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Paper 143 - Monte Carlo simulation model to determine the vessel impact energy for the design of port terminals in river and estuarine environments

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ABSTRACT: This article describes the development and implementation of a simulation model based on Monte Carlo techniques to estimate the probability distribution function of the vessel impact energy for a given structure build on a fluvial or estuarine environment. The model enables the designer to estimate the impact energy that must be used for design in order to achieve the reliability level required by standards or recommendations, providing also the set of possible combinations of ships characteristics and environmental conditions that leads to the selected energy.

1 INTRODUCTION

For the design of certain types of harbour works it is required to consider the possible impact of a vessel on the structure. In particular, for structures that support hydrocarbon pipelines this is a design requirement established in international standards (see e.g. ISO 19902). However the definition of the impact scenario (type, size and speed of the vessel) included in the standards do not necessarily fits to the specific conditions found in a fluvial or estuarine environment, since standards and recommendations are devised mainly for off-shore oil platforms.

An alternative is to define an impact scenario based on expert opinions: that is choosing a type of ship (size, type and speed) from the local fleet as well as the expected environmental conditions (winds and currents) that may lead to the occurrence of the impact. However this choice would be arbitrary and subjective and, not being guided or supported by any standard or recommendation, a significant uncertainty would remain about the level of reliability of the structure. In particular, once the impact energy is estimated from the chosen scenario, this energy could be exceeded by several different combinations of ships and environmental conditions (e.g. bigger ships and milder environmental conditions than used in design, or vice versa).

This article describes the development and implementation of a simulation model based on Monte Carlo techniques aimed to estimate the probability distribution function of the vessel impact energy for a given structure in an estuarine environment. The model enables the designer to select the impact energy that must be used in the design process in order to achieve the reliability level required by standards or recommendations, providing also the set of ships characteristics and concomitant met-ocean conditions that leads to the selected energy.

The model simulates a large number of transits from the fleet of ships transiting the area. During the simulation each ship is assigned a speed and a set of met-ocean conditions (wind and current) obtained from the local climate. Then the model estimates, depending on the type and size of the ship and on the environmental conditions, the probability that the ship drifts and impacts the structure. If a given ship does not result in an impact of the structure, then the impact energy assigned to that transit is zero. If instead the ship do drift and impacts the structure, then the model calculates the impact energy. The calculation of the drifting probabilities and of the impact energies are performed adapting the methodology described by DNV (2007) recommendations, with some specific modifications introduced to better fit our case study.

The model is applied in the design of a structure located west of the port of Montevideo, Uruguay, where the fleet that travels alongside the structure comes mainly from Buenos Aires and from the Parana and Uruguay River waterways. The obtained results show: (1) the usefulness of the model for optimizing the impact energy used in the design of the structure, and (2) that the definition of design scenarios based on expert judgment may result misleading in terms of the expected reliability of the structure.

2 OBJECTIVE

The objective is to establish the design impact energy for an offshore structure that will be located in the vicinity of the port of Montevideo, which aims to support hydrocarbon pipelines.

Given the location of the structure, one of the threats to be considered for its design is the impact of a ship (see e.g. ISO 2007, DNV 2010). For this particular structure it was found that this threat is the one that ultimately determines the main dimensions of the structure, so its correct definition and characterization is of paramount importance.

The procedure used to characterize this threat in terms of the design impact energy is described next.

3 BACKGROUND

DNV (2010) defines three scenarios that may lead to a collision between a vessel and an off-shore structure, namely:

- *DNV_S1*: Collision of ships in transit in the vicinity of the platform, either in a predefined shipping lanes or in transit with random directions.
- *DNV_S2*: Drifting of vessels that were standing by close to the platform.
- *DNV_S3*: Impact from a supply vessels approaching the platform.

Taking these scenarios as a reference, the following scenarios or working hypotheses are analysed here:

S1: Impact of a ship in transit that deviates from its predefined route. To the south of the structure there is a shipping lane for ships in route from/to Montevideo to/from several ports in Uruguay, Argentina and Paraguay. It is not expected to have ships running in random directions in the vicinity of the structure.

S2: Impact of a ship drifting towards the structures due to machinery breakdown. In this case there is neither an anchoring area nor a standby vessel close to the structure, as assumed in scenario *DNV_S2*. However it is assumed here that there is a chance of a machinery breakdown of one of the ships in transit on the shipping lane located to the south of the structure, and that, if wind are current conditions are unfavourable, this drifting ship may impact the structure.

S3: Ship approaching the structure for inspection and/or maintenance purposes. While the structure is not expected to receives ships on a regular basis, as is the case for manned platforms considered in *DNV_S3* as well as on ISO (2007,2010), NORSOK (2007) and API standards (as referenced in DNV 2012), it is anticipated that there will be occasional traffic of small ships, for the inspection and maintenance of the structure.

S4: Minor drifting objects.

Not all proposed scenarios are equally relevant to the design of the structure.

In the case of *S3*, it is anticipated that inspection and maintenance vessels will be of about 50 tons, and that such activities will be conducted under mild met-ocean conditions, so that the impact associated with this scenario is characterized by assuming a *high energy impact* (as defined in DNV 2007) equivalent to that defined in *DNV_S3*, with an approach speed of 2 m/s, in agreement with what is proposed in ISO (2007) and NORSOK (2007).

For *S4* it is sufficient to include some protective elements that prevent smaller objects from impacting critical elements supported by the structure (as pipelines, etc.).

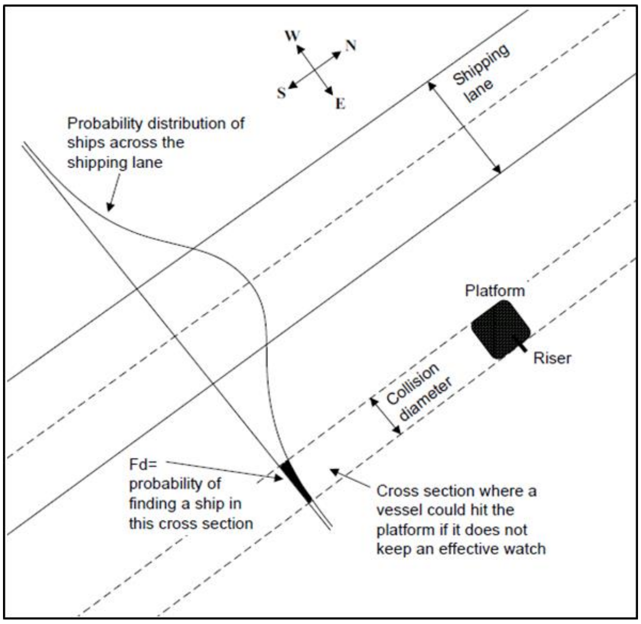

Figure 1: Scheme of the calculation methodology for the impact probability under scenario *S1* (taken from DNV 2007).

The probability of a collision occurring under scenario *S1* depends on the number of transits that take place on the shipping lane located at the south of the structure, on the distance between the axis of the shipping lane and the structure, and on the dispersion of the transits around the axis (see figure 1). For this case study it has been determined (calculation not shown here) that the likelihood of a collision under this scenario is reduced to negligible values by slightly moving the shipping lane to the south, so no further analysis is performed for *S1* here.

Regarding scenario S2, it is clear that conditions defined for scenario DNV S2 do not apply here. For scenario DNV S2 (see DNV 2007) it is assumed that machinery breakdown occurs for a particular type of vessel, that is in standby next to the platform, and that a hurricane wind speed occurs with the vessel located upwind of the platform. On the other hand, it is no straightforward to establish whether the probability of a machinery breakdown and drifting to collision of a passing vessel is negligible under scenario *S2*, nor to estimate how this probability is affected by moving the shipping lane further to the south. Moreover, it is neither straightforward to define collision characteristic (type of ship, drifting speed and, ultimately, impact energy) in case of occurring a collision.

Therefore we proceed to develop a simulation model for calculating the probability of occurrence of a collision under scenario *S2*, and for estimating impact energies reached as well as the conditions in which they occur.

4 SIMULATION MODEL

4.1 Introduction

Section 5.4.2.3 of DNV (2007) establish that the probability of a platform being collided by a standby vessel that drifting due to a machinery breakdown is calculated as (scenario *DNV_S2*):

$$F_{collision} = NP_1(P_2T)P_3P_{riser}$$

where ***N*** is the number of standby ships per year; $\boldsymbol{P_1}$ is the geometric probability of impacting the platform, estimated as ***(W+0,5(B+L))/(2πR)***, being ***W*** the diameter of the platform, ***B*** the width of the vessel, ***L*** its length and ***R*** the radius of the standby zone; $\boldsymbol{P_2}$ is the hourly probability of machinery breakdown of the ships; ***T*** is the number of hours per year that a vessel is the vicinity of the platform; $\boldsymbol{P_3}$ is the probability of failure to correct the situation (normally taken as 1), and $\boldsymbol{P_{riser}}$ is the probability of hitting the riser given a hit with the platform (in this case equal to 1 since we are estimating the probability of hitting the structure).

According to DNV (2007), in this calculation it is assumed that the standby vessel is always upwind of the platform, and that the drifting speed is 3% to 5% of the wind speed, with the wind speed being 32.6 m/s, corresponding to hurricane conditions.

In this study the above formulation is modified for the estimation of the probability of occurrence of an impact energy greater than $\boldsymbol{E_D}$, being $\boldsymbol{E_D}$ the impact energy used for the design of the structure, under scenario *S2*, that is: drifting vessels are not standby vessels but vessels in transit on the shipping lane located to the south of the structure.

4.2 *Methodology*

The methodology developed to calculate the probability of exceeding a given impact energy $\boldsymbol{E_D}$ is based on the use of Monte Carlo simulation techniques.

Starting from the information regarding the fleet that transits on the shipping lane located in the vicinity of the structure, several transits are are randomly simulated. For every transit ship dimensions and met-ocean conditions are simulated, accordingly to the fleet information and the local climate, respectively.

The probability of occurrence of a collision *Prob(Impact | Transit)* is estimated based on the ship dimensions, on its transit speed and on the wind direction (see section 4.3). A uniformly distributed U(0,1) random number is then generated. If it is higher than the estimated probability, then there is no impact for the given transit and the impact energy for this transit is zero. Otherwise the collision occurs and we proceed to estimate the impact energy as a function of the ship characteristics, and of the wind and current speeds, as described on section 4.4.

Once simulated a high number of transits, the probability distribution of the impact energy is calculated and, from it, the return period (or annual probability) of the impact energy used for the design of the structure is estimated (see section 5.1). Additionally, typical impact conditions are identified from the simulations (i.e. size of the ship and concomitant met-ocean conditions).

4.3 *Probability of an Impact given a Transit; Prob(Impact | Transit)*

It is assumed that the impact can only happen if the ship is upwind of the structure. The time that the ship is upwind of the structure is calculated based on the angle between the wind direction and the lane direction and on the size and speed of the ship (see Figure 3) according to the following expression:

$$T_{upwind} = (W + L)/(\mathrm{v_s}\cos(\theta_{wind} - \theta_{lane}))$$

where ***W*** is the characteristic diameter of the structure, ***L*** is ship length (randomly simulated for each transit) and $\boldsymbol{v_s}$ is the ship speed in m/s, randomly simulated from an uniform distribution U(4,8).

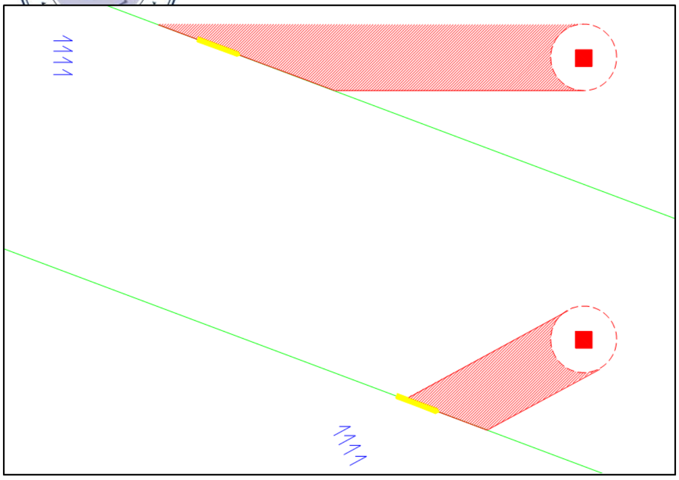

Figure 3: Scheme of the calculation of the time during which the ship is upwind of the structure, for a W wind (top) and for a SW wind (bottom). Shipping lane is represented by the green line, structure represented by red square, ship represented by yellow rectangle and collision drifting trajectories represented by red shadow.

The probability of an impact given a transit is then calculated as:

$$Prob(Impact\ |Transit) = \frac{P_{f,hourly} C_S T_{upwind}}{3600}$$

where $\boldsymbol{P_{f,hourly}}$ is the machinery breakdown probability in an hour, that in the absence of specific information is taken as 2×10^{-5} (DNV 2007), $\boldsymbol{C_s}$ is a factor used to penalize (increase failure probability) certain types of ships (see section 5) and $\boldsymbol{T_{upwind}}$/3600 is the time in hours that the ship is upwind of the structure.

4.4 Calculation of the impact energy given a collision

In case there is a collision, the impact energy of the collision is calculated by means of:

$$E_I = \frac{1}{2} M C_a v^2$$

where ***M*** is the mass of the ship, ***Ca*** is the added-mass coefficient and ***v*** is the drifting speed of the ship.

According to ISO (2007) the added–mass coefficient ***Ca*** is 1.4 for a 5,000 ton supply vessel, being higher for smaller vessels (e.g. 1.6 for a 2,500 ton ship). According to ROM 2.0-11 (Puertos del Estado 2011) the added-mass coefficient used for estimating berthing energy is between 1.5 and 1.8, depending on the under keel clearance.

Here, the added-mass coefficient ***Ca*** used in calculating the impact energy is given in figure 4. For vessels over 5,000 ton ***Ca*** is 1.4. For vessels under 5,000 ton ***Ca*** decreases linearly, being 1.6 for a 2,500 ton vessel. Figure 5 shows de distribution of the total mass (***MCa***) for the design fleet, considering only ships with draft under 6.5 m, since those are the only ships that can reach the structure.

Drifting speed of the ship is estimated based on wind and current speeds, by means of:

$$v^2 = \left(C_w V_{w,X} + V_{c,X}\right)^2 + \left(C_w V_{w,Y} + V_{c,Y}\right)^2$$

where $\boldsymbol{C_w}$ is a coefficient relating wind speed and drift speed that varies between 0.03 and 0.05 (DNV 2007), that is randomly generated for every transit from an uniform distribution U(0.03,0.05), $\boldsymbol{V_w}$ is the wind speed, randomly generated from the local wind climate, $\boldsymbol{V_c}$ is the current speed, randomly generated from the local currents climate estimated at the south of the structure, and subscripts ***X*** and ***Y*** refers to W-E and S-N components of the speeds.

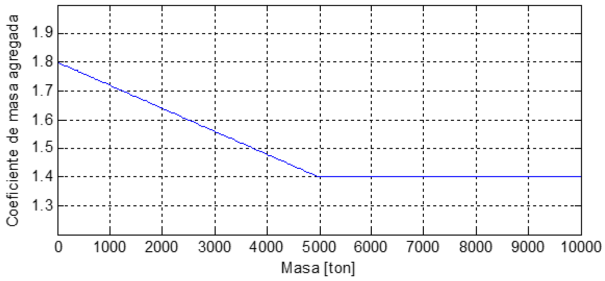

Figure 4: *Ca* coefficient as a function of ships tonnage.

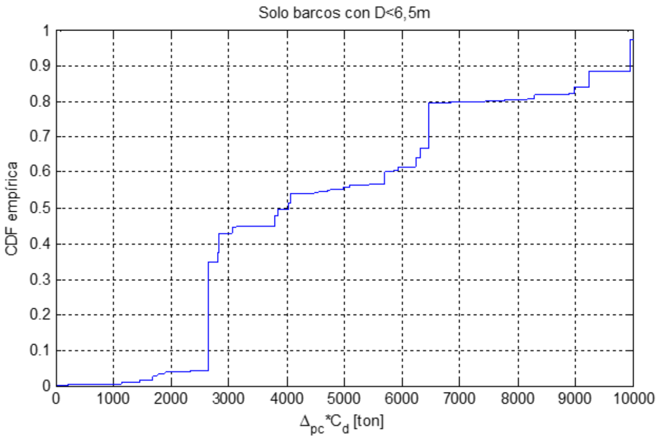

Figure 5: Probability distribution of the total mass (*MCa*) for the design fleet, considering only ships with draft under 6.5 m.

5 RESULTS

5.1 Impact energy distribution

The probability distribution of the impact energy is calculated by means of the model described on section 4. Here, towed barges coming from inland waterways are penalized by imposing Cs=10 (i.e. it is assumed that the drifting probability of a towed barge is ten times that of the self-propelled barges and ships).

One of the many possibilities given by the proposed model is that it allows to evaluate the probability of occurrence of the design impact energy ED under several fleet growth scenarios. Here, two scenarios are analysed, namely:

(0) Current fleet
(1) Future fleet (100% increase on the number of ships and 25% increase on the size of the ships)

Figure 6 shows the probability distribution of the impact energy, conditional to the occurrence of a collision, estimated for both scenarios. Table 1 summarizes results obtained when taking E_D=2.5 MJ.

Table 1: Annual probability of exceedance of E_D for scenarios (0) and (1).

Scenario	**Impact Energy**	**Annual exceedance probability**
0	E_D	5.7 x10^{-6}
1	E_D	2.0 x10^{-5}

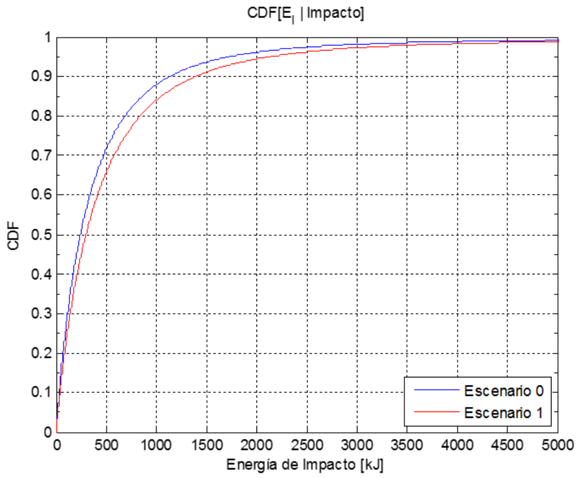

Figure 6: Probability distribution function of the impact energy, conditional to the occurrence of a collision, estimated for scenarios (0) and (1).

5.2 Sensitivity analysis

The proposed model also facilitates performing a sensitivity analysis of the results against different factors involved. In this case the sensitivity of the probability of exceedance of the design impact energy (E_D) is analysed by varying E_D and by varying the added-mass coefficient Ca. To this end the following probabilities are estimated:

(a) The probability of an impact exceeding more than 20% ED under scenarios (0) and (1) previously studied.

(b) The probability of exceeding ED if an added-mass coefficient Ca=1.8 is imposed irrespective of the size of the ships under scenario (0).

Obtained results are summarized on table 2, next.

Table 2: Results obtained from the sensitivity analysis

Scenario / variation	**Impact Energy**	**Annual exceedance probability**
0/a	1.2xED	4.2 x10^{-6}
1/a	1.2xED	1.4 x10^{-5}
0/b	ED	8.3 x10^{-6}

5.3 Characteristic impact conditions and concomitant met-ocean conditions

It is useful to provide designers as well as decision makers with a characterization of the typical conditions that result in the design impact energy. This gives confidence in the results of the proposed model and may be useful in the design of certain geometrical aspects of the structure.

In order to associate the design impact energy with realistic conditions, the probability distribution of both wind speed (V_w) and total mass (MCa) were obtained for transits with in impact energy around E_D, under scenario (0). Figures 7 and 8 show the obtained distributions. Mean of the distribution is 15.3 m/s (55 km/hr) for the wind speed and 10,400 ton for the total mass. The mode of the total mass is 7,100 ton.

A typical impact condition of E_D impact energy is obtained with the mean values of total mass and wind speed (10,400 ton and 15.3 m/s, respectively) by assuming that the drifting speed is 4.5% of the wind speed and that the current speed is zero. A total mass of 10,400 ton is obtained by assuming a ship of M = 7,400 ton and an added-mass coefficient Ca=1.4.

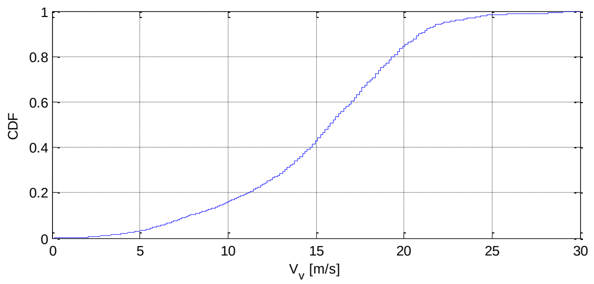

Figure 7: Probability distribution of wind speed conditions (V_w) with which impact energy E_D is obtained.

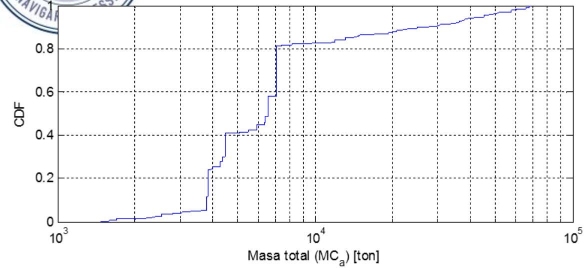

Figure 8: Probability distribution of total mass conditions (*MCa*) with which impact energy E_D is obtained.

Alternatively, ED is obtained by assuming a ship of total mass of 7,100 ton (mode of the distribution on figure 8), a wind speed of 15.3 m/s (mean value of figure 7), and a drifting speed of 4% of the wind speed plus a current speed of 0.2 m/s. The total mass of 7,100 ton is obtained, for example, if a ship of 5,000 ton is used, along with an added-mass coefficient equal to Ca = 1.42.

Moreover, by knowing the probability distribution of the wind speeds that results on the design impact energy, it is possible to characterize the met-ocean conditions that are concomitant with the impact, in order to fully define the working conditions required to reify the structure. To this end, the probability distribution of sea level and waves conditional to the wind speed is required.

For example, if the 99% non-exceedance probability wind speed is taken from figure 7 (i.e. 27 m/s), and taking into account that only wind directions from the W to the SE can result in a collision, it is straightforward to use the extreme weather generator described on Solari et al. (2014) in order to obtain the distribution of the sea level (SL) and the significant wave height (Hm0) conditional to the wind speed (figure 9).

6 DISCUSSION

The proposed model is a powerful tool not only to determine the impact energy to be used for designing a structure in order to fulfil with the required reliability level, but also to characterize the type of vessel that produces this energy and the met-ocean conditions concomitant with the impact.

However the implementation of the model requires a volume of information that is not always available in the early stages of a project, namely: wind and currents climates (a joint characterization is preferable), expected fleet of vessels in the vicinity of the structure, including dimensions and loads of each ship, probability of loss of control of the ships (machinery breakdown).

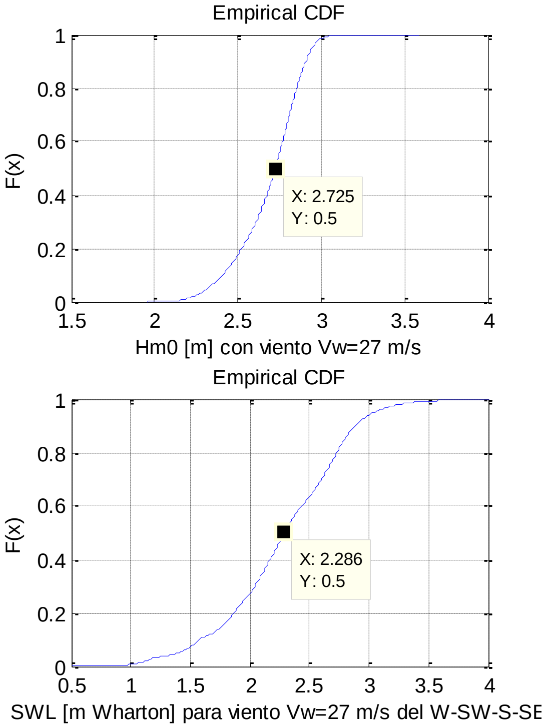

Figure 9: Probability distribution of the significant wave height (top) and sea level (bottom), conditional to a wind speed of 27 m/s from directions W to SE, passing by the S.

In so far as that some of the required information is not available, figures included in international and local standards and recommendations may be used, though this implies an increase in the uncertainty of the results when such figures have not been estimated for local conditions.

An advantage of the model is that, in the absence of precise information, it is easy to conduct sensitivity analysis of the results to various parameters. This allows designers and decision makers to gain confidence in the result and, also, facilitates the identification of those parameters that most affect the outcome and therefore deserve greater analysis.

7 CONCLUSIONS

The development and implementation of a simulation model based on Monte Carlo techniques to estimate the probability distribution function of the vessel impact energy for a given structure was introduced.

The model enables the designer to more accurately select the impact energy that must be used for the design in order to achieve the reliability level required by standards or recommendations, providing also the set of combinations of ships and environmental conditions that leads to the selected energy.

The proposed model was applied to a case study close to Montevideo Harbour (Uruguay), showing its applicability and usefulness.

Main drawback of the proposed model is the amount of information required for its implementation, some of which is hardly available for many worldwide locations, being necessary to resort to recommended figures that are included in international standards and recommendations, but that may not be representative for every study case. This issue is partially addressed by performing sensibility analysis, something for which the model is particularly well suited.

The proposed model was introduced mainly by showing a case study. However the methodology described here is general and, therefore applicable at any other case study in which a structure is being designed next to a shipping lane.

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