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Probabilistic risk, sustainability, and utility associated with ship grounding hazard

Yan Liu, Dan M. Frangopol *

Department of Civil and Environmental Engineering, ATLSS Engineering Research Center, Lehigh University, 117 ATLSS Drive, Bethlehem, PA 18015-4729, USA

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ABSTRACT

Ship grounding is a major maritime hazard that poses great consequences. Risk and sustainability associated with ship grounding need to be rationally assessed for a safe and sustainable maritime traffic. This paper presents a probabilistic risk analysis of ship grounding hazard considering damage caused by bottom penetration. Sustainability is introduced for ship grounding risk analysis for a synthesized assessment of the damage consequences. Sustainability indicators assess the economic, social, and environmental performance following a hazard event. In terms of ship grounding incident this includes the ship damage repair, operational delay, cargo loss, injury or fatality of crew, and environmental impact such as clean-up of oil spill. The economical, social, and environmental metrics are evaluated separately and then converted into an integrated monetary metric. Utility function that can incorporate attitude towards risk taking is used in the analysis for decision making purposes in risk control. The proposed approach is illustrated using a hypothetical oil tanker grounding in the Delaware Bay region.

1. Introduction

Ship groundings, accounting for about one third of commercial ship accidents, are significant structural hazard events that put maritime system at risk. Considering the vital importance of ship transportation activities in global economic, it is necessary to develop a risk-informed model of ship grounding accident that properly accounts for uncertainty and helps to manage risk in pertinent hazard consequences. This paper aims to investigate the ship grounding of oil tankers and assess overall damages in an utility-informed risk and sustainability assessment framework.

Ship grounding is a marine accident that describes the impact of ship on seabed or waterway side. This impact applies extreme loads and hence damage on the submerged ship hull in particularly the bottom structure. In severe damage scenarios, grounding might lead to hull breach and result in cargo spills, loss of vessel, and human casualties in the worst case. Ship grounding incident is a complex phenomenon in its causality, as it involves numerous initiators such as human error, machine failure, or system failure. Though human error (Martins and Maturana, 2010) is considered the major reason of the grounding incident, researchers have been studying other factors in grounding for probabilistic analysis of the event. Probabilistic grounding models were first presented by Fujii et al. (1970) and Macduff (1974) based on ship geometrical probability and causation probability function. Pedersen (1995) and Simonsen (1997) adopted and extended grounding models for wide applications. The probabilistic powered grounding and drift grounding are discussed in Fowler and Søgård (2000) and COWI (2008) from scenario-based analysis. Infrequent and rare as the ship grounding seems, Eleftheria et al. (2016)'s statistics revealed that ship grounding accidents actually increased over the last decade despite of the improved navigation technology. Therefore, continued investigation on the safety of maritime waterway against grounding hazard is necessary.

The consequence of ship grounding can be evaluated in many ways. Otto et al. (2002) evaluated grounding consequences of ferry ship with damage criteria based on damage size and location. Yamada (2009) proposed a method to estimate the cost of oil spill with regression analysis using historical oil spill data. However, the existing evaluation models of ship grounding consequence do not provide a comprehensive assessment of the overall damage associated with the grounding incident. A rational assessment model for calculating the result of grounding is still in need (Pedersen, 2010). The ultimate implications of an incident should be defined in terms of the environmental, economic, and social consequences of the event. To address these aspects, this paper presents a framework for risk analysis of ship grounding that includes the consideration of sustainability. Sustainability is generally defined as meeting the needs of present without compromising the future (Lounis and

* Corresponding author.
E-mail address: dan.frangopol@lehigh.edu (D.M. Frangopol).

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McAllister, 2016). It is being recognized as an important performance indicator assessing the life-cycle performance of infrastructure systems (Brundtland and Khalid, 1987). Maritime community has also started promoting the sustainability principles across maritime transport activities (UNCTAD, 2015). Sustainability metric has been introduced to investigate marine incidents like collision in Dong and Frangopol (2015). As sustainability concept spans a broad range of issues, investigating relevant sustainability indicators for ship grounding is in need for an applicable and comprehensive risk assessment. In this paper, the sustainability metrics are integrated into risk assessment of ship grounding to determine the overall hazard impact for risk management and decision making purposes.

Appropriate risk assessment also requires the consideration of risk attitude of decision makers. The attitude towards risk can be described as risk averse, risk neutral, or risk taking (Pratt, 1992) depending on the decision maker. Utility theory (Von Neumann and Morgenstern, 1953) has proved to be very effective in reflecting risk attitude in risk evaluation (Sabatino et al., 2016; Ruan et al., 2015; Frangopol and Soliman 2016; Frangopol et al., 2017). Utility theory is incorporated in this paper to examine the preference of decision makers. The effects of the risk attitude in ship grounding risk and sustainability analysis are considered in the proposed framework.

A model for preliminary assessment of risk and sustainability associated with ship grounding hazard is presented. The probabilistic damage of ship grounding is computed by considering the penetration extent in double hull tanker design. The consequences of ship grounding are evaluated in terms of the environmental, economic, and social impacts in a sustainability perspective. Risk attitude of decision maker is incorporated into the risk assessment by applying utility theory including both single-attribute utility and multi-attribute utility analysis. The proposed framework is illustrated through a hypothetical oil tanker grounding scenario in the Delaware Bay region.

2. Risk analysis of ship grounding with sustainability and utility

The general framework for the risk-based decision process is illustrated in Fig. 1. Risk-based assessment for maritime safety decision making process was proposed in (IMO, 2002). Extreme events like grounding, collision, fire and flooding, despite of their low-probability of occurrence, cause significant damage on maritime systems. Risk metric is aimed to quantify hazard events with low-probability, high-consequence like ship grounding. Risk assessment of maritime hazard received growing attention from scholars (Paik et al., 2012; Silveira et al., 2013; Mazaheri et al., 2014; Goerlandt and Montewka, 2015; Dong and Frangopol, 2015). Generally, risk of single hazard event can be quantified as follows (Ellingwood, 2009):

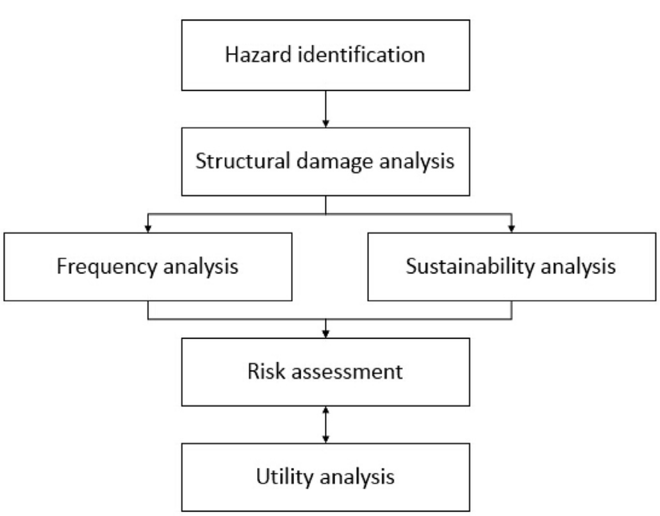

Fig. 1. Process of risk and sustainability assessment considering risk attitude.

$$R = P(H)\sum_{DS_i} C(Cons|DS_i)P(DS_i|H) \tag{1}$$

where $P(H)$ is the probability of occurrence of the hazard event; $C(Cons|DS_i)$ is the conditional consequence given the damage state DS_i; and $P(DS_i|H)$ gives the conditional probability in a damage state when the hazard H occurred.

Risk assessment requires not only the calculation of probability of hazard occurrence, but also a rational way in evaluating the consequences. Grounding incidents can cause major social, economic, and environmental problems. The consequences include the damage on ship structure, for example rupture on ship bottom, and penetration of hull. For passenger ships, fatalities are more likely associated with grounding than other incidents (Vanem and Ellis, 2010). Severe grounding incidents also raise environmental issues. The *Exxon Valdez* grounding led to significant oil spill that caused devastating environmental impact (Peterson et al., 2003). The concept of sustainability of infrastructure attracts growing attention due to its emphasis on the balanced performance on various metrics. Hence, it is argued that sustainability concept should be adopted for damage assessment on the ship grounding hazard event. Sustainability indicators that cover the major consequences associated with grounding are shown in Fig. 2. The introduced sustainability metrics are integrated into a probabilistic grounding damage model. The quantified probability-based risk and sustainability will help to give insight of risk management on maritime waterway safety to policy makers.

The perception of risk is also a major component in the risk assessment. The attitude towards risk can be classified into risk aversion, risk neutral, and risk taking based on decision makers. Utility theory can well represent the risk attitude in risk assessment process. The trend of utility value is effective in reflecting the impact of risk attitude and providing feedback to decision makers in the overall risk framework shown in Fig. 1. The remaining of this paper will illustrate the process of computing the risk and sustainability associated with a ship grounding incident, and the utility analysis of various risk-taking attitudes and decision making criteria.

3. Probabilistic ship grounding model

Most ship grounding models are inherited from the study of (Macduff, 1974) as follows:

$$P = P_a P_C \tag{2}$$

where P is the probability that a ship is involved in an accident in its waterway; P_a is the geometrical probability that a vessel encounters an object; and P_C is the causation probability, which is the conditional probability that grounding occurs in the accident scenario. Many scholars have conducted research on estimating geometrical probability and calibrating the causation probability from accidents statistics (Mazaheri, 2009).

Research on estimating geometrical probability and calibrating the causation probability from accidents statistics have been reported in (Macduff, 1974; Pedersen, 1995; COWI, 2008; Kristiansen, 2013). Considering practical application and availability of input parameters, the grounding model presented in COWI (2008) is adopted in this paper to calculate the grounding probability. COWI follows Pedersen (1995)'s approach by performing fault tree analysis in grounding accidents. In COWI's model, grounding is due to two causes: imprecise navigation and missed turn in the route.

Probability of ship grounding is computed with the distribution of ship course over ground, which is defined in normal distribution for ship's heading. The maneuverability of ship in avoiding the grounding is not considered in this model. However, COWI calibrated the accuracy of