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Probabilistic approach for collision risk analysis of powered vessel with offshore platforms

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ABSTRACT: The continuous increase in marine traffic and the construction of several offshore installations has led to a serious concern regarding the risks to offshore platforms from ship collisions. The main aim of this study was to carry out a probabilistic collision-risk analysis for offshore platforms exposed to powered collisions with passing vessels using an automatic identification system (AIS) database. The paper first describes the statistical distribution of the ship traffic under study and then considers how this information can be effectively used to estimate collision frequencies and impact energies for various categories of vessel, based on a simple probabilistic method. The effects of various collision mitigation measures, such as the use of enhanced collision alarming devices and the ability of platforms to rotate using thrusters, are considered in the frequency calculations. The risk method presented in this paper can be applied in the design and development phase of both new and existing platforms.

Keywords: Ship–platform collision, Probabilistic risk method, AIS database, Powered collision, Collision frequency.

1. Introduction

Over time, the ocean has become busy with various types of vessels and offshore platforms. To meet the continuous increase in the demand for hydrocarbons, exploration and drilling have increased, several offshore structures have been constructed, and new ships and shipping routes have been introduced. Because marine transportation remains the cheapest way to transport cargo, there is increasing concern about collisions between vessels and offshore structures.

The risk of collision with offshore platforms is increased in areas of dense ship traffic, such as near coastal areas or naval bases. Effective planning of ship traffic is needed, along with more stringent rules and regulations for marine activities around platforms, from the planning and exploration stages to the operational stage of platform deployment.

Fig. 1. Ship and offshore platform collision accidents (a) Mumbai High North complex platform accident arising from attendant vessel collision (Daley, 2013); (b) capsize of a monopod platform after a collision in Madura Island, Indonesia (Widjaja et al., 2013); (c) passing vessel *Marbella* after collision with an accommodation platform (MAIB, 2003) (d) accident statistics based on vessel type.

The ships that collide with offshore platforms can be generally classified as visiting vessels or passing vessels (Vinnem, 2007; Moan et al., 2002). The vessels that visit platforms, such as supply boats, service vessels, and shuttle tankers that routinely berth at the offshore facilities, contribute significantly to collision accidents. Fig. 1 (a) shows the total loss of the Mumbai High North complex platform in July 2005 after a collision with a multipurpose support vessel, and Fig. 1 (b) shows the capsize of a monopod platform after a boat collision. Passing vessels may also pose a serious threat, especially if the offshore facility is located within a frequently sailed route (see Fig. 1 (c)) (Paik and Thayamballi, 2007). Fig. 1 (d) shows the distribution of the types of vessel involved in collision accidents according to the Worldwide Offshore Accident Databank (WOAD), obtained from the International Association of Oil and Gas Producers (2010). It shows that nearly 23% of the total collision accidents involved a passing vessel. A study of the United Kingdom continental shelf (UKCS) found that passing-vessel collisions occur an average of once every 2 years (Oil & Gas UK, 2010).

The estimation of collision risk requires the quantification of credible collision frequency and associated consequences, which is integral to the safe design and robust building of a platform (Bai and Wei-Liang, 2015). DNV (2002) classified risk assessment techniques into qualitative, semi-qualitative and quantitative techniques. Quantitative risk assessment (QRA) is considered to be the most sophisticated numerical technique that can provide useful guidance for predicting collision accidents, but it is associated with a large degree of uncertainty and requires expert judgement.

Based on the extent of damage to the structures, a collision event can be categorised as minor or major collision. A minor collision is characterised by only repairable damage of the structure and probably will not call for cease of operation. On the other hand, a major collision will damage the platform globally and most certainly require a cease of operation.

However, it seems extremely uneconomical to design a platform to withstand a major collision and remain operational. Therefore, in order to practically while at the same time economically solve the offshore collision problems the probability of major collisions should be kept at a low level by defining adequate preventive measure and minor ones should be considered in the design stage of the platform. This is the design concept of offshore structures against collision adopted by many classification societies.

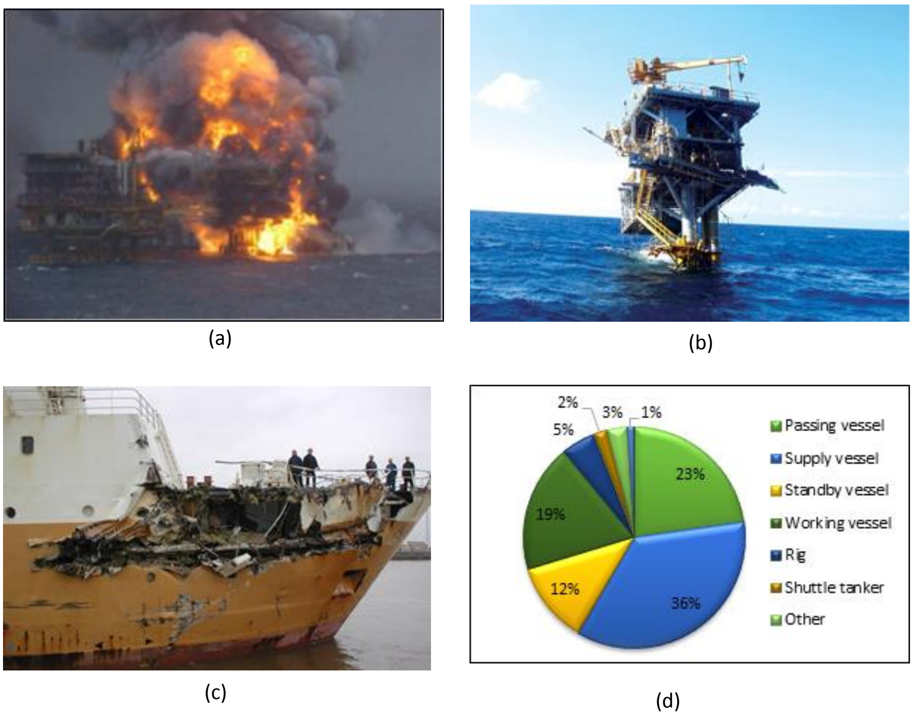

Fig. 1. Ship and offshore platform collision accidents (a) Mumbai High North complex platform accident arising from attendant vessel collision (Daley, 2013); (b) capsize of a monopod platform after a collision in Madura Island, Indonesia (Widjaja et al., 2013); (c) passing vessel *Marbella* after collision with an accommodation platform (MAIB, 2003) (d) accident statistics based on vessel type.

Most studies on the estimation of collision frequency have taken a scenario-based approach, which uses historical accident databases such as WOAD (DNV.GL). Extensive accident reports and statistical analyses are recorded for the UKCS by the UK Health and Safety Executive (HSE) (see DNV 2007a, 2007b; Robson (2003)). Muncer (2003) analysed accident statistics for floating production storage and offloading (FPSO) and floating storage unit (FSU) structures from 1996 to 2002 and compared them with fixed installations in the UKCS area. The study revealed a 5% increase in the number of FPSO/FSU structures. The UK Offshore Operators Association (UKOOA) (2002) concluded that the collision probability for an FPSO subjected to passing traffic is increased due to the increased length of the FPSO, combined with a shuttle tanker, compared to fixed platforms. Furnes and Amdahl (1980) developed a drifting vessel collision-risk model for a shuttle tanker colliding with an offshore platform using Monte Carlo simulation techniques.

Ship traffic databases are also used for estimating passing-vessel collisions. Automatic identification systems (AIS) are considered to be the most advanced and efficient tools for tracking vessel movements, providing up-to-date information on location, heading, course and other details of the ship. Since 2002, IMO regulations have required new ships and all larger seagoing vessels (greater than 300 gross tons) and all passenger vessels to carry AIS on board (IMO, 2001). The AIS messages are transmitted from ship to ship and ship to port using very high frequency (VHF) radio wave signals in a limited geographical space (Eriksen et al., 2006). There are two methods by which AIS tracks ship movements: terrestrial and satellite. Terrestrial AIS is cheaper, but satellite AIS is more useful when a vessel is in open seas and out of range of the network of terrestrial AIS receivers.

Most studies have used AIS marine traffic information to study ship-ship collision probability. Several researchers have used AIS information to analyse safety and the risk of ship collisions in busy sea areas such as the Singapore Strait (Qu et al., 2011), the Gulf of Finland (Goerlandt and Kujala, 2011) and the Malacca Strait (Zaman et al., 2015). Xiao et al. (2015) analysed and compared AIS data for narrow and wide waterways. Zhang et al. (2016) proposed an advanced method to detect possible near-miss ship collisions using AIS data. All of these researchers studied ship-ship collisions; there have been very few studies of ship–platform collision frequency using AIS information (Haugen, 1998). Recently Hassel et al. (2017) used AIS data to study change in passing vessel traffic pattern found before and after platforms were installed and concluded that the current risk assessment practices are overly conservative.

Several commercial software programs are available for estimating collision risk, such as COLLIDE (Safetec), COLLRISK (Anatec UK Ltd.), Computerised Risk Assessment of Shipping Hazards (CRASH) (DNV), SOCRA (MARIN) and COLWT (GL). With the objective of harmonising various assumptions followed in the models, Safeship (2005) compared the models of MARIN, GL and DNV.

The existing software is based on model assumptions; however, improvements taking into account the advanced technologies now in use and the stricter rules and regulations have not been made. For instance, Hassel et al. (2014) highlighted improvements required in the collision-risk model, which was introduced about 20 years ago for the Norwegian continental shelf (NCS), and noted that the ability of the platform to physically get out of the way of a vessel on a collision course was not considered and that there was also inaccurate modelling of the failure factors considered for both the ship and offshore platform.

Geijerstam and Svensson (2008) also reviewed various risk models and concluded that ship watchkeeping failure is the main factor in collision risk. Flohberger (2010) concluded that passing-vessel accidents have not been reduced, despite the introduction of modern technology, because the majority of collisions reported are caused by watchkeeping failures. Upgrading collision-risk software to take account of technological advancements remains a major challenge.

The main objective of this paper is to present a simple probabilistic collision-risk analysis method for offshore platforms subjected to a powered collision by a passing vessel, using a real ship traffic data. A detailed statistical assessment of a traffic database is presented and a simple probabilistic method is used by following a real industrial procedure to estimate the collision frequency, considering various causal factors and the collision mitigation measures in place.

A case study uses ship traffic data in the vicinity of the Busan coast. The database provides information regarding the general trends for the various types of ship traversing the sea, which in turn provides an estimation of all possible threats to the platform. Finally, collision frequency and the corresponding impact energy curves are derived for the various categories of vessel identified in the database.

2. Collision risk assessment

Offshore platforms located in heavy ship traffic regions demand a comprehensive quantitative collision-risk model. Fig. 2 shows the general procedure for performing a QRA of ship to offshore platform collision following IMO (2002). Although the concept of 'risk' is referred to in the paper, the current study mainly focuses on risk analysis, i.e., the quantification of collision frequency and impact energy, using marine traffic data to obtain a frequency vs. impact energy exccedance curve for each collision scenario (shown as red boxes in Fig. 2).

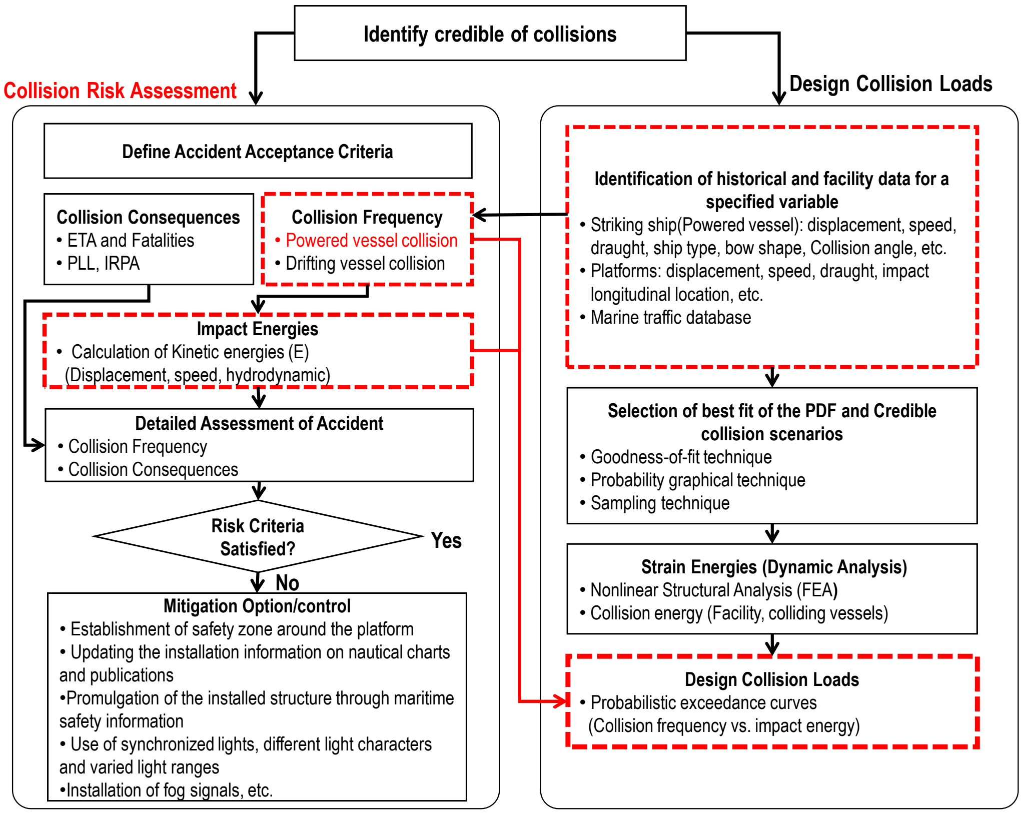

Fig. 2. Risk assessment flowchart for ship to offshore platform collision.

2.1 Collision description

Fig. 3 depicts the major elements involved in ship to platform collision accidents. These include geographical location, type and age of the platform, density and mode of operation of the colliding ship; collision mitigation measures on platforms, such as an automatic radar plotting aid (ARPA), vessel traffic service (VTS) and standby vessel (SBV); external environmental conditions such as wind, wave, current, tide and visibility; and navigational control failures such as human error or mechanical or watchkeeping failure. These parameters are not always independent. For instance, a collision may be due to a communication error between the platform and the ship's crew members and bad visibility leading to watchkeeping failure.

The probability of collision from a ship-initiated recovery failure is higher than that of a platform-initiated recovery failure, as ships are in dynamic motion, whilst platforms are either moored or fixed in place. Because the current study deals with collisions by passing vessels, the influence of external factors such as wind, wave, current and tide are not considered, and human factors or equipment failure are assumed to be the major causes of accident. However, bad visibility due to fog or heavy rain leading to watchkeeping failure is considered.

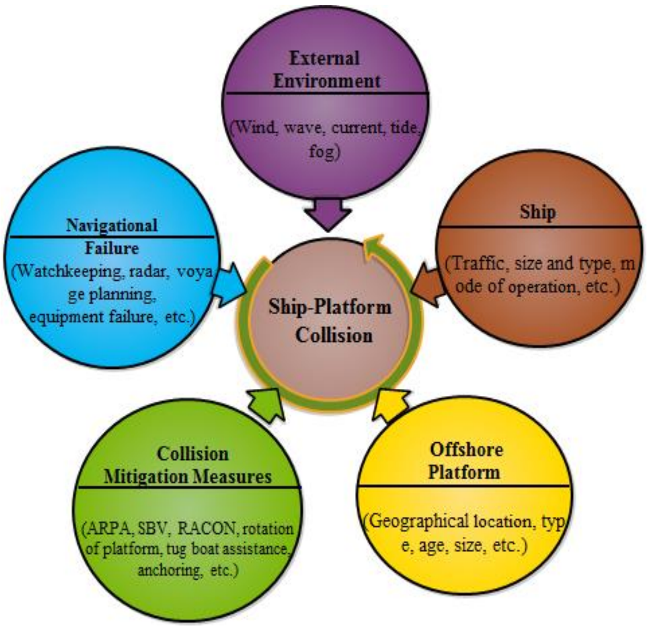

Fig. 3. The main elements involved in a ship-platform collision.

2.2 Hazard identification

Fig. 4 shows the risk analysis flowchart followed in the study. The initial stage of the risk assessment is the identification of all the credible types of rogue passing ship causing a threat to the platform. The degree of collision hazard depends mainly on traffic density, marine operations and the location of the facility. In general, marine traffic databases and historical databases are used to identify various hazards that could threaten a facility. To examine hazards, historical data are combined with an analytical model because historical data cannot always be used to predict future events. This is particularly true for passing-vessel collisions, because the traffic pattern varies from one location to another.

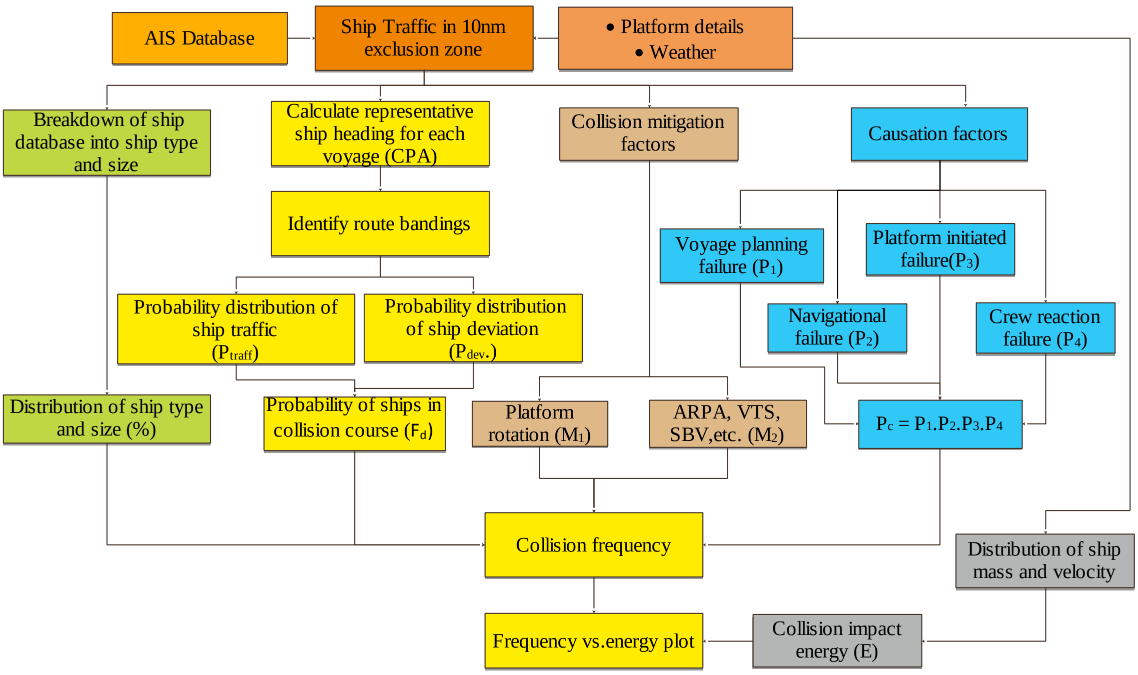

Fig. 4. Risk analysis of ship–offshore platform collision.

3. Probabilistic modelling

3.1 Assumptions followed in the study

The following main assumptions are followed in this paper:

1. Offshore platforms considered in the study are assumed to be stationary, i.e. the position of the platform remains unaffected by mean wind, current and steady wave drift force.
2. There has been an accident record on a collision between German submarine U27 and Oseberg B jacket platform in the Norwegian Continental Shelf (NCS) (Vinnem, 2007) with a little damage was caused to the platform. However, the probability of collision by this vessel type is generally negligible compared to other vessel types, considering their low frequency and the strict rules

and standards that govern their movement. Therefore, these vessels are typically excluded in the current study.

3. Thrusters that are installed on installations having ship-shaped hull such as tanker-converted FPSOs and floating liquefied natural gas (FLNG), can be used to rotate the platform when the incoming ships are in collision mode. In such cases, it is assumed that the thruster is 100% efficient in rotating the platform to prevent a head-on collision with the errant ship.
4. Probability that the vessel on a collision course having powered collision with the platform depends upon the factor that the ship is unaware of the presence of the platform and there has been no or failure in recovery measures from either ship or platform side.

3.2 Ship heading

To determine the heading angle of an errant vessel colliding with a platform, the voyage segment that comes close to the platform is taken to be the representative heading for the whole ship course. Fig. 5 illustrates this concept with a schematic diagram in which the ship traverses a 10-nm exclusion zone. Ship locations are marked as a series of points in the diagram, where θ represents the heading angle of the vessel close to the platform and A denotes the corresponding minimum distance to the platform.

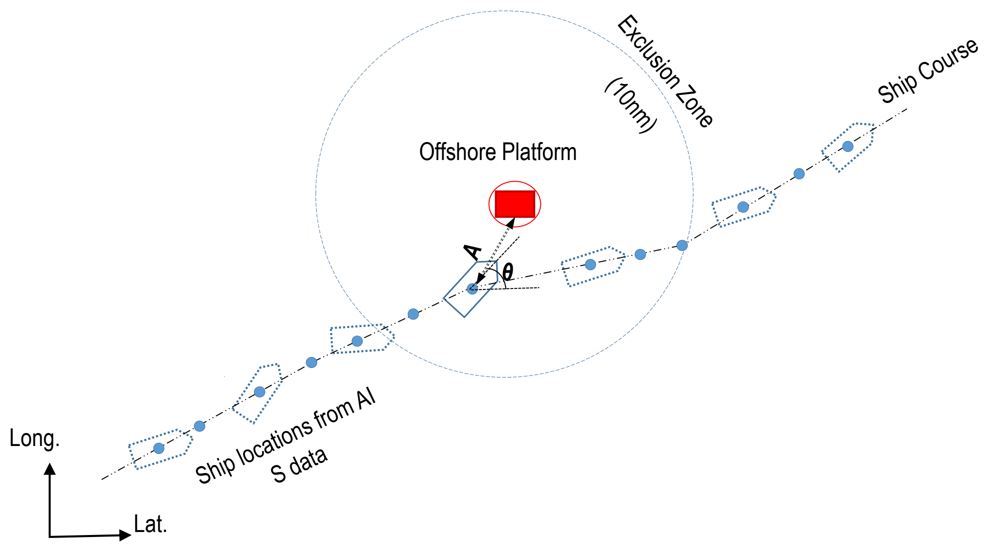

Fig. 5. Example of a ship's voyage close to a platform.

3.3 Collision diameter

Collision diameters for ship-ship collisions have been discussed extensively in the literature (see MacDuff, 1974; Montewka et al., 2010; Fuji. et al., 1970). For offshore platforms, collision diameter is defined as the width of that part of the shipping lane cross-section from which the ship would hit the platform unless it changes course (CMPT [Centre for Marine and Petroleum Technology], 1999).

Thus, it represents the relative length of the vessel and platform in the event of a collision and directly depends on the route taken by the different vessels.

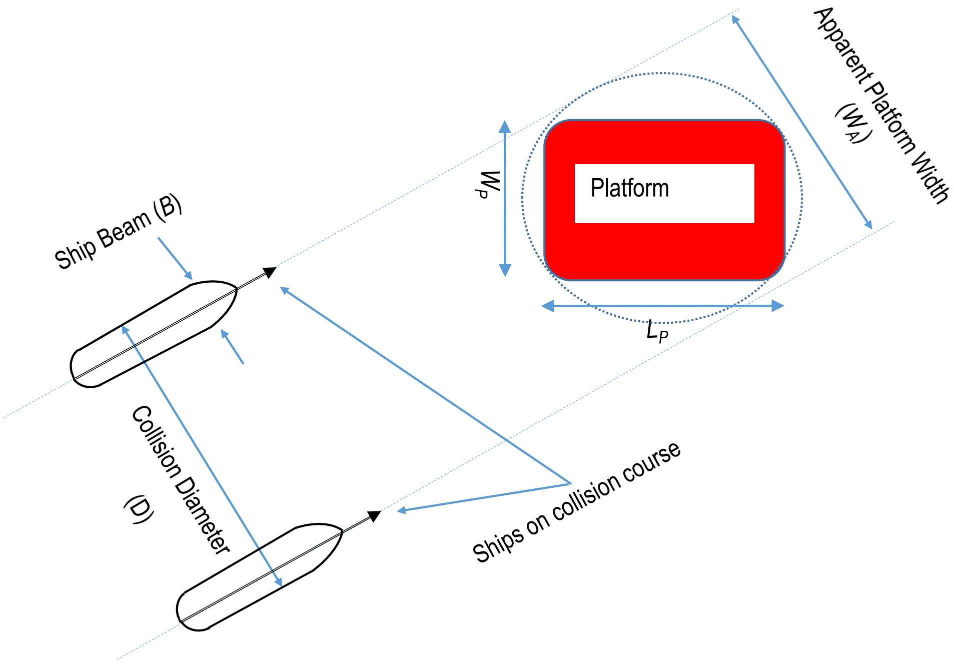

Fig. 6. Collision geometry.

Fig. 6 is a schematic diagram of collision geometry, in which the ships are on collision course with the platform. The apparent width of the platform represents the width of the platform in orientation with an incoming rogue ship (θ). For example, for a platform with a rectangular shape like semisubmersible, TLP, etc., the apparent width (W_A) is given by

$$W_A = L_p|sin\theta| + W_P|cos\theta|, \quad (1)$$

where L_p and W_p are the length and width of the platform, respectively. Considering that the ship route is distributed more or less uniformly around the platform and the errant ship collides at an arbitrary angle with the platform, the apparent width is calculated by assuming an average cross-sectional area of the platform. This is calculated by integrating the collision diameter by using Eq. (1) as follows:

$$W_A = \frac{2}{\pi}\left(L_p + W_p\right) \quad (2)$$

Finally, the collision diameter (D) is given by

$$D = W_A + B \quad (3)$$

3.4 Causation factors

In this study, the following four main factors of a collision are identified and accounted for in the calculation of collision frequency.

1. Probability of failure of pre-voyage planning (P_1)
2. Probability of failure of vessel-initiated recovery (P_2)
3. Probability of failure of platform-initiated recovery (P_3)
4. Probability of failure to fix navigational error (P_4)

The probability of failure of pre-voyage planning (P_1) includes unawareness of the platform's location. One of the main reasons is a lack of communication and awareness of the situation, because before exploration, drilling, or construction of the new platform, the information must be passed to the master of the ship and should be updated in nautical charts. It is assumed that the ship is 100% effective in amending its route, once it is aware of the platform's presence. Therefore, only the ships that are unaware of the platform and have not planned to avoid it (P_1) contribute to the collision probability.

The main factor that determines the P_1 value is the age of the platform. The P_1 value is highest when a platform is new and ships are not yet informed of its location, which is estimated based on judgement. CMPT (1999) has formulated an empirical function for merchant vessels relating the age of a platform to the probability of a voyage plan. When the platform is new and ships are not yet aware of its location, the P_1 value for merchant vessels is 95% and this drops exponentially with time to 12% after 5 years.

The P_1 value also depends on the type of platform in operation and the type of passing vessel. The value for mobile platforms (such as jack up drilling platforms) is higher in comparison to fixed platforms because they are likely to be recently introduced and their location changes with time for exploration and other drilling operations. In addition, larger ships such as merchant ships with more sophisticated navigational aids and knowledge of offshore operations will be more effective at planning their voyages accurately and thus their P_1 values are lower than those of smaller vessels such as fishing vessels.

In this study, the values of P_1 are the same as those in the front-end engineering design (FEED) method and are taken from Spouge (1991). Table 1 presents the values for new platforms (mobile platforms) and platforms that have been in place for a long time (fixed platforms). It can be seen that for merchant ships (1500 to 40,000 DWT), P_1 = 0.95 for a new platform, i.e., 95% of ships are unaware of the platform's location and therefore do not amend their route. As time passes, this reduces to P_1 = 0.1 or 10% of ships, an order of magnitude less. Assuming that the platform has been in place for a long time, P_1 values that correspond to fixed platforms are used in the study. The values chosen are of a magnitude less than those for a new platform, but this is justified because it is expected that the platform locations will be well communicated in advance to passing ships, considering the drilling campaign preceding the installation of a platform.

Modelling P_1 does not consider the exclusion zone implemented to offer added protection to the platform, because this is expected to change the route of a ship's voyage and should reduce the collision risk from these vessels. Therefore, the model effectively assumes that the risk due to ships planning to avoid the installation is zero, regardless of whether an exclusion zone is present, and only estimates the risk due to the vessels unaware of the platform (P_1 fraction of vessels).

The probability of vessel-initiated recovery (P_2) represents an incoming errant ship under collision mode with the platform. The main factors contributing to this failure include human errors such as crew being absent, busy with other tasks, asleep, incapacitated by accident, under the influence of alcohol or drugs; bad visibility due to fog, rain, etc.; and errors resulting from radar or its operation (Tvedt, 2014). The effect of all these human errors in the P_2 values is analysed using a fault tree combined with expert judgement (Geijerstam and Svensson, 2008).

Table 1. Collision probabilities (CMPT, 1999).

Vessel Type	P_1	P_2P_3		$P_1P_2P_3$	
		Good Visibility	Bad Visibility	Good Visibility	Bad Visibility
Mobile Platforms					
Supply	0.1	7.6E-03	5.2E-02	7.6E-04	5.2E-03
Standby	0.1	1.0E-02	8.2E-02	1.0E-03	8.2E-03
Merchant 0–1500 DWT	0.95	1.3E-02	6.5E-02	1.2E-02	6.2E-02
Merchant 1500–40,000 DWT	0.95	9.1E-03	6.6E-02	8.6E-03	6.3E-02
Merchant >40,000 DWT	0.95	4.8E-03	5.5E-02	4.6E-03	6.3E-02
Fishing	0.5	2.6E-03	1.3E-02	1.3E-03	6.5E-03
Fixed Platforms					
Supply	0.05	7.6E-03	5.2E-02	3.8E-04	2.6E-03
Standby	0.05	1.0E-02	8.2E-02	5.0E-04	4.1E-03
Merchant 0–1500 DWT	0.15	1.3E-02	6.5E-02	2.0E-03	9.8E-03
Merchant 1500–40,000 DWT	0.1	9.1E-03	6.6E-02	9.1E-04	6.6E-03
Merchant >40,000 DWT	0.05	4.8E-03	5.4E-02	2.4E-04	2.7E-03
Fishing	0.25	2.6E-03	1.3E-02	6.5E-04	3.3E-03

The probability of failure of platform-initiated recovery (P_3) represents the failure from the platform side to avert the vessel collision (for instance due to SBV or watchkeeping failures). Because of the short time available in which to react, the low speed of SBVs and difficulty in communicating with incoming ships, this type of recovery is difficult.

Table 1 presents the P_2 and P_3 values obtained for the different vessel categories. The combined values of P_2 and P_3 are given instead of individual values because they are dependent. In other words, the success of platform-initiated recovery depends upon the ship's watchkeeping and on the prevailing visibility conditions, which are obtained from ocean meteorology data. To calculate the overall combined result for P_2P_3, each mode of failure needs to be accounted for with an event tree method. For example, CMPT (1999) presents one of the event trees used in the CRASH method to calculate a P_2P_3 value for the special case of supply vessels in good visibility. From that example, it is clear that $P_3 = 1$ for most watchkeeping failures, that is, platform-initiated recovery is ineffective in 100% of cases. The mode of failure with the largest probability value is due to the crew being asleep (= 6.5×10^{-3}), and this dominates the overall result (7.6×10^{-3}). In bad visibility, ineffective radar is considered to be the dominant factor. For a merchant vessel of 1500 to 41,000 DWT in bad visibility, $P_2P_3 = 9.1 \times 10^{-2}$, i.e., the probability increases by an order of magnitude.

The probability of ship crew members being unable to react in time to fix the navigational error (P_4) is mainly dependent on the distance between the platform and the position of the ship at the time of navigational failure (A). MARIN provides different empirical relations for the estimation of P_3 in terms of the distance between the platform and the position of the ship (Ellis et al., 2008). As a conservative approach, $P_4 = \exp(-0.2A^{1.5})$ is used in the current study along with other causation factors.

3.5 Collision mitigation measures

To reduce risk to an acceptable level, priority should be given to reducing the frequency of events leading to a collision accident rather than its consequences. This consists of mitigation measures on the platform as well as the ship side. An extensive study on the decision making process for collision avoidance can be found in the literatures for ship-ship collisions. For instance, Line of Sight Counteraction Navigation (LOSCAN) algorithm developed by Wilson et al. (2003), neurofuzzy predictor modelling for ship obstacle avoidance by Harris et al. (1999). Zhao et al. (1994) and Zhao (1996) studied mariners behaviour and psychology in the decision making process using fuzzy sets.

Oil & Gas UK (2010) guidelines include contingency plans and collision avoidance measures for ship-installation collision. They also discusses the efficiency of various collision detection systems. The existence of the platform should be communicated to the ship’s operator in advance of its voyage. NORSOK (2001) describes general risk preparedness and guidelines for all accidental events related to offshore structures. The HSE (2000) considers different passing-vessel collision scenarios based on ship traffic density, weather, visibility and vessel speed. UKOOA (2002) suggests collision preventive measures such as enhanced detection systems and rotation of the platform (with thrusters) to reduce collision damage to FPSOs. Based on a study conducted by Kenny (1988), the following two factors are considered in the present study:

1. Use of enhanced collision alarming technologies such as ARPA, VTS, and a radar early warning system (REWS) (M_1). Fig. 7 presents the combined effect of the introduction of these

technologies on the overall reduction of estimated collision probability, taken from CMPT (1999). Factors for ARPA located on SBVs and for VTS are similar, with VTS offering the best reduction with a mean value of 0.87, i.e., 87% of collisions averted. Thus, a multiplier of 1–0.87 = 0.13 times the overall passing ship collision probability is used in this study.

2. The ability of the platform such as turret-moored FPSO and FLNG, to rotate using its thrusters (M_2). Doing this minimises exposed areas of the vessel by avoiding sideways-on collision by orienting the platform in the direction of an incoming ship on a collision course. This action will only result in reducing damage incurred on a platform presenting its width, by reducing the collision diameter. However, it is assumed here that heading control is possible under all weather conditions using thrusters, and the efficiency and number of thrusters in use are not considered. For the platform considered in the study, a collision reduction factor (F_d) of 0.28 can be achieved and for other platforms that cannot rotate to significantly reduce their exposure, this value becomes unity.

The combined effect of the two mitigating factors considered above leads to a reduction in collision probabilities of $0.13 \times 0.28 = 3.6 \times 10^{-2}$, that is, a reduction of about two orders of magnitude.

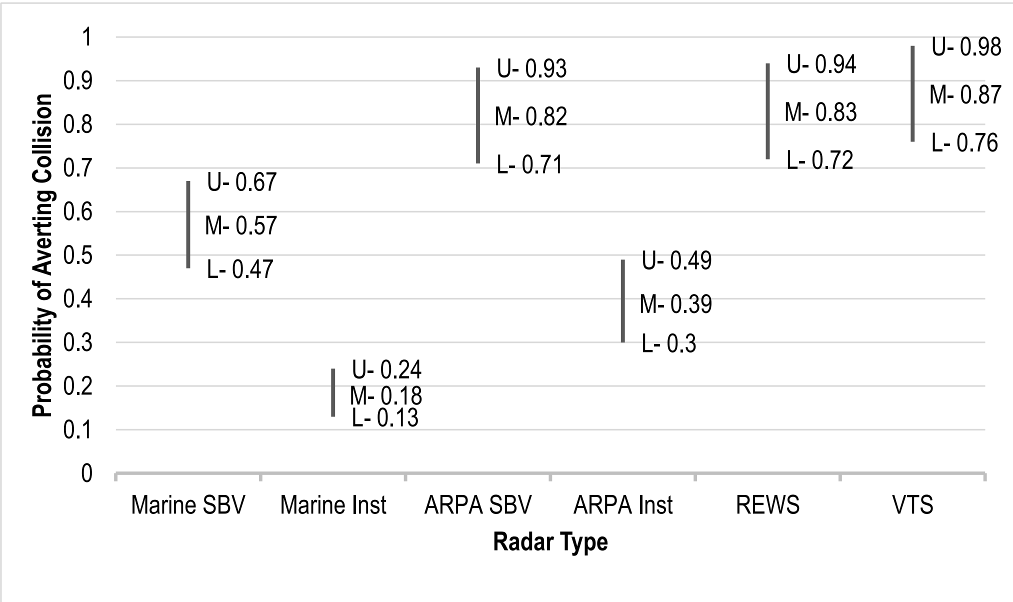

Fig. 7. Effects of collision mitigation measures (reproduced from CMPT (1999)).

3.6 Collision probability

The probability of an incoming ship on collision course depends not only on the deviation of the ship’s route from its original path but also deviation of the ship’s heading. Fig. 8 illustrates the lateral distribution of ship traffic (normal distribution) across a shipping lane. To account for the uncertainties arising from the randomness of ship traffic distribution across each route, we use the probability distribution to study their characteristics (Hughes et al., 2010).

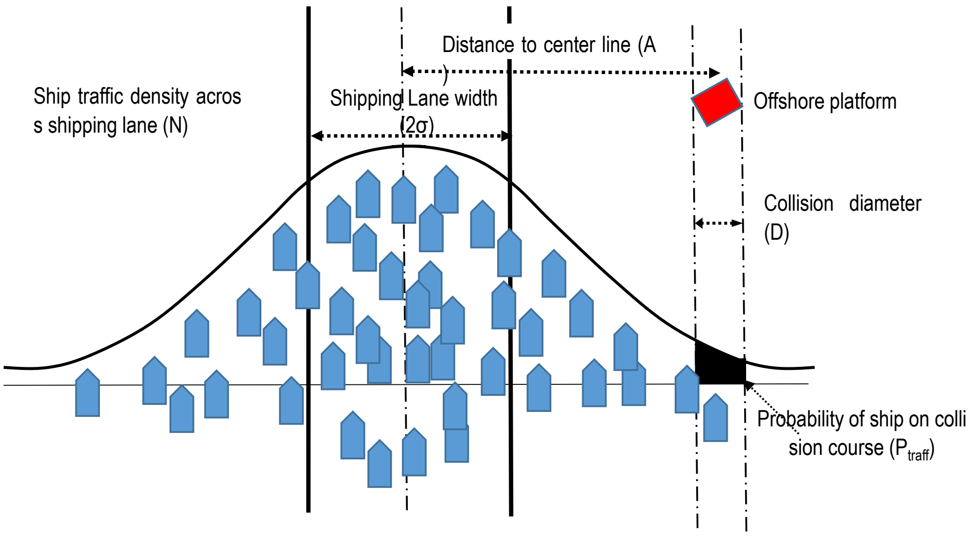

Fig. 8. Lateral distribution of ship traffic across a shipping lane.

Considering the dynamic nature of the traffic distribution and the fact that vessels most often try to avoid a collision, Bai and Wei-Liang (2015) found that a skewed distribution is normally observed rather than a normal distribution. To calculate the probability distribution of vessels in each vessel route (P_{traff}), because the collision diameter is small compared to the lane width (2σ), we assume a normal distribution across the shipping lane and its width is defined as +/− one standard deviation (CMPT, 1999). In other words, the width of the shipping lane contains 68.2% of the traffic within the lane. The deviation of a ship's course varies independently from the ship's offset from the platform. From AIS data, for each identified route, course deviation is obtained by the difference of heading and course of each voyage. A Gaussian distribution is usually assumed to find the probability of course deviation (P_{dev}) (Ellis et al., 2008). The actual probability of a vessel being in collision mode (F_d) is then given by the product of P_{traff} and P_{dev}.

The proportion of the vessels that are in the shipping lane directed towards the platform (P_{traff}) is thus given by

$$P_{traff} = D \times f(A) \quad (4)$$

where D, $P(A)$ and A denote the collision diameter, probability density at the centre of the platform and distance from the platform to the lane centreline closest point of approach, respectively.

The probability distribution of normal distribution, $f(A)$, is given by

$$f(A) = \frac{1}{\sqrt{2\pi}\sigma} exp - \frac{k^2}{2} \quad (5)$$

where σ is the standard deviation of the traffic distribution and $k = A/\sigma$ is the number of standard deviations that the platform is from the lane centreline.

3.7 Collision frequency

The frequency of ships passing in the near vicinity of the platform is analysed, and the probability of a rogue ship in collision mode is identified and calculated using probabilistic methods. Based on the number of vessels, the probability of collisions by each vessel and causation factors, the frequency of passing-vessel collision (*F*) is calculated using the equation

$$F = N \times F_d \times P_1 \times P_2 \times P_3 \times P_4 \times M_1 \times M_2 \quad (6)$$

where *N* is the density of ship traffic in the shipping lane per year.

3.8 Uncertainties

a. The P_1 values used were derived from data dating back to the 1990s. However, improved chart updating and the advanced communication methods currently available have probably led to a reduction of actual P_1 factors. Considering current advances in communication and the fact that extensive drilling activities will take place prior to installation of the platform, the study used least conservative or minimum P_1 values.

b. The P_2P_3 values considered in the study are subject to uncertainty because a variety of recommended methods give differing results.

c. The mitigating effect of ship detection technologies such as ARPA and VTS was taken into account, based on estimated factors provided in CMPT (1999). Based on that information, an average collision reduction factor of 0.87 for VTS was chosen, which is based on expert estimates rather than actual historical data. In addition, the effectiveness of the collision avoidance measures depends on several factors that are difficult to quantify accurately and that need to be considered using a detailed fault tree approach.

d. Passing ships modify their journeys in response to a new facility, leading to a reduction in collision frequency. Estimation of this reduction is subject to some uncertainty, considering that the ship route is dynamic and there has been continuous improvement in navigational safety through improved technologies, navigation standards and marine operations. The method used in this study was the standard approach (as set out in CMPT (1999)).

e. This study has assumed that heading control against an errant ship coming on a collision course is possible via FLNG thrusters, under all weather conditions, thereby allowing the thrusters to minimise the impact probability by aligning head-on to any incoming collision threat from passing vessels.

4. Collision impact energy

A collision event can be divided into external dynamics and internal mechanics (Pill and Tabri, 2011; Zhang, 1999). External impact energy influences the time-dependent rigid-body motion of the ship and the associated hydrodynamic effects (Paik and Thayamballi, 2003). Since Minorsky (1958), a number of studies have estimated collision impact energy and associated damage to offshore structures (see DNV, 2010; NORSOK, 2004). Table 2 shows the representative collision energies for powered passing vessels given by CMPT (1999). When considering the impact energies of passing vessels, the size distribution and the velocity of the ships in the shipping lanes are used to calculate the associated collision energy based on the typical distribution of the velocities presented in Table 2. The velocity of the ship at the time of collision is assumed to be constant and the same as the normal operating velocity of the vessel. This is justified by the fact that during powered vessel collision, the navigator is completely unaware of the presence of the platform.

Table 2. Velocity and impact energy for different sized vessels.

Vessel size (tons)	Vessel speed (knots)	Impact energy (MJ)
1000	11.1	18
2200	11.6	43
6500	13.2	165
18,000	15.3	612
100,000	15.3	3400

Internal mechanics determine the local and global damage of the offshore platform by absorbing part of the kinetic energy in the form of strain energy. The collision impact load is estimated by either simplified analytical modelling with single-DOF (degree of freedom), multi-DOF modelling using FEA software, or by experiment.

A passing vessel can either result in a drifting or powered collision with a platform. Drifting collision is generally characterised by low-energy impact (Jin et al., 2005; Zhang et al., 2015), whilst powered collision results in high-energy impact, causing serious damage to the platform (Hong et al., 2009; Storheim and Amdahl, 2014). The accuracy of the damage estimation on the platform and the colliding ship depends upon how well the interaction of external and internal energies are coupled (Travanca and Hao, 2015, 2014; Yu et al., 2016).

5. Application

The ship traffic database forms the basis for probabilistic modelling of a ship's collision with a platform. It not only provides the longitudinal and latitudinal positions of all vessels but also includes maritime mobile service identity number (MMSI), vessel type, vessel dimensions, cruising speed, heading and course.

Fig. 9 shows the geographical region over which the ship movements are measured, with red marks indicating the position of a ship recorded at every instant. The database is defined over a rectangular area coordinate with latitude from 35° 12′ 00.66″ N to 34° 56′ 48.79″ N and longitude from 129° 00′ 49.76″ E to 129° 17′ 14.82″ E shore (approximately 13 nautical mile radius from the coast). Vessel locations are traced approximately every 5 seconds, with 1,885,716 AIS-terrestrial ship positions and 30 AIS-satellite ship positions and the corresponding summer DWT, heading, course and cruising speed of the vessel recorded. The database contains vessel movements from 17/03/2014 to 17/06/2014 with records of 1,885,716 AIS-terrestrial and 40 AIS-satellite positions. The entire database contains close to 4,800 unique voyages.

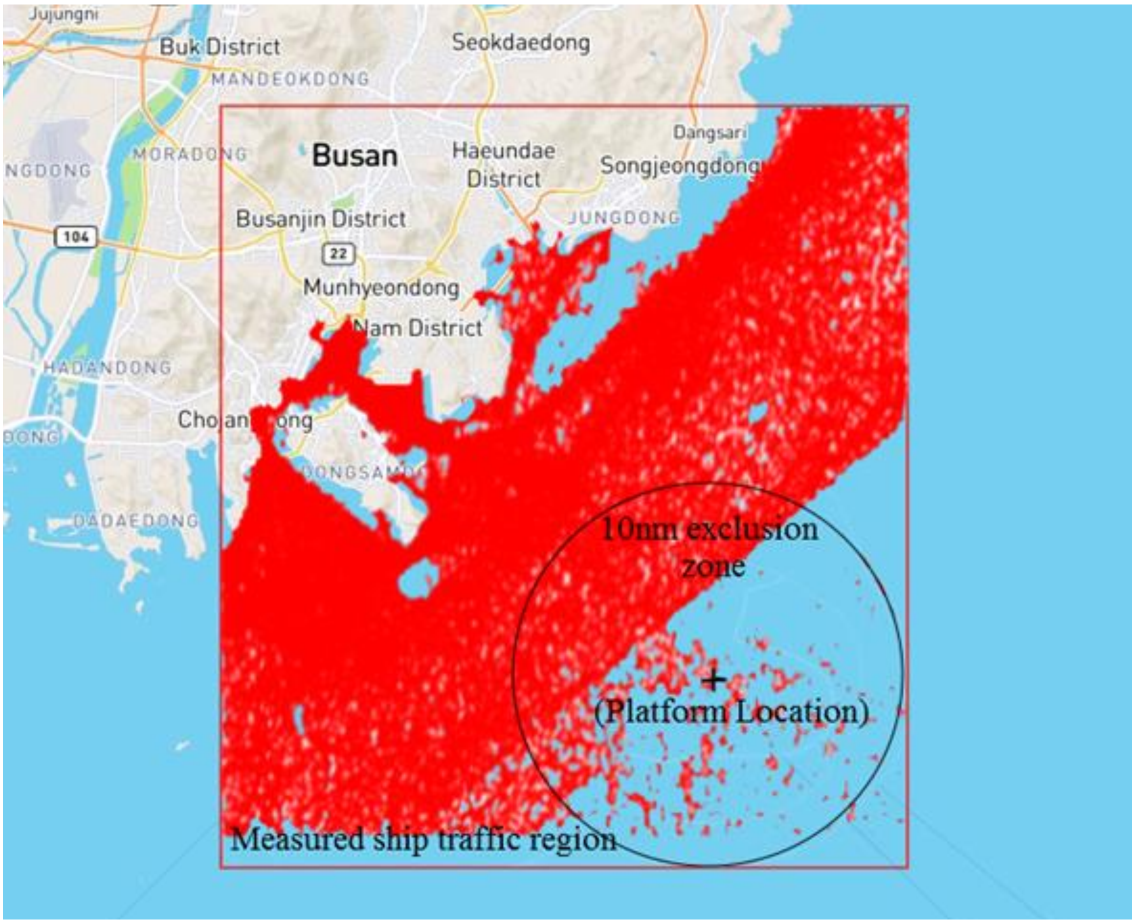

Fig. 9. Ship traffic based on database measurements. Ship positions are indicated in red.

Because the Busan coast is one of the busiest ports in the world, with dense ship movements throughout the year, we obtained a very complex pattern of ship movements and so the collision risk was expected to be high. A detailed study of the database revealed that the majority of vessels are more or less evenly distributed over the measured region, with thick traffic density observed near the port. For the current study, it is hypothetically assumed that a Prelude FLNG offshore platform with dimensions of 486 m × 74 m is located at (129.1859lat. 35.03016long.), with an exclusion region of 10 nautical mile diameter defined around the platform, see Fig. 9. Therefore, for this study, the collision diameter calculated using Eq. (2) and Eq. (3) is 390 m.

5.1 Analysis of ship traffic database

A detailed analysis of the different types of ship observed in the database revealed 39 vessels and 4847 appearances. The database is dominated by merchant vessels such as cargo, tanker and passenger vessels, with significantly more cargo vessels than other vessels (approximately 3.5 times more than the next most common i.e., tanker vessels). Further details of the database are given in Table A.1. The vessels are categorised into four major groups – supply, standby, merchant and fishing – according to the potential consequences associated with them. Unknown, unspecified and naval vessels, and other structures such as buoys are neglected in the further study. A 10 nautical mile radius of exclusion is generally defined for ships passing a platform (Lloyd’s Register, 2014). A total of 3725 ships passed within the exclusion zone.

Table 3. Breakdown of merchant ship types by DWT.

	DWT (tons)			
Ship type	<1500	1500–40,000	>40,000	Total
Cargo	155	1283	276	1714
Cargo: Hazard A (Major)	0	99	81	180
Cargo: Hazard B	0	3	6	9
Cargo: Hazard C (Minor)	0	6	10	16
Cargo: Hazard D (Recognisable)	0	12	30	42
Passenger	8	15	10	33
Tanker	56	283	38	377
Tanker: Hazard A (Major)	1	54	6	61
Tanker: Hazard B	5	72	2	79
Tanker: Hazard C (Minor)	2	13	1	16
Tanker: Hazard D (Recognisable)	0	18	0	18
Grand total	227	1858	460	2545
%	8.92	73.01	18.07	100

Table 3 illustrates the breakdown of different types of merchant ship based on DWT. It can be seen that 73% of all vessels fall within the range 1500 to 40,000 DWT, with significant contributions from cargo ships. Also, it is notable that the total number of merchant ships recorded is 2545, which is less than number of merchant vessels mentioned in Table A.1, because not all DWT information is available in the database. Hence, only vessels whose DWT is included in the database are considered further in our analysis.

Table 4 shows the classification of fishing vessels. Almost 50% of the fishing vessels identified in the database do not give information on DWT, possibly because most of the fishing vessels have not upgraded their details with the AIS database.

Table 4. Breakdown of fishing vessels by DWT.

DWT	Fishing	Pleasure Craft	Grand total	%
<1000	73	7	80	57.55
1000–5000	43	5	48	34.53
>5000	7	4	11	7.91
Total	123	16	139	100

Fig. 10 illustrates the breakdown of ship traffic for supply, standby, merchant and fishing vessels based on DWT and ship type. As expected, cargo vessels in the merchant category dominate the database with a large number of vessels falling within 1500 and 40,000 DWT. This distribution is then applied equally to all shipping lanes.

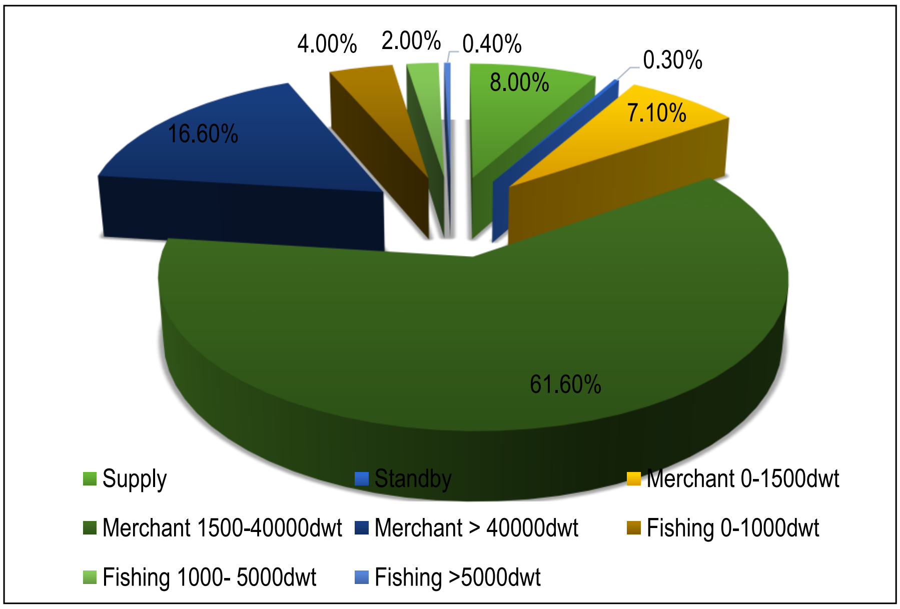

Fig. 10. Overall distribution of ship traffic within 10 nm exclusion zone

5.2 Identification of major shipping lanes

AIS provides details like geographic location, course and heading on average every 2 to 3 seconds for each ship voyage. Based on the closest-point approach method (Mou et al., 2010), the normalised heading distribution (i.e., those in the range 180° to 360° have been rotated by 180°) for all the voyages identified in the database 10 nautical mile around the platform are plotted, see Fig. 11. From the graph, it can be seen that most vessels (more than 60%) fall within a heading range of 20° to 60°. All heading angles are measured with respect to the global coordinate system.

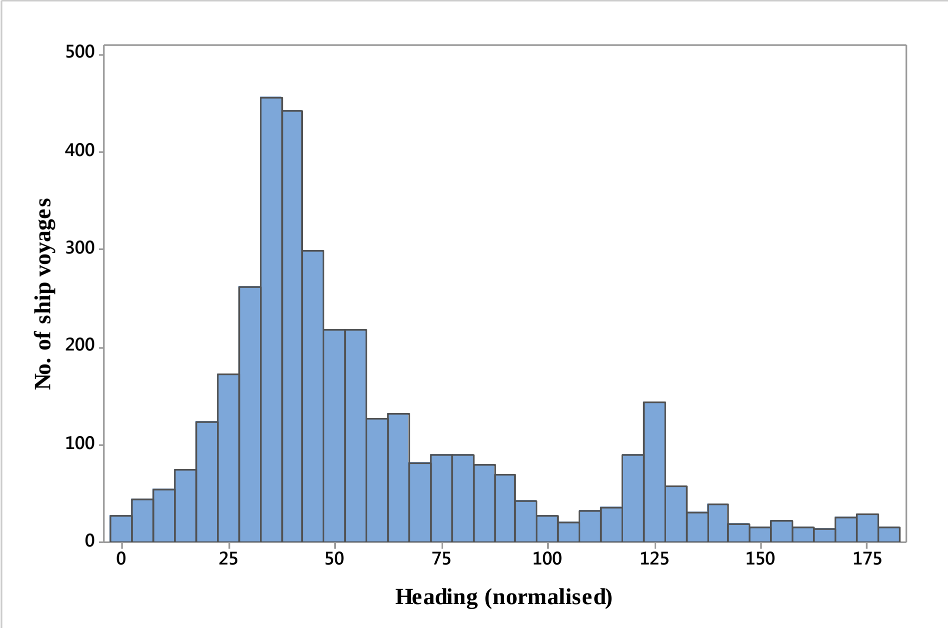

Fig. 11. Normalised headings of the voyage segments.

To identify the major shipping lanes, voyages with similar heading angle are grouped into Routes *A*, *B*, *C*, *D*, *E* and *F*, assuming average heading angles for each of the route bandings.

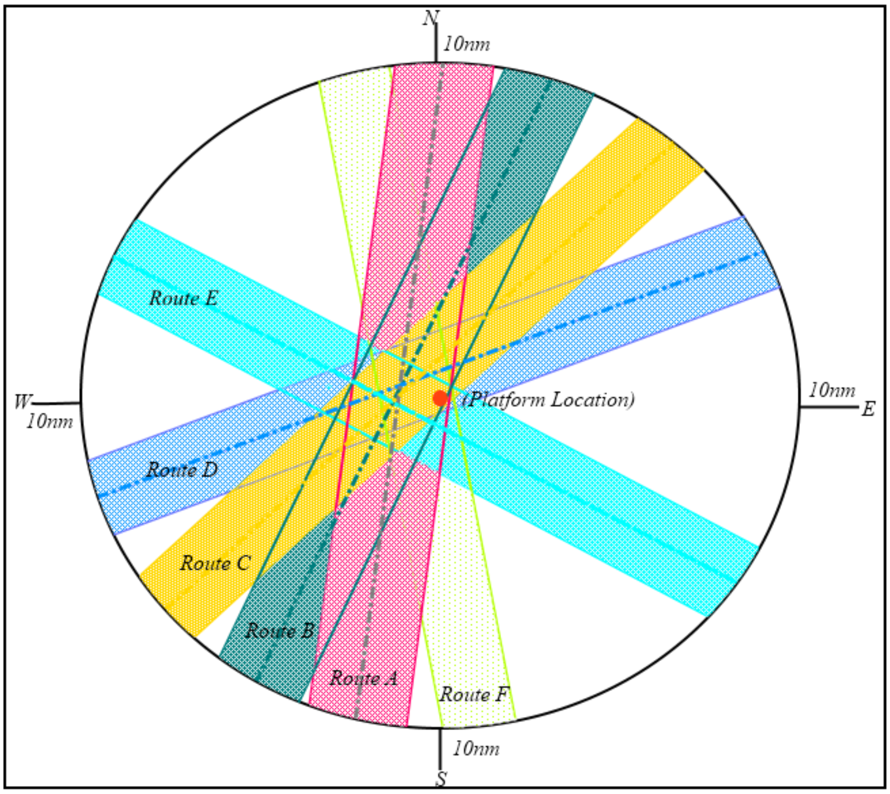

Fig. 12. Schematic plot of the main shipping routes identified around the platform location.

5.3 Displacement of the ship

To calculate the impact energy, it is necessary to know the displacement of the passing vessel accurately. The database contains information about ship weights given in terms of DWT (cargo carrying capacity). Based on discussion with ship masters and the shipping industry, the mass of cargo and bulk carrier ships is in the range of 20% to 25% of the cargo carrying capacity of the ship. In other words, to carry a cargo weight of 40,000 DWT, the mass of a ship will be 8,000 to 10,000 tons. A conservative upper limit of 10,000 tons displacement is chosen. Thus, the displacement of the ship is its physical mass plus cargo weight, that is, 50,000 tons. The assumption that ships are filled with their maximum cargo carrying capacity may be slightly conservative, but this can be justified by the fact that the ship must take on ballast water to ensure that its propeller remains submerged even when it is not carrying cargo or other loads. For supply, standby and fishing vessels, the approximate relations of displacement given in BS 6349 (1994) are used, which are derived from block coefficients.

Table 5. Breakdown of database by ship type and physical mass.

Ship category	Displacement (tons)					
	1000	2200	6500	18,000	100,000	Total
Supply	67	1	3	1	0	72
Standby	2	2	2	0	0	6
Fishing	63	31	34	10	1	139
Merchant 0–1500 DWT	90	137	0	0	0	227
Merchant 1500–40,000 DWT	0	60	701	569	528	1858
Merchant >40,000 DWT	0	0	0	0	460	460
Total						2762

Table 5 shows the vessels in the database grouped by vessel size. The total number of vessels is 2762, which is slightly lower than the total in Table 2, because the vessels in the database that have unknown DWT values are discarded.

6. Results and discussion

Fig. 13 shows the probability distribution of course deviation for the six major routes identified in the database. The course deviations are plotted between −90 and 90 degrees, with the assumption that the ships will not sail in the opposite direction. The maximum value of standard deviation is 14.60 degrees for Route *A*. This falls within the 15 degrees assumed by MARIN in the estimation of course deviation (Ellis et al., 2008). Table 6 summarises the heading range of each route banding and its properties. Among the different routes identified, Route *C* is the most densely populated. From the collision probability (F_d) estimated for each shipping route, it can be found that the maximum collision probability is for route *D*. This is due to the higher probability of ship traffic and course deviation in Route *B*. Fig. 12 is a schematic plot of all the ship routes showing their position and orientation, centred on the platform.

Table 6. Route bandings and their properties.

Route	Heading Range	Average Heading	Number in Route	*A* (nm)	σ (nm)	P_{traff}	P_{dev}	F_d
A	0°–14°	7°	151	-2.51	3.03	0.019	0.012	0.0002
B	15°–34°	24°	773	-2.55	2.77	0.012	0.035	0.0007
C	35°–56°	45°	1422	-2.04	2.59	0.024	0.023	0.0005
D	57°– 80°	68°	516	-1.67	2.53	0.027	0.036	0.001
E	81°–160°	120°	777	-1.73	2.72	0.025	0.028	0.0007
F	161°–180°	170°	86	-1.5	2.19	0.030	0.010	0.0003

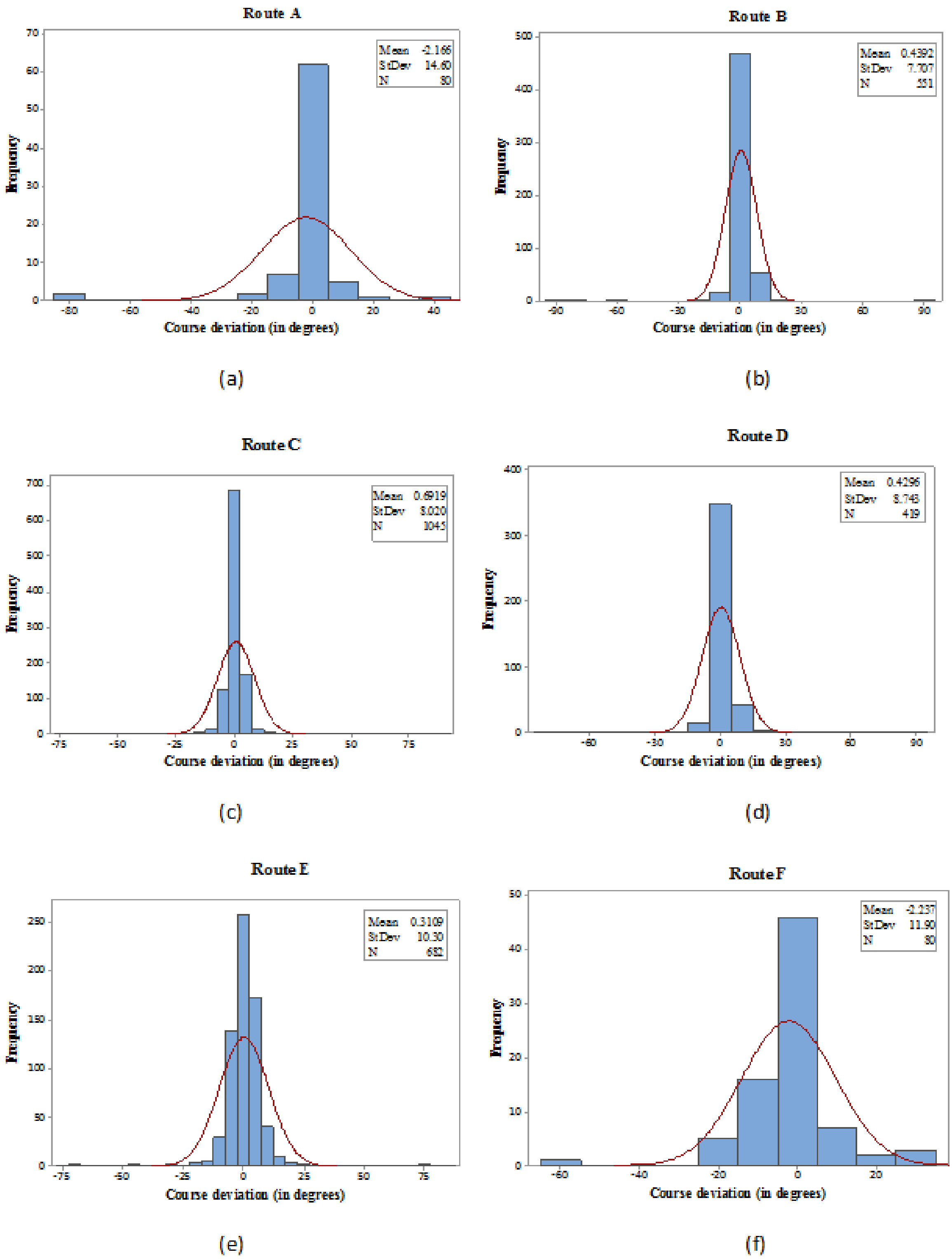

Fig. 13. Probabilistic distribution of ship course deviation for different routes.

6.1 Calculation of collision frequency

Based on Eq. (6), Table 8 lists the estimated collision frequency for the different identified routes and ship categories. Amongst the routes identified, Route *F* has a lower collision frequency, but a higher collision probability value, because the number of vessels in this shipping lane is lower compared to other routes. As expected, the maximum frequency of collision is for route *C*. Table 7 presents a summary of the overall frequency of collision of different ship categories obtained from all the routes. Merchant vessels of 1500 to 40,000 DWT exhibit a maximum frequency of 1.70E^{-04} per year. This constitutes almost 90% of the total collision frequency of other vessels. For the initial design stage of platforms, CMPT (1999) classifies the collision frequencies (per year) into high (>10^{-2}), medium (10^{-2} to 10^{-4}) and low (<10^{-4}). Based on this classification, the overall predicted collision frequency value is 1.9E^{-04}, which falls within the medium category of collision frequency.

Table 7. Overall passing-vessel collision frequencies.

All Routes	Mitigation factor	Frequency (per annum)
Supply	3.6E-02	2.13E-06
Standby	3.6E-02	3.16E-07
Merchant 0–1500 DWT	3.6E-02	2.51E-06
Merchant 1500–40,000 DWT	3.6E-02	1.70E-04
Merchant >40,000 DWT	3.6E-02	8.42E-06
Fishing	3.6E-02	4.19E-06
Total		1.88E-04

Table 8. Collision frequencies for different routes.

Route	Ship category	Number of vessels (*N*)	F_d	Causation factor $P_1P_2P_3$	Causation factor P_4	Mitigation factor (*M*)	Frequency (per year)
A	Supply	12.0	0.0002	3.80E-04	0.451	3.60E-02	7.2E-08
	Standby	0.5	0.0002	5.00E-04	0.443	3.60E-02	1.1E-08
	Merchant 0–1500 DWT	11.5	0.0002	2.00E-04	0.558	3.60E-02	8.5E-08
	Merchant 1500–40,000 DWT	94.7	0.0002	9.10E-04	0.649	3.60E-02	5.7E-06
	Merchant > 40,000 DWT	23.5	0.0002	2.40E-04	0.634	3.60E-02	2.8E-07
	Fishing	8.8	0.0002	6.50E-04	0.693	3.60E-02	1.4E-07
	Total	**151**					**6.3E-06**
B	Supply	61.2	0.0007	3.80E-04	0.451	3.60E-02	3.7E-07
	Standby	2.5	0.0007	5.00E-04	0.443	3.60E-02	5.5E-08
	Merchant 0–1500DWT	59.1	0.0007	2.00E-04	0.558	3.60E-02	4.4E-07
	Merchant 1500–40,000 DWT	484.8	0.0007	9.10E-04	0.649	3.60E-02	3.0E-05
	Merchant >40,000 DWT	120.2	0.0007	2.40E-04	0.634	3.60E-02	1.5E-06
	Fishing	45.3	0.0007	6.50E-04	0.693	3.60E-02	7.3E-07
	Total	**773**					**3.3E-05**

C	Supply	112.6	0.0006	3.80E-04	0.451	3.60E-02	8.2E-07
	Standby	4.6	0.0006	5.00E-04	0.443	3.60E-02	1.2E-07
	Merchant 0–1500 DWT	108.7	0.0006	2.00E-04	0.558	3.60E-02	9.6E-07
	Merchant 1500–40,000 DWT	891.8	0.0006	9.10E-04	0.649	3.60E-02	6.5E-05
	Merchant >40,000 DWT	221.1	0.0006	2.40E-04	0.634	3.60E-02	3.2E-06
	Fishing	83.3	0.0006	6.50E-04	0.693	3.60E-02	1.6E-06
	Total	**1422**					**7.2E-05**
D	Supply	40.9	0.0010	3.80E-04	0.451	3.60E-02	3.3E-07
	Standby	1.7	0.0010	5.00E-04	0.443	3.60E-02	4.9E-08
	Merchant 0–1500 DWT	39.5	0.0010	2.00E-04	0.558	3.60E-02	3.9E-07
	Merchant 1500–40,000 DWT	323.6	0.0010	9.10E-04	0.649	3.60E-02	2.7E-05
	Merchant >40,000 DWT	80.2	0.0010	2.40E-04	0.634	3.60E-02	1.3E-06
	Fishing	30.2	0.0010	6.50E-04	0.693	3.60E-02	6.6E-07
	Total	**516**					**2.9E-05**
E	Supply	61.5	0.0007	3.80E-04	0.451	3.60E-02	4.7E-07
	Standby	2.5	0.0007	5.00E-04	0.443	3.60E-02	7.0E-08
	Merchant 0–1500 DWT	59.4	0.0007	2.00E-04	0.558	3.60E-02	5.6E-07
	Merchant 1500–40000 DWT	487.3	0.0007	9.10E-04	0.649	3.60E-02	3.8E-05
	Merchant >40,000 DWT	120.8	0.0007	2.40E-04	0.634	3.60E-02	1.9E-06
	Fishing	45.5	0.0007	6.50E-04	0.693	3.60E-02	9.3E-07
	Total	**777**					**4.2E-05**
F	Supply	6.8	0.0003	3.80E-04	0.451	3.60E-02	6.3E-08
	Standby	0.3	0.0003	5.00E-04	0.443	3.60E-02	9.4E-09
	Merchant 0–1500 DWT	6.6	0.0003	2.00E-04	0.558	3.60E-02	7.4E-08
	Merchant 1500–40,000 DWT	53.9	0.0003	9.10E-04	0.649	3.60E-02	5.0E-06
	Merchant >40,000 DWT	13.4	0.0003	2.40E-04	0.634	3.60E-02	2.5E-07
	Fishing	5.0	0.0003	6.50E-04	0.693	3.60E-02	1.2E-07
	Total	**86**					**5.6E-06**

6.2 Frequency vs. energy plot

For each passing vessel, the impact energy is determined by combining the values presented in Table 2 and Table 5. Table 9 lists the overall frequency of all categories of ship identified and their corresponding collision impact energies for five categories of collisions.

Table 9. Frequency and impact energy by ship weight for all categories of collision.

Ship weight (tons)	Energy (MJ)	Frequency (per annum)	Cumulative frequency (per annum)
1000	18	4.98E-06	1.88E-04
2200	43	8.07E-06	1.83E-04
6500	165	6.53E-05	1.74E-04

18,000	612	5.24E-05	1.09E-04
100,000	3400	5.68E-05	5.68E-05
Total		1.88E-04	

Fig. 14 displays annual collision frequencies and their corresponding impact energies for each category of vessel. In all cases, the energies quoted are the kinetic energies of the incoming ship.

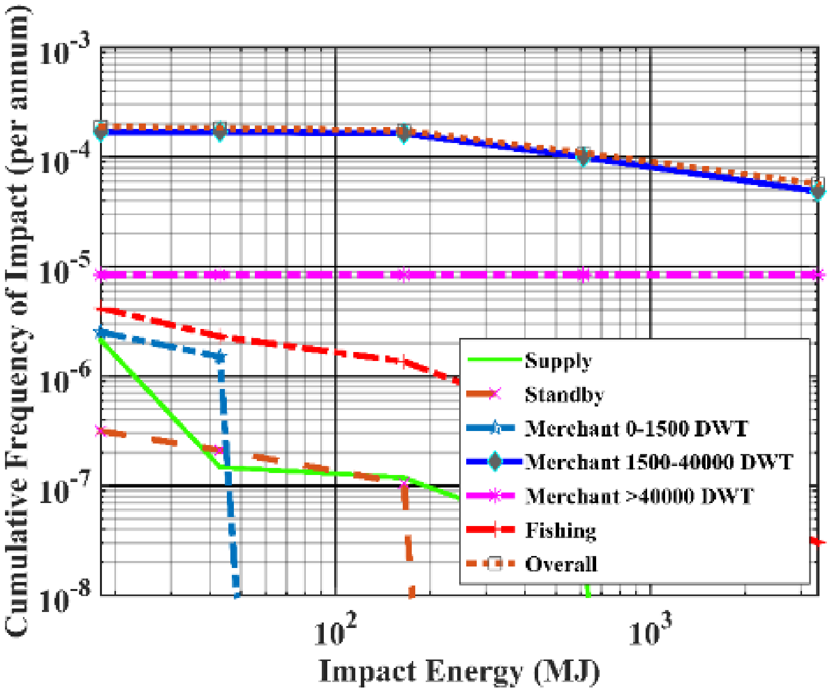

Fig. 14. Frequency vs. impact energy curves for all impact energies categories.

It can be seen that large and medium-sized merchant vessels contribute the largest risk to the platform as a result of their combination of large mass, higher cruising velocity and the large number of appearances within the database.

Further, the offshore platforms are designed such that it cannot withstand severe collisions involving higher level of impact energy, particularly for the three energy categories (165MJ, 612MJ and 3400MJ) mentioned in the table 2. Therefore, to study the effect of lower impact energy collision, the two less severe categories of impact energies are considered separately. The collision impact energies corresponding to different categories of ships are estimated by quadratic interpolation and the corresponding frequencies are calculated by following the same method as discussed before. The consequences of collisions in low energy collisions are calculated in terms of energy absorbed by the platform, assuming that a 32% of the impact energy is absorbed by the platform during the collision.

This value is taken from the reference CMPT (1999) based on the experience from the highest impact energy value measured in a supply vessel collision with a semi-submersible in the UK sector. Fig.15 shows the cumulative frequency and their corresponding absorbed energy for different categories of vessel. Since the merchant vessels with displacements greater than 40000 dwt are always associated with more severe collision, it is not included here. Although the absorbed energy considered in the analysis is greater than the design value of 4MJ (Lloyds Register), the maximum collision frequency (3.9×10^{-5} per year) for overall vessel category is found to be acceptable within the design criteria of 10^{-4} annual probability of occurrence. Also, the overall collision frequencies are still dominated by the contribution of the merchant vessel with 1500-40000 dwt, as the vessel traffic region considered in the present study is dominated by the merchant vessels.

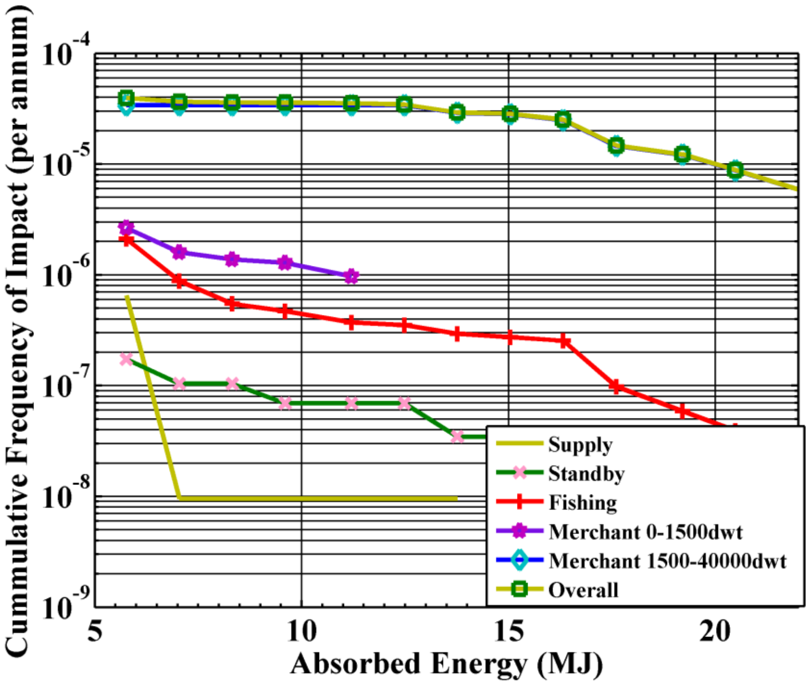

Fig. 15. Frequency vs. absorbed energy curves for lower impact energies categories.

6.3 *Comparison of the result with previous studies*

Collision accident statistics are generally used to validate collision frequencies obtained in studies. These values are quite uncertain because only a few accidents are included in the database. OGP (2010) summarises accident and collision events, including near-miss statistics for the UKCS and worldwide from 1980 to 2005. The worldwide passing-vessel collision frequencies from 1980 to 1989 and 1990 to 2002 were found to be 5.9×10^{-4} and 2.5×10^{-4} per year, respectively, which clearly shows a significant reduction. Because the predicted frequency is strongly location dependent, the typical values are impossible to present because they are largely determined by the characteristics of the shipping lane and its distance from the platform. Also, great uncertainties exist among the software programs that are used in the estimation of collision frequency. Moan et al. (2002) provided an extensive review of risk assessments of FPSO collision involving supply ships, shuttle tankers and passing vessels in the North Sea and Gulf of Mexico and concluded that collisions from passing vessels depend on the location of the FPSO and the annual impact probability, which varies from 10^{-3} to 10^{-6} or less. CRASH gave an average collision frequency value of 8.7×10^{-3} per platform year for the fixed platforms in the UK and Irish Sectors in 1990. CMPT (1999) estimated average passing-vessel collision frequencies for fixed platforms to be 1.2×10^{-3} and 3.8×10^{-4} per platform year from 1970 to 1992 for the UK and worldwide, respectively. For individual platforms, the collision frequency varied from below 10^{-7} per year to as high as 0.12 per year. Therefore, we may conclude that the collision frequency of passing vessels is strongly location specific and time dependent. The overall collision frequency obtained in the study ($1.9E^{-04}$ per year) seems to be reasonably acceptable, considering the dense ship traffic in the studied area.

7. Conclusions

Offshore platforms installed in high-density ship traffic areas are prone to a high risk of collision by passing ships. This study describes a simple probabilistic approach to risk analysis for powered ship collisions with offshore platforms, using a marine traffic database. The primary focus of the study was to estimate the collision frequency from AIS data for different categories of vessel identified in the database, accounting for various collision mitigating factors such as enhanced ship detecting systems and the ability of platforms to rotate against the collision impact. In this context, AIS data available around the Busan coast was investigated to describe the proposed model. Amongst the various classes of vessel observed, large merchant vessels, in particular, cargo vessels of 1500 to 40,000 DWT possess a high risk of collision with platforms because of their large mass, higher cruising velocity and frequent appearance in the database, along with busy marine trade activities in this particular region.

The proposed method considers various factors such as the distribution of vessel traffic, changes of shipping lanes with time and the efficiency of thrusters to rotate the platform in time before a collision occurs. This model can be effectively used in the industry during the initial design and operation stages of risk assessment. From AIS information, it is relatively easier to understand how platforms affect shipping routes and how collisions vary with time. Future research in this area includes the estimation of collision consequences in terms of loss of life and damage to the platforms and the environment.

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Appendix A. Ship traffic data

Table A.1. Vessel traffic recorded in the database

Sl. No.	Ship type	Total unique voyages	Sl. no.	Ship type	Total unique voyages
1	Antipollution	6	21	Passenger	52
2	Beacon, Port Hand	1	22	Pilot Vessel	6
3	Cardinal Mark N	1	23	Pleasure Craft	92
4	Cargo	2149	24	Port Tender	13
5	Cargo-Hazard A (Major)	194	25	Reserved	18
6	Cargo-Hazard B	14	26	Sailing Vessel	8
7	Cargo-Hazard C (Minor)	22	27	SAR	6
8	Cargo-Hazard D (Recognisable)	45	28	SAR Aircraft	5
9	Dredger	11	29	Special Craft	1
10	Dive Vessel	1	30	Starboard Handmark	1
11	Fishing	230	31	Tanker	613
12	High Speed Craft	17	32	Tanker: Hazard A (Major)	74
13	Isolated Danger	1	33	Tanker: Hazard B	100
14	Law Enforcement	27	34	Tanker: Hazard C (Minor)	19
15	Light Vessel	1	35	Tanker: Hazard D (Recognisable)	27
16	Local Vessel	2	36	Tug	311
17	Military OPS	4	37	Unknown	152
18	Navigational Aid	6	38	Unspecified	487
19	Null	38	39	Wing In Grnd.	12
20	Other	80		Total	4847