Zhang, M. Y.; Zhang, D.; Yan, X. P.; Goerlandt, F.; Kujala, P.

Collision risk factors analysis model for icebreaker assistance in ice-covered waters

Published in:
Marine Design XIII

Published: 01/01/2018

Please cite the original version:
Collision risk factors analysis model for icebreaker assistance in ice-covered waters

M.Y. Zhang, D. Zhang & X.P. Yan

Intelligent Transportation Systems Research Center, Wuhan University of Technology, China
National Engineering Research Center for Water Transport Safety (WTS), WoTS, China

F. Goerlandt & P. Kujala
School of Engineering, Department of Mechanical Engineering, Marine Technology, Aalto University, Espoo, Finland

ABSTRACT: With the global warming and a large amount of sea ice melting, the available Arctic Sea Route has greatly enhanced the value of Arctic shipping. Ship operations under icebreaker assistance have become an essential way to facilitate the safe navigation of merchant vessels sailing through the Arctic Sea Route in ice-covered waters, but they can also put the crew and the ship in danger caused by a possible collision between the assisted ship and the icebreaker. In this paper, a dedicated Human and Organizational Factors (HoFs) model of ship collision accidents between an assisted ship and an icebreaker is developed and analyzed with the aim to identify and classify collision risk factors. A modified model of the Human Factors Analysis and Classification System (HFACS) for collision accidents between a ship and an icebreaker in ice-covered waters is proposed, which helps to analyze ship collision reports. An important guidance for the risk control of ship collisions during icebreaker assistance in ice-covered waters is provided for policy makers and shipping companies.

1 INTRODUCTION

With the global warming and a large amount of sea ice melting, the extremely valuable Northern Sea Route (NSR) has led to an increased interest in Arctic activities of ships (Fu et al., 2017). In this area, navigational operations under icebreaker assistance are key to the success of the safe navigation of merchant vessels (Zhang et al., 2017; Montewka et al., 2015; Valdez Banda et al., 2015). It is very difficult to ensure the safety of navigation in Arctic waters when vessels sail independently facing harsh conditions, such as the presence of sea ice, low temperatures, electromagnetic interference, and other complex environmental conditions (Stoddard et al. 2015; Goerlandt et al., 2016; Fu et al., 2017; Khan et al., 2017; Ostreng et al., 2013). At the same time, many merchant vessels lack the capability of ice-breaking, so they are unable to sail independently in a harsh ice environment, which can easily lead to ice accidents (Kum et al., 2015; Zhang et al., 2017; Fu et al., 2016). Hence, navigational operation under icebreaker assistance represents a typical model of ship operation in ice-covered waters. In 2016, 62.5% of General Cargo Carriers were under icebreaker assistance in the ice-covered waters of the NSR which provided by Northern Sea Route Information Office (Transit Statistics 2011–2016). In addition, icebreaker assistance operations also play an essential role in the ice-covered waters of the Baltic Sea in winter. The numbers of vessels under icebreaker assistance during the icebreaking season in the Baltic Sea in different years are shown in the following picture taken from Baltic Sea Icebreaking Report 2007–2016 provided by the Baltic Organization.

Icebreaker assistance is a widespread method used in navigation in ice-covered waters. Navigational operations under icebreaker assistance are organized into four identified icebreaker operations: Escort operations, Convoy operations, Breaking a ship loose operations and Towing operations (Goerlandt et al., 2017; Valdez Banda et al., 2015), where escort operations and convoy operations are key to the success of the safe navigation of merchant ships. Convoy operations are similar to escort operations, where several ships follow an icebreaker at a short distance in case the ice channel is filled with ice cakes (Zhang et al., 2017). Escort and convoy operations under icebreaker assistance reduce the risk of frequent accidents, such as ice collisions and propeller or rudder damage. Nevertheless, collision accidents do occur between icebreakers and assisted ships. The statistics of accidents occurred in ice-covered waters of Russian sea area (Loanov et al., 2013) and Finnish
sea area (Valdez Banda O.A. 2017) are presented in Figure 2. It can be seen that in Finnish sea area the percentage of collisions is 48% out of all accidents, and 95% out of all accidents under icebreaker assistance, the analysis of statistics and ship collision risk factors in ice-covered waters also indicates that ship collision accidents under icebreaker assistance should be avoided.

Collision risks between icebreakers and assisted ships sailing within a close distance cannot be ignored in ice-covered waters. In the scientific literature, the risks of collisions under icebreaker assistance are different from other ship collision accidents. Accidents in icebreaker assistance are more likely to occur than in open water conditions, but typically have lower severity in terms of consequences (Zhang et al., 2014; Franck and Holm Roos, 2013; Sulistiyono et al., 2015; Goerlandt et al. 2017). Accordingly, it is meaningful to investigate collision risk factors under specific conditions. There exists literature on accidents analysis in open waters and ice-covered waters. The risks of ship collisions are assessed, which is of significance importance for narrow, shallow and busy waterways (Qu et al., 2011; Klanae et al., 2010; Zhang et al., 2016). Furthermore, the analysis of the risks of navigational operations in ice-covered waters suggests that escort and convoy operations under icebreaker assistance are quite dangerous operations performed in the ice-covered waters. Overall, collisions between assisted ships and icebreakers present the most significant risk (Valdez Banda et al., 2016; Goerlandt et al. 2017). A root cause analysis method is presented to analyze the risks of collisions and grounding in Arctic waters, which aims at proposing a recommendation to reduce the occurrence probability based on fuzzy fault tree analysis (Kum et al., 2015). An Arctic shipping accident scenario is analyzed to identify essential accident risk factors in a potential accident scenario (Afenyo et al., 2017). Risk analysis models of ships stuck in ice are proposed (Fu et al., 2014, 2016; Montewka et al., 2015). Another line of work focuses on the application of risk-based design principles to Arctic shipping (Bergström et al. 2015, Ehlers et al. 2017).

However, these studies are limited in terms of the risk analysis of typical operational conditions or accidents, such as collisions between ships or a ship and ice, grounding accidents, and ship stuck incidents in ice-covered waters, not focusing specifically on collision risk factors during icebreaker assistance operations in ice-covered waters.

Icebreaker assistance operations in ice-covered waters refer to a team navigation system consisting of an icebreaker and an assisted ship. The detuning of the navigational conditions between the icebreaker and the assisted ship is the cause of a collision accident after a change in the team navigational system. Accordingly, human and organizational factors are main factors contributing to the occurrence of collision accidents. In the scientific literature, a number of human error analysis models and frameworks have been proposed to aid in the understanding of faults and errors related to human and organizational factors in complex systems where such
accidents occur, such as the four stage information processing model presented by Wickens et al. (1988), the SHEL model (Edwards, 1972), the multiple SHEL model (IMO, 1999), and the GEMS (Generic Error Modeling System) proposed by Reason et al. (1990). These models and frameworks focus on the human errors of operators.

The framework of the Human Factors Analysis and Classification System (HFACS) was presented by Wiegmann et al., 2003, which was used to classify and identify contributing factors in accident factors analysis. The HFACS-framework was used to analyze maritime accidents (Chauvin et al., 2013; Chen et al., 2013), grounding accidents (Mazaheri et al., 2015) and road traffic accidents (Baysari et al., 2008; Reinach et al., 2006; Patterson et al., 2010), and classify and identify fundamental risk factors based on accident reports.

In this paper, an analysis model of ship collision risk factors under icebreaker assistance is established based on the HFACS to solve the problem of accurate classification and identification of collision risk factors under icebreaker assistance in ice-covered waters. In particular, the systematic and multi-factorial analysis of collision factors under icebreaker assistance is presented, which aim at identifying and classifying collision risk factors. The research relies on the HFACS, which are utilized to identify and classify collision risk factors that are mentioned in reports on accidents between icebreakers and assisted ships in ice-covered waters. In this paper, a dedicated Human and Organizational Factors (HoFs) model for collision accidents between assisted ships and icebreakers is developed and analyzed, by reviewing collision accident reports, and identifying and classifying collision risk factors. A collision risk factors analysis method for ship collision accidents between assisted ships and icebreakers in ice-covered waters, named the HFACS-SIBCI model, is proposed.

The rest of this paper is organized as follows. Section 2 describes the theoretical framework along with the problem statement. The HFACS-SIBCI model of collision accidents under icebreaker assistance in ice-covered waters are presented to classify and identify ship collision risk factors based on accident reports in Section 3. We examine ship collision risk factors using the statistics of factors mentioned in accident reports in order to evaluate the proposed method’s performance in Section 4. Section 5 presents our conclusions.

2 THEORETICAL FRAMEWORK

According to accident statistics and scientific literature, accidents caused by human and organizational factors (HoFs) account for 90% of the total number of maritime accidents (Chauvin et al., 2011; Hetherington et al., 2006). At the same time, the lack of system coordination after detuning the navigational conditions between the icebreaker and the assisted ship resulting from human and organizational factors without effective Risk Control Options (RCOs) leads to ship collision accidents. Therefore, human errors and hidden organizational factors play vital roles in the ship collision risk factors classification and identification under icebreaker assistance. In view of this, this paper proposes a HFACS-based framework of ship collision risk factors under icebreaker assistance to solve the problem of the identification of human and organizational factors in ship collision risk factors classification under icebreaker assistance. We discuss the initial framework of the HFACS in what follows. The research flowchart is presented in Figure 3.

The initial Human Factors Analysis and Classification System (HFACS) framework (Wiegmann et al., 2003) consists of four layers: organizational factors, unsafe supervision, preconditions for unsafe acts, and unsafe acts. Reinach and Viale (2006) proposed a fifth layer, External factors. They believed that the identification of accident risk factors should consider the economy, law and policy as a supplement in the HFACS. Chauvin et al. (2013) developed a model to analyze human and organizational factors in maritime accidents using the five layers of the HFACS. The framework of the HFACS-Ground with five layers was presented to classify and identify contributing factors using accident reports and incident reports by Mazaheri et al. (2015). In these applications of the HFACS framework to specific contexts, the contributing factors of each layer are interpreted in specific situations considering accidents. Overall, the HFACS framework is approved by scientific literature for risk assessment and risk analysis, where the factors of each layer change continuously based on the research object (Chauvin et al., 2013; Chen et al., 2013; Mazaheri et al., 2015). This paper constructs
3 METHODOLOGY

3.1 Collision accident reports

Official accident reports play an essential role in risk factors analysis and being analyzed by an accident investigation board usually present valuable and detailed information about accidents (Mazaheri et al., 2015). We processed 17 accident reports on ship collision accidents between icebreakers and assisted ships in ice-covered waters. We utilized 14 ship collision reports on icebreaker assistance selected from Swedish Accident Investigation Board (SHK), two collision reports from the UK Marine Accident Investigation Branch (MAIB) and one collision report from Russian FleetMon. A total of 17 accidents during 1989–2017 were analyzed using the proposed approach. 16 collision reports contained detailed information including the summary, general description of the ship, external conditions and conclusion of the investigation. One collision report only described the process of the collision accident.

3.2 HFACS-Ship-Icebreaker collision in Ice-covered waters (HFACS-SIBCI)

In this paper, the 17 accidents during 1989–2017 are used for detailed analysis. The HFACS-based ship collision risk analysis model of the HFACS-SIBCI (HFACS-Ship-Icebreaker Collision in Ice-covered waters) is established to classify and identify ship collision factors. Only the collision risk factors mentioned in the accident reports were considered and further classified based on the proposed model. The HFACS-SIBCI model consists of five ship collision risk analysis levels and 28 classification categories, as shown in Figure 3. The HFACS-SIBCI is established as a five levels framework, which is similar to the HFACS-Coll, HFACS-Grounding and HFACS-MA (Chauvin et al., 2013; Chen et al., 2013; Mazaheri et al., 2015). In particularly, the 28 classification categories contain collision fundamental risk factors affecting collision accidents under icebreaker assistance.

The systematic methodology of the HFACS and the corresponding risk factor classification can assist in reducing the shortcomings of the subjective bias, experience restrictions and accident information omission in investigations and analyses of ship collision risk factors under icebreaker assistance in ice-covered waters. Accordingly, this paper constructs the ship collision risk factors identification and classification model of ship collisions under icebreaker assistance using the HFACS-SIBCI model, as shown in Figure 4, to solve the problem of ship collision risks under icebreaker assistance. This paper retains the four original levels of the HFACS framework: (1) Unsafe acts of the operator; (2) Preconditions for unsafe acts; (3) Unsafe supervision; (4) Organizational factors, and supplements them with (5) External factors causing icebreaker-ship collision accidents during icebreaker assistance; and further proposes the HFACS-SIBCI model with five levels.

3.2.1 Analysis on risk factors of ship collisions under icebreaker assistance

The contributing factors mentioned in the accident reports were identified as risk factors. In this paper, in order to establish collision risk factors classification, the collision accident risk factors analysis model is presented based on the HFACS-SIBCI. First, ship collision risk factors under icebreaker assistance are identified using the five-layer HFACS-SIBCI model introduced in Section 3.2. The classification model is utilized to classify ship collision factors based on the classification categories that contain the five collision risk analysis levels, and 28 classification categories, such as decision errors, technical errors, legislation gaps and so on. The HFACS-SIBCI accident risk factors classification model is shown in Figure 5.

In order to classify accurately ship collision risk factors under icebreaker assistance, the understanding of the HFACS-SIBCI accident risk factor analysis model is required.

3.2.2 Ship collision risk factors classification and hierarchical structure model

Icebreaker assistance operations are typical team operations in ice-covered waters involving icebreakers and assisted ships sailing in complex environments with harsh weather conditions. Ship collision accident reports under icebreaker assistance in ice-covered waters and accident research literature are analyzed according to experts’ knowledge. The collision contributing factors mentioned in the accident reports are considered and classified based on the proposed model. Then, the HFACS-SIBCI model constructed in Section 3.2 is used to classify and identify the collision risk factors, namely, External factors, Organizational factors, Unsafe supervision, Preconditions for unsafe acts and Unsafe actors, of the navigational system in ice-covered waters. At the same time, the hierarchical structure of ship collision risk factors is constructed based on the HFACS-SIBCI.

We classify ship collision accidents between icebreakers and assisted ships and establish the hierarchical structure of ship collision risk factors.
Figure 4. HFACS-SIBCI.

Figure 5. Accident risk factors classification model based on HFACS-SIBCI.
The collision risk classification procedure is presented as follows. First, we preliminary select ship collision contributing factors mentioned in the accident reports described in Section 3.1. Second, ship collision factors are identified and some other risk factors are presented by experts. Even if we do not have many accident reports, this way we will not miss ship collision risk factors. At the same time, literature is referenced to check the results regarding ship collisions in open water (Chauvin et al., 2013) and in Arctic ice-covered waters (Kum et al., 2015), as shown in Table 1.

The collision risk classification procedure is presented as follows. First, we preliminary select ship collision contributing factors mentioned in the accident reports described in Section 3.1. Second, ship collision factors are identified and some other risk factors are presented by experts. Even if we do not have many accident reports, this way we will not miss ship collision risk factors. At the same time, literature is referenced to check the results regarding ship collisions in open water (Chauvin et al., 2013) and in Arctic ice-covered waters (Kum et al., 2015), as shown in Table 1.

The results on ship collision factors are classified by four experts who have experience to carry out assistance operations in ice-covered waters, according to the five collision risk levels, namely, unsafe acts, preconditions for unsafe acts, unsafe supervision, organizational factors and external factors. If more than three classification results of the four experts are consistent, they are adopted. Otherwise, we adopt the classification results of the expert who is always consistent with other experts’ results, which is discussed by the four experts. The four experts are described as follows.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Maneuver failures of the assisted ship</td>
<td>Maneuver failures of the assisted ship cause an unsafe situation during icebreaker assistance.</td>
</tr>
<tr>
<td>2 Maneuver failures of the icebreaker</td>
<td>Maneuver failures of the icebreaker cause an unsafe situation during icebreaker assistance.</td>
</tr>
<tr>
<td>3 Lack of situational awareness</td>
<td>Uncertainty or unawareness of what is happening regarding the dangerous situation between the icebreaker and the assisted ship, such as the distance between the icebreaker and the assisted ship, speed etc.</td>
</tr>
<tr>
<td>4 Negligence</td>
<td>In emergency, the crews fail to take proper actions preventing the process of the unsafe situation.</td>
</tr>
<tr>
<td>5 Judgment failures</td>
<td>In emergency, the chosen action is inadequate or wrong, resulting in an undesired state.</td>
</tr>
<tr>
<td>6 Ice conditions</td>
<td>Ice conditions ranging from slush ice to solid pack. Ice conditions can be defined by ice concentration, ice thickness and ice type. Such as POLARIS, EGG CODE, etc.</td>
</tr>
<tr>
<td>7 Ice ridge</td>
<td>The edge of the ice is superimposed, which is called ice ridge, and it is easy to cause sudden breaking of the icebreaker.</td>
</tr>
<tr>
<td>8 Bad visibility</td>
<td>Poor visibility due to fog or snow that influences radar visibility.</td>
</tr>
<tr>
<td>9 Snow or rain weather</td>
<td>Hazardous natural environmental phenomena.</td>
</tr>
<tr>
<td>10 Engine failure</td>
<td>Mechanical failure related to the power of the icebreaker.</td>
</tr>
<tr>
<td>11 Steering gear failure</td>
<td>Mechanical failure related to the control of the course.</td>
</tr>
<tr>
<td>12 Anti-collision system failure</td>
<td>Mechanical failure related to the equipment of anti-collision, such as ECDIS, ARPA etc.</td>
</tr>
<tr>
<td>13 Communication equipment failure</td>
<td>Mechanical failure related to the equipment of communication between the icebreaker and the assisted ship.</td>
</tr>
<tr>
<td>14 Poor communication between ships</td>
<td>Given emergency, there is a communication gap between the icebreaker and the assisted ship regarding cooperative actions. Or there is misunderstanding.</td>
</tr>
<tr>
<td>15 Improper route selection</td>
<td>The design of the route makes it hard or dangerous to navigate. Or the severe ice environment influences the navigation system.</td>
</tr>
<tr>
<td>16 Wrong course of icebreaker</td>
<td>The icebreaker sails along a wrong course, which causes a collision between the ice edge and the bow of the icebreaker in the ice channel.</td>
</tr>
<tr>
<td>17 Over safety speed</td>
<td>The speed of the icebreaker and the assisted ship is higher than the standard set by Sailing Directions, which causes an unsafe situation. Or the speed is so high that the assisted ship cannot stop in a short distance.</td>
</tr>
<tr>
<td>18 Unmaintained safety distance</td>
<td>The distance between the icebreaker and the assisted ship is shorter than the standard set by Sailing Directions, which causes an unsafe collision situation.</td>
</tr>
<tr>
<td>19 Deviation from suggested route</td>
<td>Not being in the planned route or being in a waterway with severe ice conditions causes an unsafe situation.</td>
</tr>
<tr>
<td>20 Lack of emergency operation</td>
<td>Lack of emergency training involving both icebreaker and assisted ship.</td>
</tr>
<tr>
<td>21 Lack of icebreaking ability</td>
<td>The icebreaker class is lower than one required by the current ice environment. In particular, the ship’s hull is not strong enough. It also is a relative parameter.</td>
</tr>
<tr>
<td>22 Lack of engine power</td>
<td>The icebreaker lacks the power to move forward, which causes a sudden break related to the current ice environment. It is also a relative parameter.</td>
</tr>
<tr>
<td>23 Anti-collision rule gap</td>
<td>Given emergency, there is no unified ship collision avoidance rule during icebreaker assistance, which results in an unsafe collision situation.</td>
</tr>
</tbody>
</table>
• One captain: the captain of a research ship with more than fifteen years' navigation experience in ice-covered waters, including the experience of carrying out icebreaker assistance operations.
• One professor: a professor engaged in navigation safety in Arctic ice-covered waters for more than twenty years, conducting research on communication equipment for navigation in polar conditions.
• Two pilots: each of them with more than five years of experience in icebreaker assistance operations in Bohai Bay of China during wintertime.

When the ship collision factors are classified, the hierarchical structure model of ship collision risk factors is established, as shown in Figure 6.

### 3.3 Statistical analysis

Each ship collision accident is caused by many factors, where main contributing factors are different for different accidents. The proposed statistical analysis procedure can be divided into two steps: (a) the contributing collision factors are selected one by one in the 17 accidents, and (b) hazard situations caused by the contributing collision factors are defined and analyzed, where this step similar to Cause-Consequence Analysis (Chen et al., 2013). At the same time, the consequences, such as hazard situations, caused by the contributing collision factors are elaborated and defined. For example, on 20th of January 2011 at 0057 LT, a ship collision happened between an icebreaker and an assisted ship during an icebreaker assistance operation at 65°05.1'N, 026°41.0'W. The icebreaker was damaged to the rubber fender of the towing notch. The escorted ship got a 1.5 m hole in the port bow, and was also damaged to the plating and frames in ice-covered waters. This ship collision accident is analyzed based on the HFACS-SIBCI model according to the two steps shown in Figure 7.

According to the proposed procedure, the statistical analysis of the collision risk factors present in the 17 accidents is conducted according to the accident reports, as shown in Figure 8.

The statistics on the occurrence frequency of the corresponding accidents shows that Preconditions for unsafe acts and unsafe acts exert greater impact on ship collision accidents under icebreaker assistance, where the factor ice ridge [L2–2] is related to all 17 accidents. In addition, some collision risk factors are not mentioned in the 17 accident

---

![Figure 6. Hierarchical structure of ship collision risk factors.](image-url)
reports, such as engine failure [L2–5], anti-collision system failure [L2–7] etc., but they are also main collision risk factors according to the experts and literature described in Section 3.2.2. So, the frequencies of collision factors are different. But they all can cause ship collision accidents. In brief, the classification and identification of the risk factors of collisions between icebreakers and assisted ships can be realized using the proposed model, which is a basis for the risk analysis modeling of collision accidents.

4 DISCUSSIONS

In the paper, the HFACS-SIBCI model is established, and the contributing factors of collision accidents are identified and classified. Then, the hierarchical structure model of the ship collision risk factors is presented according to the results of the classification. At the same time, statistical analysis is carried out. The results of the research indicate that the most frequent active failure mentioned in the accident reports is "Preconditions for
unsafe acts”. “Unsafe acts” contribute second, followed by “External factors”, “Unsafe supervision” and “Organizational factors” (Figure 7), which can provide theoretical guidance to policy makers and shipping companies regarding the prevention of ship collision accidents between icebreakers and assisted ships in ice-covered waters.

The ship collision accident reports were taken from three different accident investigation boards. At the same time, the number of the ship collision reports is small, which is a limitation of the research, but it is enough for an exploratory qualitative analysis. However, this may question the reliability of the ship collision accident reports when used to determine ship collision risk factors in accident risk modeling. Besides, the research involves uncertainties. The research relies on accident reports formulated in a specific format, where a larger number of accident reports would reduce the uncertainty of the collision risk factors. We will improve the research in the terms of uncertainty analysis in the future. The proposed method of collision risk factors analysis has also some potential benefits to the analysis of collision risks between icebreakers and assisted ships in ice-covered waters.

5 CONCLUSIONS

The paper provides comprehensive analysis of ship collision risk factors under icebreaker assistance using the HFACS-SIBCI model based on accident reports. Ship collision risk factors are identified and classified into five levels, including “Preconditions for unsafe acts”, “Unsafe supervision”, “External factors”, “Organizational factors” and “Unsafe acts”, where the HFACS-SIBCI model-based hierarchical structure of ship collision risk factors is shown in Table 1 and Figure 6. The results obtained are promising as they can help to understand ship collision factors during icebreaker assistance. In addition, several advantages of the proposed method for ship collision risk factors analysis are elaborated with the focus on collision risk analysis under icebreaker assistance in ice-covered waters.

ACKNOWLEDGMENT

This study was supported by the National Science Foundation of China (NSFC) under Grant No. 51579203 and 51711530033 and the Excellent Dissertation Cultivation Funds of Wuhan University of Technology under Grant No. 2016-YS-041. This work has also been supported by the H2020-MCSA-RISE project “RESET—Reliability and Safety Engineering and Technology for large maritime engineering systems” (No.730888). We thank professor Wu from Wuhan University of Technology, Captain Wang from Polar Research Institute of China and pilot Wang and Tao from Pilot Station of Tianjin. We are also grateful to Chengpeng Wan, Chi Zhang and Kai Zhang for their assistance in this research.

REFERENCES


of wintertime navigational accidents in the northern baltic sea. Safety Science, 92, 66–84.


