Safety Analysis Methodology in Marine Salvage System Design

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Abstract. In order to assess the risk of marine salvage system, the paper introduced a safety analysis method based on fuzzy-logic theory, which could deal with the uncertainties in scheme design process. The method consisted of three steps: (i) problem setup, (ii) risk assessment, (iii) risk mitigation and decision making. Then two mission phases were identified in typical salvage system, namely, refloating the vessel and towing the vessel. Main hazardous events of each mission phase were researched and a safety analysis model was introduced subsequently. An example was studied to demonstrate the application of the model, and the results showed that salvage method, the operation of pontoons and the safety of towline should be taken into account seriously in salvage system design.

Introduction

Marine salvage is the process of recovering a ship, its cargo, or other property after a shipwreck. Salvage encompasses towing, refloating a sunken or grounded vessel, or patching or repairing a ship. Today the protection of the environment from cargoes such as oil or other contaminants is often considered a high priority. A range of accidents happened in marine salvage, and has caused lots of people injured and property lost recently. Therefore, it is necessary to take the mission's safety into account at the very beginning of schemes design process.

There are lots of uncertainties in marine salvage system design, and the risk of hazardous events could not be calculated accurately. Conventional risk assessment tools are not appropriate in this system, because it is difficult to assess the probabilities and consequences. A safety analysis method based on fuzzy-logic theory is introduced to deal with these difficulties. And then a case was studied to demonstrate the application.

Safety Analysis Methodology in Marine Salvage System

Problem Setup. Marine salvage, such as refloating and towing, is a complicated process. It is difficult to evaluate a mission's safety and decide which mission scenario is the most appropriate. Therefore, it is necessary to analyze the structural links of marine salvage system and find a way to assess the mission's risk.

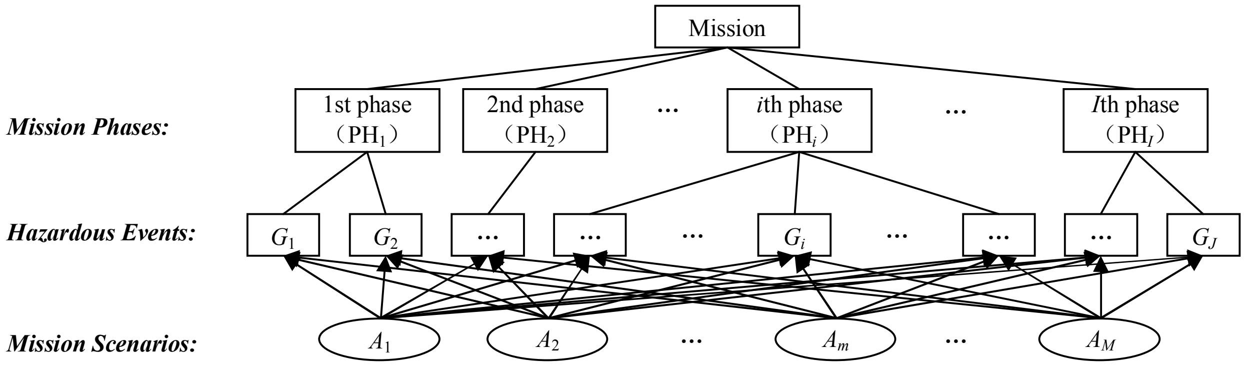

Fig. 1 Typical structural links in marine salvage system

Conducting interviews with technical experts and integrating their own experience, decision makers identify the mission phases and hazardous events, which are criteria for safety analysis. The typical mission phases and risky events are shown in Fig. 1. The mission is subdivided into I mission phases and J hazardous events. Then the problem is to choose the best alternative from M mission scenarios when risk assessment has been conducted.

Risk Assessment. This area aims at assessing risks influencing the level of system safety. It takes information from the problem setup step and delivers information that can be used in the risk mitigation and decision support step. Generally, the following mathematical model is used to quantify the overall risk level (RL) of the system:

$$S = \sum_{j=1}^{J} R_j W_j \tag{1}$$

where S is overall risk value of the system, J is the number of components of system risk, W_j is the weight of jth component of system risk which could be estimated by AHP, and R_j is the risk value of jth component. The value R_j is derived from the following steps (i)~(v).

(i) *Risk assessment approach based on fuzzy-logic system* Risk assessment based on conventional tools may not be suited for dealing with systems having a high level of uncertainty, particularly in ship salvage system design. However, a fuzzy-logic-based approach to qualitative safety assessment may be more appropriately used in engineering design, and more details about fuzzy-logic system are addressed in references [1-2].

(ii) *Linguistic variable sets and fuzzy rule base* The two fundamental parameters used to assess risk level (RL) of the system are failure likelihood (FL) and consequence severity (CS). In fuzzy-logic system, the linguistic variables are usually used to describe the FL, CS and RL expressions. The typical linguistic variables for FL, CS and RL of a particular system may be defined as follows:

To estimate the failure likelihood (FL), one may choose to use such linguistic variables as '*unlikely*', '*possible*' '*probable*' and '*frequent*'. Similarly, some linguistic variables are used to describe the consequence severity (CS) and risk level (RL).Table 1 and Fig. 2 show the fuzzy FL, CS and RL expression sets.

Table 1 Definition of fuzzy FL, CS and RL expressions

Fuzzy Rank	Failure likelihood (FL)	Consequence severity (CS)	Risk level (RL)
0, 0.1, 0.2	*unlikely*	*negligible*	*low*
0.3, 0.4, 0.5	*possible*	*moderate*	*reasonable*
0.6, 0.7, 0.8	*probable*	*severe*	*high*
0.9, 1.0	*frequent*	*catastrophic*	*unacceptable*

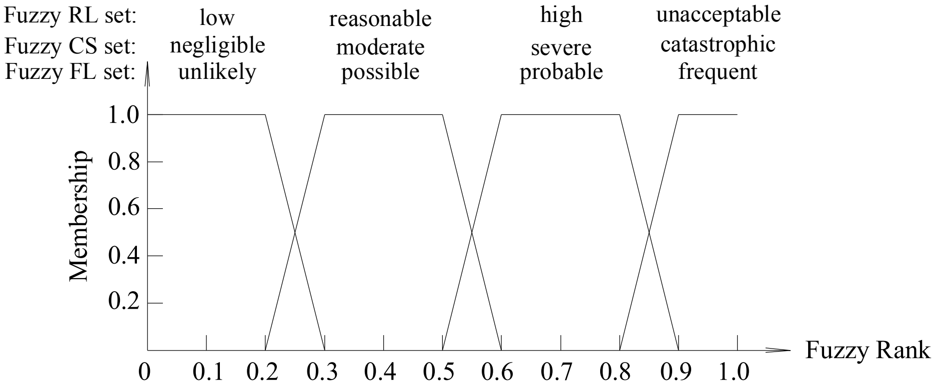

Fig. 2 Definition of linguistic variable sets on FL, CS and RL

Fuzzy rules are the basis of fuzzy inference. A commonly used method is Risk Matrix Approach and it uses a matrix to assess risk levels. An example of the 'Risk Matrix' is shown in Fig. 3.

Based on the risk matrix (as shown in Fig. 3), we can get 16 fuzzy rules which are expressed in the form of 'IF-THEN'. For example, Rule #1 in the example shown in Fig. 3 reads as:

IF FL is *unlikely* AND CS is *negligible* THEN RL is *low*.

(iii) *Fuzzification of input variables* Take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. If the input is a crisp numerical value, then fuzzify the input with Fig. 2. The output is a fuzzy degree of membership in the qualifying linguistic set and is always between 0 and 1.

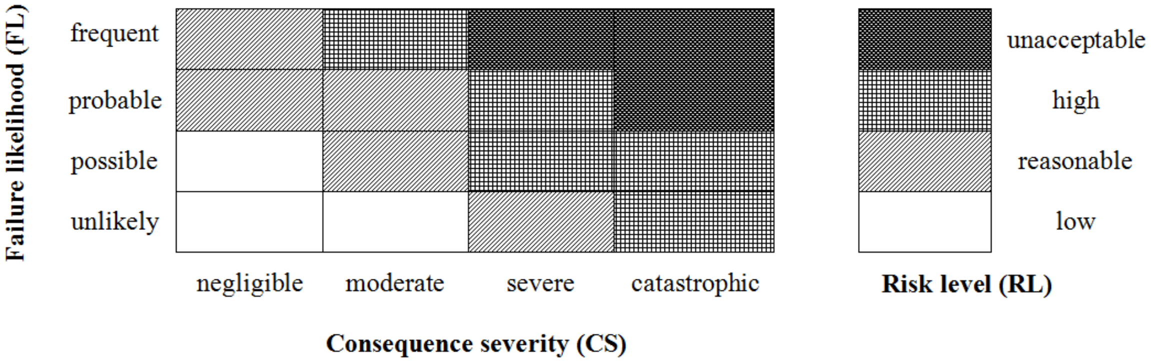

Fig. 3 Typical risk matrix

(iv) *Fuzzy inference* Once the inputs have been fuzzified, the degree to which each part of the antecedent has been satisfied for each rule is determined. If the antecedent of a given rule has more than one part, the fuzzy operator such as AND or OR operator is applied to obtain one value (membership) that represents the result of the antecedent for that rule. The following expression is used in the paper to produce the single truth value for *i*th rule:

$$\mu_i = \mathrm{Min}(\mu_{\mathrm{FL},i}, \mu_{\mathrm{CS},i}) \tag{2}$$

where μ_i is the single truth value for *i*th rule, $\mu_{\mathrm{FL},i}$ is membership value of the first input variable FL for *i*th rule, and $\mu_{\mathrm{CS},i}$ is membership value of the second input variable CS for *i*th rule.

In order to reach a final decision, all rules must be combined in some manner since decisions are based on the testing of all the rules in a fuzzy inference system. Aggregation is a process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. The output of the aggregation process is one fuzzy set for each variable. The aggregation of consequent, LR_j is expressed as follows:

$$LR_j = \{\mathrm{Max}(\beta_{1,i}, low); \mathrm{Max}(\beta_{2,i}, reasonable); \mathrm{Max}(\beta_{3,i}, high); \mathrm{Max}(\beta_{4,i}, unacceptable)\} \tag{3}$$

where i=1, 2, …, I; I is the number of rules fired in the evaluation; and $\beta_{n,i}$ is the belief assigned to the *i*th rule.

(v) *Defuzzification* Defuzzification process transforms the fuzzy results into a crisp output. And center average defuzzifier is the most commonly used defuzzifier in fuzzy system. If the centre values of the fuzzy set (*low*, *reasonable*, *high*, *unacceptable*) are y_1, y_2, y_3 and y_4, and the corresponding membership are w_1, w_2, w_3 and w_4 , then the value which represents the set LR_j is expressed as following:

$$R_j = (y_1 w_1 + y_2 w_2 + y_3 w_3 + y_4 w_4)/(w_1 + w_2 + w_3 + w_4) \tag{4}$$

where R_j is the risk value of the set LR_j.

Risk Mitigation and Decision Making. Risk mitigation and decision making are based on system safety level. A safety level used in special marine system is defined in Table 2. According to the process of risk assessment and safety goal, we know that the higher of system risk level, the more uncertain is the corresponding alternative. Obviously, the best alternative is the one with the lowest value of the risk level, S.

Table 2 Definition of safety level in marine salvage system

The value of risk (S)	Risk level (RL)	Description
$S \le 0.20$	*Low*	Risk is acceptable.
$0.20 < S \le 0.55$	*Reasonable*	Optimization measures are taken as necessary.
$0.55 < S \le 0.85$	*High*	Risk reduction measures should be taken.
$S > 0.85$	*Unacceptable*	Risk is unacceptable.

Hazardous Events in Typical Marine Salvage System

Marine salvage is composed of towing, refloating, environment protection and other recovering measures. And the mission is different in different situation after a shipwreck. However, it is common to refloat a sunken vessel firstly and tow it into a harbor then. In this process, two typical mission phases are identified in brief, namely, refloating the vessel and towing the vessel[3-5].

Refloating the Vessel. During the salvage of a sunken vessel, refloating is usually the first step in most salvage technics. So it is one of the most important task area. When preparing to refloat a vessel, the information of tides, currents and wind has to be considered properly.

Towing the Vessel. Towing the vessel is another crucial step in salvage. This step is subdivided into three parts: towing preparation, towing at sea, and terminating the tow. Safe towing speed, appropriate towline scope and routine towing watch are also vital for the task.

Main hazardous events of each mission phase in typical marine salvage are summarized in Table 3.

Table 3 Main hazardous events in typical marine salvage

Mission Phases	Hazardous Events	Symbols
Refloating the vessel	*Information of tides, currents and wind is not sufficient.*	G_1
	Refloating the vessel in heavy weather.	G_2
	Refloating method is not appropriate.	G_3
	Salvage pontoons are used in a wrong way.	G_4
	Other unpredictable accidents happens.	G_5
Towing the vessel	*Tugs and towing rigs are not suited for the task.*	G_6
	Towing rigs are not equipped reliably.	G_7
	Course changes frequently and suddenly.	G_8
	Towline scope is not appropriate.	G_9
	Towline is broken down.	G_{10}
	Collision when disconnecting the tow.	G_{11}

Case Study

An Example. One merchant ship sunk in the sea last year, and ship-owner would refloat it and tow to a harbor. As a result, three mission scenarios, A_1, A_2, A_3, were proposed. However, it was difficult to decide which one to be chosen, so the risky factors of each alternative had been evaluated by experts, and the corresponding information was given in Table 4.

Table 4 Hazardous events' information in mission scenarios

Attributes		G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}	G_{11}
Failure likelihood	A_1	0.303	0.162	*unlikely*	*possible*	*unlikely*	*unlikely*	*unlikely*	0.900	0.150	*probable*	0.500
	A_2	0.150	0.199	*unlikely*	*unlikely*	*probable*	*unlikely*	*possible*	0.750	0.300	*possible*	0.700
	A_3	0.203	0.116	*possible*	*possible*	*unlikely*	*unlikely*	*possible*	0.700	0.150	*possible*	0.650
Consequence severity	A_1	0.655	0.700	*catastrophic*	*severe*	*severe*	*severe*	*moderate*	0.455	0.350	*catastrophic*	0.500
	A_2	0.655	0.700	*severe*	*severe*	*severe*	*severe*	*severe*	0.500	0.350	*catastrophic*	0.500
	A_3	0.655	0.700	*catastrophic*	*moderate*	*severe*	*severe*	*severe*	0.500	0.400	*catastrophic*	0.500

The weights of hazards events were estimated by AHP. With the safety analysis methodology introduced previously, the risk level of each mission scenario were evaluated, and the results were given in Table 5.

Table 5 Three mission scenarios' risk values

Attributes		G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}	G_{11}	Total
Weights (W_j)		0.092	0.078	0.131	0.152	0.016	0.120	0.053	0.098	0.062	0.162	0.036	1.00
Risk values	A_1	0.700	0.400	0.700	0.700	0.400	0.400	0.100	0.700	0.100	1.000	0.400	0.61
	A_2	0.400	0.400	0.400	0.400	0.700	0.400	0.700	0.400	0.400	0.700	0.400	0.47
	A_3	0.508	0.400	0.700	0.400	0.400	0.400	0.700	0.400	0.100	0.700	0.400	0.50

According to the safety level (as in Table 2), the alternatives A_1 was in *high* risk level, while A_2 and A_3's risk levels were *reasonabl*e. Obviously, the second alternative (A_2) was the optimum, because its risk was the lowest. In view of important weights of hazardous events, salvage method, the operation of pontoons and the safety of towline should be taken into account seriously in scheme design process.

Conclusions

A fuzzy-logic-based safety analysis method was introduced to evaluate the risk level of marine salvage system in scheme design process, and it was appropriate to deal with the uncertainties in safety assessment. Refloating and towing the vessel were two kinds of mission phases in typical marine salvage, and their hazardous events were analyzed in detail. And then a case was studied to demonstrate the application and the results showed that the method is feasible.

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