DRAGGED ANCHORS INTERACTION SCENARIOS: DETAILED FREQUENCY ANALYSIS FOR PIPELINE DESIGN

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Abstract: Offshore pipelines provide a vital means and a safe mode to transport commodities such as oil and natural gas, as witnessed by the few recorded incidents of fatality or injury despite the millions of kilometers of pipelines in use worldwide. However an accident to an offshore pipeline can lead to several issues ranging from people safety, impact on the environment to the expensive and time consuming repair operations. Pipelines located in areas with intense ship traffic are exposed to the risk of damage or failure due to interactions with third parties (i.e. dragged anchors, dropped objects and sinking ships). Certainly, one of the most serious ship traffic related threats is due to the dragged anchors. This scenario may result as a consequence of two events: anchoring in an emergency situation or accidental drop of the anchor and uncontrolled dragging. This paper focuses on the methodology for the evaluation of the interaction frequency between dragged anchors and a subsea pipeline.

Keywords: Interaction frequency, uncontrolled dragged anchors, ship traffic, subsea pipeline, risk.

1. INTRODUCTION

Pipelines located in areas with intense ship traffic are exposed to threats such as dragged anchors, dropped objects, sinking ships, and so forth..
For a safe design the interaction scenarios between the ship traffic and the subsea pipelines shall be analyzed and the pipeline annual failure probability due to ship traffic shall be compared with the acceptability targets provided by the end-users or by design standards such as DNVGL-ST-F101 [4] in order to establish the need of specific pipeline protection.
Typical interaction scenarios related to the ship traffic are:

- Sinking vessels;
- Dragged anchors;
- Dropped anchors,
- Dropped objects;
- Grounding vessels.

Among these scenarios the most serious in terms of annual failure probability is certainly the dragged anchor one, as demonstrated by the several recorded incidents [14]. This scenario could result as a consequence of two events:

- Anchoring in an emergency situation (leading to emergency dragged anchor);
- Uncontrolled drop of the anchor (leading to accidental dragged anchor).

Some examples of emergency dragged anchors leading to pipelines damage are the APL Sydney dragged anchor due to bad weather leading to damages on a gas pipeline [2] or the Young Lady dragged anchor due to bad weather and machinery failure leading to damages on the CATS pipeline [12].
One of the most serious incident to pipelines caused by an accidental dragged anchor involved the Trans Mediterranean gas pipelines in 2008 which led to catastrophic failure of one of the Transmed pipelines and to critical damage of another Transmed pipeline [15].
Also in the North Sea in 2007 a dragged anchor has damaged a pipeline (the Kvitebjørn gas pipeline) and it could probably be attributed to an accidental dragged anchor incident.
However from incident statistics it is difficult, to distinguish between the accidental and the emergency dragged anchor, due to lack of details in the incidents records. Thus it is not possible to estimate the pipeline failure frequency due to dragged anchor scenarios from the statistics. This paper

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focuses on the development of a methodology to evaluate the accidental and emergency dragged anchor frequency and presents the results of its application to a case study.

2. STATE OF PRACTICE

Several standards, such as DNV [4], ISO [9] and ASME [1], require guarantees for the pipeline integrity and compliance with a target expressed as pipeline failure per year per km for the accidental loads. The ship traffic impact usually falls among these accidental loads. For this reason, for the pipeline design to be in accordance with these standards, ship traffic threats cannot be neglected and shall be analyzed in detail, especially in proximity to shipping lanes.
Moreover this is a requirement given by the pipeline end-users, who want to ensure the pipeline integrity during the entire design life in order to avoid and minimize the repair interventions, that for the subsea pipelines could be very onerous both in terms of costs and schedule.
The topic of the interaction between the ship traffic and the subsea pipelines or cables has been widely discussed in the literature [4, 5, 11, 16]. DNV [3] proposes a methodology to evaluate the threats due to the interaction between the subsea pipeline and the uncontrolled drop of the anchor. This approach and the one proposed by [16] have been used as a basis to develop the methodology presented in this paper.
In particular, [16] provides a generic approach to evaluate the frequency of interaction between the ship traffic and the pipeline. The article suggests to calculate the interaction frequency per kilometer as a function of the ship class (i.e. GRT or DWT), the hazardous scenario frequency (e.g. dragged anchor, dropped object, sinking ship, grounding ship), the geometric probability of interaction (i.e. the probability that the ship or the object is in the area where the interaction with the pipeline may occur) and the number of ships crossings per kilometer. The same approach is followed in this paper.
Generally the emergency dragged anchor scenarios is considered to be predominant with respect to the accidental one which is sometimes neglected. However after the Transmed pipeline incident more attention from the industry was dedicated to the evaluation of this possible incident.
DNV [3] provides a specific guideline for the scenario of uncontrolled anchor drop. It divides the consequences of an uncontrolled anchor drop in three interaction outcomes:

- Outcome 1: Drop discovered within 1 km and actions are taken;
- Outcome 2: Anchor seated within 1 km, maximum penetration depth and anchor holding power;
- Outcome 3: Anchor does not get seated. One projected fluke length penetration depth. Dragged in/along seabed for longer distance.

For each outcome the relevant frequency is calculated considering the sequence of events leading to that scenario and the associated dragging length. Considering the available guidelines, this paper presents a more detailed methodology for the evaluation of the dragged anchor interaction frequency taking into account specific aspects of this scenario.

3. METHODOLOGY

3.1. Introduction

The aim of the ship traffic interaction assessment is to ensure that the targets given for accidental loads are satisfied. In the proposed methodology the annual pipeline failure probability given in DNVGL-ST-F101 [4] is considered.
The target shall be verified by taking into account all the ship traffic related threats (i.e. sinking vessels, emergency dropped and dragged anchors, accidentally dropped and dragged anchors, dropped objects from commercial vessels and grounding vessels).
This paper focuses on the dragged anchor scenario due to the uncontrolled drop that is usually neglected compared to the emergency dragged anchor.
The model developed for the dragged anchor scenario is based on the analysis of the available statistical data regarding the causes of anchor loss and ship accidents so as to establish the potential sequence of events leading to anchor dragging on the pipeline, either as a result of an emergency on board or due to an uncontrolled accidental loss of the anchor. The other parameters considered in the

analysis are the ship traffic intensity, the soil characteristics, the water depth and the pipeline geometric interaction probability calculated as a function of the pipeline geometry and the dragging length.
As stated above, the dragged anchor scenario can be divided in two groups:

- Emergency dragged anchor;
- Accidental dragged anchor.

The first can happen following an emergency situation on board, possibly inducing the vessel crew to drop the anchor outside dedicated anchoring areas. Examples of emergency situations are:

- Bad weather;
- Mechanical failure;
- Collision;
- Fire on-board;
- Steering failure.

In these cases, the anchoring is an intentional action.
The accidental dragged anchor may occur due to an unintentional drop of the anchor. This scenario can be caused by a failure of the equipment used for securing the anchor on-board (i.e. windlass motor, windlass brake, chain stopper) or by an operational error (e.g. a seafarer forgets to secure the anchor).

3.2. General model

The total ship traffic interaction frequency ($F_{int,tot}$) is calculated per 1 km of pipe, since the DNV criteria per accidental loads can be expressed per km in case of local loads, such as the ship traffic. It is calculated by means of the following equation:

$$F_{int,tot}\left(\frac{events}{km\cdot y}\right) = \sum_k F_{int,k} \quad (1)$$

where:
k = interaction scenario (i.e. sinking, emergency dragged anchor, accidental dragged anchor, emergency dropped anchor, accidental dropped anchor, dropped object or grounding);
$F_{int,k}$ = interaction frequency of the scenario k.
$F_{int,k}$ is expressed by the following equation:

$$F_{int,k}\left(\frac{events}{km\cdot y}\right) = \sum_{j=1}^{n}\left(1-\left(1-F_{k,j}\cdot P_{g,k,j}\right)^{N_j}\right) \quad (2)$$

where:
j = j-th ship class/object type;
n = number of ship classes/object types considered in the analysis;
$F_{k,j}$ = frequency of ship accident (events per ship);
$P_{g,k,j}$ = geometric interaction probability (i.e. probability that a ship/object is in the critical interaction area);
N_j = number of ships/objects crossing per km and per j-th ship class/object type (ships or objects per km per year).
In the following paragraphs the parameter $F_{k,j}$ and $P_{g,k,j}$ for the emergency and the accidental dragged anchor are analysed in detail.

3.3. Emergency dragged anchor interaction frequency

The emergency anchoring scenario has been evaluated as a consequence of the following causes:

- Collision;
- Mechanical Failure;
- Other failure/accident (e.g. storm, ice damage, fire, etc.).

The frequency of emergency dragged anchors has been estimated by means of the following equation:

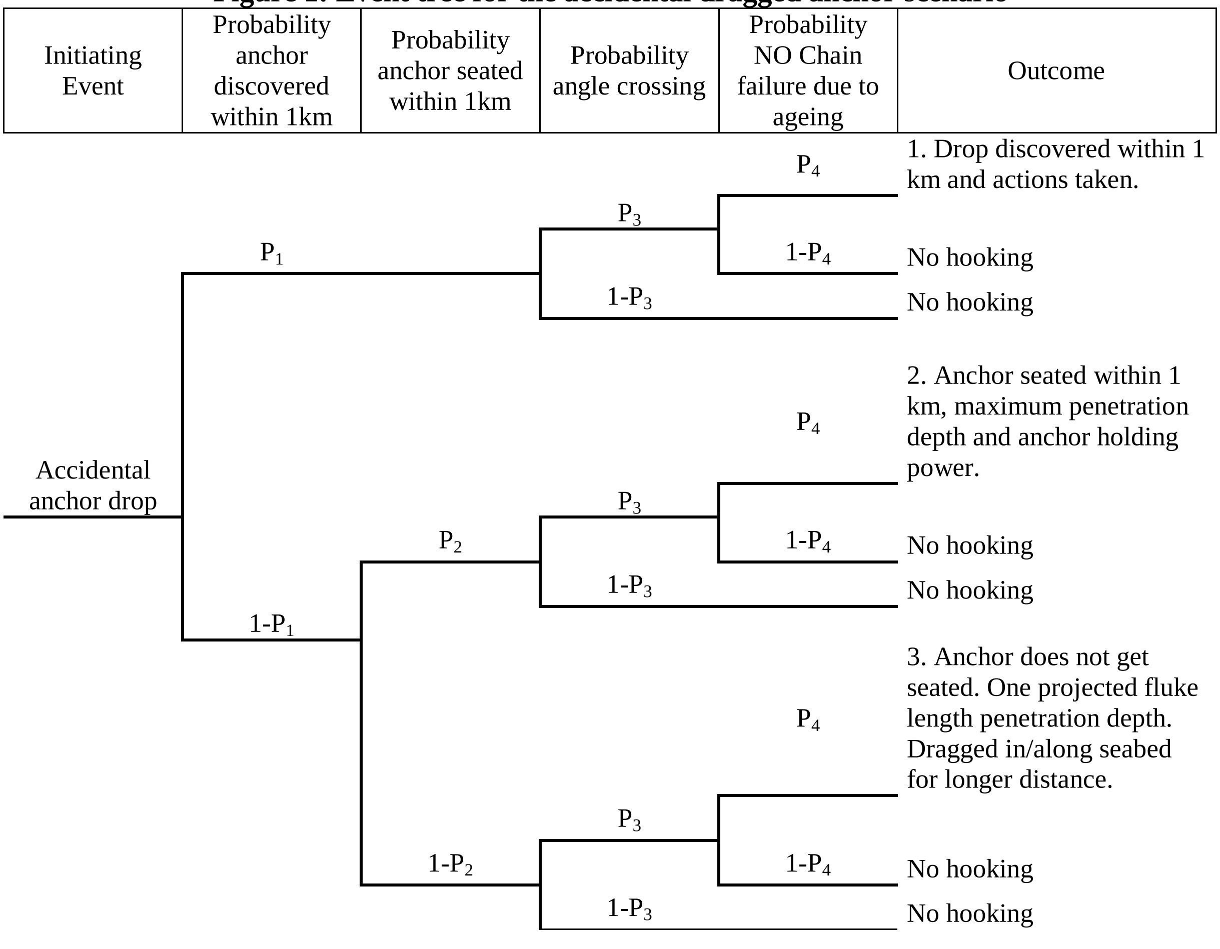
$$F_{emdrag.j}\left(\frac{events}{ship}\right) = \left[F_{coll,j}\cdot P_{anch|coll} + \left(F_{mf,j}+F_{other,j}\right)\cdot P_{anch|other}\right]\cdot L_{lane} \quad (3)$$

where:
$F_{emdrag,j}$ = frequency of emergency dragged anchors for the ship class j (events/ship);
$F_{coll,j}$ = frequency of collision for the ship class j (events/ship/km);
$F_{mf,j}$ = frequency of machinery failure for the ship class j (events/ship/km);
$F_{other,j}$ = frequency of other emergencies for the ship class j (events/ship/km);
$P_{anch/coll}$ = anchoring conditional probability given collision;
$P_{anch/other}$ = anchoring conditional probability given an emergency situation different from collision;
L_{lane} = shipping lane length (km).
$F_{coll,j}$, $F_{mf,j}$ and $F_{other,j}$ can be obtained from the literature data, such as [7], [13] or [10].
$P_{anch/coll}$ and $P_{anch/other}$ can be calculated from the statistical data, such those given in [10].

3.4. Accidental dragged anchor interaction frequency

The frequency of accidental dragged anchors is evaluated by means of the event tree reported in Figure 1. This represents the sequence of events leading to accidental drop and drag of the anchor across the pipeline.

Figure 1: Event tree for the accidental dragged anchor scenario



Based on the event tree, pipeline hooking may occur as a result of three outcome scenarios.
The first two outcomes are characterised by a dragging length of 1 km, whereas outcome 3 is characterised by a dragging length higher than 1 km.
The sequence of events leading to these three outcomes is characterised by the following probabilities, each one representing an event:

- P1: probability of discovering the anchor accidentally dropped within 1 km.
- P2: probability that the anchor accidentally dropped seats within 1 km.
- P3: probability that the anchor hooks the pipeline on the basis of the anchor crossing angle.

- P4: probability that the anchor chain does not fail due to ageing in case of pipeline hooking.

3.4.1. <u>Accidental Anchor Drop Frequency</u>

The first branch of the event tree is the accidental anchor drop frequency; it is calculated by means of the following equation:

$$F_{accdrop,j}\left(\frac{events}{ship}\right) = \frac{(F_{AL}\cdot f_1\cdot f_2\cdot f_3\cdot f_4)\cdot L_{lane}}{v_j} \qquad (4)$$

where:
$F_{accdrop,j}$ = frequency of accidental anchor drop for the ship class j (events/ship);
F_{AL} = frequency of anchors lost (events/ship/year);
f_1, f_2, f_3, f_4 = corrective factors;
v_j = average speed of the ship class j (km/y).

According to [6] and [8] the anchors lost (F_{AL}) vary between 0.01 to 0.005 events/ship/year. In this paper the value of 0.0067 is used (corresponding to 1 anchor lost every 150 ships per year).
f_1 is a conservative factor that takes into account the fact that not all the accidental dragged anchors are lost and therefore included in the insurance data relevant to anchor loss. Based on engineering judgement, in this methodology f_1 is assumed equal to 2. This means that the number of anchors accidentally dragged but not lost are comparable to the anchors accidentally dragged and subsequently lost.
f_2 takes into account the fact that not all the anchors lost are able to drag, since in some cases only the anchor is lost. This factor considers that the data reported by insurance include both the cases of anchor loss and anchor and chain loss.
The cases of anchor loss are due to the failure of the D-shackle, Swivel, Chain and Kenter shackles, therefore they cannot lead to the dragged anchor scenario (i.e. the anchor is not able to drag due to the failure of a link between the anchor and the ship). For this reason these cases shall not be considered. The fraction of anchor and chain loss is equal to 0.358 [6].
f_3 takes into account the fact that some anchors can be lost following an intentional anchor drop while others are lost as a result of an unintentional and uncontrolled drop.
Starting from the scenario of loss of anchor and chain the factor f_3 can be calculated more accurately considering the causes distribution shown in the Table 1.

Table 1: Events causing loss of anchor/chain [6]

Causes	Distribution
Black-out	6%
Winch / motor	25%
Chain stopper	3.5%
Operational	22%
Current	6%
Weather	34%
Depth	3.5%

The causes black out, current, weather and depth are not associated to an unintentional anchor drop leading to anchor loss, but they are associated to intentional anchor drop that resulted in anchor loss due to adverse conditions (such as bad weather, excessive current, etc.).
Moreover, not all the events due to winch/motor can be connected to accidentally dropped anchors: for example, the winch/motor failure could lead to anchor loss when the anchor cannot be recovered and the anchor chain shall be cut; in this scenario the anchor does not drop accidentally and does not drag.
Similarly, not all the events due to operational issues can be connected to anchors dropped accidentally and dragged; for example, the anchor can be lost due to some wrong operations related to the lowering of the anchor, the use of the brake, the lifting of the anchor, the lack of attention to bad weather. The accidental drop of the anchor leading to dragging can be associated only to the wrong fastening of the anchor onboard.

Considering the above, f_3 is equal to the following values for the causes reported in Table 1:

- 0.5 for winch/motor;
- 1 for chain stopper;
- 0.1 for operational;
- 0 for the other causes.

f_4 takes into account the fact that not all the accidental dropped anchors and chains can drag; in some cases the anchor chain can break following the events mentioned above (winch/motor failures, chain stopper failure and operational issues). It is assumed that, in the event of failure of winch/motor or chain stopper, the chain failure is more likely than the operational cause.

The following values for f_4 have been considered:

- 0.1 in case of winch/motor failure;
- 0.1 in case of chain stopper failure;
- 0.9 in case of operational issue.

3.4.2. $\underline{P_1}$

The first branch of the event tree is represented by P_1, the probability that the anchor is discovered within 1 km. This probability increases if the accidental anchor drop causes noise and vibration on-board or if the ship speed decreases; instead P_1 decreases in case of bad weather because the noise and vibration may not be associated to the anchor loss.

P_1 is also affected by the navigational area. In areas with intense traffic it is more likely that an accidental dropped anchor does not go unnoticed, since the crew is more alert to the sea traffic conditions in order to avoid any collision with other vessels. Instead, in open sea the crew is less vigilant and in some cases also the automatic pilot is used.

In this methodology, P_1 has been evaluated on the basis of the navigational area (level of attention), ship class and causes of anchor loss.

Three categories of navigational areas have been considered on the basis of the expected level of attention:

- Open area: with less than 10 ships per year crossing the pipeline;
- Low-Medium traffic: 10-250 ships per year crossing the pipeline;
- High traffic: more than 250 ships per year crossing the pipeline.

The same three causes of anchor loss leading to accidental anchor drop and drag identified above have been considered:

- Winch/motor;
- Chain stopper;
- Operational.

In the case of operational issues (such as not securing the anchor on board), the crew is less likely to notice that the anchor has dropped; conversely, in the case of winch/motor failure or chain stopper failure the crew is more likely to notice the accident due to the significant noise associated with these types of failures.

Considering the above, the probabilities for all the possible combinations described are shown in Table 2.

Table 2: P_1 - probability that the anchor is discovered within 1 km

GRT Class*	Cause	Open Sea	Low-Medium Traffic	High Traffic
1	Winch/Motor	0.5	0.7	0.8
	Chain Stopper	0.5	0.7	0.8
	Operational	0.5	0.7	0.8
2	Winch/Motor	0.5	0.7	0.8
	Chain Stopper	0.5	0.7	0.8
	Operational	0.5	0.7	0.8
3	Winch/Motor	0.6	0.8	0.9
	Chain Stopper	0.6	0.8	0.9
	Operational	0.5	0.7	0.8
4	Winch/Motor	0.6	0.8	0.9
	Chain Stopper	0.6	0.8	0.9
	Operational	0.5	0.7	0.8
5	Winch/Motor	0.6	0.8	0.9
	Chain Stopper	0.6	0.8	0.9
	Operational	0.5	0.7	0.8
6	Winch/Motor	0.6	0.8	0.9
	Chain Stopper	0.6	0.8	0.9
	Operational	0.5	0.7	0.8

* GRT: Gross Registered Tonnage, which indicates the ship's size

3.4.3. P_2

The second branch of the event tree is represented by P_2, the probability that the anchor gets seated in 1 km. This probability depends on various factors such as the vessel speed, the anchor chain length, the water depth, the anchor size and type and the soil characteristics. It should be evaluated specifically for each ship and pipeline location.
A simplified approach is suggested in this paper and the proposed values for P2 are only dependent on the soil characteristics, while the effect of other factors is neglected:

- For soft soils (e.g. soft sand and clay) P2 is assumed equal to 0.75 as the anchor is more likely to get seated rapidly;
- For hard soils (e.g. gravel and rock) P2 is assumed equal to 0.5.

3.4.4. P_3

The third branch is represented by P_3, the hooking probability as function of the ship crossing angle. It depends on the pipeline geometry, ship velocity and anchor size and type; it shall therefore be evaluated on a case by case basis.

3.4.5. P_4

The fourth branch is represented by P_4, the probability that the chain will not break due to ageing in the event of pipeline hooking (i.e. the chain has lost its strength and does not have its design holding power); this has been assumed equal to 0.9.

3.5. Geometric Interaction Probability for dragged anchor

The geometric interaction probability model is based on [16]. For the dragged anchor scenario the main parameter for the calculation of this probability is the dragging length. For the emergency dragged anchor the dragging length can be calculated considering the vessel stopping distance in an emergency situation as a function of the vessel speed and the soil characteristics. For the accidental dragged anchor, on the other hand, this dragging length is equal to 1 km for the outcomes 1 and 2, but

it is very difficult to estimate for the outcome 3. If the outcome 3 occurs, a vessel can continue to sail for a couple of kilometres as well as for a hundred kilometres.
The dragging length for the outcome 3 can be estimated considering aspects specific to the location and selecting an average value for each pipeline section.
The main parameters considered for the evaluation of the dragging length for outcome 3 are:

- Average distance sailed by a ship for each voyage;
- Distance between the main ports in the area;
- Density of the obstacles on the seabed (such as pipelines, subsea structures, cables, outcrops, etc.).

The geometric interaction probability is set equal to zero in the following cases:

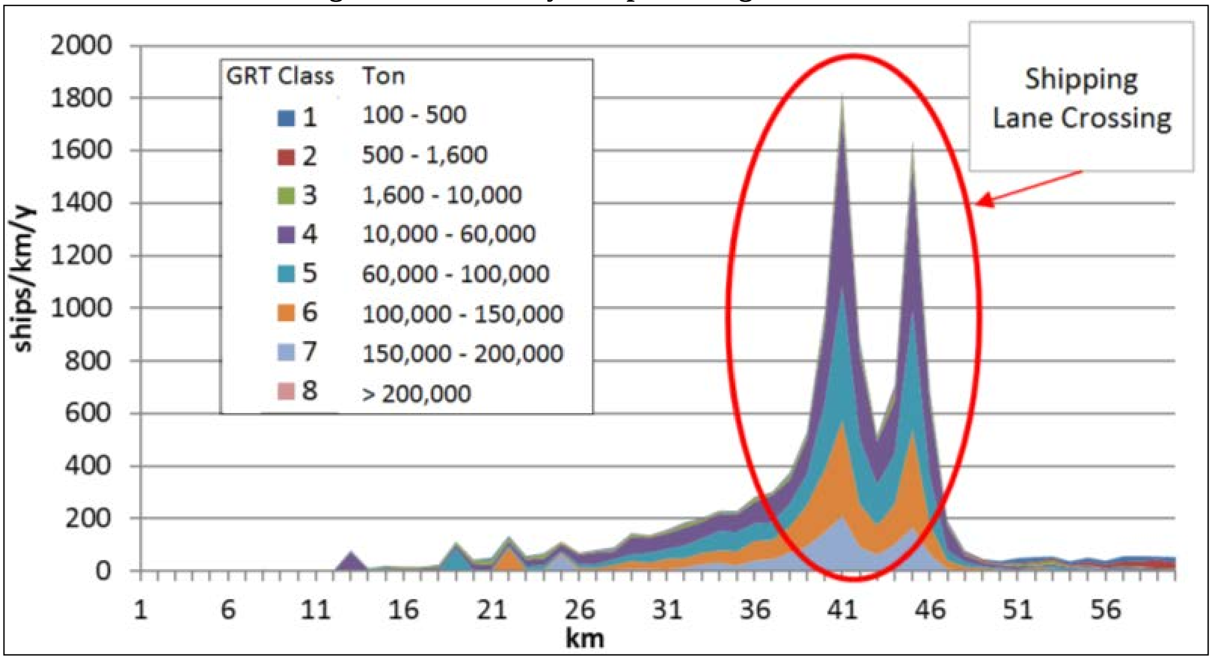
- The water depth is greater than the anchor chain length;
- The pipeline is laid in a trench and the trench depth is greater than the anchor penetration depth;
- The anchor is not physically able to hook the pipe. This occurs when the pipe diameter is large compared to the size of the anchor (i.e. the projected anchor fluke length is equal to or greater than half of the pipe diameter [3]).

DNV [3] provides some reference values for the anchor chain lengths and the anchor penetration depth in relation to the ship's size.

4. CASE STUDY

The methodology is applied to a case study. A 30" pipeline is located in an area of the Mediterranean Sea that crosses the shipping lane to/from the Suez Canal. In proximity to the shipping lane the number of vessels crossing the pipeline reaches the peak of 1800 crossing per km per year. Figure 2 shows the ship crossing distribution per km in proximity to the shipping lane and in relation to the GRT (Gross Register Ton) classes.

Figure 2: Case study – ship crossing distribution



The water depth in proximity to the shipping lane is about 20 m and the soil is soft.
The methodology reported in paragraph 3 has been applied considering also the other ship traffic interaction scenarios (i.e. sinking vessels, dropped anchors, dropped objects and grounding vessels).
For this case study, P_3 is assumed equal to 0 if the crossing angle is less than 30° and equal to 1 if the crossing angle is greater than 30°.
Three sensitivity cases have been performed considering 3 dragging lengths for the outcome 3: 1 km, 10 km and 100 km.

Figure 3, Figure 4 and Figure 5 show the total interaction frequency with the interaction scenarios distribution for the three sensitivity cases. For all the cases, the highest contribution to the interaction frequency is due to emergency dragged anchor, followed by the dropped object scenario. Only for the sensitivity case with a outcome 3 dragging length equal to 100 km, the accidental dragged anchor is not negligible compared to the emergency dragged anchor.

Figure 3: Total Interaction Frequency – Sensitivity case 1km

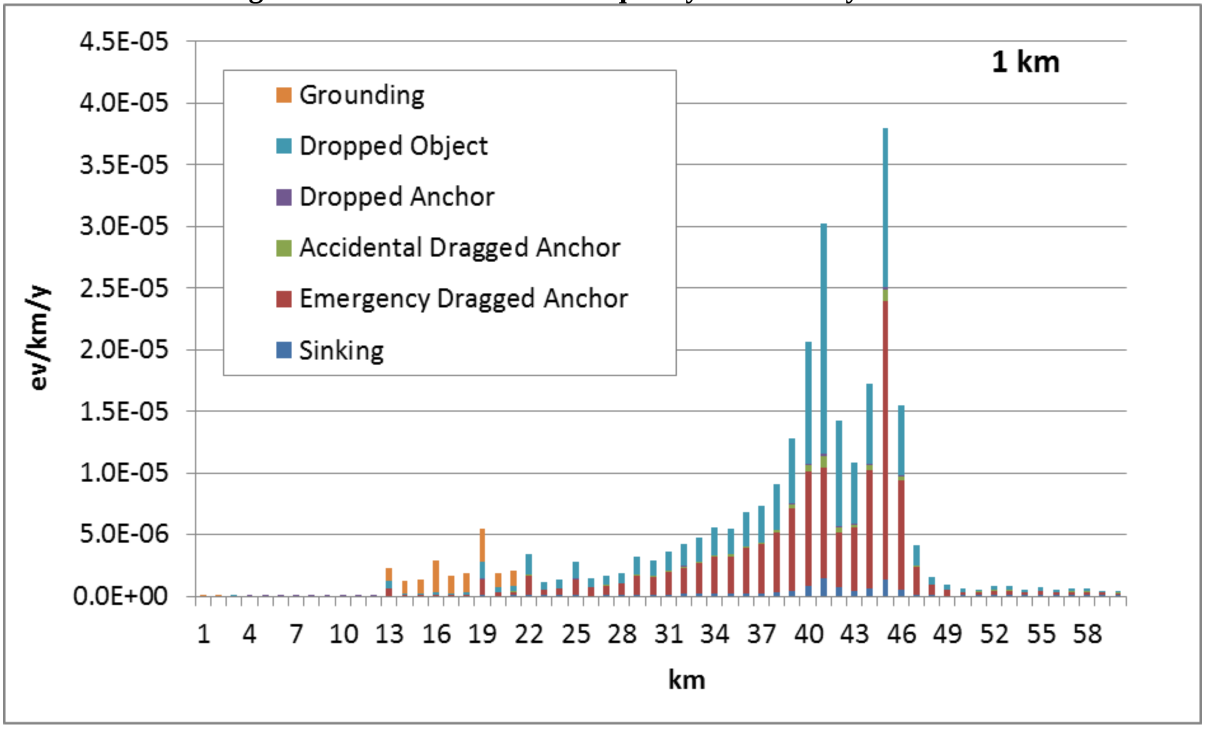


Figure 4: Total Interaction Frequency – Sensitivity case 10km

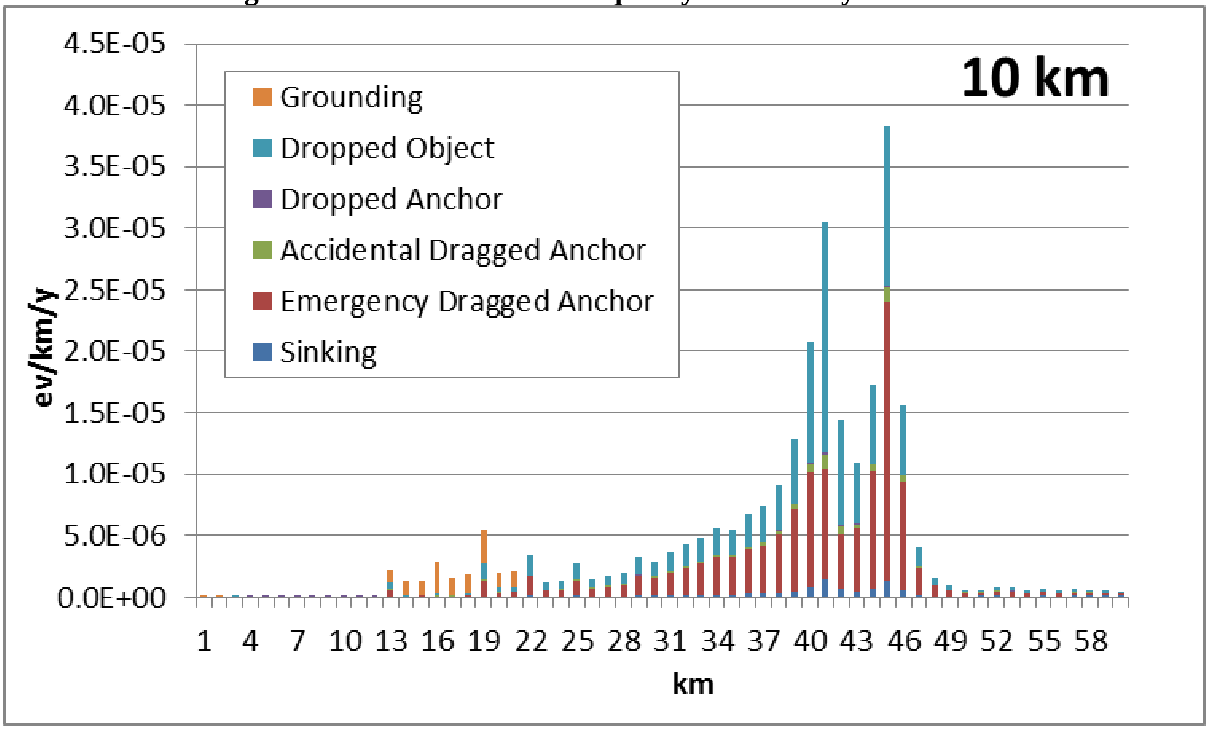


Figure 5: Total Interaction Frequency – Sensitivity case 100km

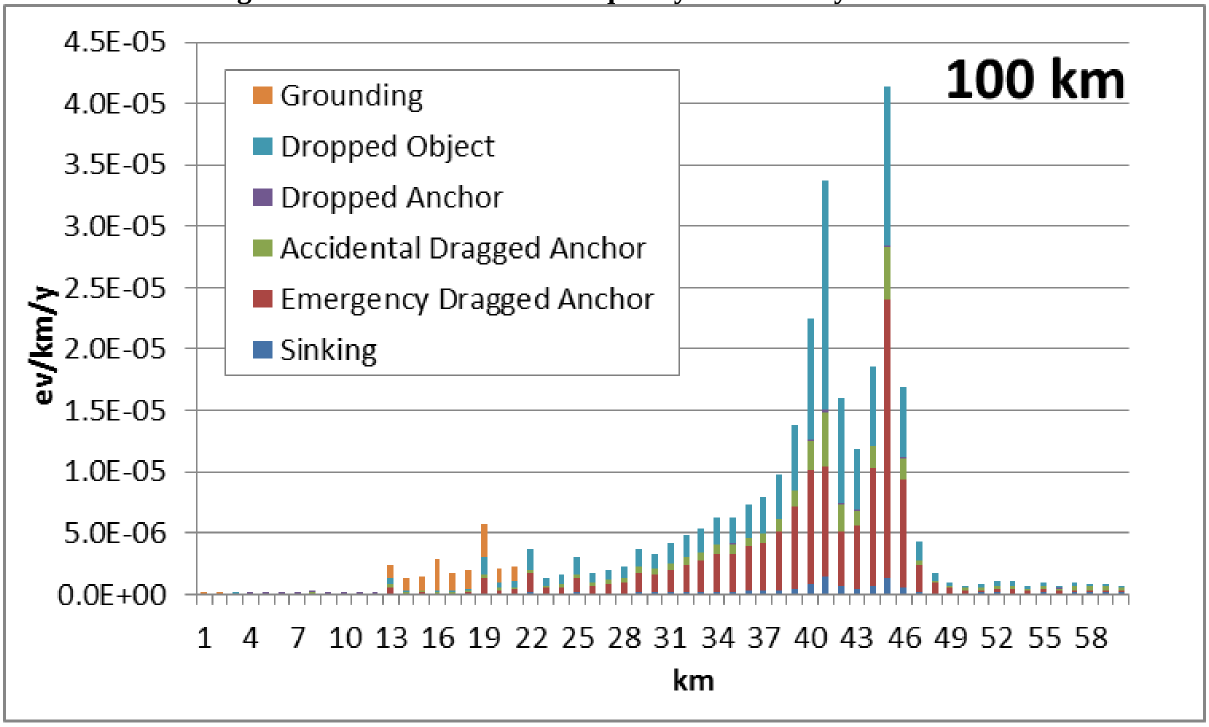


Table 3 summarizes the details of the interaction frequency for 1 km pipe section characterized by the highest total interaction frequency (between km 44 and 45).

Table 3: Interaction Frequency between km 44 and 45

	Interaction Frequency (events/km/year)		
Case	**1 km**	**10 km**	**100 km**
Sinking	1.3E-06	1.3E-06	1.3E-06
Emergency Dragged Anchor	2.3E-05	2.3E-05	2.3E-05
Accidental Dragged Anchor	8.7E-07	1.2E-06	4.3E-06
Dropped Anchor	1.7E-07	1.7E-07	1.7E-07
Dropped Object	1.3E-05	1.3E-05	1.3E-05
Grounding	0	0	0
Total interaction frequency	**3.8E-05**	**3.8E-05**	**4.1E-05**

Considering the total interaction frequency the DNV target criteria is exceeded for all the three sensitivity cases. Moreover, for all the sensitivity cases, the target is exceeded from km 38 to 46 and the highest contributions are emergency dragged anchor and dropped object. The pipeline section between km 38 and 46 overlaps the shipping lane crossing.
Therefore adequate protection measures shall be foreseen in correspondence of the shipping lane crossing.

5. CONCLUSIONS

The dragged anchor scenario represents one of the most serious threats for subsea pipelines, both in terms of frequencies and consequences. Generally only the emergency dragged anchor scenario is considered in the pipeline design. However recent incidents have shown that also the accidental dragged anchor scenario can also occur. This paper suggests a methodology to evaluate both the dragged anchor scenarios. The model is based on the analysis of the available statistical data regarding the causes of anchor loss and ship accidents. It identifies, by means of event tree analysis, the potential sequence of events leading to anchor dragging on the pipeline, either as a result of an emergency on board or due to an uncontrolled accidental loss of the anchor. The other parameters considered in the

analysis are the ship traffic intensity, the soil characteristics, the water depth and the pipeline geometric interaction probability calculated as a function of the pipeline geometry and the dragging length.
In this case study the accidental dragged anchor scenario is negligible compared to the emergency one for two of the dragging length considered. Therefore the usual approach that neglects the accidental dragged anchor scenario would have been acceptable. However, it is also good practice to evaluate case by case the contribution of the accidental dragged anchor, since it can vary on the basis of the various parameters considered in the proposed methodology.

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