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Oil spills: from statistical analysis to quantitative risk assessment

Bruno Fabiano, Fabio Currò, Renato Pastorino and Marco Del Borghi
Chemical and Process Engineering Department DIChe P "G.B.Bonino"
Genoa University, Italy

Abstract

This paper is focused on the development of a formalised approach to the quantification of risk in probabilistic terms, according to the methods already applied in the process industry. The study is structured into linked stages that were undertaken sequentially, as follows.

The first part was dedicated to the analysis of the long-term accident trends in open sea and to elaborate world-wide statistics on the number and frequency of spills, immediate and underlying causes, as well as on accident evolving scenarios. The statistics about the frequency of casualities can provide an overall view of the level of safety involved in the shipping activity.

In facing the whole risk two aspects can be outlined: risk in open sea and risk in harbour area. Therefore, in the subsequent applicative phase, an Italian case-study was considered, by developing a quantified risk assessment methodology. Starting from the elaboration of the collected yearly data on hydrocarbon transport and type of tankers in the considered port, it was possible to perform a statistical reinforced analysis of the expected accident frequency.

A range of possible accident scenarios was selected, starting from the analysis of oil related activities and the type of hydrocarbon handled or transported in the area. The analysis of the consequences of the oil spill and the subsequent accident in case of ignition was performed considering, in detail, the study of the pool fire and the connected thermal radiation. Based on these findings, conclusions are drawn, with emphasis on some risk control options and practical recommendations, according to inherent safety principles.

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1 Introduction

The ever increasing energy demand has given rise to a significant increase of oil extraction and transportation: in the time span 1985-1999 the total amount of oil transported at sea raised from 1159 10^6 to 1890 10^6 tonnes. As a consequence, the hazards connected to the transport phase, particularly the possibility of oil spills, are to be evaluated carefully, considering both environmental and accident risk. It should be noted that the number of large spills (> 700 Mg) has decreased significantly during the last thirty years. The average number of large spills per year, during the 90s is about a third of that witnessed during the 70s [1].

In facing the whole risk two aspects can be outlined: risk in open sea and risk in harbour area. Generally speaking, the concept of risk is the relation between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards [2].

As reported by different researchers, a specifically tailored Quantitative Risk Assessment methodology can represent an effective tool to assess the risk to people associated with the transport of dangerous substances.

The four normal stages of a full or classic risk assessment are: hazard identification; failure frequency specification; consequence calculation and risk estimation. The hazard assessment usually involves the utilization of P&I diagrams and may involve the utilization the results of HAZOP/HAZAN studies; the objective should be to obtain a comprehensive set of failure cases that typify the spectrum of events which could occur at the installation [3].

If the event likelihood exceeds the limit criterion further consideration needs to be given to reduce the residual risk in terms of hardware (additional plant safeguards, protective equipment etc.) and software (operational procedures, maintenance etc.).

2 Open sea risk

The statistics about the frequency of casualities provide an overall view about the levels of safety involved in the shipping activity. They allow the quantification of the real safety levels for different ship types, as well as the main modes of failure [4].

The expected frequency and extension of spills and the types of oil likely to be encountered is to be evaluated. A quantitative assessment can be performed starting from historical spill data. The analysis of long term trend can be particularly useful for assessing the risk of oil spills for contingency planning as well as for evaluating the possible mitigation consequences due to changes in tanker design and operation.

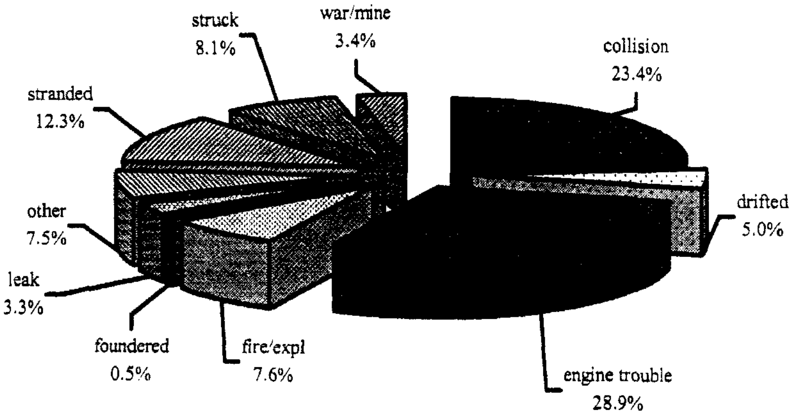

Figure 1: Cause of accident during sea transport, 1987 – 1998.

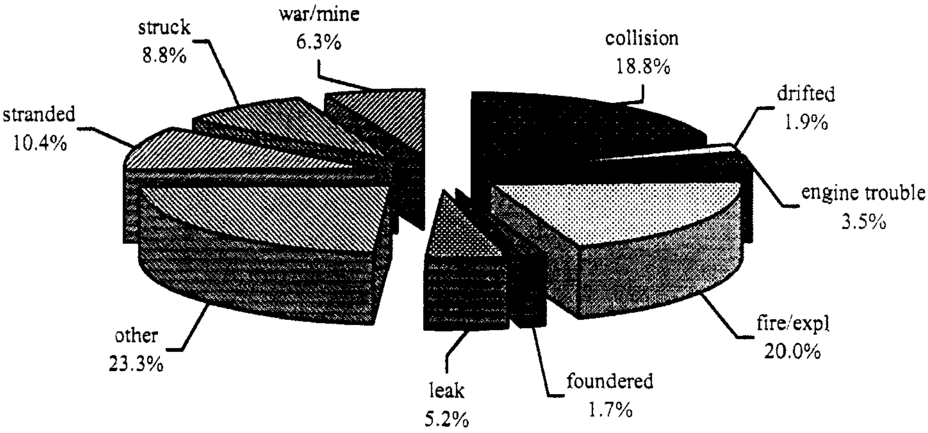

Figure 2: Cause of accident with a consequent spill or fatality

In the first step of this paper we considered, in detail, the analysis of accidents during open sea transport of both petrochemical and chemical products, over the time span 1987-1998. A detailed database was elaborated, with a total accident number of 6111. It collects detailed information on the vessel involved, owner, nationality, dead weight tonnage, ship age, amount and immediate cause of oil spilt, location, event magnitude.

By analysing Fig. 1, it can be noted that the three main causes of accidents are, respectively, mechanical and electrical failures with engine troubles (30%);

collisions (24%) and strandings (12%). The majority of these accidents however resulted in low magnitude damages, often limited to the ship equipment. By considering only major accidents, causing large spills and/or life losses, it is apparent from Fig. 2 that the immediate causes are mainly human errors or severe atmospheric events (23%). Other primary accident causes are on-board fires and explosion (20%), followed by collision (19%). The percentage of high magnitude events caused by technical troubles or failures is as low as 4%, to be compared with the previous striking percentage of 30%.

These first considerations highlight the importance of the navigational aids, of training of both ship crew and oil terminal/port personnel and, mainly, technological equipment and structural reliability of the ship. An important role is played by human errors, to be considered in all phases of the process i.e. design, construction, operation and ship management. Recently, concerns about the poor management standards and the contribution of the human error and management shortcomings on marine casualities have motivated the introduction of the International Safety Management (ISM). The high striking percentage of accidents caused by technical troubles is to be connected to the old age of board machineries that are often outdated: the ship age represents one of the main parameter in safety analysis. By considering the total number of accidents without war events, corresponding to 5905 accidents, the average ship age can be calculated as corresponding to 14.2 years. If one limits the analysis to accidents giving rise to spills, the average ship age is 16.2. This observation is statistically confirmed by the data shown in Fig. 3, evidencing that the average ship age is correlated with the causes of the event: accidents causing the founding of the ship and consequently major spills, involved ships with average age of 23.2 years.

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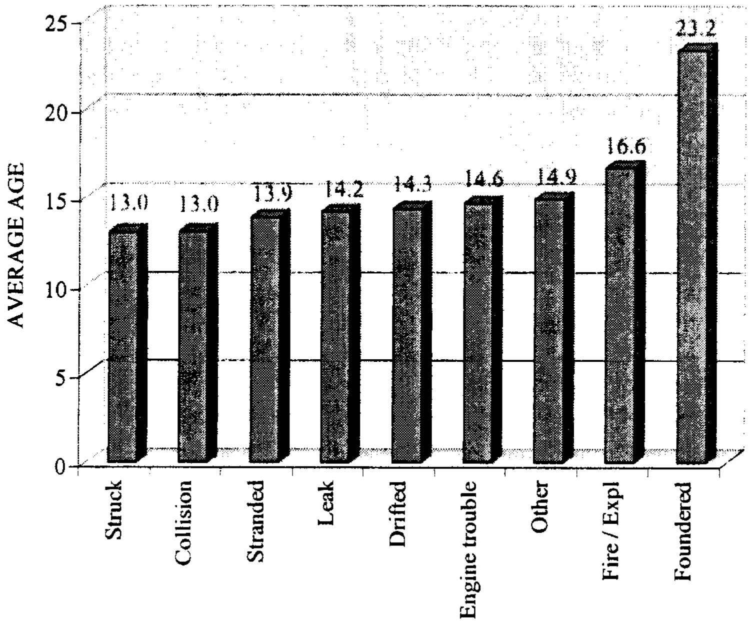

Figure 3: Average age and causes of the accident

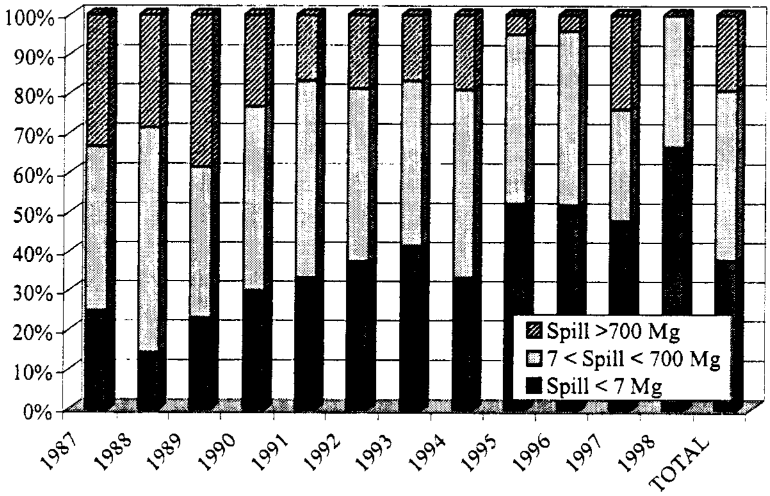

Figure 5: Distribution of spill size over the time span 1987-1998 [%].

According to Lloyd's data [5], the world tanker fleet is constituted for 27% by ships with an age higher than 24, while the starting of the obsolescent phase is usually set at 20 years. By considering strictly spill accidents, it results that about 80% of hydrocarbon spills result from routine operations such as loading,

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discharging and bunkering; the average quantity on a world basis is in the range $1\text{-}2.5\cdot10^6$ Mg, with more than 10^5 Mg in the Mediterranean Sea.

In the period considered, 250 major accidents caused, in the whole, 9 fatalities and a total spill into the sea of $17\cdot10^5$ Mg of hydrocarbons. The average age of the ships involved in major accidents is 15.3 years, while the immediate accident causes are human errors or bad weather conditions during the navigation (see Fig. 4).

By analyzing Fig. 5, it is evident that 81% of the spills involved quantities of less than 700 Mg and 39% involved quantities less than 7 Mg, typical of errors in routine operations. It is notable that few very large spills are responsible for a high percentage of the oil spilt: this is clearly illustrated in 1991 by ABT Summer – Angola incident ($2.6\cdot10^5$ Mg) and Haven – Genova Italy ($1.44\cdot10^5$ Mg); in 1989 by Exxon Valdez – Alaska ($3.7\cdot10^4$ Mg) and Khark V- Atlantic coast of Marocco ($8\cdot10^4$ Mg) and, at last, Sea Empress - Galles UK ($7.2\cdot10^4$ Mg) representing 95% of the total oil spilt in 1996.

According to these data, it is possible to define a frequency of accident during open sea transport of both petrochemical and chemical products:

$$f = 5.15\cdot10^{-2}\ \frac{accident}{year\cdot ship} \qquad (1)$$

However it is important to underline that there is considerable annual variation in both the incidence of oil spill and the amounts of oil lost and any averages derived from them should be viewed with caution [1].

3 Port area risk

In approaching risk assessment in port area, we started from the analysis of the port of Genoa (Italy), one of the most important in the Mediterranean Sea.

The oil port of Genoa is located in Multedo, nearby the built-up area. The harbour premises are northerly closed by the railway line Genoa-Ventimiglia. The highway Aurelia stretches nearby, while the motorway runs among the mountains. In the stretches of water opposite the piers, the embankment houses the runway of the local airport C. Colombo (see Figures 6 and 7).

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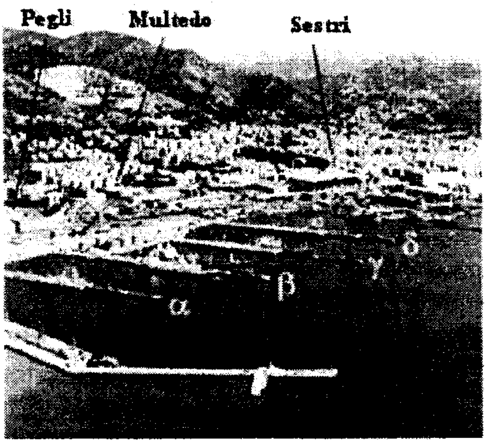

Figure 6: View of the Oil port of Genoa

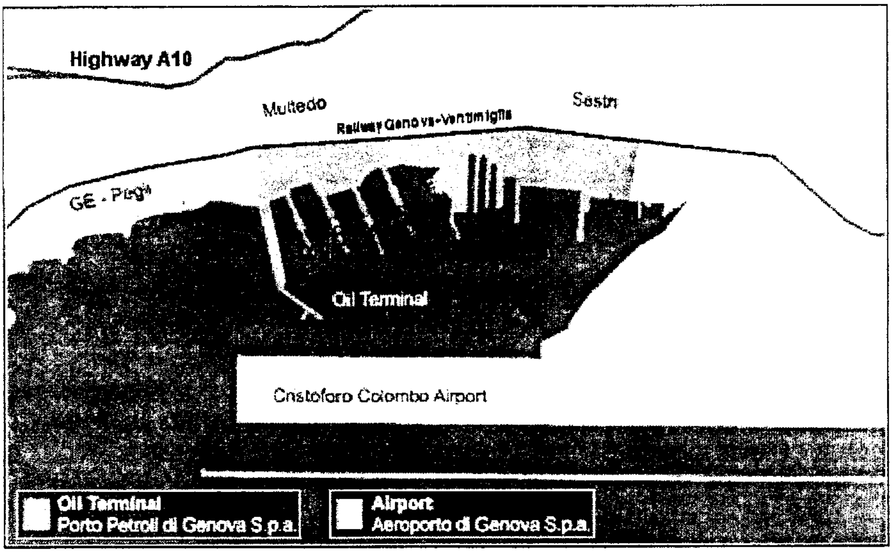

Figure 7: Plant of the Oil port of Genoa

The oil port is provided with eight berthings along four piers (α, β, γ and δ) and other two berthings along the western quay. Moreover, there are two off-shore single mooring structures for big oil-tankers. In the oil port, chemical, petrochemical and oil products, especially crude oil, are currently handled. LPG is not currently included among the handled products, even if, in the past, equipment facilities for the loading and unloading of LPG ships were designed and installed. Among the reasons that led to the dismissal of the equipment for LPG, the risk exposure was not the last one [6]. It must be also noted that the recent EEC Directive 96/82/EC implies the evaluation of risk in highly industrialized areas by means of Quantitative Area Risk techniques. The routes starting from the Genoa port area towards the industrialized North Italian and Central Europe districts are characterized by high truck traffic (mainly ADR) and inherent factors determining to a major accident risk, with reference to both individual and social risk, defined according to European limits [7].

Table 1: Technical characteristics of the lines and equipment of the oil terminal.

Pier	Lenght [m]	Depht [m]	Light products pipelines	Heavy products pipelines	Crude pipelines	Chemical pipelines
α – Alfa	208 / 235	11	4 × 10”	4 × 10”		
β - Beta	232 / 252	12.65	4 × 12”	4 × 10”		
γ -Gamma	290 / 262	14 / 13.41	2 × 12”	3 × 10”	4 × 16”	
δ – Delta	330 / 320	14	4 × 12”	4 × 10”	4 × 16”	
West wharf	180 / 180	11				2 × 10”
Off shore platform		50				1 × 48”
Mooring buoy		650				1 × 42”

Technical characteristics of the lines and equipment of the oil terminal are summarized in Table 1. Five fixed roof tanks, each having nominal capacity of 5000 m^3, are utilized for supplying water; two fixed roof tanks are utilized for sedimentation of line draining water and 3 floating roof tanks, having a total capacity of 3600 m^3, are utilized for slop storage. A pump station allows cargo operations and handling of oil, hydrocarbons products and water. Table 2 summarizes the average yearly handling of petroleum products and special chemical and oil products.

As concerns the terminal safety, the Oil Port is equipped with all active and passive protection systems, feeded by foam or water and suitable to protect every jetty and all tanks.

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Table 2: Average yearly handling of products

Product	Terminal	Number of ships	Load [Mg]	Mean Load [Mg/ship]
Crude oil	Offshore	22	2 414 626	109 756
Crude oil	Mooring buoy	12	1 168 285	97 357
Crude oil	Piers	135	8 935 042	66 185
Fuel oil	Piers	61	1 265 228	20 741
Diesel fuel	Piers	80	1 699 948	21 249
Gasoline	Piers	33	526 109	15 943
Naphta	Piers	14	275 242	19 660
JP1 - Oil	Piers	1	5 729	5 729
Chemical products	West wharf	125	339 441	2 072
Slop		6	3 335	556

A range of possible spill scenarios can be developed from an analysis of oil related activities and the types of oil handled in, or transported through the port area under investigation.

Table 3 summarizes the results, in terms of expected frequency, obtained by considering possible unwanted events and immediate causes [8].

Table 3: Expected frequency of unwanted events and immediate cause

	Collision between moving boats	Collision with a moored ship	Struck	Strand
Sea port	$5.0 \cdot 10^{-4}$	$4.0 \cdot 10^{-6}$	$2.2 \cdot 10^{-3}$	$6.5 \cdot 10^{-5}$
River estuary	$4.0 \cdot 10^{-5}$	$4.0 \cdot 10^{-6}$	$2.2 \cdot 10^{-3}$	$8.0 \cdot 10^{-5}$
Big river	$1.2 \cdot 10^{-4}$	$9.0 \cdot 10^{-6}$	$2.1 \cdot 10^{-3}$	$1.6 \cdot 10^{-5}$
Small river	$5.0 \cdot 10^{-4}$	$4.2 \cdot 10^{-5}$	$6.5 \cdot 10^{-3}$	$6.5 \cdot 10^{-5}$

Moreover, we considered hydrocarbon spills resulting from routine operations such as loading, discharging and bunkering. From a statistical analysis of unwanted events, it results that fire/explosion is by far the most significant immediate cause of accidents in tankers, while grounding, fire/explosion and hull problems are important initial causes of accidents for bulk carriers. Table 4 shows the expected frequency of fire/explosion as a function of the ship type, taking into account that such kinds of events are strictly correlated to the real

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safety level for different ship types, rather than to the port intrinsic characteristics.

Table 4: Expected frequency of release and fire/explosion

	Release	Fire/Explosion
Crude oil	$1.9 \cdot 10^{-4}$	$1.9 \cdot 10^{-5}$
Light oil products	$1.8 \cdot 10^{-4}$	$1.5 \cdot 10^{-6}$
Heavy oil products	$1.8 \cdot 10^{-4}$	$3.5 \cdot 10^{-6}$
Flammable LPG	$7.6 \cdot 10^{-5}$	-
Toxic LPG	$7.6 \cdot 10^{-5}$	0
Light flammable chemicals	$1.5 \cdot 10^{-4}$	0
Heavy flammable chemicals	$1.5 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$

On the basis of these data it is possible to calculate a statistic frequency of accidents in the port considered of:

$$f = 4.18 \cdot 10^{-5} \text{ release/ship}$$

Taking into account, as well, the average ship traffic and hydrocarbon handling in the port area, we can calculate an overall accident frequency of

$$f = 3.06 \cdot 10^{-2} \text{ release/year}$$

Considering all potential scenarios it is possible to evaluate the individual risk, defined as "the frequency at which an individual may be expected to sustain a given level of harm from the realization of a specific hazard" [9].

The purpose of individual risk acceptance criteria is to limit the risk to people onboard the ship or to individuals who may be affected y a ship accident. Individual risk criteria may be proposed for ships according to the approach of the U.K. Health and Safety Executive [10]:

- maximum tolerable risk for crew members 10^{-3} per year;
- maximum tolerable risk for passengers and public ashore 10^{-4} per year;
- negligible risk 10^{-6} per year.

The consequence of an accident to the surroundings of its immediate source of occurrence can be measured by plots of the cumulative frequency (abscissae axis) of a specified consequence e.g. fatalities (ordinatae axis) equalling or exceeding a certain magnitude (F-N curve). While deaths and injuries are the most immediate relevant and usually most easily identified consequences associated with accidents, other consequences, such as material damages, environmental impact, ecological harm, social disruption etc. must be considered in detail when addressing the social dimension of an oil spill accident.

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If the event likelihood exceeds the limit criterion further consideration needs to be given to reduce the residual risk in terms of hardware (additional plant safeguards, protective equipment etc.) and software (operational procedures, maintenance etc.)

Dealing with the magnitude of the unwanted event, we limited the analysis to the case of spillage and subsequent pool-fire.

For unconfined pool fires on land or on water a number of calculation step can be distinguished. In the heat radiation for pool-fire the main step can be defined as:

- calculation of the liquid pool diameter;
- calculation of the burning rate;
- calculation of the flame dimension of a pool fire;
- calculation of the surface emissive emissive power;
- calculation of the heat flux at a certain distance [11, 12].

The value of the maximum heat flux at a certain distance *d* can be defined as

$$q'' = SEP_{act} \cdot F_{view} \cdot \tau_a$$

where:

q'' = heat flux $[J \cdot m^{-2} \cdot s^{-1}]$
SEP_{act} = average emissive power of the flame surface $[J \cdot m^{-2} \cdot s^{-1}]$
F_{view} = geometric view factor [-]
τ_a = atmospheric transmissivity [-]

The value of the emissive power of the flame surface, for a tilted cylindrical flame, can be calculated, as follows:

$$SEP_{max} = F_s \cdot m'' \cdot \Delta H_c \cdot (1 + 4 \cdot L/D)^{-1}$$

where:

F_s = fraction of the generated heat radiated from the flame surface $[J \cdot m^{-2} \cdot s^{-1}]$
m'' = burning flux at still weather conditions $[kg \cdot m^{-2} \cdot s^{-1}]$
ΔH_c = heat of combustion of the combustible $[J \cdot kg^{-1}]$
L = average flame height [m]
D = pool diameter [m]

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Table 4: Heat flux calculated from an hydrocarbon pool-fire

Distance [m]	Maximum Heat flux [kW·m^{-2}]	Vertical Heat flux [kW·m^{-2}]	Horizontal Heat flux [kW·m^{-2}]	Smokeless Theoretical Radiation [kW·m^{-2}]
5	12.51	6.80	10.50	101.05
10	10.26	7.65	6.84	82.87
15	8.01	6.36	4.86	64.65
20	6.76	5.49	3.94	54.56
25	6.07	5.00	3.44	49.01
30	5.56	4.63	3.07	44.88
35	5.12	4.32	2.76	41.36
40	4.73	4.03	2.48	38.27
45	4.39	3.77	2.24	35.41
50	4.07	3.53	2.02	32.86

According to the proposed modelling, the calculated values of the heat fluxes under different conditions, are shown in table 4. The subsequent stage of the approach to the estimation of domino effects is based on the evaluation of radiation and overpressure effects, taking into account the threshold limits (e.g. 0.7 atm for overpressure and 37.5 kW·m^{-2} for radiation).

4 Conclusions

A risk analysis involves the identification of adverse events that lead to the materialization of a hazard, the estimation of the extent, magnitude and likelihood of any harmful effect. Oil spill risk assessment must consider two different incident scenarios: open sea navigation and port area activities. In each context, consequence analysis is based on intrinsically different events and different frequencies of occurrence of identified hazardous events are expected.

In open sea navigation high severity events are correlated to the release of substances, with possibility of total spill of the transported material and consequences mainly due to ecological impact. Risk prevention is based on technical requirements (i.e. double hull), operational measures for tankers (e.g. periodic gauging; navigation safety standard, etc.) and personnel requirements (e.g. bridge resource management training; minimum rest period for crew; review of alcohol and drug use before issuing licenses etc.) Mitigation is mainly based on preparedness to respond to a spill (i.e. each ship transporting oil must have a response plan and a spill management team).

In harbour area, usually the quantity of oil spilt is lower, but the possibilities of fire/explosion and subsequent knock-on effects are to be carefully estimated. Again, operative measures for tankers play an important role (e.g. overfill and tank level monitoring). A formalised approach to safety management is needed, with appropriate response equipment and salvage, fire-fighting and lightering resources. Moreover, capabilities for the implementation of corrective and/or

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contingency functions should be built into the port design in order to prevent the propagation of these events.
Risk based management and mitigation techniques must therefore consider the different peculiarities, through effective regulations and legislation, port infrastructure design and emergency planning.

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