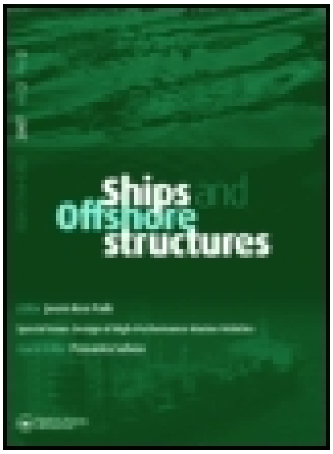

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Environmental consequences associated with collisions involving double hull oil tanker

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As the total world trade of oil by tankers grow, the potential risk to the marine environment increases. When oil tankers are involved in accidents (e.g., collision or grounding), a consequence of the resulting damage could be the release of crude oil or petroleum products into the sea. The aim of the present study is to investigate the environmental consequences of the involnement of oil tankers in collision. Using probabilistic approaches, credible scenarios of ship–ship collision are selected to create a representative sample of the most possible ones. The LS-DYNA non-linear finite element method is used to predict the resulting damage or opening associated with the individual scenarios. The environmental consequences are then estimated by calculation of the amount of oil spilled in each scenario. In addition, the potential damage to the environment is presented in terms of monetary units that can be understandable to all stakeholders.

Keywords: double hull oil tanker; collision; oil outflow; environmental effect

1. Introduction

A significant amount of pollution is reportedly caused by shipping and maritime activities. Even before the oil spill caused by an explosion on the Deepwater Horizon in the Gulf of Mexico, a large number of major oil spills occurred, most of which were caused by oil tanker accidents. Tanker collisions are one of the most hazardous accidents and can potentially lead to the total loss of the ships involved. Ship–ship collisions have serious effect related to human life and environmental disasters, as well as economic consequences, especially when large tankers are involved.

The release of oil into the sea can affect the water and coastlines due to the weather, waves and currents, which may affect the tourism industry. In addition, marine life and wildlife can be affected by the oil spill and may even lead to death. On 16 February 2014, on the coast of Busan city in Korea, a collision occurred between the bulk carrier *Captain Vangelis L* and the oil supply vessel *Green Plus*. About 237,000 litres of oil leaked into the water near Busan from a hole in the hull of the Liberian-registered freighter *Captain Vangelis L*. Figure 1 shows the *Captain Vangelis L* after the collision.

On the basis of statistics presented by the International Tanker Owners Pollution Federation (ITOPF 2012), Youssef et al. (2014) summarised the incidence of spills of greater than 700 tonnes by cause across four time periods, as shown in Figure 2. According to these statistical analyses, the most common causes of oil spills are ship collisions and groundings. The percentage of oil spills caused by collisions increased in the periods 1970–2004, 1970–2007 and 1970–2009, but decreased slightly (0.1%) for the overall period 1970–2012. This means that oil spill due to collision could not be prevented despite developments in marine technology operated and constructed to reduce the amount of oil spilled in the event of an accident. There is still room for further analysis and investigation related to all aspects of collisions between ships (Youssef et al. 2013).

This study deals with the environmental consequences of collision. These consequences are predicted in terms of the amount and costs of the oil spill for various collision scenarios that are randomly selected on the basis of statistical analysis by Youssef et al. (2014). This analysis can be useful and more understandable to all stakeholders. As an illustrative example, a full-scale Suezmax-class double hull oil tanker is assumed to play the role of the ship that is struck by various ships.

2. Literature review

The size of the oil spill is an important factor in the total cost; larger spills require more oil to be removed than do small spills, and the remediation process is therefore

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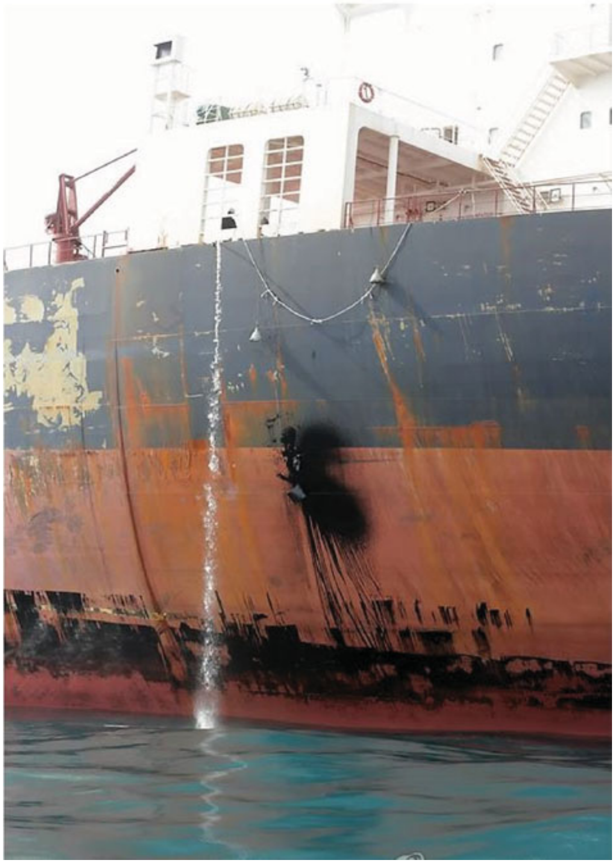

Figure 1. Bulk carrier *Captain Vangelis L* after collision. (This figure is available in colour online.)

more expensive (Etkin 1999, 2000). In this regard, several models have been proposed for estimation of the expected quantity of oil spilled in an accident, based on analytical and experimental works.

To estimate the oil outflow after a collision, an analysis of structural crashworthiness is also needed for impact damage. Zheng et al. (2007) compared the structural crashworthiness for single sided and double sided oil tankers in different scenarios by use of the ANSYS/LS-DYNA program.

The International Maritime Organisation (IMO) suggested guidelines for the oil outflow performance of double hull tankers (IMO 2003). The IMO used historical data from collisions to establish collision oil spill models. There are two IMO-approved methods designed to assess the extent of the pollution prevention level of a particular tanker: (1) probabilistic (IMO 2003) and (2) simplified probabilistic method for evaluation of cargo oil outflow from a tanker (simplified probabilistic methodology) (IMO 2004). Tabakli et al. (2011) experimentally investigated the amount and behaviour of oil spills for different tank designs with holes in the bottom and sides to represent the damage caoused by collision and grounding. Tavakoli et al. (2012) developed an analytical model for the estimation of oil spills caused by tankers involved in a collision. In addition, a computational fluid dynamics simulation has been used to validate the developed analytical model.

Studies have been carried out to estimate the costs of oil spills according to regression models based on large databases of oil spill incidents. Many studies have developed collision oil spill models for the costs of an oil spill (Hansen and Ditlevsen 2003; Yamada 2009). Yamada and

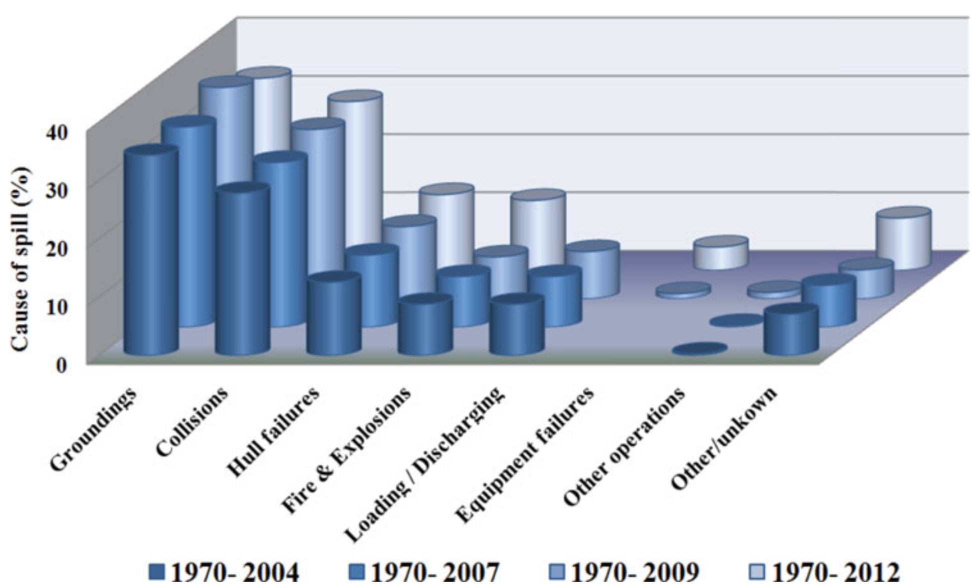

Figure 2. Incidence of oil spills greater than 700 tonnes by cause (ITOPE 2012; Youssef et al. 2014). (This figure is available in colour online.)

Montewka calculated the oil spill cost based on IOPCF database using regression analyses (Montewka 2009; Yamada 2009). In another study based on historical data from past oil spills obtained from the IOPCF statistics, Psarros et al. found an oil spill cost model (Psarros et al. 2011). Furthermore, such models are developed with the use of data on spill sizes that fall in a certain range, usually with a small median value for spills (Kontovas et al. 2010). Ventikos and Sotiropoulos compared previous methods of measuring the cost of oil spills with this method (Ventikos and Sotiropoulos 2014).

3. Procedures of this study

This study evaluates the environmental consequences involved in collisions of target structures that are struck by various striking ships with different sizes, bow shapes, speeds, etc. Figure 3 shows the procedures of this study. Using probabilistic approaches, 30 credible scenarios of ship–ship collision are randomly selected to create a representative sample of all possible scenarios (Youssef et al. 2014). Each scenario is a function of the colliding vessels' speed, displacement and draught as the required parameters for the finite element modelling of the colliding vessels are determined. The collision simulations are performed using the non-linear structural analysis program LS-DYNA to predict the resulted structural damage for the struck tanker. On the basis of the numerical results, the resulting opening in the side of the struck tanker is investigated for each scenario to estimate the amount and cost of oil spilled.

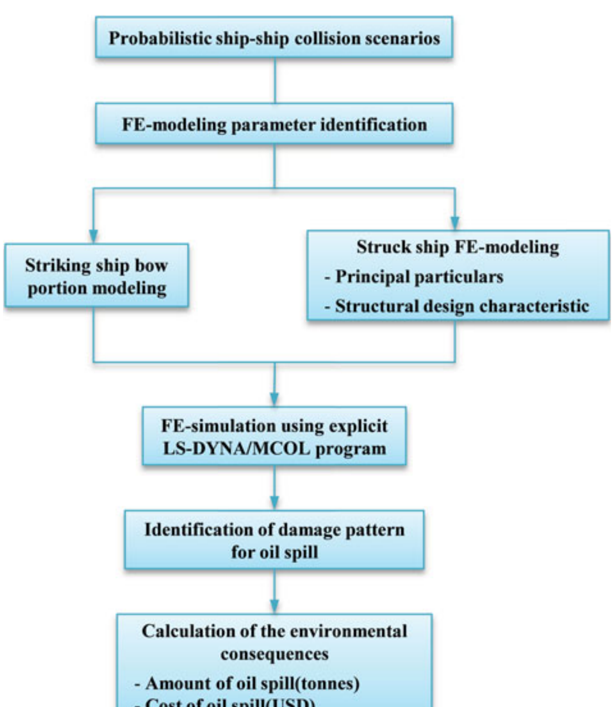

Figure 3. Collision involved oil spill assessment procedure. (This figure is available in colour online.)

Table 1. Principal particulars of a Suezmax-class double hull oil tanker.

Items	Dimension
Overall length (m)	272.00
Moulded breadth (m)	48.00
Moulded depth (m)	23.70
Design draft (m)	16.00
Deadweight (DWT)	157,500.00
Double side width (m)	2.64
Double bottom height (m)	2.64
Transverse frame spacing (m)	4.80

4. Applied example

4.1. *Target structures*

In this study, a Suezmax-class double hull oil tanker plays the role of the struck vessel. The structural condition of the target tanker is as built, considering no impairment in the structural thickness. Table 1 indicates the principal dimensions of the object ship. The geometric model of the Suezmax-class double hull oil tanker is shown in Figure 4.

In addition, all of the plates and stiffeners in the struck ship are modelled with piecewise linear plasticity. This material type uses a Cowper–Symonds model to deal with strain effects and complete material fracture. This study uses a fracture strain value $\varepsilon_f = 0.1$, which is commoly used in the material industry (Paik et al. 1999; Servis et al. 2002; Sajdak and Brown 2005; Jones 2006; Paik et al. 2009).

To allow for more reasonable analysis and to save simulation time, this study focuses on the part of the ship at which the collision occurs. Therefore, mesh convergence study was conducted for the object ship's double side structure, with the consideration of the accuracy of the intended results with reasonable computational time. The meshes chosen were 100, 150, 200, 250 and 300 mm with 71,027, 39,955, 20,958, 14,426 and 9986 elements, respectively. Figure 5 shows the mesh convergence results in terms of the energy absorbed by the double side structure and penetration of the rigid indentor into the double side structure versus the number of elements. It shows that the energy absorbed by the side structure has very approximate values for all of the chosen meshes (with 0.76% maximum deviation). On the other hand, the penetration value converged when using 71,027–20,958 of elements, where the mesh size in this range is between 100 and 200 mm, respectively. Above this size (i.e., 200 mm), there is a significant variation (see Figure 5). Therefore, a 200 mm element size is chosen as the collision damage area (i.e., along the ship's side with some part of the deck and bottom). In addition,

Figure 4. Geometric model of the struck ship. (This figure is available in colour online.)

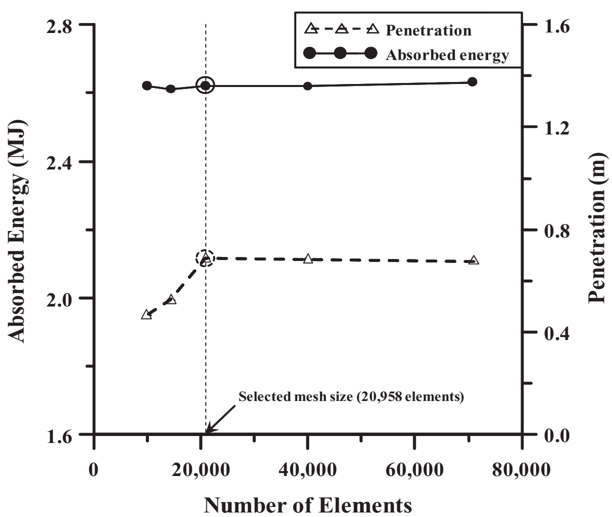

Figure 5. Mesh convergence results.

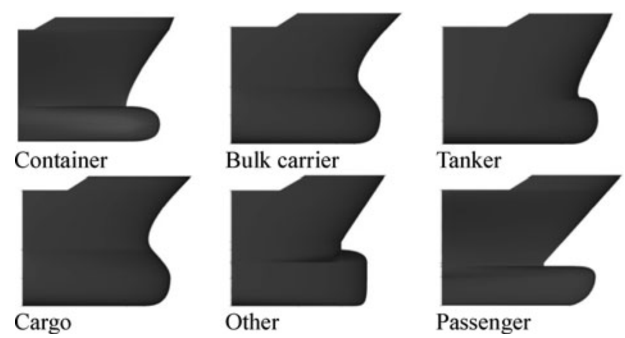

Figure 6. Bow model of the striking ship. (This figure is available in colour online.)

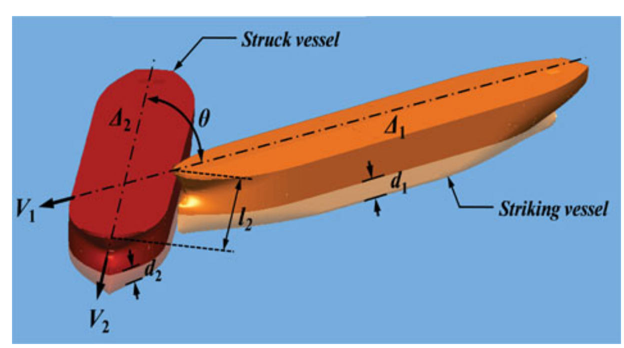

Figure 7. Schematic of a ship–ship collision. (This figure is available in colour online.)

coarse mesh is used outside the collision area to reduce the computational time (Sajdak and Brown 2005).

The bow shape of the striking ship is determined for each case using the bow shape model produced by Lützen (Lützen 2001). A sample of the geometric model of the striking bow portion used in this study is shown in Figure 6.

4.2. *Collision scenarios selection*

Youssef et al. (2014) suggested a sample of possible ship–ship collision scenarios using probabilistic approaches that may represent all possible scenarios on the basis of random variables. Accident variables identification is an important step of the proposed method, because each scenario will be described by these variables. The resulting parameters for each scenario are defined and indicated in Figure 7 and listed as follows:

- striking ship displacement (Δ_1),
- struck ship displacement (Δ_2),
- striking ship speed (V_1),
- struck ship speed (V_2),
- striking ship draught (d_1),
- struck ship draught (d_2),
- striking ship type,
- striking bow shape,

Table 2. Selected 30 scenarios.

Scenario	Striking ship type	Δ_2/Δ_1	V_2/V_1	$(d_2/D_2)/(d_1/D_1)$	l_2/L_2	θ (°)
1	Container	0.875	0.332	0.910	0.145	9.8
2	Container	0.924	0.389	0.930	0.200	18.5
3	Container	0.969	0.435	0.950	0.238	25.8
4	Container	1.012	0.475	0.970	0.269	32.2
5	Container	1.054	0.510	0.990	0.296	37.9
6	Container	1.094	0.541	1.010	0.321	43.3
7	Container	1.132	0.571	1.031	0.343	48.2
8	Container	1.170	0.598	1.052	0.365	52.9
9	Bulk carrier	1.207	0.623	1.073	0.385	57.4
10	Bulk carrier	1.244	0.648	1.094	0.405	61.8
11	Bulk carrier	1.280	0.671	1.116	0.423	66.0
12	Bulk carrier	1.317	0.694	1.139	0.442	70.1
13	Bulk carrier	1.353	0.717	1.162	0.460	74.2
14	Bulk carrier	1.390	0.739	1.186	0.478	78.2
15	Bulk carrier	1.427	0.761	1.210	0.496	82.2
16	Bulk carrier	1.465	0.783	1.235	0.514	86.2
17	Bulk carrier	1.504	0.805	1.261	0.532	90.2
18	Bulk carrier	1.544	0.827	1.289	0.550	94.3
19	Tanker	1.585	0.850	1.317	0.568	98.5
20	Tanker	1.629	0.873	1.347	0.587	102.7
21	Tanker	1.675	0.898	1.378	0.606	107.1
22	Tanker	1.724	0.923	1.411	0.626	111.6
23	Tanker	1.776	0.950	1.446	0.647	116.4
24	Tanker	1.834	0.978	1.483	0.669	121.4
25	Cargo ship	1.899	1.009	1.524	0.692	126.9
26	Cargo ship	1.972	1.043	1.568	0.717	132.8
27	Cargo ship	2.059	1.081	1.617	0.744	139.3
28	Cargo ship	2.166	1.125	1.672	0.775	146.9
29	Other	2.311	1.179	1.735	0.810	156.0
30	Passenger	2.548	1.248	1.809	0.852	168.0

- struck ship impact longitudinal location (l_2) and
- collision angle (θ).

Each parameter is considered a random variable with its own probability density function (PDF). Although consideration of all possible collision scenarios is not practical, the method developed by Youssef et al. is applied in this study to select 30 scenarios. Table 2 shows the randomly selected collision scenarios.

4.3. Collision simulations

To assess the consequences of the selected ship–ship collision scenarios, the non-linear explicit finite element software LS-DYNA is used. Figure 8 shows an example of the tanker–tanker collision for scenario 19.

Because many collisions occur when the collision candidates are sailing in high-traffic routes, for example, harbours, channels, rivers and narrow passages, it is assumed that the speed of the struck ship is 2 knots.

To make the simulations more realistic, the effects of the surrounding seawater are considered. In this study, the external ship dynamics are considered and defined in terms of hydrodynamics and the ship motions. The ship hydrodynamics represent the effect of the surrounding seawater in case of virtual added masses and the ship motions are calculated by conducting rigid-body motion analysis. Therefore, virtual added mass to the struck ship that considers surge, sway and yaw is used (Törnqvist 2003; Sajdak and Brown 2005). This added mass effect is calculated by the ship motion sub-program MCOL (Ferry et al. 2002). This program is used in the LS-DYNA program that determines the buoyancy forces and puts together all mass approximations (Ferry et al. 2002).

Paik et al. (1999) developed a method to define the damage volume as the space of the damaged side structure of the colliding vessel that approximately corresponds to the volume of the penetrated bow, whereas the original Minorsky method (Minorsky 1959) used the total volume of the affected structural members themselves. Figure 9 illustrates the difference in the damaged volume definition between Minorsky and Paik et al. In this study, Paik et al. method is employed as total damage volume. Table 3 shows the values of the resultant damage (i.e., penetration), absorbed energy and the damage volume for each collision scenario based on the collision results genetated by LS-DYNA.

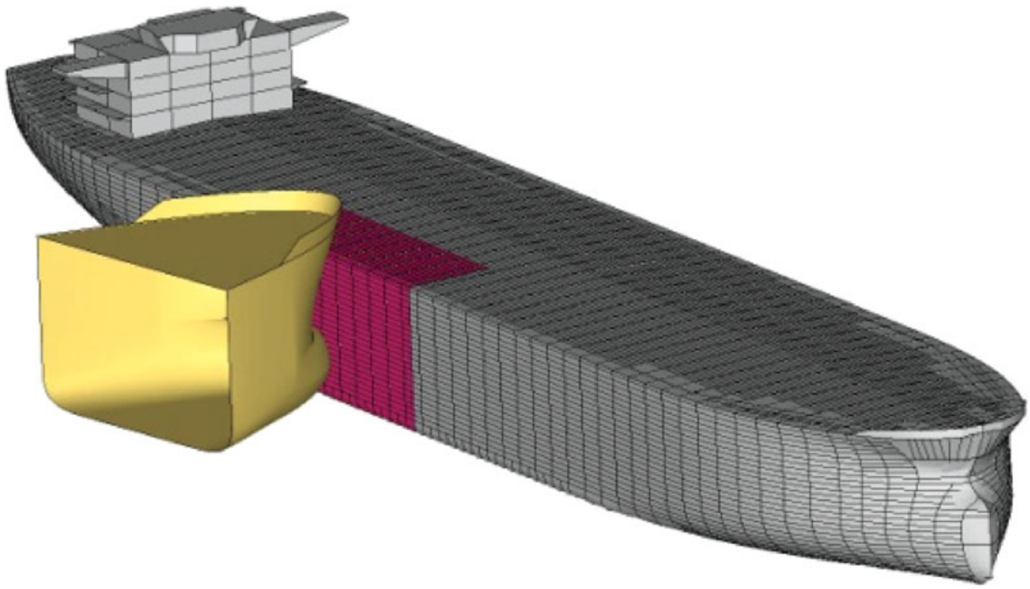

Figure 8. Example of a finite element simulation of a ship–ship collision. (This figure is available in colour online.)

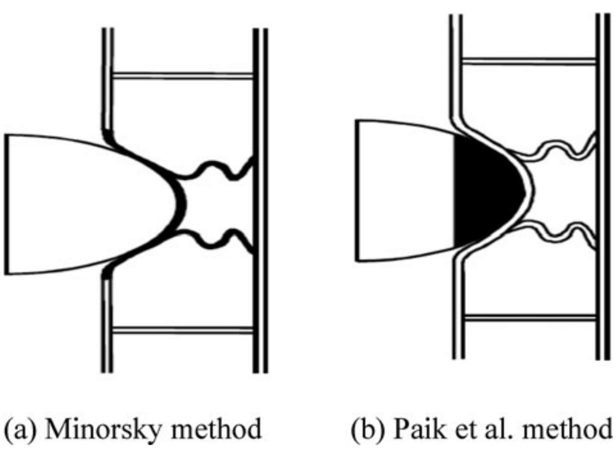

Figure 9. Method to calculate the damage volume of the struck ship structure (Paik et al. 1999).

Table 3. Simulation results of 30 collision scenarios.

Scenario	Maximum penetration (m)	Total absorbed energy (MJ)	Total damaged volume (m^3)
1	0.040	0.356	0.001
2	0.242	1.989	0.723
3	1.214	7.175	15.379
4	2.144	13.417	28.797
5	2.054	15.812	29.522
6	2.486	18.451	30.791
7	3.124	21.446	80.269
8	3.763	23.513	135.347
9	3. 603	42.855	176.211
10	3.857	45.458	306.402
11	4.147	48.62	351.879
12	4.523	55.891	375.384
13	4.605	64.08	454.045
14	4.817	70.939	528.393
15	5.383	63.646	556.312
16	4.433	58.245	386.352
17	4.288	49.129	325.446
18	3.432	43.369	279.741
19	2.450	38.154	164.246
20	2.342	32.046	154.732
21	2.274	26.703	140.836
22	1.968	21.454	98.648
23	1.321	17.704	29.425
24	1.164	13.334	18.847
25	1.060	7.390	12.646
26	0.888	5.522	5.354
27	0.709	2.742	2.992
28	0.407	1.472	0.904
29	0.053	0.600	0.012
30	0.004	0.058	0.001

4.4. Oil spill size measurement

For the calculation, the ship is assumed to be carrying its maximum load without trim and heel. The cargo tanks are assumed to be filled to 98% of their capacity (IMO 2003). In this study, the Suezmax-class double hull oil tanker has six oil cargo holds. Table 4 shows the capacity of each cargo hold.

Based on IMO suggestions (IMO 2003), this study considers two assumptions: an intact load condition is developed with the vessel at its maximum assigned load line with zero trim and heel, and the entire contents of all of the damaged cargo oil tanks are assumed to spill into the sea.

Table 4. Capacity of the cargo tanks of the struck ship.

Items	Capacity
No.1 cargo tank (m^3)	22,446.4
No.2 cargo tank (m^3)	30,440.3
No.3 cargo tank (m^3)	30,440.3
No.4 cargo tank (m^3)	30,440.3
No.5 cargo tank (m^3)	30,440.3
No.6 cargo tank (m^3)	28,636.5
Total cargo tank (m^3)	172,844.1

Table 5. Collision simulation results involved in oil outflow.

Scenario no.	Striking ship type	No. of damaged cargo tank	Size of oil spill (m^3)
7	Container	1 (No.3)	15,220.15
8	Container	1 (No.3)	15,220.15
9	Bulk carrier	1 (No.3)	15,220.15
10	Bulk carrier	1 (No.3)	15,220.15
11	Bulk carrier	2 (No. 3 & 4)	30,440.30
12	Bulk carrier	1 (No. 4)	15,220.15
13	Bulk carrier	1 (No. 4)	15,220.15
14	Bulk carrier	1 (No. 4)	15,220.15
15	Bulk carrier	1 (No. 4)	15,220.15
16	Bulk carrier	1 (No. 4)	15,220.15
17	Bulk carrier	1 (No. 4)	15,220.15
18	Bulk carrier	2 (No. 4 & 5)	30,440.30

Table 5 indicates the number of damaged cargo tanks and the resulting oil spill size for each scenario studied. Most of the scenarios in which the inner side hull is ruptured have one damaged cargo tank. However, scenarios 11 and 18 have two ruptured cargo tanks because the striking ship's bow hit the struck ship at the transverse bulkhead. Figures 10 and 11 show the results of the finite element collision simulations involving one and two ruptured cargo tanks, respectively.

4.5. *Cost of oil spill*

In this section, six models from the literature are used to estimate the total cost of the oil spills that result from each numerical simulation studied. These models calculate the total cost of an oil spill as a function of the amount of spilled oil. The cost herein represents the cost of the environmental clean-up (i.e., the removal of oil) and the claims paid for compensation (i.e., property damage of economic users such as fisheries, tourism and recreational users). Figure 12 compares the regression models of the total cost based on the quantity of spilled oil (Montewka 2009; Yamada 2009; Kontovas et al. 2010; Psarros et al. 2011; IMO 2013; Ventikos and Sotiropoulos 2014).

Using the above-mentioned regression models, the total cost of an oil spill and its increment rate are calculated as indicated in Table 6. Furthermore, a comparative study between the oil spill cost models is performed to investigate the relationship between the total size of the oil spill and the costs for the cases in which one and two cargo tanks ruptured (see Figure 13). Each regression model used different accident data period, repairing cost and so on. For example, Kontovas et al. (2010) only includes information from the IOPCF, which excludes several regions, such as US water.

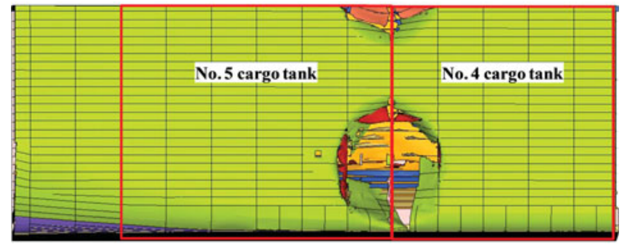

Figure 11. Scenario 18 result involving the rupture of two cargo tanks. (This figure is available in colour online.)

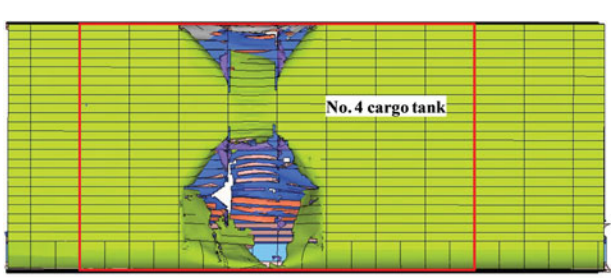

Figure 10. Scenario 15 result involving the rupture of one cargo tank. (This figure is available in colour online.)

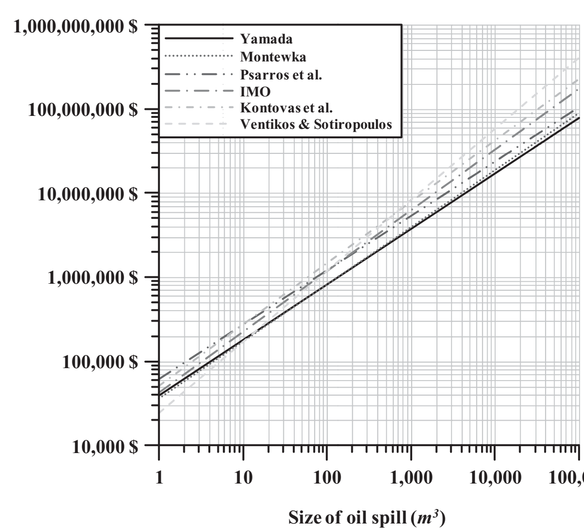

Figure 12. Comparison of the total costs per tonne from previous studies. (This figure is available in colour online.)

Table 6. Oil spill cost estimates.

Total cost equations	Size of oil spill (m^3)	Cost of oil spill (US$)	Increment rate (%)
Yamada (2009)	15,220.15	22,407,939	100
$y = 38{,}905x^{0.66}$	30,440.30	35,406,395	158
Montewka (2009)	15,220.15	25,104,747	100
$y = 35{,}951x^{0.68}$	30,440.30	40,221,313	160
Kontovas et al. (2010)	15,220.15	57,020,943	100
$y = 51{,}432x^{0.728}$	30,440.30	94,446,144	166
Psarros et al. (2011)	15,220.15	31,138,200	100
$y = 61{,}155x^{0.6472}$	30,440.30	48,766,335	157
Ventikos and Sotiropoulos (2014)	15,220.15	81,933,645	100
$y = 24{,}020x^{0.8447}$	30,440.30	147,143,917	180
IMO (2013)	15,220.15	44,822,311	100
$y = 42{,}301x^{0.7233}$	30,440.30	73,999,578	165

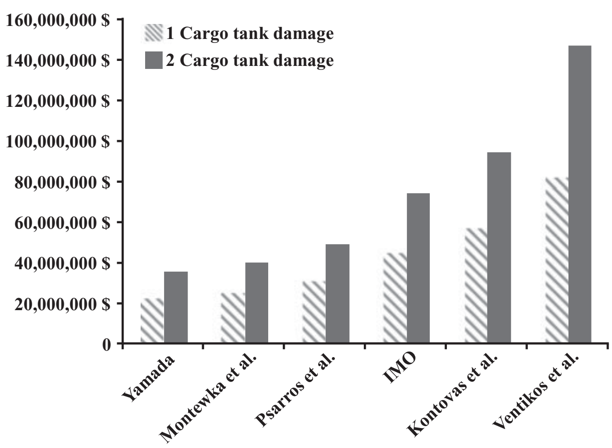

Figure 13. Oil spill cost estimates. (This figure is available in colour online.)

5. Conclusions

This study presents an analysis of the environmental consequences of oil tankers involved in collisions. Thirty collision scenarios are selected using probabilistic approaches. As an applied example, a Suezmax-class double hull oil tanker is assumed to be struck by various types of vessels. Based on the selected collision scenarios, the bows of various striking ships are modelled. The non-linear finite element analysis program LS-DYNA/MCOL is used in the collision numerical simulations to predict the resulting damage or openings associated with individual scenarios.

According to the resulting damage in the structure of the struck ship for the studied scenarios, the inner hull plating is ruptured in some cases, causing oil outflow. The amount of each scenario's oil spill is calculated. The cost of the oil is calculated using various cost models found in the literature. In addition, the perfomeances of existing regression models in calculating the total oil spill are compared. Through these results, the following conclusions are made.

- Regardless of the collision scenarios, the IMO assumption (i.e., that all of the oil will be spilled after an accident) results in the same amount of oil spilled in each scenario. It seems that a more accurate means of measuring the size of the oil spill involved in an accident is needed. However, the IMO suggestion might be reasonable in the case of accidents occurring in harsh seas (e.g., large waves, strong currents, high wind) that cause heavy ship motion.
- The regression model of Ventikos (2014) results in the highest total oil spill cost, almost twice as high as the others.
- The total cost of an oil spill in which two cargo tanks are ruptured is not double that of cases in which one cargo tank is ruptured (see Section 4.5). This indicates that the cost of the oil outflow does not depend on the size of the oil spill.

This study contributes an environmental consequence analysis of tankers involved in collisions. If the collision frequency is available for each scenario, the environmental risk for the target ship can be obtained. Furthermore, the probability of exceeding the oil spill size and costs can be obtained, which may contribute to the establishment of accidental limit state design criteria to mitigate the oil spilled from tankers.

Disclosure statement

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