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Abstract

This study aims to explore the relationship between the severity of marine accidents and influencing factors. An ordered logistic regression model is used to reflect the relationship between these factors and the severity of marine accidents using the worldwide accident investigation reports in the period of 2010-2019. The obtained results show that the marine accident severity is positively associated with sinking accidents, far away from port, strong wind, heavy sea, strong current and/or good visibility. With respect to ship types, fishing vessels, yachts and sailing vessels, and other ship types are the ship types most involved in accidents of higher severity. The severity level is higher for ships having incomplete or invalid seafarers' certificates, inadequate ship manning, incomplete or invalid ship certificates and/or over 30 years of age. Seafarers with poor theoretical knowledge and less sea experience are more likely to be involved in accidents of serious consequences. Small water depth and ship types such as chemical tankers, oil tankers, container ships and/or bulk carriers are negatively related to the accident severity. The results of this study can be used to assist the relevant maritime authorities in taking effective measures of preventing the occurrence of serious marine accidents.

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1. Introduction

With the recovery of global economy since 2009, the demand for seaborne trade has grown steadily, rising to a new all-time high of 11 billion tons in 2018 [1]. However, the increasing shipping activities inevitably lead to maritime accidents. The annual overview of marine casualties and incidents 2019 [2] reports an average of 3,239 marine casualties or incidents recorded in the European Marine Casualty Information Platform (EMCIP) between 2014 and 2018. Allianz Safety & Shipping Review 2019 [3] also reveals a total of 2,698 shipping casualties or incidents in 2018. Considering the under-reporting of marine casualties and incidents, the number of occurrences per year would be much larger. Despite the continuous development of science and technology, maritime accidents still cause serious casualties and property losses, as well as pollution and ecological damage to the marine environment. It was reported that 176 water traffic accidents that occurred in China waterways in 2018 resulted in 237 deaths or missing persons, and sinking of 83 ships [4]. European Maritime Safety Agency (EMSA) also reported a total of 230 ship losses over the 2011-2018 period [2].

Therefore, it becomes necessary to conduct systematic and in-depth studies on maritime safety. Though lagged far behind that on road traffic safety and aviation safety, many studies [5-7] have been conducted on the causation mechanism and contributing factors of marine accidents based on various theories. Zhang et al. [8] developed a Bayesian belief network model for the prediction of accident consequences in Tianjin Port. Some researchers [9, 10] also modified Bayesian network to assess the distribution of relative accident probabilities or to establish maritime accident prevention strategies. Some researchers [11-13] also investigated the relationship between the contributing factors and accident severity. However, the results and findings of these studies are only applicable to certain ship types [5, 6, 14-16] or specific water areas [7, 17]. Moreover, only the injury severity and/or ship damage severity were considered in these studies, the consequences of environment pollution were not taken into account, which is also an indispensable index for determining the severity of marine accidents.

Hence, the objective of this study is to examine the factors associated with each marine accident category severity based on the data extracted from the relevant marine accident investigation reports published by major maritime authorities. The rest of the paper is structured as follows. Section 2 identifies the research gap based on the analysis of past studies on marine accident severity, which are mainly focused on ship types and accident locations. An ordered logistic regression model and the data for the study are introduced in Section 3. Section 4 presents the results of data processing using the model and analyses the risk factors affecting marine accident severity. The conclusion of this study is summarized in the final section.

2. Literature Review

Though the people are concerned about the number of marine accidents, serious accident consequences, such as the foundering of M.V. Sewol [18] and the collision and explosion of M.T. Sanchi [19], always attract the attention of the public. Generally speaking, previous studies on marine accident severity are primarily focused on the crew injury severity and/or ship damage severity of accidents of specific ship types in particular water areas.

As fishing vessels are considered to be the most unsafe type of ship, a number of studies have been conducted on fishing vessel accidents. Jin et al. [15] found that the severity of crew injuries in fishing vessels was directly proportional to the loss of stability and sinking of the vessel. Jin [14] emphasized that the severity of fishing vessel damage was positively associated with overturning, foundering, daytime wind speed, ship age and distance from the shore while it was inversely proportional to the length of the vessel. Wu [20] and Wu et al. [21] reported that wave height and ice concentration were decisive factors for the severity and relative accident rate of fishing vessel accidents in Atlantic Canada. Roberts et al. [22] found that winter months and night time hours were mostly associated with the mortality of fishing vessel accidents in the UK from 1948 to 2008. In addition to these studies, there are many investigations related to the analysis of fishing vessel accidents from different angles [23, 24].

It should be pointed out that the effects of the contributing factors on accident severity differ among different ship types. Therefore, many researchers have investigated the determinants of the accident severity of passenger ships, oil tankers and container ships. Talley [16] and Talley et al. [6] found that the risk of casualties in fire/explosion was the highest in ferry/cruise vessel accidents, and the crew injury risk in ocean cruise vessel accidents was higher than that of inland waterway cruise vessel accidents. Yip et al. [25] and Puisa et al. [26] investigated the injury severity in passenger vessel accidents and analyzed the role of the wider socio-technical context in accident causation. Eliopoulou and Papanikolaou [27], Uğurlu et al. [28] and Chen et al. [29] analyzed the casualty data of oil tanker accidents and found that ship size, ship type, fires/explosions and collisions were critical to the consequences of oil tanker accidents. The study of Bye and Aalberg [30] also shows that some vessel types, such as bulk and tanker, increase the probability of accidents. Lu and Tsai [31] and Papanikolaou et al. [32] also conducted investigations of the recorded casualties of containerships and analyzed the impact of safe climate on the crew mortality rate of container ship accidents.

Considering that most maritime accidents have certain regional characteristics, many researchers have studied the accidents occurring in different sea regions. Wang et al. [7] evaluated the shipping safety along the South China Sea routes through a spatial analysis and indicated that the risk of the navigation environment gradually decreased from the north to the south. Wang and Yang [17] emphasized that the type and location of accidents and the type and age of the ship were the key factors influencing the accident severity in waterborne transportation in China. Goerlandt et al. [33] conducted an analysis of the wintertime navigational accidents in the Northern Baltic Sea from 2007 to 2013 and identified the impact patterns of prevailing sea ice and atmospheric conditions in different accident and operation types. Kum and Sahin [34] investigated the root causes of Arctic marine accidents from 1993 to 2011 and proposed suggestions to prevent human negligence in Arctic waterways in the future.

A number of studies have also been conducted on the analysis of maritime accidents occurring at ports, coastal waters, and narrow waterways, where a relatively higher risk was deemed to exist. Yip [35] showed that ship types and types of accidents are closely associated with personal injuries and fatalities of marine accidents in the Port of Hong Kong. Chin and Debnath [36] and Debnath and Chin [37] explored the factors influencing collision accidents in Singapore Port waters. Erol and Başar [38] and Zhang et al. [39] conducted an analysis of the influencing factors of marine accidents that occurred in the departure ports of the Black Sea and in Tianjin Port, respectively. There are also many investigations related to the analysis of accidents occurring in major waterways, such as the Bosphorus [40-42], the Istanbul Strait [43, 44], the Singapore Strait [45] and the Strait of Gibraltar [46]. In addition, some researchers have made efforts to study the problem from a global perspective. Knapp et al. [47, 48] analyzed the effect of significant wave heights and wind strengths on the probability of ship casualties. Weng and Yang [12] predicted the probability of fatal shipping accidents and corresponding mortalities using a zero-truncated binomial regression model. Baalisampang et al. [49] conducted a detailed review and analysis of fire and explosion accidents that occurred in the maritime transportation industry during 1990-2015. Chen et al. [11] analyzed the factors influencing total-loss marine accidents based on ship types and sea regions.

The above studies have some limitations and shortcomings. Firstly, the existing literatures on maritime accident severity were mainly focused on specific ship types or water areas. The results and findings of these studies are not applicable to other ship types or water areas. Secondly, the data used in the reported studies was usually obtained directly from existing databases rather than compiled from investigation reports. However, inaccuracies or missing data are widespread in databases on maritime casualties. Previous studies [50-52] uncovered a relatively large degree of underreporting, indicating that the data availability and quality in some available maritime casualty databases are far from optimal. Incomplete or inaccurate information of the databases may lead to the biased results of the studies. Thirdly, the marine accident severity analyzed in most of these studies does not include the index of environmental pollution. The majority of existing studies focused on the mortalities or ship damages resulting from marine accidents although the classification of ship casualties by the International Maritime Organization (IMO) is based on the severity of casualties, ship damage and environmental pollution. Therefore, the novelty of this study is its attempt to explore the influencing factors from primary data directly derived from accident investigation reports and analyze the relationship between these factors and each accident severity level, which is categorized into different levels according to the consequences of casualties, ship losses and environmental pollution.

3. Data and Methodology

3.1 Classification of accident severity

Accident severity is usually defined as a categorical variable. The level of severity is represented by the values of accident severity in an ordinal scale by the authority responsible for the accident investigation. In terms of marine accident severity, the classification standard varies among different authorities. For example, the severity of water transportation accidents in China is classified into 5 levels, namely catastrophic, critical, major, general and minor [53], while that in the UK is classified into 4 levels by the Merchant Shipping (Accident Reporting and Investigation) Regulations 2005 [54]. For the purpose of reporting information to the Organization, ship casualties are classified into 4 categories by the IMO [55], namely “very serious casualties”, “serious casualties”, “less serious casualties” and “marine incidents”. The definitions of these categories are as follows:

(1) “Very serious casualties” are casualties to ships which involve total loss of the ship, loss of life, or severe pollution.

(2) “Serious casualties” are casualties to ships which do not qualify as “very serious accidents” and which involve a fire, explosion, collision, grounding, contact, heavy weather damage, ice damage, hull cracking, or suspected hull defect, etc., resulting in:

- immobilization of main engines, extensive accommodation damage, severe structural damage, such as penetration of the hull under water, etc., rendering the ship unfit to proceed, or
- pollution (regardless of quantity); and/or
- a breakdown necessitating towage or shore assistance.

(3) “Less serious casualties” are casualties to ships which do not qualify as very serious casualties or serious casualties.

(4) “Marine incidents” include “hazardous incidents” and “near misses” that have occurred directly in connection with the operations of a ship that endangered, or, if not corrected, would endanger the safety of the ship, its occupants or any other person or the environment.

Considering the difficulty of collecting marine incident data, the above fourth category is not included in this study. For the ease of investigation into factors affecting accidents of high severity, marine accidents are categorized into three categories in terms of the accident severity. These are “very serious accidents”, “serious accidents” and “less serious accidents”.

3.2 Data

Accident investigation reports are a very important source to obtain complete and reliable accident data. Extracting information from accident reports can be time-consuming compared to obtaining data directly from existing databases, but it will bring more detailed information that can facilitate the use of primary data in maritime accident analysis. The investigation reports of maritime accidents are often available from maritime authorities. In this study, accident investigation reports prepared by different agencies such as Australian Transport Safety Board (ATSB), Federal Bureau of Maritime Casualty Investigation (BSU), China Maritime Safety Administration (China MSA), National Transport Safety Board (NTSB), Transportation Safety Board of Canada (TSB), Marine Accident Investigation Branch (MAIB) and Japan Transport Safety Board (JTSB) are used for data collection. The percentage of accident investigation reports from different agencies is given in Fig. 1. 1207 accidents that occurred in the period of 2000-2019 are analyzed, among which there are 87 collision accidents. Since each collision accident involves 2 ships, there are in total 1294 ships investigated in these investigation reports.

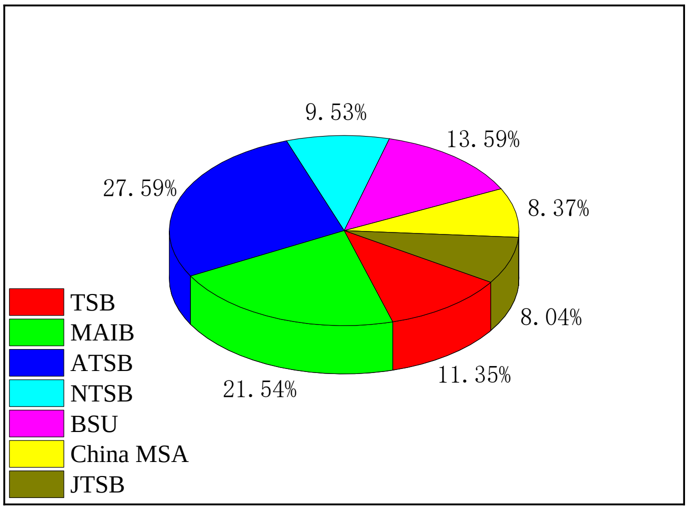

Fig. 1 The sources of marine accident investigation reports

These reports provide detailed information about each maritime accident investigated. Although the format and structure of accident investigation reports vary from agency to agency, the main elements contained in these reports are generally the same. Almost every report includes modules such as an executive summary, factual information, analysis, conclusions and recommendations. The factual information, which will be used in the study, includes the accident narrative (e.g. nature, injuries and damage), ship information, crew information, weather condition, environmental information, and training and qualifications. To make the analysis results accurate and effective, the following 6 factors are extracted, including accident types, human elements, ship types, ship conditions, environment conditions and accident severity levels.

Some accident investigation reports provide accident severity levels directly, while many other accident investigation reports only provide the information of the mortalities, the ship damage and/or the quantity of oil spills. Therefore, the severity of these accidents has to be determined based on the information obtained, which may lead to severity bias because the taxonomies and the criteria used in the accident reports vary across different authorities. To avoid such biases, the severity levels should be determined in line with the IMO's categorization. For example, if an accident involves the loss of the vessel, loss of any life/serious injuries or severe pollution (e.g. spill of 500 tons of oil [53]), then it is classified as a very serious casualty. If an accident involves any serious ship damage, any injuries or any environmental pollution (regardless of quantity), then it is categorized as a serious casualty. All other accidents belong to the less serious category. It is worth noting that accidents of the same severity level may have a wide range of consequences. For example, a loss of a fishing vessel may be less serious than a loss of five lives or a spill of 500 tons of crude oil in terms of the impact on the public and the financial penalties.

In this study, accident types are divided into seven categories: collision, grounding, fire/explosion, contact, sinking, equipment failure and others. Hereafter, a collision refers to the situation where a ship struck or was struck by another vessel on the water surface, regardless of whether the ship was under way, anchored or moored. Grounding means a situation where the ship was aground, or hitting/touching shore or sea bottom or objects on the sea floor. Contact is defined as a situation where a ship struck any fixed or floating objects other than those included under collision or grounding. Equipment failure includes machinery/hull damage or failure not caused by collision, grounding, contact or fire/explosion. Other types of accidents refer to any accidents not covered by the above categories, including occupational accidents and accidents due to miscellaneous non-classified reasons. As many as 10 ship types are considered in this study, including bulk carrier, container ship, oil tanker, passenger ship, chemical tanker, general cargo ship, fishing vessel, tug and harbor work boat, yacht and sailing vessel, and other ship types.

The factors under the umbrella of ship conditions include ship age, ship manning, the ship's certificates and seafarers' certificates. The human elements include detailed information with regard to sea experience, the period in present rank, human erroneous action and violation. Environment conditions include detailed information with regard to the visibility, wind, wave, accident location, and water depth. For the independent variables that can be categorized into several subclasses, such as sea experience (< 5 years, 5-10 years, > 10 years), ship age (< 10 years, 10-20 years, 20-30 years, > 30 years), et al., Pearson correlation and covariance tests are applied during the statistical analysis to check which factor may covariate with other factors. Those that are closely linked to one factor will be combined into one group in order to avoid variable covariance problems [13]. After several attempts, it is found that there exists no variable covariance problem if some changes on grouping are made. For example, in terms of sea experience, "5-10 years" and "> 10 years" are merged into one group "rich sea experience", and "< 5 years" is renamed as "less sea experience". In the same way, "ship age > 30 years" is defined as "old ships", "visibility > 5 nm" is defined as "good visibility", "wind force scale > 10" is defined as "strong wind", "current speed > 4 kn" is defined as "strong current", "h/d<1.2 (water depth to draft ratio<1.2)" is defined as "small water depth". Referring to the categories of accident location in the study of Weng et al. [56], the accident location is divided into two categories: “near the port”, if the distance to the port is less than 25 km; otherwise, “far away from port”.

In general, there are 511 very serious accidents, 449 serious accidents and 334 less serious accidents. The statistics of the variables used for the modeling of accident severity is shown in Table 1. The value “1” represents that the variable is related to the accidents of a certain severity level, while the value “0” represents that the variable is not related to the accidents of a certain severity level. The variable whose value is “0” is chosen as the reference group. The number of accidents of a certain severity level related or not related to the factor is then calculated. For example, there are 322 collision-related accidents, of which there are 94 less serious accidents, 164 serious accidents and 64 very serious accidents. There are 966 accidents related to “less sea experience”, among which 225 minor accidents, 335 serious accidents and 406 very serious accidents. It can also be concluded from Table 1 that collision and grounding are the primary accident types, bulk carrier and fishing vessel are the major ship types involved. The majority of very serious accidents occurred far away from ports and the seafarers involved have less sea experience.

Table 1 Variable description

Category	Variable	Values	Less serious accident	Serious accident	Very serious accident	Total
Accident types	Collision	1	94	164	64	322
		0	240	285	447	972
	Grounding	1	88	94	27	209
		0	246	355	484	1085
	Fire/explosion	1	24	59	50	133
		0	310	390	461	1161
	Contact	1	25	91	28	144
		0	309	358	483	1150
	Sinking	1	9	15	133	157
		0	325	434	378	1137
	Equipment failure	1	57	17	102	176
		0	277	432	409	1118
	Other accident types	1	37	9	107	153

		0	297	440	404	1141
Human elements	Poor theoretical knowledge	1	19	44	85	148
		0	315	405	426	1146
	Less sea experience	1	225	335	406	966
		0	109	114	105	328
	Human erroneous action	1	171	228	239	638
		0	163	221	272	656
	Violation in operation	1	183	191	212	586
		0	151	258	299	708
Ship Types	Bulk carrier	1	133	140	90	363
		0	201	309	421	931
	Container ship	1	44	56	36	136
		0	290	393	475	1158
	Oil tanker	1	26	41	24	91
		0	308	408	487	1203
	Passenger ship (including cruise/ro-ro passenger ship)	1	25	55	28	108
		0	309	394	483	1186
	Chemical tanker	1	13	14	9	36
		0	321	435	502	1258
	General cargo ship	1	9	12	21	42
		0	325	437	490	1252
	Fishing vessel	1	16	37	152	205
		0	318	412	359	1089
	Tug, harbor work boat	1	30	32	55	117
		0	304	417	456	1177
	Yacht and sailing vessel	1	15	26	40	81
		0	319	423	471	1213
	Other ship types	1	23	36	56	115
		0	311	413	455	1179
Ship conditions	Over 30 years of age	1	27	46	100	173
		0	307	403	411	1121
	Incomplete or invalid ship's certificates	1	10	18	37	65
		0	324	431	474	1229
	Inadequate ship manning	1	9	22	46	77
		0	325	427	465	1217
	Incomplete or invalid seafarers' certificates	1	12	17	52	81
		0	322	432	459	1213
Environment conditions	Far away from port	1	172	261	338	771
		0	162	188	173	523
	Good Visibility	1	130	197	293	620
		0	204	252	218	674
	Strong wind	1	2	4	20	26

	0	332	445	491	1268
Heavy sea	1	2	1	7	10
	0	332	448	504	1284
Strong current	1	10	12	31	53
	0	324	437	480	1241
Small water depth (h/d)	1	144	184	190	518
	0	190	265	321	776

Fig. 2 graphically indicates the accident severity distributions of different variables under various circumstances associated with the factors of accident types, human elements, ship types, ship conditions and environment conditions. It can be clearly seen that the accident severity distributions vary substantially among ship types and accident types. It can be observed from Fig. 2(a) that, in terms of accident types, sinking accounts for the largest proportion of very serious accidents, while contact accounts for the largest proportion of serious accidents. This may be closely related to the criteria of accident severity classification, by which sinking with total loss of ships is defined as very serious casualties. The largest proportion of very serious accidents are associated with fishing vessels, as shown in Fig. 2(c). It can be observed from Fig. 2(b) that the contribution of human elements increases with the accident severity level. Compared with poor theoretical knowledge, the distributions of other human elements in accident severity are relatively uniform. It implies that all kinds of human elements appeared in maritime accidents of different severity levels. In addition, the proportion of very serious accidents are larger for the conditions characterized by strong wind/current and heavy sea state. It can be observed from Fig. 2(d) that, in terms of ship conditions, the proportion of very serious accidents are higher than those of other severity levels, which means that poor ship condition is more likely to lead to very serious accidents.

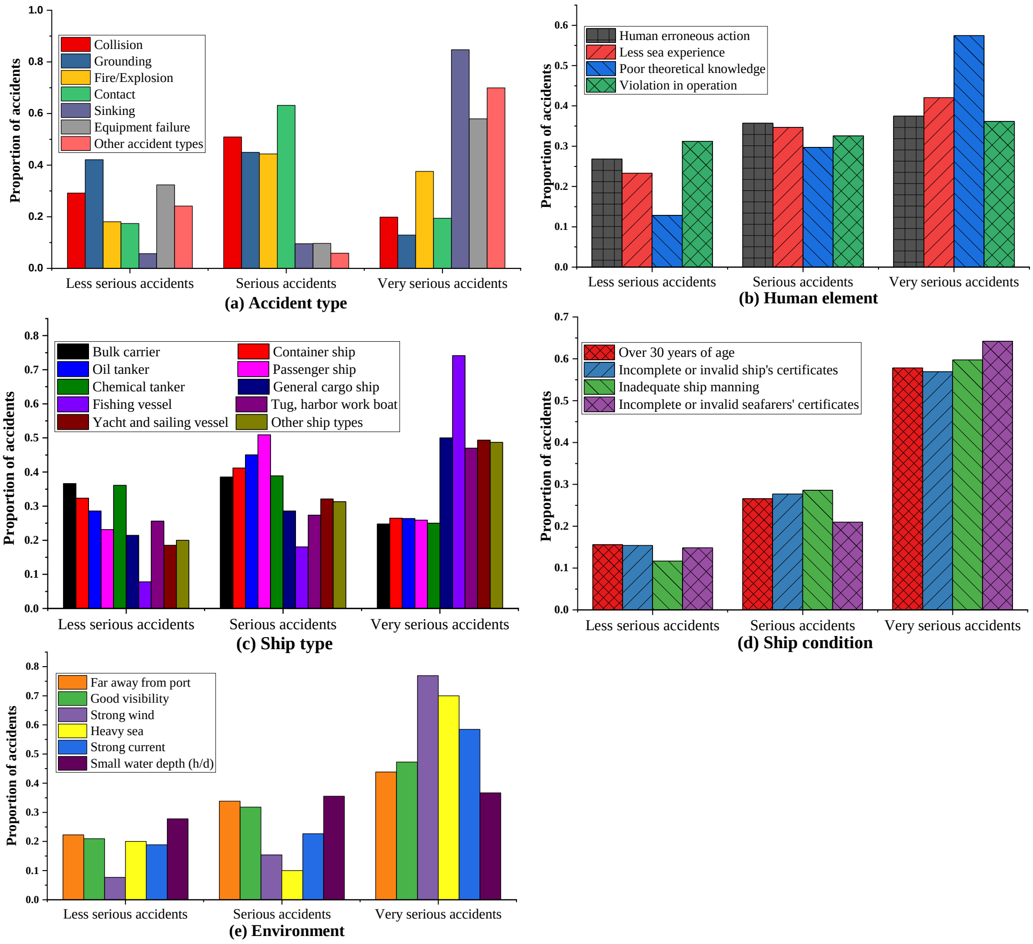

Fig. 2 Distributions of accident severity

3.3 Ordered logistic regression model

There are several approaches for logistic modelling. When the outcome represents an underlying continuous scale subdivided into several categories, the most adequate modelling framework is the cumulative approach [57]. Logistic regression is one of the most common and also simplest statistical approaches to model a categorical outcome variable in dependence of a set of predictor variables [13, 58]. An ordered logistic regression model is a commonly used one that extends a logistic regression model to take into account multiple classification dependent variables. The model is suitable for cases where the dependent variable is discrete and includes at least 3 ordered categories [59, 60].

In this study, the ordered logistic regression approach is applied to modelling the accident severity. The ordered logistic regression model for marine accident severity can be constructed by the following equation:

$$y^* = a + \sum_{i=1} \beta_i x_i + \varepsilon_i \tag{1}$$

where y^* is a vector of variables determining the discrete ordering of severity for each accident, a is the intercept, x_i represents the influencing factors of accident severity, β_i is a vector of estimable parameters, and ε_i is a random error term.

When the dependent variable (accident severity) has *J* categories ($j = 1, 2, \cdots, J$), for example, the severity of the accident is divided into less serious accidents ("1"), serious accidents ("2"), and very serious accidents ("3"), there are $J-1$ threshold μ_j to distinguish the adjacent categories. The regression equation can be expressed as follows:

$$\begin{aligned} \ln\left[\frac{P(y \le j|x)}{1-P(y \le j|x)}\right] &= \ln\left[\frac{P(y^* \le \mu_j|x)}{1-P(y^* \le \mu_j|x)}\right] \\ &= \mu_j - (a + \sum_{i=1} \beta_i x_i) \\ &= \beta_{0j} - \sum_{i=1} \beta_i x_i \end{aligned} \tag{2}$$

where, β_{0j} is the synthesis of the intercept a and the threshold μ_j of the dependent variable.

Since the dependent variable is an ordered multiple classification variable, an ordered logistic regression model containing 2 cumulative logit functions can be established and estimated during data analysis. The cumulative logit functions can be formulated as follows:

$$\begin{aligned} \ln\left(\frac{P_3}{P_1 + P_2}\right) &= \beta_{01} - \sum_{i=1} \beta_i x_i \\ \ln\left(\frac{P_2 + P_3}{P_1}\right) &= \beta_{02} - \sum_{i=1} \beta_i x_i \end{aligned} \tag{3}$$

where P_1, P_2 and P_3 represent the occurrence probability of less serious accidents, serious accidents and very serious accidents, and $P_1 + P_2 + P_3 = 1$. Eq. (3) represents the logarithmic occurrence ratio of "very serious accidents" to pairs of "less serious accidents" and "serious accidents" (P_3 vs. P_1 & P_2), and the logarithmic occurrence ratio of pairs of "serious accidents" and "very serious accidents" to "less serious accidents" (P_3 & P_2 vs. P_1).

In the analysis, there are different estimates β_{0j} for each of the *J-1* logits in the ordered logistic regression model. However, there is only one estimate β_i for the variable x_i because it is assumed that the coefficients of the independent variables in the multiple regression equations are the same and only the intercept parameters are different. Therefore, the parallelism test, also known as the ratio hypothesis test, should be carried out on the ordered logistic regression model. The established ordered logistic regression model is only effective when the null hypothesis that the coefficients of all variables are not equal is rejected, that is, the result of the parallelism test is $p > 0.05$ [61, 62].

The sign of estimation parameter β_i can explain the positive or negative influence of influencing factors. Positive numbers mean positive influence and negative numbers mean negative influence, but either can indicate the degree of influence [13]. Odd ratio (OR) can represent the marginal effect of a certain factor, that is, under the condition that other factors remain unchanged, the independent variable increases or decreases 1 unit, the change degree of the dependent variable. The odd ratio can be defined in Eq. (4).

$$OR = e^{\beta_i} \quad (4)$$

4. Results and discussion

4.1 Univariate statistical analysis results

Univariate statistical analysis can describe or deduce the quantitative characteristics of a variable, and reflect the basic information contained in a large number of data in a simplest way. One of the mostly widely used univariate statistical techniques is the quasi-induced exposure technique, which is usually applied to measure the relative propensity of different groups [13, 63]. To explore the impacts of accident types, human elements, ship types, ship conditions and environment conditions on maritime accident severity, the proportion of accidents of a certain severity level are compared with those of different severity levels under the influence of a certain factor. Similar to the relative human error ratio [13], the relative accident severity ratio (RASR) is thus adopted to measure the relative effect of the above factors, which is defined as:

$$RASR_{k,i}^{m} = \frac{N_{k,i}^{m} \Big/ \sum_{j=1}^{n_i} N_{j,i}^{m}}{N_{k,i}^{0} \Big/ \sum_{j=1}^{n_i} N_{j,i}^{0}} \tag{5}$$

where $RASR_{k,i}^{m}$ is the relative ratio of the *m*th accident severity level under the *k*th condition for variable *i*; n_i is the number of conditions associated with the variable *i*; $N_{k,i}^{m}$ is the number of accidents of the *m*th accident severity level under the *k*th condition for variable *i*; $N_{k,i}^{0}$ is the number of accidents not of the *m*th accident severity level under the *k*th condition for variable *i*. According to the above definition, an accident more likely belongs to the *m*th accident severity level if $RASR_{k,i}^{m} > 1.0$, and less likely belongs to the *m*th accident severity level if $RASR_{k,i}^{m} < 1.0$.

Fig. 3 depicts the relative accident severity ratio for different situations characterized by accident types, human elements, ship types, ship conditions and environment conditions. It can be inferred that the accident severity level is closely related to human elements and environment conditions. Fig. 3(b) shows that the RASRs for “less sea experience” are larger than 1.0, indicating that accidents of all severity levels are more likely to occur if the officers on watch have less sea experience. Similarly, Fig. 3(e) also shows that the RASRs for “far away from port” are larger than 1.0, indicating that accidents of all severity levels are more likely to incur far away from port. Moreover, one interesting finding is that the RASRs for "good visibility" are larger than 1.0 for very serious accidents, illustrating that good visibility is closely associated with very serious accidents.

However, the above quasi-induced exposure technique only allows the analysis of a single categorical factor at a time. This may lead to biased or incorrect results due to the isolation of a single factor for analysis while other factors are held fixed [13, 63]. Moreover, the significance and influence degree of the influencing factors cannot be revealed in univariate statistical analysis. In reality, the accident severity may be affected by multiple factors at the same time. Thus, it is necessary to study the influence of various factors on marine accident severity.

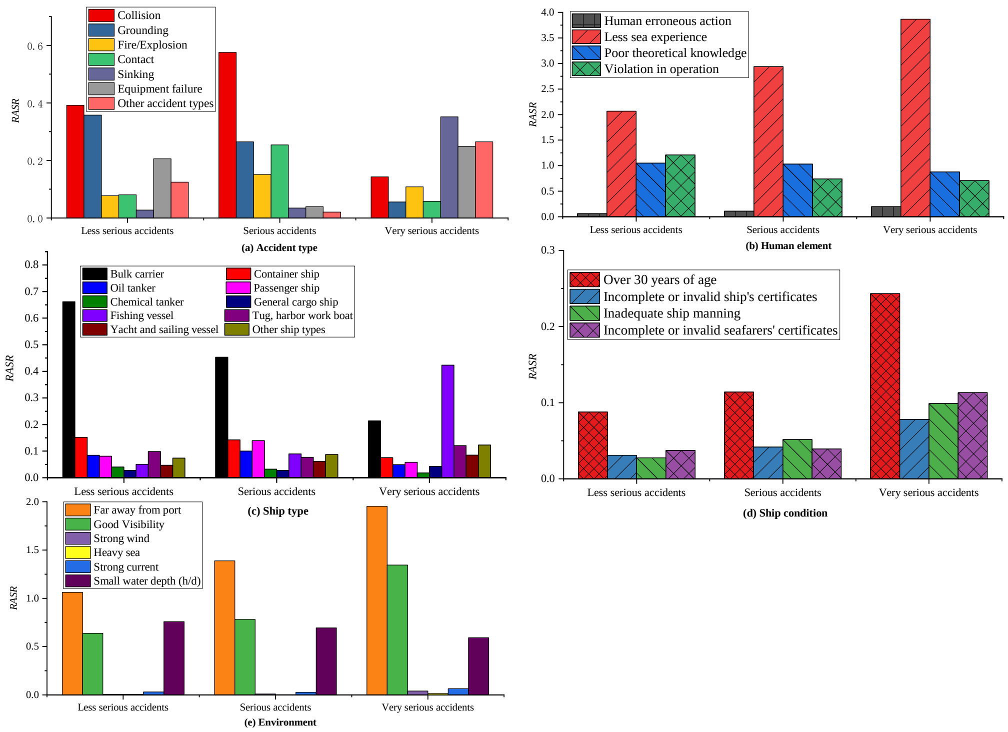

Fig. 3 Relative severity ratios of different influencing factors

4.2 Ordered logistic regression model results

The logit procedure in the Statistical Product and Service Solutions (SPSS, 22.0; Armonk, NY: IBM Corp) is applied to estimate the coefficients of independent variables for the ordered logistic regression model. Taking the 31 variables described in Table 1 as independent variables, accident severity levels as dependent variables, a series of ordered logistic regression models are established using Eqs. (1), (2) and (3). Categorical variables, such as ship age, are treated as dummy variables before the analysis. Chi-square statistics are used to verify the model and Wald chi-square statistics are used to check the variable significance. This study only shows the influencing factors that have passed the parallelism test (see Appendix A) and whose influence is statistically significant ($p < 0.1$), as shown in Table 2.

Among accident types and human elements, at a 99% confidence level, the effects of sinking, poor theoretical knowledge and less sea experience on accident severity have statistical significance. As to ship types, at a 90% confidence level, 7 ship types, such as bulk carrier, oil tanker, fishing vessel, et al., are statistically associated with accident severity. Among these 7 ship types, the regression coefficients of bulk carrier, oil tanker, container ship and chemical tanker are negative, suggesting that such ship types have negative effects on accident severity and are rarely involved in serious and very serious accidents. The regression coefficients of fishing vessel, yacht and sailing vessel, other ship types are positive, indicating that these ship types have positive effects on accident severity. In particular, the regression coefficient of fishing vessels is the largest (1.742), indicating that the proportion of fishing vessels involved in serious accidents and very serious accidents are the highest. This may be explained by the fact that most fishing vessels are small, thus it is more likely to lead to total loss of the ship if an accident happens.

With regards to ship conditions, at a 95% confidence level, the effects of the 4 sub-factors on accident severity have statistical significance. The regression coefficient is positive, suggesting that ship conditions have a positive effect on accident severity. Thereinto, the regression coefficient of invalid seafarers' certificates is the largest (1.017), which indicates that the factor "invalid seafarers' certificates" has the strongest association with serious and very serious accidents. It is easy to understand that invalid certificates mean competent seafarers are not guaranteed. As to environment conditions, at a 90% confidence level, the effects of the 6 subclass variables on accident severity have statistical significance. Except the factor of small water depth, the regression coefficients of the other factors are positive, suggesting that small water depth has a negative effect on accident severity and the other factors have a positive effect on accident severity. The regression coefficient of strong wind is 1.644, indicating that it has a strong correlation with serious and very serious accidents.

Table 2 The results of ordered logistic regression analysis of accident severity

Category	Variable	Coefficient	Standard error	Wald	p-value
Accident types	Sinking	2.374***	0.228	108.783	< 0.001
Human elements	Poor theoretical knowledge	0.849***	0.171	24.754	< 0.001
	Less sea experience	0.461***	0.118	15.226	< 0.001
Ship types	Bulk carrier	-0.828***	0.116	51.002	< 0.001
	Oil tanker	-0.392**	0.200	3.830	0.050
	Container ship	-0.500**	0.167	8.943	0.003
	Chemical tanker	-0.580*	0.312	3.454	0.063
	Fishing vessel	1.742***	0.169	106.180	< 0.001
	Yacht and sailing vessel	0.436**	0.217	4.044	0.044
	Other ship types	0.397**	0.184	4.659	0.031
Ship conditions	Over 30 years of age	0.827***	0.159	27.093	< 0.001
	Incomplete or invalid ship's certificates	0.730**	0.247	8.701	0.003
	Inadequate ship manning	0.900***	0.233	14.914	< 0.001
	Incomplete or invalid seafarers' certificates	1.017***	0.231	19.297	< 0.001
Environment conditions	Far away from port	0.453***	0.105	18.550	< 0.001
	Good visibility	0.576***	0.104	30.651	< 0.001

Strong wind	1.644***	0.463	12.595	< 0.001
Heavy sea	1.114*	0.660	2.852	0.091
Strong current	0.714**	0.272	6.873	0.009
Small water depth (h/d)	-0.187*	0.105	3.179	0.075

* $p < 0.1$ (two-tailed), statistically significant at the confidence level of 90%;

** $p < 0.05$ (two-tailed), statistically significant at the confidence level of 95%;

*** $p < 0.01$ (two-tailed), statistically significant at the confidence level of 99%;

4.3 Marginal effects of influencing factors

Although the signs of the estimated coefficients for the ordered logistic regression model could provide information on whether changes in given variables increase or decrease the occurrence likelihood of marine accidents of a certain severity level, they do not provide information on the extent to which the underlying accident probabilities change. For example, there is a critical need to examine the impact of changes in the influencing factors on the occurrence probability of very serious accidents. In this study, the odds ratio (OR) is employed to represent the marginal effect for a given variable that is defined as the relative amount by which the odd ratios of accident severity increase or decrease when the corresponding variable's value increases by one unit. The marginal effects of influencing factors on the occurrence likelihood of maritime accidents across different accident severity levels are calculated using Eq. (4), and the results are presented in Fig. 4. For each variable, Fig. 4 shows the ratio of occurrence likelihood of adjacent severity levels (very serious vs. serious, and serious vs. less serious) in the presence of the variable, compared to the case without the presence of the variable. For clarity, the marginal effect results are discussed according to the categories mentioned earlier.

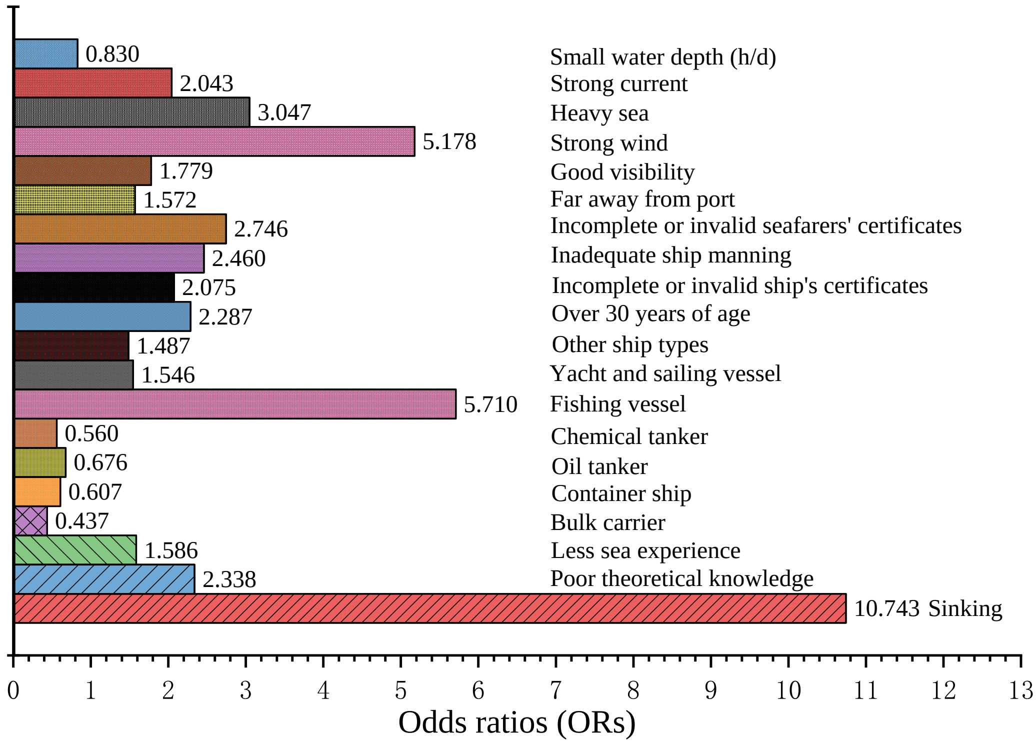

Fig. 4 The marginal effects of influencing factors on the occurrence likelihood of accident severity

4.3.1 Marginal effects of accident types and location

Fig. 4 shows that higher accident severity levels are closely associated with sinking (OR=10.743), which implies that the severity of sinking accidents is 10.743 times higher than that of accidents not related to sinking. Previous findings [11, 64] found that grounding and sinking are the major influential factors of the total-loss marine accidents in the world. Weng et al. [56] found that sinking can cause the highest loss of life compared to all other accident types. Weng et al. [65] and Jin [14] also found that sinking is strongly connected with crew injury severity. The significantly high severity level of sinking accidents can possibly be explained by the criteria of accident severity classification of the IMO, by which casualties to ships involving total loss of the ship or loss of life are classified as very serious casualties, while those resulting in severe structural damage rendering the ship unfit to proceed, a breakdown necessitating towage or shore assistance are classified as serious casualties. In fact, due to the limited reaction time, a large proportion of sinking accidents, especially those involving small vessels, usually lead to total loss of ships and/or loss of life. In order to prevent sinking accidents, ship safety inspection should be strengthened to ensure that ships are in good condition. In addition, training is also required to ensure that seafarers can respond quickly and correctly in the event of a sinking accident.

Another finding from Fig. 4 is that accident location also has a significant influence on accident severity. The OR associated with "far away from port" is higher than 1.0, suggesting that the severity level of accidents occurring far away from port water area is 1.572 higher than that of accidents occurring near port water area. The result is consistent with previous research findings [12, 56, 65] that more fatalities are caused by accidents that occur far away from port. Jin [14] also found that if the accident location is further offshore, the probability of total loss of the fishing vessel becomes higher. This may be explained by the fact that it takes time for professional maritime rescue forces to arrive at the scene if the accident occurs far away from port. Another possible reason is that the watch-keeper will be less vigilant in ocean waters so that the emergency response to accidents is not adequate. Therefore, more emphasis should be put on careful navigation behaviors for the ship sailing far from port, which can greatly reduce the accident severity level within this area. However, it should be noted that different types of accidents may have different patterns in terms of locations. Goerlandt et al. [33] analyzed winter navigation in the Northern Baltic Sea area and found that groundings occurred in port areas and archipelagic waterways, and that collision occurred in open sea areas and archipelagic waterways.

4.3.2 Marginal effects of human elements

Human elements have been widely accepted as the main contributors to maritime accidents. Among the human elements, poor theoretical knowledge and less sea experience are found having significant effects on the accident severity. More specifically, ships whose seafarers involved in accidents have poor theoretical knowledge have a 233.8% higher probability of accidents of higher severity levels (OR=2.338 for poor theoretical knowledge), while those with less sea experience have a 158.6% higher probability of accidents of higher severity levels (OR=1.586 for less sea experience). The result is in line with the findings from the study of Xu and Wu [66] where seafarers' age, maritime education, time in present position and the experience at sea were found to be associated with the occurrence of marine accidents of different severity levels. In order to mitigate the influence of such human elements on the occurrence of accidents, it is necessary to improve the maritime education quality and provide knowledge update training regularly. In addition, supervision over the sea experience should be strengthened to ensure the competency of seafarers for their current positions.

4.3.3 Marginal effects of ship types

Ship types have a significant effect on accident severity. Fig. 4 reveals that accident severity is most likely to be associated with fishing vessels (OR=5.71), followed by yachts and sailing vessels (OR= 1.546) and then other vessels (OR=1.487). Fishing vessels, yachts and sailing vessels are the primary ship types which have relatively higher accident severity levels because their corresponding ORs are larger than the ones of other ship types. It suggests that marine accidents involving fishing vessels, yachts and sailing vessels are more likely to lead to serious consequences. The result is evidenced by the studies of Bye and Aalberg [30], which found that ship categories have a statistically significant influence on the outcome of accidents. The study of Goerlandt et al. [33] also found that cargo ships are most frequently implicated in all accident types. This may be explained by the fact that these ships are usually small and the professional quality of their crew members is relatively low. In addition, fishing vessels had more reports of alcohol use and fatigue than merchant ships [67, 68].

From Fig. 4, it can also be seen that chemical/oil tankers are less likely to have serious or very serious accidents as the ORs for these ship types are smaller than 1.0.

This result is consistent with our expectation because the crew members are more vigilant in shipping operations considering the characteristics of oils or other hazardous/dangerous liquid goods. However, the result seems contradictory with the findings of previous research of Chen et al. [11]. They argued that the LPG, Ro/Ro and Chemical tankers were the ship types most closely related to the total-loss marine accidents in the world. One possible reason might be that there is a large gap in the proportion of fishing vessels in the data we used in our studies. In addition, their research focused on the analysis of influencing factors for the total loss accidents, while very serious accidents in our study include the total loss of the ship, loss of life and environment pollution.

4.3.4 Marginal effects of ship conditions

Many studies (e.g., Talley et al. [69]) reported that ship conditions could impact ship accident consequence significantly. Actually, the marine accident severity is greatly affected by ship conditions. In general, accident severity is most likely to be associated with incomplete or invalid seafarers' certificates (OR=2.746), followed by inadequate ship manning (OR= 2.460), over 30 years of age (OR= 2.287) and incomplete or invalid ship certificates (OR=2.075), as shown in Fig. 4. The results are supported by the studies of Jin [14] and Li [70], which also found that vessel age and the probability of the total loss of a ship are highly correlated. The study of Baniela and Vinagre-Rios [71] indicates a positive correlation between ship age and accident severity, while that of Ventikos et al. [72] shows that most of the ships involved in accidents are over 25 years old. However, the relationship between accident severity and ship age is proved more complex than it was usually thought. The study of Li et al. [73] even suggests that an increase in vessel age is associated with an increase in the vessel safety level, which is contrary to our findings. Incomplete or invalid ship certificates (i.e. certification(s) or legal paper(s) are missing or outdated) is believed to affect the working environment, especially the attitude the crew has towards safety on-board [74]. Inadequate ship manning levels are also believed to have important influences on seafarers' fatigue [75]. Therefore, major efforts should be placed in Port State Control (PSC) inspections and company management in order to ensure the validity and adequacy of ships' certificates, seafarers' certificates and ship manning. In addition, the management of old ships should also be enhanced to mitigate the occurrence of serious or very serious accidents. Good management and timely maintenance can keep old ships in good condition, which could ultimately reduce the occurrence of accidents due to ship conditions.

4.3.5 Marginal effects of environment conditions

Among the sub factors of environment conditions, strong wind, heavy sea and strong current are found having close relevance with accident severity, especially strong wind, whose OR value is 5.178. This result implies that the severity of accidents under strong wind condition is 5.178 times higher than those not under strong wind condition. This result is consistent with the previous finding [14] that an increase in daytime wind speed obviously increases the probability of the total loss. Similar to the factor of strong wind, the factors of heavy sea and strong current are also found having significant effects on accident severity. More specifically, the severity level is 204.7% higher for accidents under heavy sea (OR= 3.047 for heavy sea) and 104.3% higher for accidents under strong current (OR=2.043 for strong current). This result is consistent with the previous finding [14] that the damage severity of fishing vessel is significantly affected by weather conditions. The study of Weng and Yang [12] and Pitman et al. [76] also indicate that a large number of mortalities are associated with adverse weather conditions. Therefore, particular attention should be paid to ships sailing under severe weather conditions, especially small vessels with poor resistance to wind and waves, such as fishing vessels. In addition, small water depth is found negatively related with accident severity (OR=0.83), implying that the severity of accidents in deep waters is larger than that in shallow waters. This can be probably explained that the vessels in shallow waters are usually not far from the port, thus shore assistance and rescue can be easily accessed in the case of accidents.

Interestingly, it is found that the presence of good visibility could increase the accident severity level, which is not consistent with our expectation. Fig. 4 shows that the OR associated with good visibility is 1.779, implying that the severity level of accidents in good visibility is 1.779 times higher than those in poor visibility. The result might be explained by the fact that ships usually proceed at a relatively higher speed in good visibility and the watch-keepers on the bridge and neighboring vessels are less vigilant. It may be more likely for the lookout to neglect the potential hazards under the good visibility condition. For instance, it is found that the proportion of accidents involving lookout failures in good visibility are about twice of that in poor visibility [33]. The finding, however, seems contradictory with the findings of Chauvin et al. [77], which indicates that marine navigational accidents are associated with low visibility. Bye and Aalberg [30] also reveal that poor visibility conditions increase the probability of a navigational accident. However, the number of grounding and collision accidents in restricted visibility might decrease significantly with the introduction of unmanned ship [78].

4.4 Validity considerations

The data used in this analysis is based on accident investigation reports from seven agencies. The validity of such data influences the validity of the parameters related to the severity of marine accidents. However, potential biases related to accident investigation reports as the primary source of data still exist because the taxonomies and the criteria used in the accident reports vary across different authorities. Thus, the severity bias of these accidents may be introduced. The use of maritime accident reports from seven different sources makes the situation even worse.

Further, the degree of underreporting may also influence the validity of this analysis. In general, the reliability of accident analysis results may be affected by the proportion of missing data. Previous studies [50, 51] show that underreporting of accidents is rather common within the maritime industry. It is noted that a certain degree of underreporting exists in these agencies publishing maritime accident investigation reports.

5. Conclusions

This study employed an ordered logistic regression technique to evaluate the relationship between the marine accident severity and the corresponding contributory factors. The study was conducted based on the data extracted from 1207 marine accident investigation reports from 2010 and 2019 in the global context. With reference to the IMO's recommended categories of ship casualties, the marine accident severity was classified in 3 categories, namely less serious accidents, serious accidents, and very serious accidents. The effects of the influencing factors on each marine accident severity level were examined in this study.

The results of the study demonstrate that the marine accident severity is positively associated with the following factors: (i) sinking; (ii) far away from port; (iii) fishing vessels, yachts and sailing vessels, and other ship types; (iv) incomplete or invalid seafarers' certificates, inadequate ship manning, incomplete or invalid ship certificates and/or over 30 years of age; (v) strong wind, heavy sea, strong current and/or good visibility; (vi) poor theoretical knowledge and less sea experience. The accident severity is negatively related to (i) small water depth; (ii) chemical tankers, oil tankers, container ships and/or bulk carriers. From the results, it can be concluded that it is critical to prevent ships from sinking when an accident occurs so that the accident severity can be reduced significantly. In addition, due attention should be paid to fishing vessels, especially those operating under adverse weather and far away from port. The above results can provide helpful information for the policy-makers to develop effective countermeasures for accident prevention.

However, these results should be treated with caution due to the possible impact of underreporting and the potential biases related to the determination of accident severity. Despite the above deficiencies, this paper has also shown some limitations.

One limitation of this study is that it focuses more on objective variables and concerns little on human elements. To address this concern, data relating to human elements should be derived from accident reports and their impacts on marine accidents should be analyzed in the future. In addition, due to data limitation, management/organizational contributing factors, such as safety management and occupational health management, were not included in the collected marine accident reports. The analysis of the relationship between management factors and accident severity should be conducted after collecting relevant data.

Appendix A

Appendix-Table A1 The results of parallel line test of ship damage

Category	Variable	Chi-square	Sig.
Accident type	Sinking	2.553	0.110
Human element	Poor theoretical knowledge	0.273	0.601
	Less sea experience	0.196	0.658
Ship type	Bulk carrier	1.528	0.216
	Oil tanker	3.784	0.052
	Container ship	2.110	0.146
	Chemical tanker	0.241	0.623
	Fishing vessel	0.528	0.468
	Yacht and sailing vessel	0.006	0.938
	Others	0.053	0.818
Ship condition	Over 30 years of age	0.531	0.466
	Incomplete or invalid ship's certificates	0.043	0.836
	Inadequate ship manning	0.179	0.672
	Incomplete or invalid seafarers' certificates	1.399	0.237

Environment	Far away from port	0.007	0.934
	Good visibility	1.150	0.284
	Strong wind	0.103	0.748
	Heavy sea	1.714	0.190
	Strong current	1.350	0.245
	Small Fairway depth (h/d)	0.040	0.841

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Disclaimer

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