocation model and the values of these parameters are related to the characteristics and changes of oil spill, the performance of emergency resources, on-site environmental conditions, etc. Therefore, the values of parameters should be rationally determined case-by-case, and existing standards, product performance indicators, experiment results and empirical values are advised to be referred to.

Table 1. Analysis results of ship-source oil spill risk at wharfs

Name of wharf	Accident probability/a^{-1}	Possible maximum oil spill quantity/t	Sensitive area impact index	Accident probability index	Hazardous consequence index	Oil spill risk index	Risk ranking
Xiaohu	0.067	400	3.28	3.83	5.88	4.50	high
Sinopec Xiaohu	0.045	120	3.20	3.65	5.28	3.86	medium
Guangdong	0.032	250	2.75	3.51	5.15	3.61	medium
Gangfa	0.016	250	2.76	3.20	5.16	3.31	medium
Kingboard	0.009 6	120	2.66	2.98	4.74	2.82	low

Table 2. Calculation results of response capacity targets and resource allocation at wharfs

Name of terminal	Maximum berthing capacity/DWT	Emergency capacity target/t	Mechanical recovery capacity/$m^3 \cdot h^{-1}$	Chemical dispersion capacity/t	Adsorptive capacity/t
Xiaohu	120 000	99.42	54.11	4.38	3.65
Sinopec Xiaohu	80 000	85.27	46.41	3.76	3.13
Guangdong	45 000	79.78	43.42	3.52	2.93
Gangfa	100 000	73.10	39.79	3.22	2.69
Kingboard	50 000	62.44	33.98	2.75	2.29
Total		400	217.71	17.63	12.24

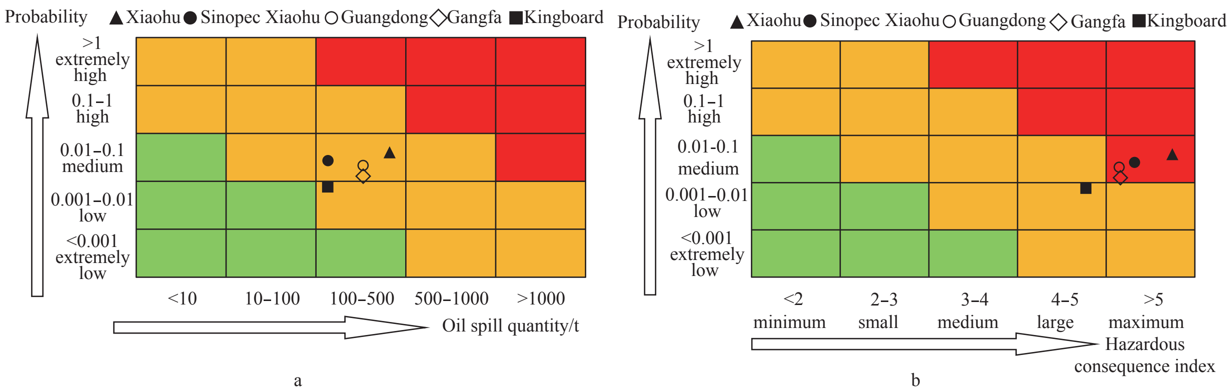

Fig. 2. Oil spill risk matrix of wharfs at Xiaohu Port area, matrix of oil spill quantity and probability (a), matrix of hazardous consequence index and probability (b).

In the case of Xiaohu Port area, the response operation is assumed to start 48 hours after the spill. Oil spill prediction software developed by Anwei, etc., is applied where wind speed is set to be 10 m/s and water temperature 20°C. The simulated evaporation rate of spilled fuel oil r_v is 26% (An et al., 2010) in 48 hours and the dissolution rate r_s is about 0.52% (Yang et al., 1994) in 48 hours. The emulsification rate E is 2 (CFR, 2011), the proportion of mechanical recovery P_1, the dispersion P_2 and oil absorbed P_3 is defined to be 60%, 30% and 10%, respectively, according to the experience from the Deepwater Horizon oil spill (USCG, 2011) and from China's oil spill accident response (China MSA, 2004). The on-site operation time is 12 hours in 2 days, and the skimmer efficiency α and the adsorption efficiency φ is defined to be 15% and 25%, respectively (Chen et al., 2011; Gowtham et al., 2016). For the ratio of concentrated oil spill dispersants and oil, the upper limit of 0.2 is taken according to *Guidelines on the Assessment of Ship-source Oil Spill Response Capability* (hereinafter referred to as "Guidelines") (Ministry of Communications and Transportation of People's Republic of China, 2014). As for the adsorption time of sorbent materials J and the oil retention rate K, the lower limit of 10 and 8% is taken according to the *Sorbents for Ship* (JT/T560-2004). The values of parameters are shown in Table 3.

3.2.3 *Comparison of modeling results*

The comparison of emergency capability target and resource allocation results calculated according to the proposed model and the Standard is shown in Table 4. The proposed model provided that the overall target of emergency response capacity is 400 t, while the result provided by the Standard is the sum of the emergency capacity of the five wharfs, i.e., 1 140 t, 2.85 times of the result of the proposed model. The mechanical recovery capacity, dispersion capacity and adsorption capacity provided by the proposed model is 217.71 m³/h, 17.63 t and 12.24 t, respectively, which are less than 280 m³/h, 18.5 t and 21 t as specified in the standard.

From the above comparison, the proposed model allocates different quantity of resources for each wharf according to the relative risk of wharfs. However, according to the provisions of the Standard, the emergency resources required are the same for wharfs of the same berthing capacity, such as Sinopec Xiaohu, Guangfa Petrochemical, Guangdong Petrochemical and Kingboard, which fails to reflect the difference of wharfs in terms of oil spill risk. It could also be seen that the quantity of resources allocated for Xiaohu Petrochemical, Sinopec Xiaohu, and Guangfa Petrochemical are less than the specified values of the standard, and the quantity for Guangdong Petrochemical and Kingboard are more than the specified values of the Industry Standard. In the same time, although the berthing capacity of Guangdong Petrochemical is 45 000 t, the quantity of resources allocated is larger than that of Kingboard Petrochemical with 50 000 t berthing capacity. The rationality of the model is demonstrated as it pro-

Table 3. Model parameter selection

Oil type	Model selection											
	r_v	r_s	E	P_1	P_2	P_3	t	α	γ	J	K	φ
Fuel oil	26%	0.52%	2	60%	30%	10%	12	15%	0.2	10	80%	25%

Table 4. Comparison of the model calculation results with the requirements of the Standard

Name of wharf	Maximum berthing capacity/DWT	Emergency capacity target/t		Mechanical recovery capacity/m³·h⁻¹		Dispersion capacity/t		Adsorption capacity/t	
		proposed model	the standard	proposed model	the standard	proposed model	the standard	proposed model	the standard
Xiaohu	120 000	99.42	400	54.11	90	4.38	5.5	3.65	7
Sinopec Xiaohu	80 000	85.27	250	46.41	30	3.76	2.5	3.13	2
Guangdong	45 000	79.78	120	43.42	65	3.52	4.0	2.93	5
Gangfa	100 000	73.10	250	39.79	65	3.22	4.0	2.69	5
Kingboard	50 000	62.44	120	33.98	30	2.75	2.5	2.29	2
Total		400.00	1 140	217.71	280	17.63	18.5	12.24	21

posed resource allocation based on risk assessment.

With regard to the capacity of individual wharf to respond to the maximum possible oil spill accidents, the Xiaohu Petrochemical Wharf with the maximum oil spill 400 t is taken as an example. As the mechanical recovery capacity, dispersion capacity and adsorption capacity of the wharf is 54.11 m^3/h, 4.38 t and 3.65 t, respectively, it is impossible for the wharf to respond to the accident with its own capacity within 48 hours. From the perspective of regional emergency response, however, the largest probability of oil spill accidents in Xiaohu Petrochemical Wharf is only 0.067 per year and there is no possiblity of spills in more than two wharfs at the same time. The maximum distance among the five wharfs is about 2.2 km. For example, Xiaohu Petrochemical Wharf is 0.8, 1.0, 1.2 and 1.5 km away from Sinopec Xiaohu, Guangfa Petrochemical, Guangdong Petrochemical and Kingboard Petrochemical respectively. Emergency resources of other wharfs could be transported to the site within 1–2 hours for jointly response.

The proposed model matches the oil spill risk assessment with the regional emergency capacity and allocates the emergency capacity targets and resources quantity according to the relative risk value of oil spill. The model also achieves appropriate preparedness in high-risk areas and saves emergency resources in the region with rational allocation.

4 Conclusions

This paper proposes an innovative regional emergency resource allocation model based on risk assessment of oil spill, which comprehensively considers factors such as the probability and hazardous consequences of oil spill accidents, the characteristics and weathering process of oil spill, and the operating efficiency. The model is capable of rationally allocating the regional emergency capacity targets and emergency resources in accordance with the oil spill risk index. This paper also analyzes the practicality of the model through application cases.

The research results indicate that the emergency resource allocation method based on risk assessment is applicable to the oil spill risk assessment and capacity building in the port area. The oil spill risk index reflects the risk for each unit in the area. The method of allocating emergency capacity targets based on the index provides effective link between oil spill risk and emergency response capability. The quantity of emergency resources allocated according to the proposed model is less than the value specified in the standard but meets the regional requirements. The emergency resources allocated of certain units in the area is more or less than the values specified in the standard but match with the oil spill risk.

Further research will be conducted to optimize the model and verify its reliability through more application cases. Theoretical analysis, simulations and experiments will also be carried out to adjust the range of key parameters of the model, to meet the requirements of various application scenarios.

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