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Development of a quantitative risk assessment model for ship collisions in fairways

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ABSTRACT

This study develops a quantitative risk assessment (QRA) model to evaluate the risk of ship being involved in ship collisions which takes into account the frequency and consequence of all possible accident scenarios. Two accident consequence types including human life loss and oil pollution which is measured in terms of the volume of oil spilled are considered in this study. The proposed QRA model consists of a collision frequency estimation model, an event tree and consequence estimation models. The event tree comprises five intermediate events including ship type, ship size, loading condition, hull damage and survivability. Two "generic" mathematic models are developed to estimate the human life loss and oil pollution caused by ship collisions, respectively. A case study is finally created using the real-time ship movement data in the Singapore Strait from the Llyod's Marine Intelligence Unit (Lloyd's MIU) database. Results show that the container ship, bulk carrier and oil tanker are the three main ship types being involved in collision accidents. Although the passenger/RORO ship has the lowest frequency being involved in collisions, it will suffer the most serious consequence in terms of the human life loss once it is involved in an accident. Considering the relative high percentage of oil tankers involving in ship collisions and their severe consequences, focus should be placed on the tracking and management of oil tanker traffic.

1. Introduction

Because of the increase of transportation demand, the marine traffic increases each year in many parts of the world and is expected to increase significantly over the next few decades. However, the significant increase in traffic demand could result in increased traffic movements in fairways. In general, the number of traffic movements in a busy fairway can be as high as 2000 per day (Yip, 2008) and this number is expected still to increase with the continuing growth of traffic demand. Such a large number of movements may result in high traffic density and the increase in the accident occurrence likelihood, especially in the busy fairway (Yip, 2008; Qu et al., 2011). Therefore, a number of maritime traffic control strategies have been implemented in order to enhance the navigational safety. For example, the Marmite Port and Authority of Singapore (MPA) has adopted the traffic separation scheme (TSS) to enable safer navigation in the Singapore Strait since 1981 (Qu et al., 2011). However, the effectiveness of these strategies on the risk mitigation is still not known perfectly. Risk assessment is a key step toward evaluating the effectiveness of risk mitigation measures in the Singapore Strait.

Although many researchers (e.g., Macduff, 1974; Fujii et al., 1974; Szlapczynski, 2006; Pietrzykowski, 2008; Wang, 2010; Qu et al., 2011) have developed various models for the navigational risk assessment, the majority of these models emphasized on the estimation of the occurrence frequency of navigational accidents. Obviously, it is inadequate to comprehensively assess the navigational risk only by evaluating the occurrence likelihood of navigational accidents. This is because the navigational risk is rendered by a broad range of accidents from frequent-minor to rare-major accidents.

The quantitative risk assessment (QRA) technique is a formal and systematic approach to estimating the likelihood and consequences of hazardous events, and expressing the results quantitatively as risk to people or the environment. In other words, the QRA not only can provide an overall risk assessment but also has the capability of describing the relationship between the occurrence frequency and consequence (Si et al., 2012; Liwang et al., 2013). A large number of existing research works have

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reported that ship collisions account for a substantial portion of the major types of accidents in fairways (Goossens and Glansdorp, 1998; Akten, 2004). For example, it was reported that a proportion of 45.5% ship accidents were collisions in the Bosphorus from 1953 to 2002 (Akten, 2004). In addition, the consequence of ship collisions in the fairway can be catastrophic for oil tankers and chemical/LNG/LPG ships which may cause serious environmental pollution and human life loss. For example, on 30 May 2010, an oil tanker and a bulk carrier collided in the eastern part of Singapore Strait, spilling an estimated 2500 tons of oil. Therefore, we are concerned about the ship collision risk in this study.

2. Literature review

A number of studies have been conducted on the navigational risk assessment in the past. However, most previous studies emphasized on the estimation of the occurrence frequency of ship collisions, which is defined as the number of ship conflicts multiplied by a causation probability (Macduff, 1974). Since the causation probability for distinct water areas is assumed to be a constant under a particular accident scenario, the major focus has been placed on the estimation of the number of ship conflicts. Various mathematical models, such as ship domain models (Macduff, 1974; Tan and Otay, 1999; Fowler and Sorgard, 2000; Szlapczynski, 2006; Pietrzykowski and Uriasz, 2009; Wang, 2010) and speed dispersion model (Qu et al., 2011), have been proposed to evaluate the ship collision frequency.

In addition, the computer simulation-based approach has been also applied to quantitatively examine various navigational safety issues. For example, Dand (2001) introduced the Permanent International Association of Navigation Congresses (PIANC) simulation approach to the water channel design. Zhang and Huang (2006) developed ship models to acquire pilot experience using the computer simulation approach. However, the simulation method is very time-consuming. It may also give rise to biased or inaccurate results because of a lack of practical criteria and incorrect interpretations of rules and seamanship.

Compared with the collision frequency estimation, the literature on the collision consequence assessment is rather limited. Both mechanical models and simulation methods have been applied to estimate the ship collision consequence. For example, Servis and Samuelides (1999) analyzed the damages to the struck ship by using finite element techniques. This method can be used to assess the ship behavior under a specific collision scenario, and also to compare the survivability of different structure arrangement. It should be pointed out that the severity of the damage to the ship caused by the impact and the volume of oil spilled depend on the ship type, ship size, loading condition, hull damage and survivability (Van de Wiel and Van Dorp, 2009).

Nevertheless, it should be pointed out that it is far not enough to comprehensively assess the navigational risk only by evaluating the occurrence frequency or the consequence of ship collisions. This is because there are a number of possible accident scenarios with distinct occurrence frequency and consequence once an accident is occurred. The quantitative risk assessment (QRA) technique is a formal and systematic approach to estimating the likelihood and consequences of hazardous events, and expressing the results quantitatively as risk to people or the environment. It is able analyze the potential accident scenarios, including consequences and initiating and controlling factors. In addition, the QRA model can provide an overall risk assessment via describing the relationship between the accident occurrence frequency and consequence (Meng et al., 2010).

3. Objectives and contributions

The objective of this study is to develop a QRA model in order to assess the ship collision risk including the frequencies and consequences of ship collisions. To achieve this objective, it is required to estimate the frequency and consequence of all possible accident scenarios. A collision frequency estimation model is first proposed to evaluate the frequency of a ship being involved in collisions. To reflect various accident scenarios triggered by a collision, an event tree comprising five possible intermediate events related to the collision is then built. Based on the event tree, the occurrence frequency of a particular accident scenario and its consequence can be evaluated. A case study is finally created using the real-time ship movement data from the Lloyd's Marine Intelligence Unit's (Lloyd's MIU) automatic identification system (AIS).

The contribution of this study is twofold. First, the proposed QRA model can be further embedded into a ship traffic simulation model which is used to generate ship movement trajectories in the future. The combination of the proposed QRA model and ship traffic simulations could be able to check the viability of new navigational safety strategy which will be implemented in fairways, by identifying whether both the estimated accident frequency and consequence exceed the acceptable risk levels or not. Second, the proposed QRA model can help shipping companies identify the risky areas of the fairway.

4. Quantitative risk assessment model formulation

Once a ship is involved in a ship collision, there will be a number of possible scenarios with distinct consequences. These possible scenarios can be logically illustrated by a tree diagram in which all possible paths following a top node can be traced. The occurrence frequency of a particular scenario hence equals to the product of ship collision frequency and the occurrence likelihood of this scenario. In this study, two types of consequences are considered, including human life loss and environmental pollution which is measured in terms of the volume of oil spilled. Therefore, the major task of the model formulation is to estimate the ship collision frequency, build event trees and consequence estimation models. The output from the ship collision frequency estimation model will be used as the input to the event tree and consequence estimation models.

4.1. Ship collision frequency estimation

According to the previous studies (e.g., Fujii et al., 1974; Mou et al., 2010), the ship collision frequency is equal to the number of ship conflicts multiplied by the probability of failing to avoid a collision for a given ship conflict. Namely,

$$f_{collision} = N_{conflict} \times p_{causation} \tag{1}$$

where

$f_{collision}$ = the ship collision frequency;
$N_{conflict}$ = the number of ship conflict;
$p_{causation}$ = the probability of failing to avoid a collision for a given ship conflict.

Montewka et al. (2010) used the minimum distance to collision (MDTC) to determine the ship conflicts. In general, a ship conflict can be defined as an overlap of two ship domains, as shown in Fig. 1(a). Hereafter, the ship domain is expressed as the area around the ship that the navigator wants to keep clear of other ships or objects. It should be pointed out that the overlap of two ship domains is equivalent to an event in which a point representing the center of one ship enters the disc of which the radius equals