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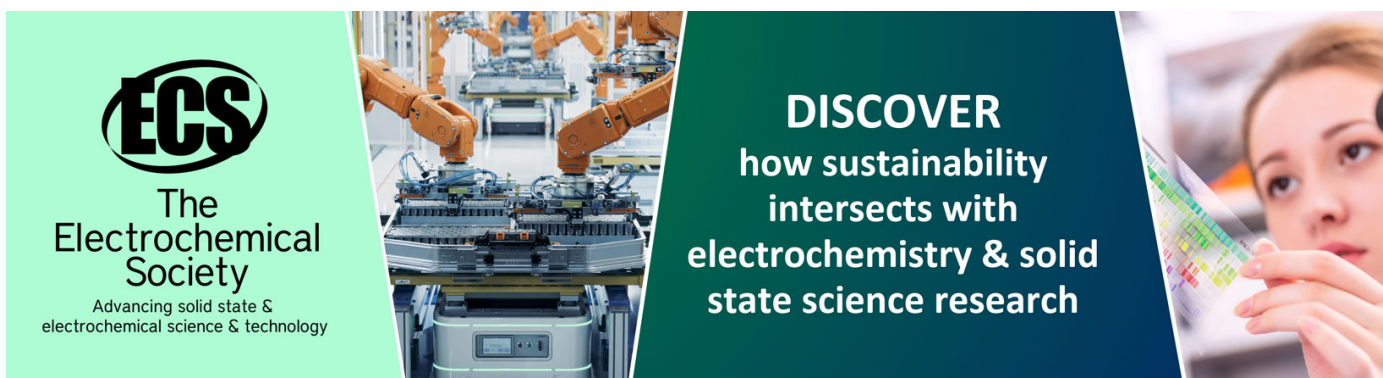
Research on risk assessment of offshore supply vessels carrying dangerous cargoes

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Research on risk assessment of offshore supply vessels carrying dangerous cargoes

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Abstract. In view of the lack of effective quantitative risk of dangerous cargoes carried by offshore supply vessels under the influence of multi-level, multi-variable and non-quantitative factors, the paper adopts the multi-level fuzzy comprehensive assessment method to screen the key risk sources of dangerous cargoes carried by offshore supply vessels, and has respectively constructed the risk possibility and hazard consequence assessment index systems and carried out the risk classification calculation. Through the calculation of the risk of carrying dangerous cargoes on an offshore supply vessel in Bohai Sea, the results show that the risk possibility of the supply vessel is medium to low level, the hazard consequence is medium to high level, and the comprehensive risk level is medium. Therefore, the minimum reasonable and feasible ALARP principle should be followed to reduce the risk. The assessment method can judge the risk level of dangerous cargoes carried by offshore supply vessels and provide technical support for emergency response of offshore supply vessels.

1. Introduction

Offshore supply vessels, as the only means of transporting materials for offshore oil and gas field development, are responsible for supplying materials and food for offshore oil operations and production facilities. Among them, there are nearly 700 kinds of polluting and hazardous goods, such as chemical agents, mud, toxic and harmful gases, explosives, etc., which pose great risks to the safety and environment of offshore transportation. The huge offshore oil and gas production is bound to be accompanied by the increasing types, quantities and voyages of offshore supply vessels transporting offshore polluting and hazardous goods. The risk of accidents in shipping is increasing day by day, bringing great difficulties to the local maritime control. Due to the inherent characteristics of offshore supply vessels carrying hazardous goods and the uncertainty of shipping environment, traffic accidents will pose a serious threat to public safety and people's lives and property.

In 2017, the International Maritime Organization (IMO) passed the *Rules for the Bulk Transportation and Loading and Unloading of Harmful and Toxic Liquid Substances on Offshore Supply Vessels* (OSV CODE), and formulated relevant measures for offshore supply vessels carrying toxic liquid substances to minimize the uncontrolled discharge of such substances into the sea. At present, the implementation of OSV CODE by various countries is still not in place. For offshore supply vessels carrying polluting and hazardous goods, especially for reloading contaminated bulk liquid for transportation, handling and compulsory pre-washing, the supervision is still not perfect, and there is a lack of targeted laws, policies and technical guidelines. Most of the researches on offshore supply vessels focus on scale [1], speed planning [2-3], route planning [4-8] and supervision [9], while



the researches on risk assessment of carrying hazardous goods on offshore supply vessels are relatively few.

Many scholars have researched the offshore oil spill risk by using stochastic theory [10], Bayesian theory [11-12], fuzzy mathematics [13-14], oil spill dynamics [15], etc., and achieved a lot of research results. The risk assessment methods for ship oil spill also include event tree, traffic flow theory, and quantitative analysis method combining system simulation with ship collision damage model or accident statistics [16-20]. A large number of risk assessment methods are applied to ships and offshore engineering, which provide valuable reference for risk assessment of offshore supply vessels carrying dangerous cargoes.

This paper establishes a scientific risk assessment index system by analyzing the risk sources of offshore supply vessels in the whole process of carrying dangerous cargoes, and analyzes the risk level of offshore supply vessels carrying dangerous cargoes through analytic hierarchy process and fuzzy synthetic assessment methods, and comprehensively analyzes the risk level of offshore supply vessels carrying dangerous cargoes, so as to provide strong technical support for improving shipping safety and offshore oil and gas field development and management.

2. Risk assessment index system

2.1. Risk source identification

As the first step of risk analysis, risk source identification is the key to the whole risk analysis process. Identifying all possible risks of the evaluated object is a process of determining the existence of risks and defining their nature. The risk of offshore supply vessels carrying dangerous cargoes exists in the whole carrying process. There are many factors affecting the safe operation of supply vessels, so the assessment factors should be comprehensive. To evaluate the risk level of dangerous cargoes carried by offshore supply vessels, consideration should be given to both the possibility of accidents and the harmful consequences. The possibility of accidents is the probability of accidents, i.e. the characteristics of the vessels themselves, as well as the meteorological and hydrodynamic environment of the nearby sea areas. The harmful consequence is the damage to the environment after the accident. The characteristics of dangerous cargoes and the leakage quantity should be considered. Therefore, the risk index system is a multi-factor and multi-level complex system with many indexes and correlations among them.

2.2. Construction of index system

2.2.1. Risk possibility assessment index system. Based on the analysis of the selected key risk assessment indexes, a risk probability index system for offshore supply vessels carrying dangerous cargoes is established. Figure 1 shows the risk probability assessment index system for offshore supply vessel. The first-level index is defined as $U = \{U_1 \text{ Ship Factor}, U_2 \text{ Environment Factor}, U_3 \text{ Man-made Factor}, U_4 \text{ Management Factor}, \dots, U_n\}$, and the second-level and third-level index systems are successively developed. Through questionnaire survey, the supply vessel operators and relevant experts will score the risk assessment index (with more than 20 participants) and preliminarily determine the weight distribution of each index in the index system. The weight shown in Figure 1 is only an example, and the evaluator can adjust it according to the specific attributes of the vessel, actual environment and conditions during operation. For example, sea ice is only an important index during ice age in Bohai sea area, and other sea areas can consider reducing the weight of this index or ignoring this index.

2.2.2. Assessment index system of harmful consequences. Once the dangerous cargoes carried by the supply vessel leak into the sea, it will cause great damage to the marine environment. The degree of harm is affected and restricted by many factors, which are interrelated and interact with each other. Leakage, nature of dangerous cargoes and accident area all affect the level of hazard consequences.

Severe weather and sea surface conditions can also lead to the expansion of hazard consequences. Leakage is the most direct factor affecting the degree of harm. The characteristics of dangerous cargoes have different harm to marine environmental resources.

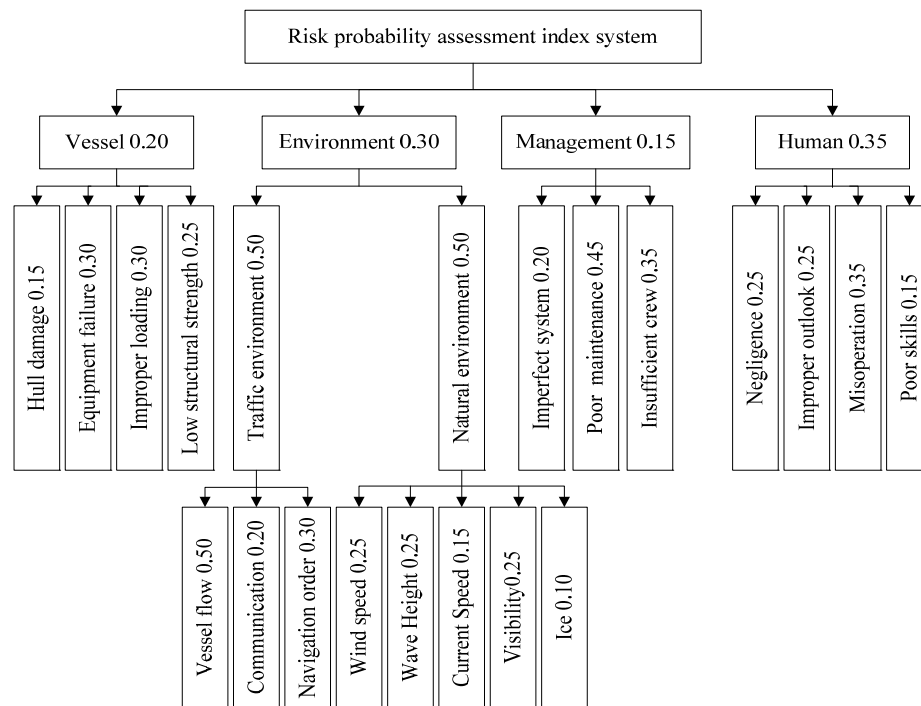


Figure 1. Risk probability assessment index system for offshore supply vessel.

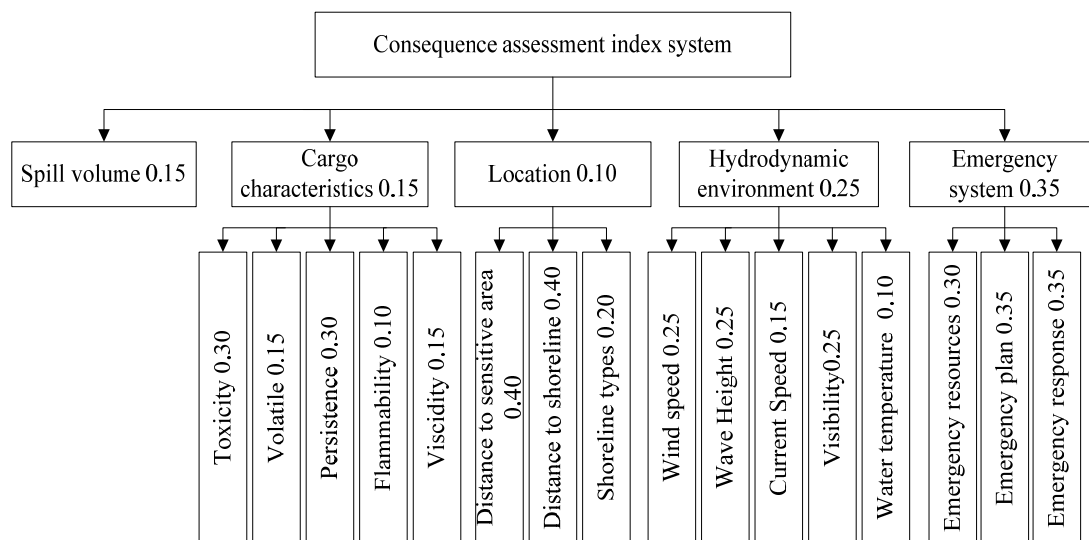


Figure 2. Consequence assessment index system for offshore supply vessel.

The indexes of accident area need to indicate whether the sensitive resources in the sea area belong to natural conservation zone, and determine the offshore distance and coastal area category, etc. The perfection of emergency system can control the movement range of dangerous cargoes and reduce the

degree of harm to a certain extent. The influencing factors of dangerous cargoes leakage hazards are analyzed, and other research results [21-22] are referred to finally determine the hazard consequence assessment index system. Figure 2 shows the consequence assessment index system for offshore supply vessel. The first-level index is defined as $U = \{U_1 \text{ leakage amount, } U_2 \text{ dangerous cargoes characteristics, } U_3 \text{ accident location, } U_4 \text{ sea area environment, } U_5 \text{ emergency system, } \dots U_n\}$, and the second-level and third-level index systems are successively developed. The risk assessment index is also scored, and the weight distribution of each index in the index system is preliminarily determined. The weight shown in Figure 2 is only an example, and the evaluator can adjust it according to the nature of dangerous cargoes, the specific environment of the sea area and the actual emergency response capability. For example, when the dangerous cargoes carried are drilling mud cuttings, the second-level indexes in the characteristics of dangerous cargoes do not include flammability and volatility, which can be ignored during assessment.

3. Risk assessment

On the basis of determining the grade standard and weight, the basic idea of fuzzy comprehensive assessment method is to use the principle of fuzzy set transformation, describe the fuzzy boundary of each factor with membership degree, construct the fuzzy assessment matrix, and finally determine the grade of the assessment object through multi-level compound operation. Risk matrix is a combination of consequence classification and risk possibility. The probability index and hazard consequence index are put into risk matrix to judge whether the risk is acceptable or not. The mathematical expression is as follows:

3.1. Establish evaluation factor set

Set factor $U = \{U_1, U_2, \dots, U_n\}$, U_i is the evaluated risk factor of oil spill.

3.2. Determination of Assessment Set

The assessment set is usually represented by V , i.e. $V = \{V_1, V_2, \dots, V_m\}$, and V_j represents the assessment result. For the classification of analysis structure grades, the characteristics of indexes should be fully considered, and should not be too fine. Generally, 4~5 indexes are appropriate. In this study, five-level comments are adopted, and the set of risk probability and hazard consequence comments is expressed as $V = \{\text{very low (VH 20), low (L 40), moderate (M 60), high (H 80), very high (VH100)}\}$;

3.3. Determination of membership degree

Membership degree is an effective method to realize the description of assessment indexes for different risk levels. It refers to the possibility that each factor corresponds to an element in the assessment set. The membership degree of risk assessment factors can reflect the change process of each assessment standard belonging to a certain risk level. At present, the main methods to determine membership degree are: expert experience method, fuzzy statistics method, binary comparison sorting method, etc. [23-31]. In this study, the expert experience method is used to construct the single factor assessment matrix. According to the experts' experience and judgment criteria, the specific assessment criteria of each index and the probability level are established to realize the comprehensive assessment of single-factor oil-spill risk level.

3.4. Fuzzy comprehensive assessment

According to the determined assessment index weight and membership degree, an oil-spill risk assessment model for offshore oil platforms is constructed. The specific methods are as follows.

According to the assessment index system, the first fuzzy comprehensive assessment is introduced taking the ship factor as an example. The membership matrix (R_i) is established by using the subset table of risk assessment criteria for each second-level index.

$$R_1 = \begin{pmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \\ r_{41} & r_{42} & r_{43} & r_{44} & r_{45} \end{pmatrix}$$

The weight of each second-level index is $A_1=(A_{11}, A_{12}, A_{13}, A_{14})$, then the fuzzy comprehensive assessment of ship factors is as follows:

$$B_1 = A_1 \bullet R_1 = (b_{11}, b_{12}, b_{13}, b_{14}, b_{15}) = (A_{11}, A_{12}, A_{13}, A_{14}) \bullet \begin{pmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{12} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \\ r_{41} & r_{42} & r_{43} & r_{44} & r_{45} \end{pmatrix}$$

Among them, B_1 is the oil spill risk assessment matrix of ship factors, A_1 is the weight distribution of second-level risk indexes in ship factor indexes, and R_1 is the membership matrix corresponding to ship factor indexes.

By the same token, by calculating the risk assessment matrix of other indexes according to this formula, the comprehensive assessment result of the risk level of dangerous cargoes carried by offshore supply vessels can be obtained.

$$B = (A_1, A_2, A_3, A_4) \bullet \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix}$$

The vector obtained from the second-level/third-level comprehensive assessment results is the assessment results of the risk levels of each first-level index, and the weighted average method is adopted to judge the level of oil spill possibility/oil spill consequence risk.

3.5. Determination of risk level

In this study, the result of risk comprehensive grade assessment is jointly determined by the possibility grade and the consequence grade. Table 1 shows the established risk grade matrix, the risk grade of the offshore supply vessel carrying dangerous cargoes is determined.

Table 1. Risk matrix of integrated risk assessment.

Probability × Consequence		Consequence				
		[0, 20]	(20, 40]	(40, 60]	(60, 80]	(80, 100]
Probability	(80, 100]	M	H	H	VH	VH
	(60, 80]	M	M	H	H	VH
	(40, 60]	L	M	M	H	H
	(20, 40]	VL	L	M	M	M
	[0, 20]	VL	VL	L	M	M

If the risk is judged to be high or very high, administrative measures or repair measures need to be taken immediately to reduce the possibility of accidents and control the harmful consequences. If the risk is judged to be medium, the ALARP principle of minimum reasonable feasibility should be followed to reduce the risk [32].

4. Application example

Take a platform supply vessel in Bohai as an example. The supply vessel was put into use in 2014, with a total length of 75.0m, a width of 17.5m, a depth of 7.5m, a maximum draft of 6.2m, a total tonnage of 3,000t, a rear deck area of 700m², and a fixed number of 10 seamen and 20 staff. The vessel is mainly used for transporting goods from the platform. The main deck surface is mainly used for stacking items such as drilling rigs, drilling tools, helicopter oil tanks, chemicals, food and the like. Under the deck, the ship has the capacity to transport fresh water, fuel oil, bulk cement, mud, brine and other items, including 750m³ of fuel oil tank, 50m³ of mud/brine/recovery oil tank, 150m³ of methanol tank and 225m³ of cement tank. Both sides of the supply vessel's rear deck are equipped with cargo blocking railings, and between the railings are laid anticorrosive wood floors to prevent the impact of cargo loading and unloading on the deck. The front driving platform of the bridge is equipped with communication and alarm equipment, and the rear driving control platform is equipped with power positioning and draught fan and oil-way cut-off equipment. The sea area where the platform served by supply vessels is located has a general wind speed of 25.0 knot, a wave height of 1.4~3.8m, a flow speed of 0.2~0.8m/s, visibility of 0.7~2.2km, annual maximum temperature of 33°C, minimum temperature of -15°C, and ice period for about 88 days. The frequency of extreme weather is not high, but it is harmful. The supply vessel route is surrounded by the national ocean conservation zone. Other ships often pass by the route. The vessel has a corresponding communication service system that can contact passing ships in time. On a daily basis, the propulsion system, fuel oil and cargo oil system, methanol-based oil system, fire fighting system and deck cargo storage area of the supply vessel shall be inspected, and meanwhile, safety records shall be made and major problems shall be highlighted. The comprehensive quality of the ship's technical personnel is at a higher level, and professional training is conducted every year. In case of emergencies, they can be handled in a timely manner. The emergency equipment of the supply vessel is relatively complete, equipped with 2 sets of clutches, 2 sets of fire pumps and 2 sets of water cannons. The ship is not equipped with oil recovery equipment, but the main deck is reserved with an area for installing oil recovery equipment.

According to the actual situation of this supply vessel and some real-time monitoring data, the risk is evaluated by using the fuzzy comprehensive assessment model. The assessment results are shown in Table 2 (*P* is probability, and *C* is consequence).

Table 2. The probability and consequence level of incident.

Risk	Factors	Initial assessment	Overall assessment	Score
<i>P</i>	Vessel	(0.33, 0.58, 0.09, 0, 0)	(0.26, 0.41, 0.26, 0.03, 0.04)	43.6
	Environment	(0.15, 0.26, 0.33, 0.11, 0.15)		
	Management	(0.44, 0.47, 0.09, 0, 0)		
	Human	(0.22, 0.42, 0.36, 0, 0)		
<i>C</i>	Spill volume	(0, 0, 0.2, 0.4, 0.4)	(0.18, 0.27, 0.26, 0.16, 0.13)	55.8
	Cargo characteristic	(0.12, 0.13, 0.27, 0.30, 0.18)		
	Location	(0, 0, 0.2, 0.4, 0.4)		
	Hydrodynamic	(0.27, 0.30, 0.38, 0.05, 0)		
	Emergency system	(0.27, 0.52, 0.21, 0, 0)		

Results in Table 3 imply that the risk probability score is 43.6, the risk level is moderately low, the hazard consequence score is 55.8, and the risk level is moderately high, which indicates that the offshore supply vessel has relatively low probability of accidents, but relatively high hazard consequence of accidents. By putting the risk probability and consequence score into the assessment matrix, it can be concluded that the risk of carrying dangerous cargoes by this offshore supply vessel is medium, and the lowest reasonable and feasible ALARP principle should be followed to reduce the risk.

5. Discussion

A weaknesses of risk matrix is that it ignores the risk accumulation. This comes from the fact that a risk matrix addresses one hazards one at a time. Thus, this may lead to the situation in which the potential accumulation of smaller risks resulting in a total unacceptable risk is not addressed.

On the other hand, qualitative risk assessment approaches such as the risk matrix technique assess the risk in descriptive terms by using experts' opinions. The use of the risk matrix has been adopted with the assistance of experts' opinions from the offshore and shipping industries whose decisions on the degree of hazard are usually based on their experience in the field [33-34].

The likelihood and consequence associated with a failure mode are weighted based on the experts' knowledge and combined by the risk matrix to obtain the risk level/index [35-36]. This implies that the results of qualitative risk assessment techniques are experts' knowledge dependent "subjective". Furthermore, the risk results obtained by these techniques are not often reproducible due to an uncertain risk level. In my opinion this issue should be adequately treated in the paper.

6. Conclusion

This study evaluates and analyzes the risks of offshore supply vessels carrying dangerous cargoes. According to the statistical data and the actual situation of offshore supply vessels, the risk possibility and hazard consequence index systems are respectively constructed, and the fuzzy comprehensive assessment method is introduced to establish the risk grade assessment method of offshore supply vessels. Applying fuzzy comprehensive assessment model to evaluate the risks of carrying dangerous cargoes on offshore supply vessels can provide reliable information for controlling key risk sources and accident impacts in practical work, thus taking immediate risk reduction measures.

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