Ocean Engineering 185 (2019) 12–26

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Lessons learned from offshore oil and gas incidents in the Arctic and other ice-prone seas

Amos Necci *, Stefano Tarantola, Bogdan Vamanu, Elisabeth Krausmann, Luca Ponte

European Commission, Joint Research Centre (JRC), Ispra, Italy

A R T I C L E I N F O

Keywords:
Offshore structure
Incident analysis
Natural hazard
Lesson learned
Safety
Oil and gas

A B S T R A C T

Specific risks to offshore oil and gas operations manifest in the Arctic and other harsh environments. Such extreme operating conditions can disrupt the offshore infrastructure and cause major accidents, posing a great challenge to operators. A thorough investigation of past incidents helps to learn lessons to ensure that a recurrence of serious accidents affecting workers and the environment can be prevented.

The analysis of past incidents is divided into two parts. First, we offer a statistical analysis of offshore incidents triggered by natural events in the Arctic and in similar harsh environments. The analysis, organised by location, cause, and type of damage, failure mechanisms, and consequences, is based on data from the World Offshore Accident Database (WOAD). Second, we analyse a selection of accidents that occurred in the recent past in ice-prone seas, with particular attention to potential deficiencies in safety measures, design requirements and design methodologies, operations planning and component reliability.

Based on the analysis, important lessons were identified which stress the need for further efforts to ensure the safety of workers and of assets and to get all actors involved in offshore operations engaged towards achieving a safer future for the exploitation of oil and gas resources.

1. Introduction

Offshore infrastructures for the exploration and extraction of oil and gas are exposed to environmental actions, particularly assets operating at higher latitudes. Considering that the Arctic contains some of the World's biggest recoverable hydrocarbon reserves, the melting of the sea ice makes the area more and more economically attractive for future exploitation of the oil and gas fields. However, offshore oil and gas operations in the Arctic and sub-arctic areas require the management of a number of hazards, both environmental and technological. Hydrocarbons inherently pose an ever-present danger of fire and explosion. In areas with a harsh climate, topside facilities are usually completely enclosed, which may allow gas from a leak to accumulate in a confined location and possibly lead to a vapour cloud explosion (Kaiser, 2007). Furthermore, the fragile environment and extreme weather conditions are the major concerns (OGP, 2013).

Offshore operations in the Arctic and sub-Arctic regions need to cope with extremely low temperatures. In low-temperature regimes, precipitation can be abundant and in the form of snow, freezing rain, sleet or ice pellets. Visibility can be very limited, because of fog, darkness or precipitation. In harsh environments, severe storms with high winds and rough seas occur throughout the year. In the North Sea, for instance, wave heights can reach 30 m or more (Kaiser, 2007). Harsh environments encompass a variety of atmospheric and marine phenomena, such as strong winds, high waves and low temperatures (Bridges et al., 2018), icebergs (Yulmetov et al., 2016) and icing (Dehghani-Sanij et al., 2017a, 2017b), which, by themselves or combined, exert significant stresses on the offshore infrastructure which can lead to incidents.

In Europe, the Offshore Safety Directive (2013/30/EU) establishes the minimum conditions for safe offshore exploration and exploitation of oil and gas with the objective to prevent major accidents or limiting the consequences for human life and health, and for the environment. The European Commission's Joint Research Centre (JRC) received the mandate from the European Commission's Directorate General for Energy to support the EU Member States in the implementation of the Directive. Following the requirements of the Directive, a European offshore authorities group, the EUOAG, of which the JRC is the Technical Secretariat, was established in 2012. Within this group, the role of

---

* Corresponding author.
E-mail addresses: amos.necci@ec.europa.eu (A. Necci), stefano.tarantola@ec.europa.eu (S. Tarantola), bogdan.vamanu@ec.europa.eu (B. Vamanu), elisabeth.krausmann@ec.europa.eu (E. Krausmann), luca.ponte@istruzione.it (L. Ponte).

https://doi.org/10.1016/j.oceaneng.2019.05.021
Received 13 December 2018; Received in revised form 17 April 2019; Accepted 12 May 2019

the JRC is to identify and exchange good industry and regulatory practices and to facilitate the capacity building of Member States' competent authorities.

The JRC has also been involved – for over a decade now – in the development of methods and tools for the analysis and reduction of the risks of "natural-hazard triggered technological accidents (Natech)" for on- and offshore industrial installations, including pipelines. In this context, the JRC performed an analysis of hurricane-triggered offshore incidents and found that offshore operations are vulnerable to extreme weather impact. The authors analysed, in particular, the losses suffered by the offshore industry in the Gulf of Mexico (GoM) due to the impact of hurricanes Katrina and Rita in 2005 (Cruz and Krausmann, 2008).

At high latitudes, technological and natural hazards coexist permanently, thus posing higher risks to both human life (Guozheng et al., 2016) and the marine environment (Bellino et al., 2013). The North Sea and the Norwegian Sea have a significant history of oil and gas employment. The need to reduce the risk for the operators, and to protect the fragile environment, contributed to the establishment of the highest safety standards in the world. However, as operations are expected to move further North to Arctic waters, new challenges and unknowns will come up with respect to new or intensified risks, emergency response, and mitigation of the consequences of potential incidents (Arctic Council, 2009).

Moreover, the global worsening of extreme weather and sea conditions poses a challenge to the future of offshore operations (Demirbiliek, 2010) and suggests that it is not sufficient to be prepared for a recurrence of events that happened in the past. The climate in the north Atlantic ocean has changed and the strength of storms has grown in recent years (Gulev and Hasse, 1999), suggesting that even worse extreme events might occur in the years to come due to climate change. Hewson and Neu (2015) gave an overview of the most important assessments with climate models of the expected climatic changes in the extra-tropical Atlantic Ocean and their impacts on extreme weather events on the neighbouring seas. Other studies indicate a future rougher maritime climate also in the North Sea (Debernard et al., 2002).

A recent study has raised concerns regarding the susceptibility of offshore structures and their equipment to natural hazards, and claimed that "it is evident from past accidents in the offshore process facility that equipment failure risk is strongly dependent on the harsh environmental operating conditions" (Deyab et al., 2018). In fact, storms and heavy seas can cause intense loading on the structural parts of offshore installations, and alongside low temperature, ice and poor visibility are promoters and triggers of incidents, resulting in fatalities, injuries, pollution and significant economic losses (Singh et al., 2010). Cold environments impose serious stress on workers and may adversely affect both their physical and cognitive performance (Bea, 2002), increasing the probability of both incidents and fatalities (Guozheng et al., 2016). Furthermore, extreme temperatures, wind, waves or other external elements may seriously deteriorate the hardware components installed in the facility under analysis, leading to an increment of failure likelihood with respect to similar facilities operating in a "normal" environment (Gao et al., 2010).

Other studies focused on single safety issues related to operations in harsh environments. Some authors addressed the issue of equipment winterization, highlighting the importance of reliable risk-based approaches to evaluate the need for winterization (Yang et al., 2013) and winterization design temperatures (Sulistiyono et al., 2015). Gao et al. (2010) showed how reliability data collected in more temperate areas cannot be directly used for performance predictions of production facilities in the Arctic harsh environment. Afenyo et al. (2017) analysed arctic shipping accident scenarios with Bayesian Networks, aiming to identify the most significant causative factors and help decision-making in case of an accident. Abaei et al. (2018) presented a model to evaluate the performance of floating structures in extreme stormy conditions. Arzaghi et al. (2018) address the issue of hydrocarbon contamination in the Arctic environment and propose a methodology for Ecological Risk Assessment (ERA) of accidental oil spills from subsea pipelines. Homlong et al. (2012) found that the harsh environment strongly affects not only the reliability, but also the maintainability of systems, by affecting all the elements it depends on resource availability (e.g. men, material, tool), accurate diagnostics, correct installation, logistic support, and accessibility. Another study (Landucci et al., 2017) relates harsh environments with a higher probability of safety barrier failure and domino effect.

All stakeholders acknowledge the hazards of the Arctic and other harsh environments, and associated safety measures are already being incorporated in regulatory frameworks, international technical standards and best practices in the industry. For example, standardized industrial practices (see General requirements, ISO 19900 (2013)) recommend the development of offshore structural design based on local environmental criteria (using information from statistical observations), and dedicated standards address the prevention of accidents in cold environments and particularly in the Arctic (see Arctic offshore structures, ISO 19906, 2010). Offshore operations in harsh environments are supposed to be performed in compliance with these standards and practices.

Despite these efforts, incidents related to environmental triggers keep occurring (EMSA, 2009). This study analyses past offshore incidents triggered by natural events, enabling an understanding of why accidents happened, their patterns of evolution, and criticalities in safety measures, and contributing to preventing their recurrence in the future. In this context, the goal of this study is two-fold: On the one hand, it provides important lessons for conducting offshore operations in harsh environments like the Arctic in a safe way by singling out areas that require additional research or simply more investments. On the other hand, it aims at raising awareness of policy makers for the development of adequate rules ensuring the highest level of safety in the Arctic region. It also aims to identify areas where future research or policy action is needed.

Previous work on this topic includes the study of Kaiser (2007) on energy loss in the offshore energy sector, mainly considering loss of production and asset damage accounted for in monetary terms, and Christou and Konstantinidou's work (2012) that provides insights into the main accidents that occurred in offshore oil and gas operations. In their work, they give an overview of the accident databases available for this sector and provide a brief statistical analysis for a generic review of past accidents, including lessons learned from the most destructive accidents that occurred in the sector.

In this study, we first analysed the World Offshore Accident Database (WOAD) (WOAD, 2013) covering the period 1970–2013 to identify the most vulnerable infrastructure components and the riskiest operations in harsh environmental conditions to better understand the risks associated with expanding offshore activities to the Arctic. This initial screening was meant to spot the risk factors at a macroscopic level, identifying criticalities simply based on the sheer number of records. Secondly, a set of iconic case studies (chosen to cover the criticalities identified in the previous step) was reviewed, highlighting the critical factors that led to past events. Design, operations, practice, maintenance and planning are discussed with the aim to improve safety, avoid major losses, and to protect the environment from accidental hydrocarbon pollution. This study concerns both process safety, which focuses on the prevention and mitigation of events that may result in the release of hazardous materials and subsequent major accidents, and on occupational safety, which aims at reducing health risks to offshore workers. The study concludes with recommendations for filling existing research and policy gaps to achieve higher offshore safety levels.

2. Methodology

2.1. Data source and analysis methodology

Both qualitative and quantitative data was retrieved from the WOAD database to allow for each incident a sufficiently accurate depiction of the natural hazard characteristics, the infrastructure damage modes, and of their consequences. As much as it was practicable, the WOAD terminology (WOAD, 2013) was used in the analysis, so as to enable the comparison with other studies originating from the same source.

A data set composed of 1085 incidents, which were caused or promoted by the effect of natural events, was created. Initially, events were selected by filtering the incidents under the WOAD label "Equipment Cause" which lists incident causes according to the WOAD terminology. Incident records featuring weather, lightning, earthquake and volcanic eruption were automatically included in the data set. However, there were many cases in which this information was unavailable, or others in which the natural events played a primary role also when the incidents were labelled under other categories, such as exceeding design criteria, structural failure, fatigue, corrosion and foundation problem.

To overcome this issue, the "Comments" field was included in the selection process. A keyword-based, semi-automatic screening was performed in the first phase, followed by the manual processing of the resulting records. Records in which the role of natural events was found relevant in either causing or promoting the incident were added to the data set. The list of the keywords used includes hurricane, typhoon, cyclone, storm, gale, fog, mist, seismic, earthquake, bad weather, wind, wave, freeze, cold, and ice. Information on damage and failure of different types of offshore facilities, as well as on hazardous-materials releases from these structures was also provided. It should be noted, however, that detailed information on the events was missing for a relevant number of the analysed incidents.

Since the goal of our study is to discuss the risks that are typical of the Arctic and sub-Arctic regions, a subset covering only the "harsh offshore environments" of the Arctic and other ice-prone seas was isolated from the data set of 1085 incident records, comprising 314 events.

2.2. Arctic and other harsh environments

In the context of hydrocarbon extraction alone, a wide range of definitions of "Arctic" exists. Given that each definition introduces variability of the key geographic and physical parameters, it is very important for this study to provide a solid definition of harsh environment. In this study, we analysed the regions where the environmental hazards are similar to those in the Arctic, in particular those that include at least four of the following elements (Homlong et al., 2012):

- low atmospheric temperatures with large variations throughout the year;
- high intensity winds, product of extratropical cyclones or polar lows;
- foggy conditions and darkness during the winter period;
- atmospheric icing due to the combined effects of precipitation and sea spray;
- waves with high fetch, propelled by strong winds;
- iceberg collision hazard;
- and presence of sea ice.

According to ISO 19906:2010 (ISO, 2010), 20 regions compose the list of "Arctic and other cold regions". Some of them are not necessarily in the Arctic geographically, but all the regions are subject to similar sea ice, iceberg and icing conditions. Therefore, the technology developed and the R&D activities related to these areas may be of relevance for the offshore petroleum activities in the Arctic seas. However, the number of records in these areas is quite limited and we decided to extend the analysis to two other areas, which also have operative challenges related to extreme weather and cold. In addition to the regions reported in ISO 19906:2010 (ISO, 2010), the North Sea and the Norwegian Sea were also included in the list of regions concerned in this study. Table 1 reports the considered regions, the main geographic area to which they belong, and the presence of incident records with environmental triggers, in the dataset on which this analysis is based.

3. Results of the statistical analysis

First, the incidents were categorized depending on their severity. Fig. 1 summarizes the number of incidents collected in the dataset by the extent of damage suffered by the structure. The WOAD database has a five-class categorization for damage, which can be "Insignificant/no damage", "Minor damage", "Significant damage", "Severe damage" and "Total loss". Using the same classification as described for Fig. 1, Fig. 2 shows different charts per geographic area, each summarizing the relative number of incidents by damage category in one region. The size of each chart is proportional to the number of incidents reported in the respective region. Note that, while Fig. 2 is meant to provide a visual and illustrative representation of the statistics, Table A1 can be consulted to complement the illustration with numerical data (see Annex A).

The majority of incidents was recorded in the North Sea region, summing up to 86% of the total number. However, prudence should be exercised when drawing any conclusions based on the interpretation of these results. The 86% share of incidents in the North Sea must not be seen as an indicator of an inadequate level of safety in the region; the reality is quite the opposite, with this region being recognized as a reference when it comes to the regulation, control, and safety of offshore operations. Hence, when reading these results one must consider:

1. The sheer *size of the offshore activities* in a particular region (quantified by the number of operational installations).
2. The *availability of information* coming from a particular region (i.e. the number of events actually *reported* by the operators) – an aspect mainly related to the regulatory framework and practices in the different jurisdictions of the region.

Intuitively, the number of incidents per category should decrease with an increase in the severity class. However, this is a pattern which was not observed in our results. The reason may be the different regulatory requirements and industry practices in the various regions of this study which can lead to different incident reporting procedures and criteria. For example, in the North Sea area, strict regulation together with a long-time tradition and solid stance of the operators with respect to the reporting of incidents covering the entire spectrum of severity, including near misses. In other jurisdictions governed by less restrictive regulatory frameworks, operators might not be obliged to report the 'less relevant' events (e.g. in the Caspian/Black Sea region there are no incidents categorized as insignificant or minor). Consequently, the ratio

Table 1
Arctic and other cold regions considered in the current study.

Region	Geographic area	Records in the subset
North Sea	Europe North Sea	Yes
Norwegian Sea	Europe North Sea	Yes
Baffin Bay and Davis Strait	North America East	No
Labrador	North America Arctic	Yes
Newfoundland	North America East	Yes
Canadian Arctic Archipelago	North America Arctic	No
Greenland	North America East	No
Beaufort Sea	North America Arctic	Yes
Chukchi Sea	North Asia	No
Bering Sea	North America West	Yes
Cook Inlet	North America West	No
Okhotsk Sea	North Asia	Yes
Tatar Strait	North Asia	Yes
Bohai Sea	North Asia	Yes
Caspian Sea	Caspian/Black Sea	Yes
Baltic Sea	Europe East	Yes
Barents Sea	Europe Arctic	Yes
Kara Sea	Asia Arctic	Yes
Laptev Sea	Asia Arctic	No
East Siberian Sea	Asia Arctic	No
Black Sea	Caspian/Black Sea	Yes
Sea of Azov	Caspian/Black Sea	No

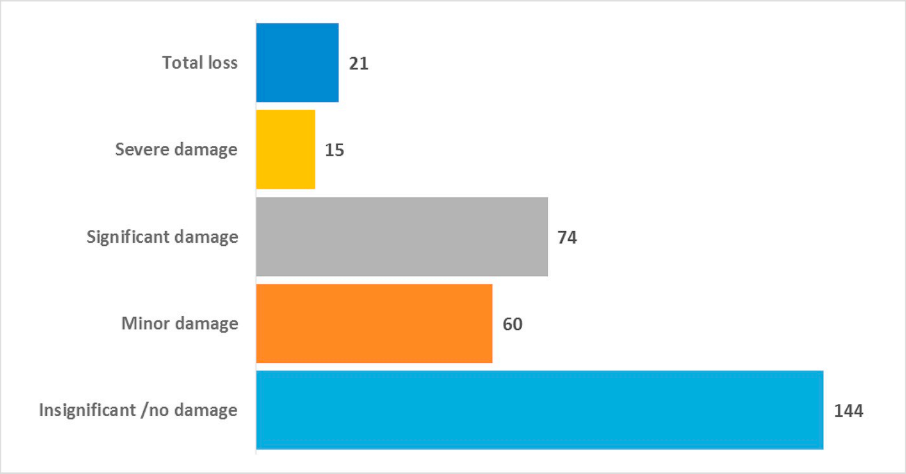

Fig. 1. Distribution of incidents into categories that define the damage extent.

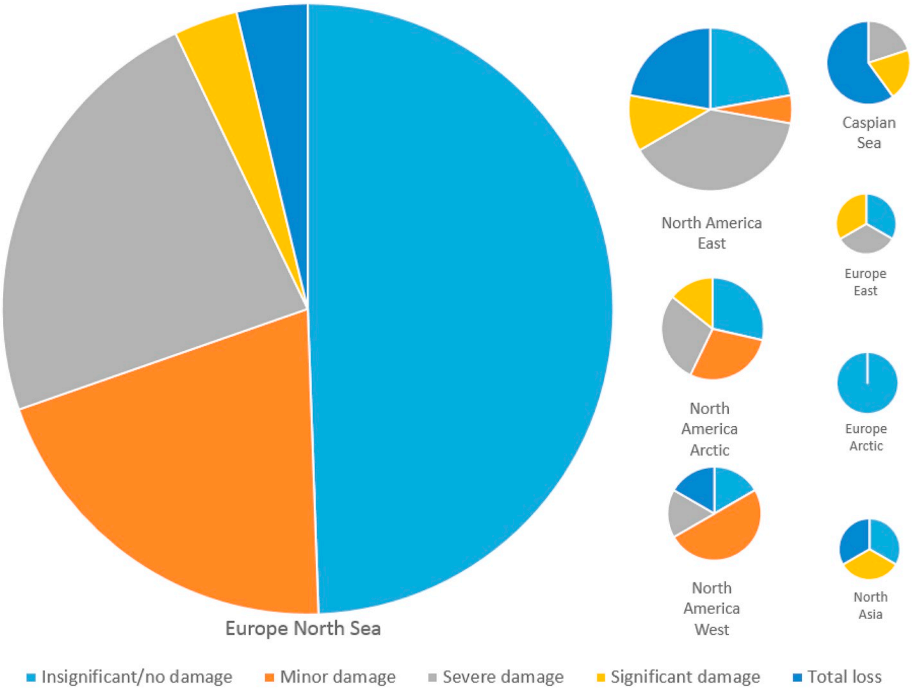

Fig. 2. Relative damage extent distribution per geographic location.

between serious and small damage is generally reversed and the number of insignificant and minor incidents is small compared to incidents that are more serious. This can partially explain the common belief of some operators, who wrongly perceive incidents triggered by environmental actions as extremely rare events with generally serious consequences (e.g. total loss events, deaths, and extensive pollution). However, as the result for the North Sea area shows, low–severity incidents have the highest frequency of occurrence.

3.1. Natural event trigger

The main natural hazards affecting offshore operations are extreme meteorological conditions. Fig. 3 summarizes the number of incidents collected in the set by type of natural hazard trigger. Natural hazard classes were not provided by the WOAD database and hence were defined in the framework of this study as: "Poor visibility/Fog", "Lightning", "Storm or bad weather", "Wave, current or swell", "Strong wind", "Ice, freeze or snow" and "Earthquake or volcano".

Using the same classification as for Fig. 3, Fig. 4 shows the relative number of incidents by natural hazard trigger and region. The size of each chart is proportional to the number of incidents reported in the respective region. While Fig. 4 provides a visual and illustrative representation of the statistics, Table A2 complements the illustration with numerical data (see Annex A).

In the WOAD, weather-related incidents were filed in the category "Equipment cause" under the label "Weather, general". Moreover, the database generally does not provide detailed information regarding the mechanisms by which the adverse meteorological conditions triggered the incident. We performed a manual screening of the incidents in an attempt to expose the nature of the natural hazard triggers. For those cases in which the incident was unmistakably caused by sea movement and wave action, we filed the event in the category "Wave, current or swell". For cases in which strong gale or high winds were to blame for the incident, we filed the event in the category "Strong wind".

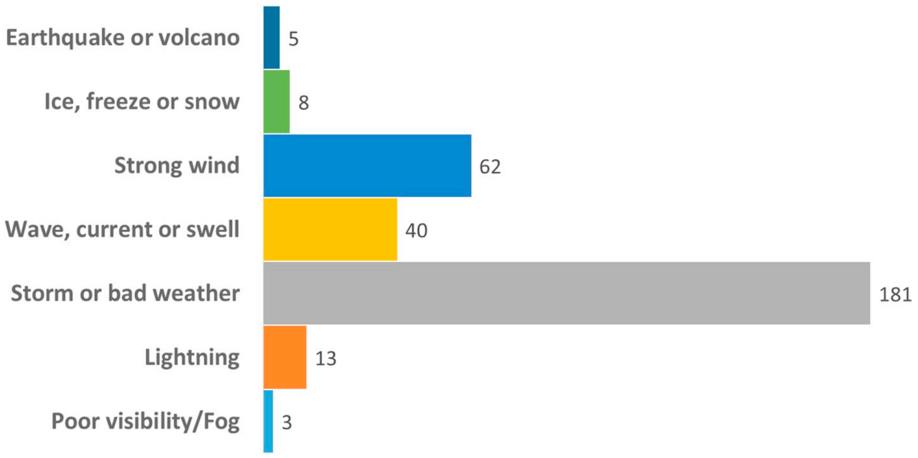

Fig. 3. Distribution of incidents by natural event trigger.

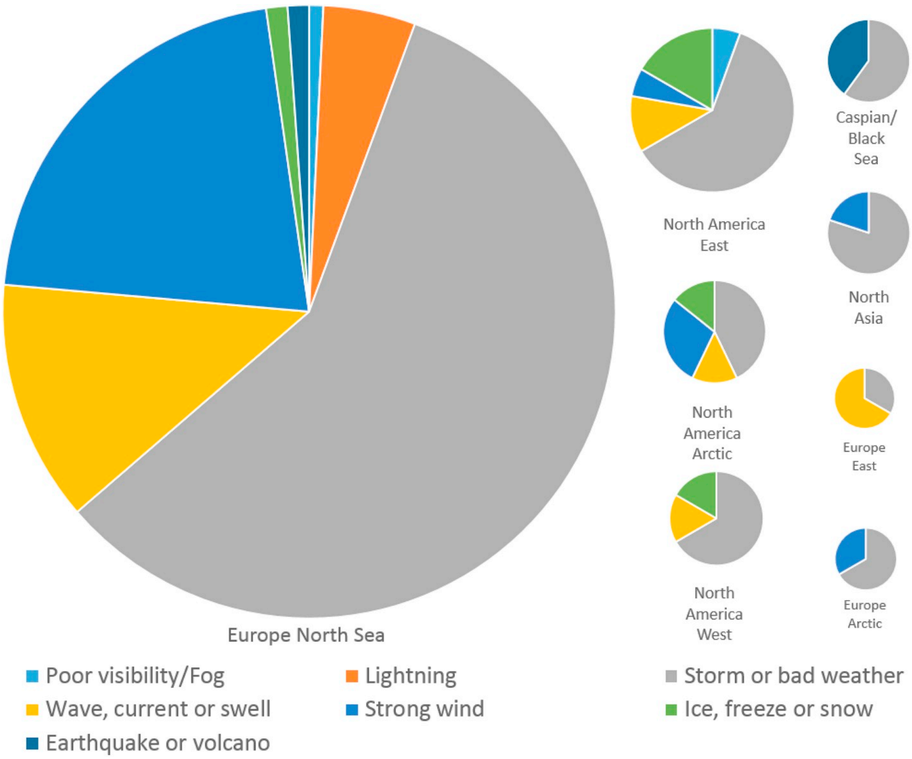

Fig. 4. Relative distribution of incidents per natural hazard trigger and geographic location.

Otherwise, where it was unclear whether sea movement or wind action caused the incident, we filed the event in the category "Storm or bad weather". These three categories were by far the most frequent triggering natural hazards, together having caused about 90% of the total number of incidents in our data set (Fig. 3). Incidents due to bad weather include *falling loads*, *collisions*, *capsizing*, *mooring or anchor failures*, *towing accidents* and *seabed erosion*.

The fourth most frequent trigger of incidents was "lightning", with 4% of incidents in the dataset. Given the safety concerns due to lightning, the WOAD database has a specific label for these incidents which is "Ignition, lightning". Lightning was responsible for fires at vent openings of tanks and for incidents during personnel transport by helicopters. It is important to highlight that incidents due to lightning were only reported in the North Sea region (Fig. 4).

Low temperatures are a major factor to consider in case of offshore operations in the northern regions. Hydrocarbon-producing areas which border the Arctic are subject to sea ice, freezing conditions, and drifting icebergs (Kaiser, 2007). Incidents related to cold (or low temperatures) are labelled in the data set as "Ice, freeze or snow". Their number, relative to the size of the data set, is, however, low (only 8 recorded occurrences), this being an indication that the risk from low temperatures is, in most of the cases, mitigated through technological and procedural means. Conversely, in some regions of North America "Ice, freeze or snow" represent a considerable threat, summing up to 15% of the recorded events. The most frequent effects of these phenomena are ice floe impingement and malfunctioning caused by ice formation on critical equipment.

Finally, the data set featured a few incidents triggered by "Earthquake or volcano" and "Poor visibility and fog". Earthquakes represent a peril to any structure fixed to the seabed in close proximity to a fault line or active tectonic region. "Earthquake or volcano" triggered five incidents, all at fixed structures, including three shut-downs and two events due to submarine gas eruptions. “Poor visibility and fog”, with a total of 3 recorded incidents, features a mix of collisions and crane accidents.

3.2. Affected types of offshore structures and operations

The number of incidents differs significantly depending on the type of structure and operations affected by a natural event. Fig. 5 reports the distribution of the events by the type of operations ongoing at the time of the incident. The WOAD database has its own classification for operations. Among those listed in the WOAD, the types of operation that appear in the selected dataset are “Accommodation”, “Construct, work unit”, “Demobilizing”, “Development Drilling”, “Drilling unknown phase”, “Exploration Drilling”, “Idle”, “Loading of liquids”, “Mobilizing”, “Other”, “Production”, “Repair work/under repair”, “Service”, “Stacked”, “Standby”, “Testing”, “Transfer (unknown dry/wet)”, “Transfer, dry”, “Transfer, wet”, “Under construction” and “Well workover”.

Using the same classification as for Fig. 5, Fig. 6 shows the relative number of incidents by type of affected structure and operation. Similar to operation types, the WOAD database has its own classification for structure types which are: “Barge (not drilling)”, “Concrete structure”, “Drill barge”, “Drill ship”, “FPSO/FSU”, “Helicopter-Offshore duty”, “Jacket”, “Jackup”, “Loading buoy”, “Mobile unit(not drill.)”, “Pipeline”, “Semi-submersible”, “Submersible” and “Tension leg platform”. The size of the charts is proportional to the number of incidents that occurred in each structure category. Fig. 6 provides an illustration of the statistics, while Table A3 in the Annex shows the numerical data that complements Fig. 6.

Although from Fig. 5 it may seem that the highest number of incidents occurred during “Production” (78), the combined number of incidents filed under activities associated with drilling operations (i.e. “Exploration drilling”, “Drilling, unknown phase” and “Development drilling”) adds up to 91 events. Moreover, the high number of events (55) that occurred during transfer operations (i.e. “Transfer, wet”, “Transfer, dry” and “Transfer, unknown dry/wet”) shows the relevance of the transportation risk, which is often underestimated (Fig. 5).

Overall, the most frequently damaged offshore structures were semi-submersible platforms, followed by jackets, jackups and concrete base structures (Fig. 6). A high number of incidents involved helicopters and loading buoys, while other structures were affected to a lesser degree by natural hazards.

For semi-submersibles, drilling operations account for the highest number of incident records (68), with a total of about 50% of incidents for this structure type (137). About 23% of the records for semi-submersibles relates to incidents that occurred during transfer operations and another 9% during production. The second most affected type of mobile structure by the number of records is “Jackup” (42). In this case, incidents during transport are the most numerous (almost 50%), doubling the number of incidents during drilling operations (about 25%). For fixed structures, the two main affected types are (steel) “Jackets” (47) and “concrete structure” (25). For these offshore structures, more than 75% of the records relate to incidents during “Production”. “FPSO/FSU” and “TLP” are two classes of floating structure with an incident distribution similar to that of fixed structures and with a share of incidents in the “Production” category reaching 83% and 75%, respectively. The structure type named “Helicopter-Offshore duty” is also numerically relevant with 20 records. All helicopter incidents fall under the operation labelled as “other”.

3.3. Incident scenarios

This section analyses the dynamics of incidents to understand the incident causes and attempts to relate the type of events to the structure types. Fig. 7 depicts the distribution of the incident categories, each representing one specific scenario. The WOAD database has its own classification for impact categories and it classifies them under the field “Main event”. Among all the categories listed in WOAD under the section “Main event”, the ones that actually appear in the dataset are: “Anchor/mooring failure”, “Breakage or fatigue”, “Capsizing, overturning, toppling”, “Collision, not offshore units”, “Collision, offshore units”, “Crane accident”, “Falling load/Dropped object”, “Fire”, “Grounding”, “Helicopter accident”, “Leakage into hull”, “List, uncontrolled inclination”, “Loss of buoyancy or sinking”, “Other”, “Out of

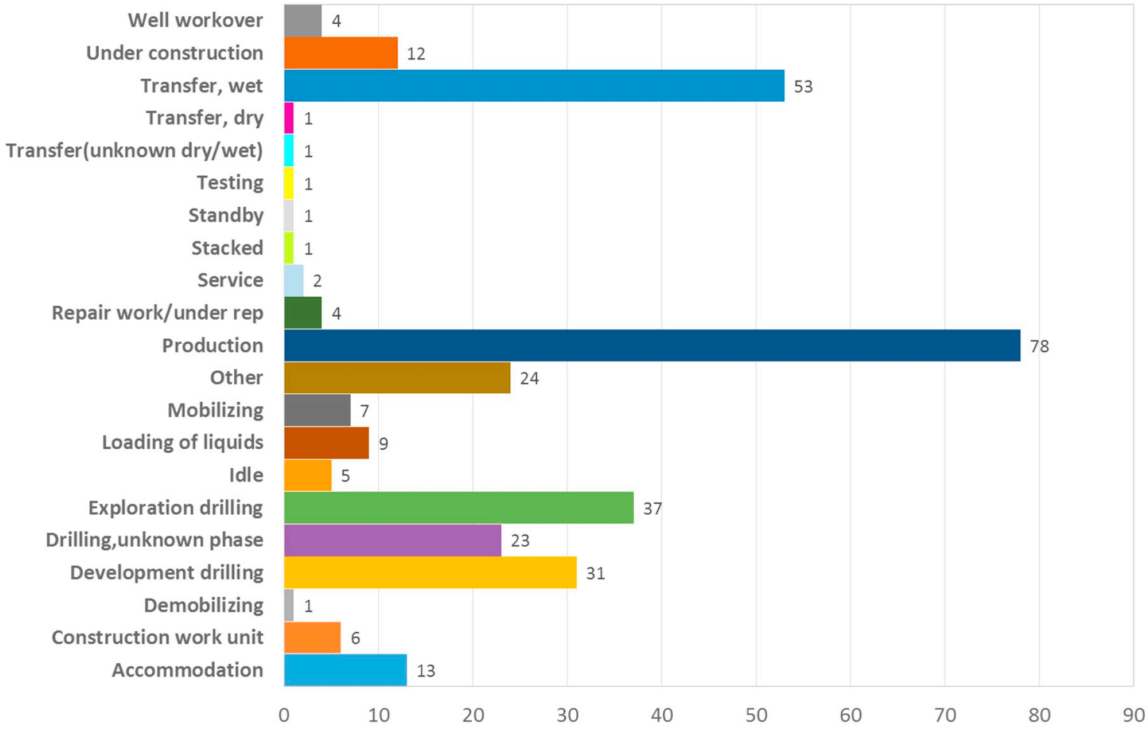

Fig. 5. Distribution of events into categories that define the type of operation performed at the time of the incident.

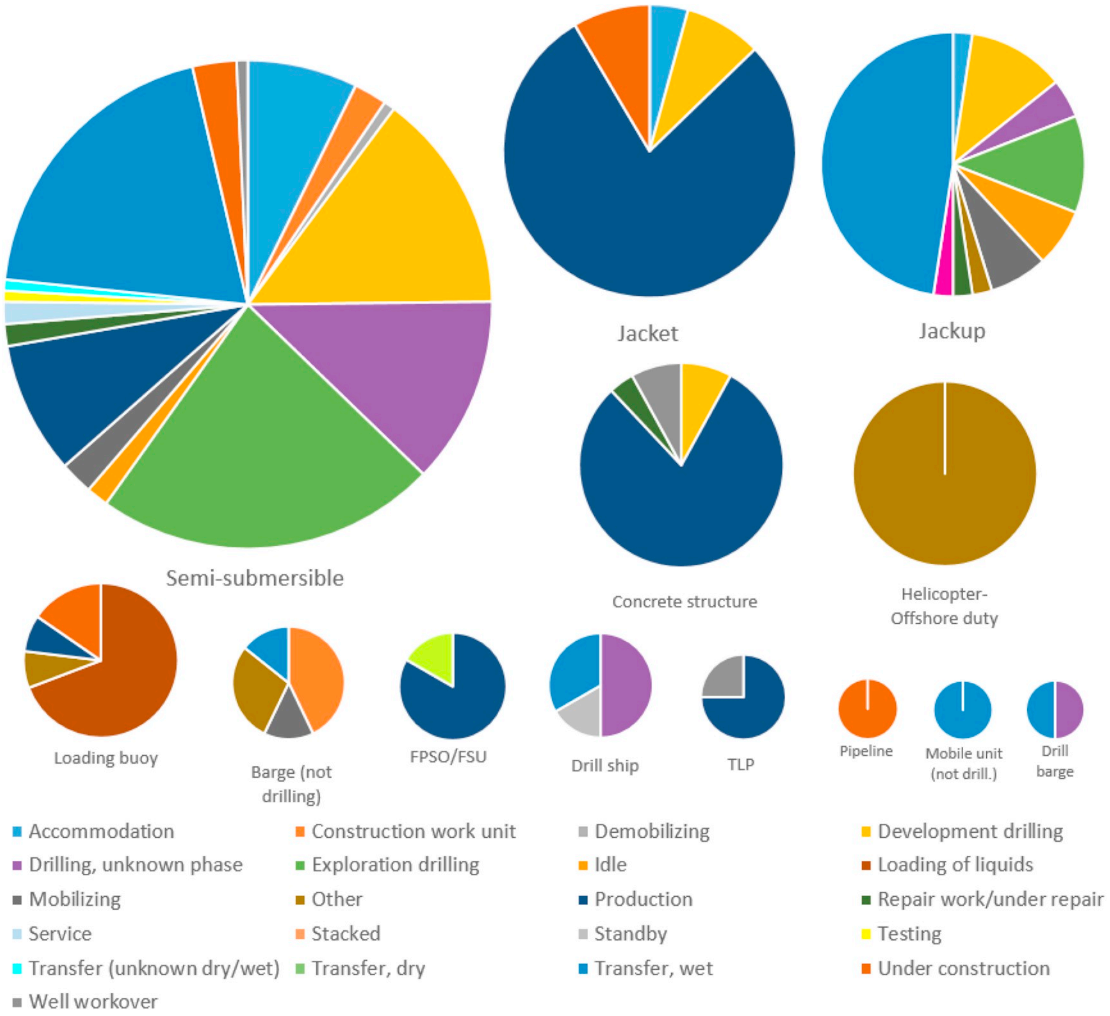

Fig. 6. Relative distribution of events by operation and structure type.

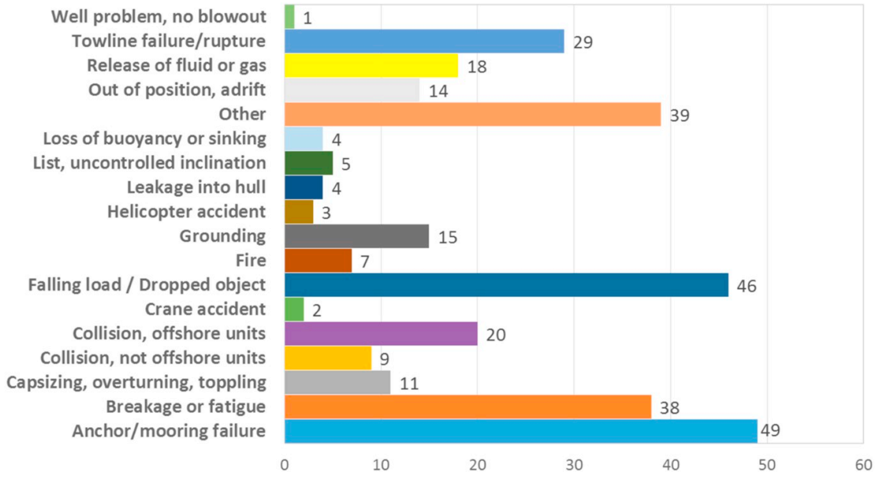

Fig. 7. Distribution of incidents into categories that define the type of impact.

position, adrift", "Release of fluid or gas", "Towline failure/rupture", and "Well problem, no blowout".

Using the same classification as for Fig. 7, Fig. 8 shows the relative number of incidents by type of affected structure and incident category. The size of the charts is proportional to the number of incidents that occurred in each structure category. Fig. 8 provides an illustration of the statistics, while Table A4 in the Annex shows the numerical data that complements Fig. 8."Anchor/mooring failure" describes incidents that follow the loss of control of the operation due to the snapping of one or more mooring lines. It is in absolute the most frequent impact scenario with 49 records (Fig. 7), affecting "Semi-submersible" rigs in particular, but also "drill ships", "FPSO/FSUs" and "Drill barges" (Fig. 8). This result confirms the vulnerability of station keeping systems of mobile drilling rigs operating in difficult environments (OGP, 2014). The problem of ensuring the reliability of mooring systems continues to be an area of concern. “Falling loads/Dropped objects” is the second most numerous impact category with 46 records. This category accounts, among others, for unsecured objects exposed to the elements (e.g. waves) and pushed down to lower decks or to the sea, crane incidents and failure of light structural parts (e.g. wind wall, lighting). Although these events rarely result in structural losses, they have often had serious consequences for the onboard personnel. Triggered by high winds or platform rocking, falling loads are mostly common at fixed offshore installations, i.e. jackets and concrete structures, although they have also been recorded – even if to a lesser extent - at semi-submersible, jackup and tension leg platforms.

The category “Other” includes helicopter incidents and many other unconventional events, like incidents during the transport of fixed structures. However, three serious helicopter accidents with many deaths have been assigned to the category "Helicopter accidents", instead. The category"Other" also includes three incidents in which the structure was evacuated fearing an impact with pack ice headed toward the facility. As shown in Fig. 7, a large number of incidents fall into this category.

“Breakage or fatigue” is a broad category of impacts. It features incidents in which one or more components were damaged, buckled, bent, cracked or ripped off. Mechanical failures are often due to corrosion and fatigue. Fatigue is structure weakening due to the constant stress exerted on the installation over its life (Kaiser, 2007). In 15 out of the 38 records in this category, multiple failures were recorded. These include a few cascading events in which the components that were ripped off also collided with other parts, damaging them. In 11 cases, the waves exceeded the design “air gap” (the distance between the underside of the lowest deck and the highest wave crest) hitting the deck’s bottom, ripping away connection bridges or washing on the deck. This event category concerns all kind of structures, but fixed structures (jacket and concrete base), semisubmersible platforms, loading buoys and jackups have the highest relative incident share for this event category when compared to other structures (Fig. 8).

Rigs, platforms, and FPSOs may capsize during heavy weather due to design issues or operations. Failure of primary structural components such as main braces, jacket legs, deck legs, and piles often lead to listing or capsizing of units (Kaiser, 2007). Incidents of this kind are collected in the categories “Capsizing, overturning, toppling” and “List, uncontrolled inclination”, which have the highest number of records (7 out of 11 and 4 out of 5, respectively) for “Jackup” structures. The number of events recorded under the label “Towline failure” is also significant. Most towline failures occurred during towing operations conducted in stormy weather. This type of failure exhibits a particular propensity to cascade into more serious events. In other more severe events (e.g. “Grounding” and “Loss of buoyancy or sinking”), the towline failure was the initial event that, in conjunction with other circumstantial factors and failures, evolved to the final aggravated outcome. “Jackup” rigs feature a worryingly high number of “Towline failures” and, in absolute numbers, the most numerous incidents during transport operations. “Semi-submersible”, “Drill barges” and other MODUs follow in this list. It is

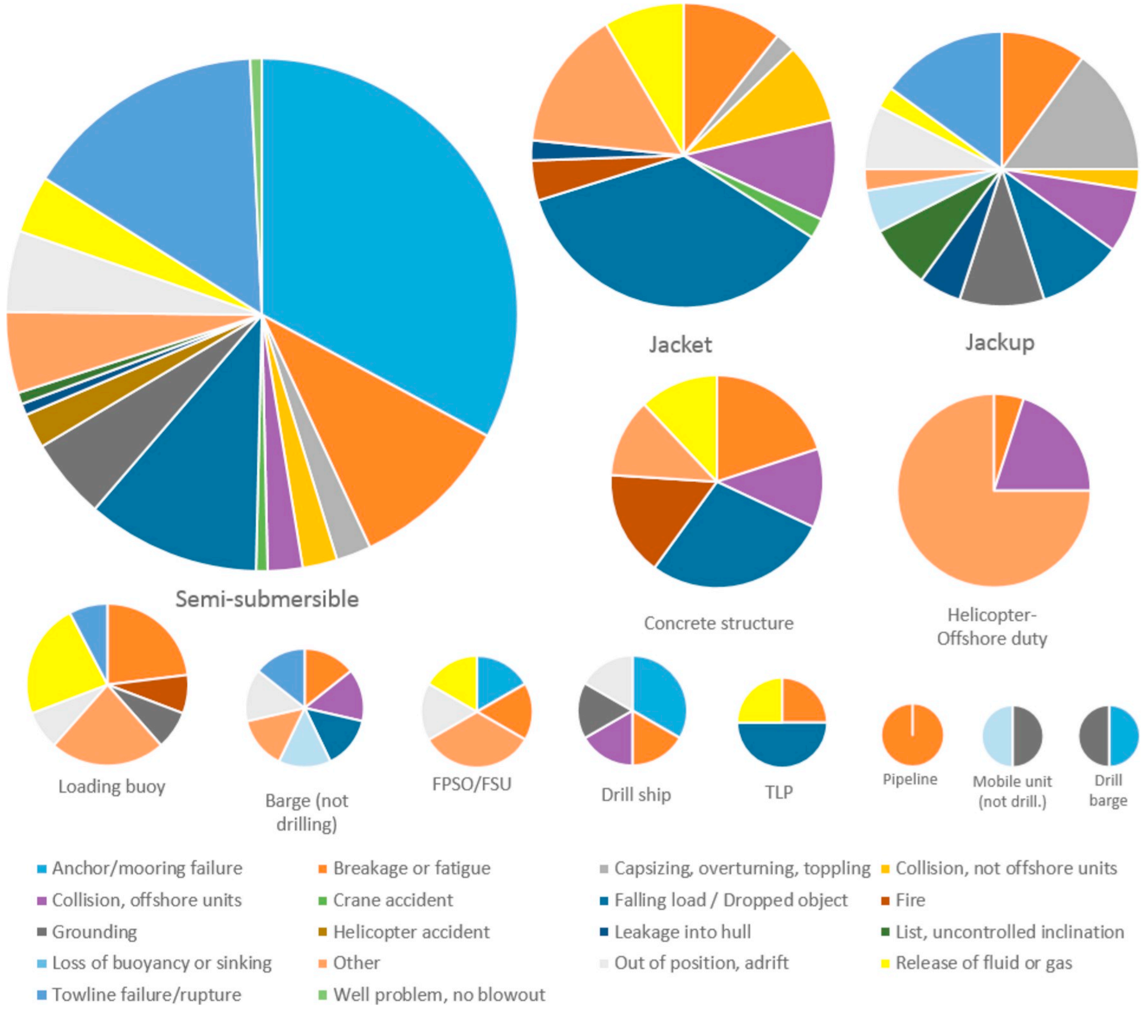

Fig. 8. Relative distribution of impact categories per structure type.

important to mention that “Grounding” and “Capsizing, overturning, toppling” are the most common incident scenarios outside the North Sea region. This is possibly due to the fact that the offshore installations in other regions are more distant from rescuers than those in the North Sea. In fact, remoteness is clearly a factor that can limit the available resources to recover control of a drifting structure.

Collisions are the result of the contact between platforms, barges, ships or third-party objects, typically other vessels. These events, which are collected in two separate categories “Collision, not offshore units” and “Collision, offshore units” (considering both offshore and non-offshore vessels), are numerous (about 10% of the data set) and mainly caused by bad weather, swells or currents. Only in one case, the collision between a platform and a supply vessel was caused by fog and in a further two cases, the rigs collided with sea ice. In fact, under poor visibility conditions, operator errors become more frequent. In addition, search and rescue operations are dramatically hampered by poor visibility and extreme weather in general.

“Release of fluid or gas“ is the category of events that resulted in spills of liquid pollutant into the sea. This category accounts for 18 events (about 6% of the data set). Fixed structures (i.e. “Jacket” and “Concrete structure”) are the most susceptible to this type of event, followed by other production structures like “Semi-submersibles”, “TLPs”, “FPSOs” and “Loading buoys”. The released quantities are extremely variable, from a few litres to several hundred cubic meters of hydrocarbons.

The category named “Fires” is related to fire scenarios. Seven events were recorded in this category. They are either fires that follow hydrocarbon releases or fires at vent openings. In particular, “Loading buoys” and “Tension leg platforms” show the highest relative occurrence of fires.

4. Analysis of recent accident case studies

Our analysis of incidents included in the WOAD encompasses events recorded over a time span of over 40 years. For this reason, some of the data is old and the lessons that can be learned might be outdated because previously identified concerns might already have been addressed. In order to learn relevant lessons regarding the underlying causes that produce accidents during offshore operations in harsh environments, some recent iconic incidents were analysed in more detail. These examples are meant to highlight specific safety flaws that are ultimately responsible for accidents, but that still need to be fully addressed. Table 2 summarizes the case studies considered for detailed accident analysis.

4.1. Ocean Vanguard semi-submersible (2004)

On 14 December 2004, Ocean Vanguard was performing exploration drilling on the well 6406/3-1 in the Norwegian Sea, when hurricane-force winds (80–110 km/h) and massive waves (10 m) pushed the rig about 524 feet (160 m) off location, after the brakes of two of the eight mooring lines failed almost at the same time (WOAD, 2013). Consequently, the tensioning system collapsed and the submerged part of the drilling riser broke. In addition, the blow-out preventer (BOP) on the sea floor tilted by 6°, and the well was lost (Kvitrud, 2014). It was only by chance that the incident did not turn into an environmental disaster. An investigation concluded that the springs in the brake cylinder did not function as intended. Prior to the incident, the manufacturer recommended to change the band brake, but this had not been done. In addition, the pawl stopping the mechanism had been installed wrongly and did not work. Even if nobody was injured and no pollution occurred, the incident resulted in a big financial loss.

Table 2
Year, name, type of structure and type of incident for the case studies analysed.

Year	Name	Type	Type of incident
2004	Ocean Vanguard	Semi-submersible/ rig	Anchor/mooring failure
2011	Transocean Winner	Semi-submersible/ rig	Anchor/mooring failure
2011	Kolskaya	Jackup/rig	Towing accident (Capsizing/Sinking)
2012	Kulluk	Ice-strengthened drill barge	Towing accident (Grounding)
2015	COSLInnovator	Semi-submersible/ rig	Breakage or fatigue
2015	Gunashli Platform No. 10	Jacket/production platform	Breakage or fatigue and Fire

Because of its potential for a catastrophic outcome, this incident represented a landmark event for the Norwegian Petroleum Safety Authority (PSA), which subsequently started a systematic process of improving the reliability of anchoring and mooring systems in the Norwegian continental shelf. As a result, a set of new standards was issued, aiming at ensuring the integrity of station keeping systems (see ISO 19901-7, 2013).

These developments shifted concerns on issues such as recertification and inspection processes, and repair traceability of the lines, alongside the effectiveness of the system for sharing experiences and training of the crew on the function and maintenance of the anchoring and mooring systems. A study of incidents affecting mooring lines was conducted to check the performance of the new standards, discovering that the number of failures was still significant (Kvitrud, 2014). These incidents highlight the importance of well-planned and well-executed procedures to ensure that the station keeping systems stay fully functional during operations and emergency situations.

4.2. Transocean winner semi-submersible (2011)

On 25 November 2011, the Transocean Winner Semi-Submersible, which was drilling on the T-Rex field in the Norwegian Sea, faced the storm Berit and was hit by winds exceeding 108 km/h, and wave heights of 24 m. A break in a polyester fibre cable in a mooring line caused the rig to drift 15–20 m off its original position (Kvitrud, 2014). Evidence on the line indicated that it had already suffered weakening due to friction with an object (e.g. trawler steel wire, subsea installation) near the seabed and, possibly, bending-loading effect. Although the eye of the fibre had been designed to be always lifted above the seabed at all times, this goal was not always achieved, allowing contact with external objects damaging the rope. Kvitrud (2014) recommended the use of subsea buoys that keep the fibres from touching the seabed for future installations.

4.3. Kolskaya jack-up rig (2011)

On 18 December 2011, the Kolskaya jack-up rig capsized and sank in the Sea of Okhotsk in the Russian Federation while the icebreaker Magadan and the tugboat Neftegaz-55 were towing it to its new working location (WOAD, 2013). The operator decided to ignore the fact that “towing in the winter, in winter seasonal zones” was prohibited according to the safety rules specified by the platform’s manufacturer. The reason for this violation was haste to conduct drilling operations on a new field as soon as possible. In addition to that, there was evidence that the hull of the oil rig was in poor condition and had been hastily repaired shortly before towing (KOLSKAYA, 2012). Of the 67 people known to have been aboard Kolskaya, 14 were rescued and 53 were declared missing or dead.

The decision taken by the ship-owner to tow the rig during the ban-on-towage period not only highlights a violation of safety practices, but it also shows ignorance or underestimation of the risks of natural hazards. In addition, insufficient safeguarding measures for the towage of the rig, as well as the large delay between the termination of towage activities and the launch of rescue operations contributed to the dramatic outcome of this tragedy.

4.4. Kulluk drill barge (2012)

Unfortunately, the Kolskaya lesson was not sufficient for some rig operators to change their practices. The following year, on 31 December 2012, the drill barge Kulluk drifted aground off Sitkalidak Island in the Gulf of Alaska (WOAD, 2013). It was being towed from Captains Bay, Alaska, to its winter home in Seattle when she encountered a storm. Four of the crew members on board of the tow vessel Aiviq suffered minor injuries as a consequence of the accident.

On 27 December, the tow line failed and Aiviq lost control of the barge. The following day, the engines on board of the Aiviq failed while trying to reconnect the tow with the help of the Coast Guard. On 29 December, the crew of 18 men was evacuated by the Coast Guard and the Aiviq's engines were repaired. On 30 December, it was decided to bring the barge to a safe harbour to wait for the end of the storm, but the towline parted again. On 31 December, the Coast Guard ship Alert managed to reconnect the tow, but the weather conditions worsened. At only three miles from the shore and unable to pull the barge, the Alert was ordered to release the tow. The Kulluk then grounded off Ocean Bay is Sitkalidak Island. Despite the 143,000 gallons of diesel oil and 12,000 gallons of other petroleum products present on board, there was no trace of environmental damage because of the grounding.

Kulluk's movement south for the winter was at least in part motivated by an effort to avoid State of Alaska property taxes on oil and gas extraction equipment. According to the investigators, this accident was due to "shortcomings in the design of a plan with an insufficient margin of safety". Additionally, the investigators added that "no regulatory requirements existed for a warranty surveyor to review and approve, […], the tow plan and its components". Instead, the operator had "retained warranty surveys on all five previous tows of Kulluk" and the surveyor "approved the tow plan in its entirety" (NTSB, 2015). Given how dangerous Alaskan waters are and that the Aiviq had proven unreliable, the company should have introduced some redundancy elements.

The company requested a Metocean study to forecast the weather conditions for the scheduled towing. Rough weather was predicted with general conditions exceeding those that would allow the Aiviq to maintain position with Kulluk in tow. Even with a formal review process involving multiple entities, the company ignored the natural hazards and the warnings of the Aiviq master, starting a risky operation in the worst environmental conditions and thereby putting the life of the drill barge crew in danger (NTSB, 2015).

There was also another issue, which regards the rules for inspections of the tow vessel main equipment. The engines had failed several times that year and had been repaired by the engine manufacturer, prior to the accident. The investigators believe that a design flaw of the fuel oil storage tanks may have allowed seawater contamination of the fuel (NTSB, 2015). The towing gear was only visually inspected, without any non-destructive testing before the towing operation. Non-destructive testing is not required by the current regulation "unless integrity of the equipment is in doubt", which is very subjective. The towing gear was used in three previous voyages to tow the Kulluk, two of which encountered bad weather (NTSB, 2015).

4.5. COSLInnovator semi-submersible (2015)

Mobile offshore drilling unit COSLInnovator was struck by a rogue wave on 30 December 2015 while pursuing well operations at the Troll field in the Norwegian continental shelf. The wave struck the rig on the top side, exceeding the design "air gap" by several meters. Six windows on the lower deck and eleven on the mezzanine deck were forced inwards (Kvitrud and Løland, 2018), while the forward bulkhead of the box girder was deformed. The unit suffered extensive damage to cabins and corridors spread over two decks forward on the port side. Consequently, one person died and four were injured (PSA, 2016).

At the time of the accident, it was not common practice to include horizontal slamming on the topside in the structure analyses, even in cases in which a negative air gap was identified. Consequently, the wave windows were not designed to withstand the horizontal force induced by the hit, but only to resist hydrostatic pressure. This allowed the water to break the windows installed on the lower decks and to flood into the living quarters (PSA, 2016).

A number of owner constellations and engineering companies were involved in the design of the structure. This complexity caused disagreements and inadequate information flow between the players. Various air gap calculations existed for COSLInnovator, some yielding positive air gaps and some negative ones, as well as a model test. The PSA observed that horizontal wave slamming had been disregarded in the design, since the analyses by DNV and Grenland Group (GG), which showed a negative air gap were not taken into account during design (PSA, 2016). Eventually, COSL used one of the initial air gap calculation, which assessed a positive air gap of only 0.57 m for the design and construction of the unit. However, the PSA investigation (PSA, 2016) highlighted a number of flaws related to the air gap in the design calculations:

- no hull-wave interactions were taken into account;
- the significant wave height considered was 0.5 m lower than that used by DNV;
- tests performed after the first design calculations were not considered for the model calibration;
- buoyancy elements added at a later stage of the design were not included;
- the air gap was calculated in relatively few points;
- the calculated air gap was lower than the minimum requirement of 1.5 m set by the Norwegian Maritime Authority.

This accident highlighted the lack of harmonization among the design procedures of different players and it showed that the resistance to horizontal forces from wave impacts needs to be taken into consideration by designers, regulatory bodies and classification societies, especially for offshore activities in harsh environments.

Although the rules state that topsides must be dimensioned to resist wave loads if a unit has a negative air gap, these rules do not distinguish specifically between vertical and horizontal wave slamming. About six months after the incident, DNV GL (2016) published a new technical guideline (DNVGL–OTG–13), providing a consistent and updated approach for calculating the air gap and wave load, and the Norwegian Authorities demanded compliance with the DNV GL guidelines by November 1, 2016.

Recently, Kvitrud and Løland (2018) analysed 29 similar wave-in-deck incidents on board of 17 platforms in Norwegian waters, considering the interval 2000–2017. The platforms' air gaps were recalculated according to the DNV GL guidelines, revealing that many of the mobile platforms had negative air gaps in a 10^{-2} annual probability range. Most mobile platforms have already implemented major changes to increase their resistance to wave actions. The authors suggest a number of structural and operational precautions aimed to reduce the risks to both the platform and its crew in storm conditions (Kvitrud and Løland, 2018).

4.6. Gunashli Platform No.10 (2015)

On 4 December 2015, a fire broke out at "Platform No. 10" in service since 1984 at the western section of the Gunashli oilfield in the Azerbaijani section of the Caspian Sea (Bagirova, 2015). A total of 30 people on board were declared missing, 33 were rescued (several of whom were hospitalized). In this area, strong winds are common during the cold season. A high-pressure subsea pipeline was damaged in a heavy storm; there was an explosion of the gas escaping from it, and a fire broke out. The high-pressure gas pipeline simply could not endure the wave impact forces. The region was battered by some of the worst weather seen in years, with 12 m waves reported in the area around the platform. In addition, another incident occurred that day in the same area where three workers went missing from a second offshore oil platform (production platform no. 501 at the Oil Rocks oil field) in the Caspian Sea, after an accident triggered by the same storm (Azvision, 2015).

The offshore workers' union published a detailed report of the accident (OWRPO PU, 2016). Because of the fire, the platform partially collapsed and 28 oil and gas wells where shut. The crew started evacuation procedures and got into the lifeboats. The vessels were lowered on cables to about 10 m above sea level when it was decided not to drop them into the water to avoid them being dashed against the platform by the storm. Due to the strong wind and waves, the hook of one of the lifeboats opened up while it was descending from the platform. The lifeboat with 34 people on board hit piles of the platform and then fell into the sea. The management of the emergency was heavily criticized (OWRPO PU, 2016). Procedures required the crew to be evacuated on lifeboats, which meant certain death given the stormy conditions at that time. According to the critics, a safer alternative would have been to wait for rescue or for the storm to reduce violence in the residential section of the platform (OWRPO PU, 2016).

Critics contend that the aging condition of the Gunashli field's facilities poses a serious safety risk. Fourteen workers died in the accidents on SOCAR's oil and gas platforms in 2014. On 26 September 2016, Gunashli Platform 19 suffered a gas leak and fire caused by bad weather, while on 15 December 2016, a 150 m section of a scaffold bridge and an accommodation unit collapsed into the sea due to high winds. Part of this structure, built in 1978, last underwent repairs six months prior to the accident (MarEx, 2018). In the accident, ten workers went missing but only the body of one worker was recovered.

5. Lessons learned and recommendations

Harsh environmental conditions and extreme weather events accelerate the ageing of offshore infrastructure and enhance fatigue, while on the other hand providing frequent high load stress during storms. When an incident occurs, the response and recovery from oil spills are challenging under any circumstance, but it is even more critical in harsh environments, particularly in the Artic, where people and animals depend on this unique ecosystem to survive. It is, therefore, crucial to learn from past incidents to prevent their recurrence. Based on the analysis carried out in this study which identified persisting problems not yet fully solved, the following summarizes lessons and associated recommendations for improving offshore safety in harsh environments.

- *Station keeping systems are vulnerable to extreme weather*. About 60% of the offshore mooring line failures on the Norwegian Continental Shelf from 2010 to 2014 occurred in heavy weather conditions, with winds gusting from 50 to 110 km/h, and significant wave heights up to 10 m. This was mainly due to the loss in the reliability of the mooring or anchor system, caused by wear, corrosion-driven fatigue, bending/twisting of line, overloading and/or mechanical damage caused by friction with third objects. Since a number of concurrent factors, such as insufficient design criteria (only adequate for short return-period natural hazards), wrong operations and poor manufacturing, are responsible for the continuing failures, it is important to raise the attention of the industry to improving the reliability of station keeping systems. This target can be achieved by implementing better procedures for the inspection, repair, and substitution of weakened parts and to ensure that their performance does not deteriorate with time. Kvitrud (2014), for instance, suggests to improve material selection and fabrication, protect against mechanical damage and corrosion, enhance maintenance and inspection, and to check limit states (ALS – Abnormal (accidental) Limit State, FLS – Fatigue Limit State, ULS – Ultimate Limit State).
- *There is too much variety amongst available design methodologies.* Depending on the method chosen for the design of components, systems or structures by various manufacturers, the final facility may ultimately be more or less resistant to environmental effects. An example is the COSLInnovator case, where an inappropriate method was applied for the calculation of the air gap. The use of unsuitable methods may result in the underestimation of critical rig features. Design calculations should be verified by using different calculation methods and builders should rely on the result that returns the most conservative configuration.
- *Transport operations are vulnerable to extreme weather.* The number of incidents during the transport of oil rigs during storms is significant, indicating that this risk is severely underestimated. Unlike in structural design, contingency management decisions, such as scheduling transport operations, seldom undergo reviews based on risk assessment, despite the availability of specific methodologies (Abbassi et al., 2017). This constantly puts the lives of the crew and the integrity of the facilities at risk. As documented by the Kolskaya's, the Kulluk's and other accidents, businesses frequently overlook environmental hazards when facilities are outside their intended design environment and when decisions are taken on economic grounds. Transport planning should seriously take into consideration the hazards due to harsh weather, and awareness of this risk needs to be raised to improve the safety culture.
- *Emergency management should take natural hazards into consideration.* Emergency management plays a decisive role in preventing major losses and protecting crew members in case of an accident. Planning for emergencies requires consideration of the possible extreme natural events at the operation site to be effective in every circumstance. This is also generally valid every time a natural hazard affects technological systems and generates Natech accidents. Necci et al. (2018) highlighted that emergency procedures were generally found to be deficient to respond to Natech accidents effectively and were subsequently updated to account for natural events. This lesson is even more important for offshore operations in harsh environments, where the remote location of some facilities can hamper the response even more. In addition, when natural hazards are not properly considered in emergency planning, procedures can potentially exacerbate the gravity of an accident, instead of mitigating it. For example, if procedures had successfully accounted for natural events, the crew of the Gunashli platform might have stayed on the platform in a temporary refuge waiting for rescue, instead of being on the half-lowered lifeboat, which eventually cost some of them their lives. It is thus recommended that emergency procedures are periodically reviewed and tested and that extreme natural events (such as stormy weather) are included as possible scenarios for emergency management planning.
- *Ultimate decision power in multi-entity decision making.* A decision on undertaking a risky procedure, such as a towing, may only be formally affected by the review of all the entities involved. Eventually, there is one party with the ultimate power of approving the decision in the face of obvious risks. This situation might encourage risk-taking behaviour when a party has an interest in favour of the outcome with the higher risks. This was the case in the Kulluk accident, where the company forced its decision to conduct towing regardless of the necessary review process, given the risks associated with towing in that time of the year. We recommend that all the parties involved in a multi-entity review process be entitled to veto the decision if a party judges the risks as unacceptably high.
- *Evacuation of non-critical personnel should be performed if possible when extraordinary events are foreseen.* Many national offshore safety rules require that most types of work should be stopped when storms are approaching, however, this is not always observed, putting lives unnecessarily at risk. When the Gunashli accident occurred, there were extra workers on the platform. Of the 63 people on the rig when the fire began, 15 were members of a construction and drilling team. Companies should have considered keeping only a minimum critical crew on the rig while evacuating the non-critical personnel in preparation for the storm.

- *Corrosion, wear, and aging are serious risks.* Low temperatures and water salinity increase the rate at which the structures age, effectively reducing the operative life of components (Karadeniz, 2001). Risks increase very quickly in marine environments when fatigue and corrosion are not coped with in due time (Dong and Frangopol, 2015). Frequent storms can increase the wear of structural components, which in turn lose their resistance rather quickly. A recent study investigated a set of major accidents that occurred in the period 2000–2011 and found that out of 183 accidents, 80 (44%) were maintenance-related (Okoh and Haugen, 2014). On top of this, the worryingly high number of serious accidents that were reported in the last five years (in particular in the Azerbaijani sector of the Caspian Sea) due to ageing-related issues further highlights the importance of maintenance, especially for structures subject to severe environmental conditions (Samarakoon and Ratnayake, 2015). For this reason, the need to keep all the components in optimal operative conditions is paramount in harsh environments, even if this implies that operators have to make an extra effort to better preserve components or even to replace entire facilities.
- *Worst-case scenarios may be exceeded.* Contingency planners generally formulate worst-case scenarios. With regard to natural events, it is the maximum critical intensity of an action that may be *reasonably* expected to occur. When planning for emergency response under natural hazard loading, safety officers should always take into account that the worst-case scenarios may be exceeded by unforeseen catastrophic events. This is particularly valid in environments such as the Arctic, where long periods of darkness, low temperatures and limited access due to sea ice would render effective emergency response in case of an accident next to impossible. If stronger environmental actions than the design values are forecast, safety precautions should be taken (Kvitrud and Løland, 2018). In addition, frequencies and intensities of extreme events are expected to increase due to climate change (Debernard et al., 2002). Met-ocean criteria need to be adapted to factor in the possible effects of climate change on offshore design and operations where needed.

6. Conclusions and outlook

This study analysed past incidents of the oil and gas offshore sector, which occurred in the Arctic and similar harsh environments and can be directly attributed to natural hazard impact. The World Offshore Accident Database was analysed to spot the main risks to offshore structures in the Arctic. A set of past relevant accidents was reviewed, highlighting the underlying causes that ultimately produced considerable losses. The study collected a set of lessons learned and recommendations for improving the safety of offshore operations in harsh environments.

This study showed that incidents in the offshore oil and gas industry due to natural hazards are a major problem, in particular in harsh environments like the Arctic or other ice-prone seas. The study concluded that incidents caused by natural hazards in the areas studied were frequent and resulted mostly but not always in low consequences. The most important incident trigger was bad weather, mainly causing loss of station keeping due to high winds and rough seas for floating structures, and falling loads due to storms for fixed structures. Another important conclusion of this work is the high vulnerability to natural events of offshore infrastructure during transfer operations, which has resulted in numerous incidents.

The high number of incidents caused by environmental factors over the last years is a direct consequence of overlooking or underestimating natural hazards during design and operation. This is combined with the tendency to keep costs to a minimum, such as by extending the operability beyond the design life limits, rushing transport operations, or delaying inspections and maintenance of vital components. In addition, some standards, design methodologies, and procedures were updated only after they had proven inadequate or ineffective when natural hazards of unexpected intensity challenged design assumptions.

If politics and industry wish to accept the challenges posed by the exploitation of hydrocarbon resources in the Arctic and in similar harsh environments, further efforts are necessary to ensure that offshore operations in these areas become both safe and economic. The Arctic is a very fragile environment that is already under scrutiny of the scientific community and the media due to the impacts triggered by climate change. Darkness, low temperatures, and limited access would severely complicate mitigating the consequences of a potential offshore incident. Policy makers and operators must be aware that in case of accidents they would be exposed to fierce criticism from the public, with potentially dramatic repercussions on their political future and on investments. For this reason, they both should set their accident prevention policy toward the goal of achieving “zero accidents”.

This study identified a number of research gaps, which need to be addressed to reduce the natural-hazard risks to offshore infrastructure in harsh environments. Most importantly, we need more knowledge of incident dynamics and consequences, as well as assessment tools. More detailed and structured loss data is required to better understand the underlying causes of accidents in the Arctic regions. Researchers should aim at the development of an incident database that focuses on harsh environments. Funding should be allocated to research to improve the level of reliability of components and structures in harsh environments. Research is needed for developing novel non-invasive diagnostic methods, which allow the evaluation of the cumulative damage of vital components exposed to recurrent harsh weather responsible for fatigue, wear, and corrosion phenomena.

More specific rules and guidelines should be prepared to address the particular challenges associated with offshore operations under the difficult environmental conditions found in the Arctic and ice-prone seas in general. There is a need for improved safety management methodologies able to cope with the interaction of both natural and technological risks, and procedures that ensure risk-informed decision-making. Furthermore, stakeholders need to be aware that with the expansion of offshore operations, also the risk of multiple and simultaneous incidents during storms will increase, as well as the risks for the Arctic environment. This phenomenon has already been observed in other parts of the world with a strong storm regime and a high density of offshore infrastructure (Cruz and Krausmann, 2008).

In addition, although a proactive attitude of the industry is required to prevent incidents, other actors, such as engineering companies, manufacturers, workers’ unions, authorities and policymakers need to work together to build a safer future for the oil and gas sector in general, and in harsh environments in particular.

Appendix

Table A 1
Number of incidents by damage extent (rows) and geographic location (columns)

	Caspian/Black Sea	Europe Arctic	Europe East	Europe North Sea	North America Arctic	North America East	North America West	North Asia	Grand Total
Insignificant/no damage	0	3	1	132	2	4	1	1	144
Minor damage	0	0	0	54	2	1	3	0	60
Significant damage	1	0	1	62	2	7	1	0	74
Severe damage	1	0	1	9	1	2	0	1	15
Total loss	3	0	0	10	0	4	1	3	21
Grand Total	**5**	**3**	**3**	**267**	**7**	**18**	**6**	**5**	**314**

Table A 2
Number of incidents by type of natural hazard (rows) and geographic location (columns)

	Caspian/Black Sea	Europe Arctic	Europe East	Europe North Sea	North America Arctic	North America East	North America West	North Asia	Grand Total
Poor visibility/Fog	0	0	0	2	0	1	0	0	3
Lightning	0	0	0	13	0	0	0	0	13
Storm or bad weather	3	2	1	155	3	11	4	4	183
Wave, current or swell	0	0	2	34	1	2	1	0	40
Strong wind	0	1	0	57	2	1	0	1	62
Ice, freeze or snow	0	0	0	3	1	3	1	0	8
Earthquake or volcano	2	0	0	3	0	0	0	0	5
Grand Total	**5**	**3**	**3**	**267**	**7**	**18**	**6**	**5**	**314**

Table A 3
Number of incidents by type of operation (rows) and type of structure (columns)

	Barge (not drilling)	Concrete structure	Drill barge	Drill ship	FPSO/FSU	Helicopter Offshore duty	Jacket	Jackup	Loading buoy	Mobile unit (not drill.)	Pipeline	Semi-submersible	Submersible	Tension leg platform	Grand Total
Accommodation	0	0	0	0	0	0	2	1	0	0	0	10	0	0	13
Construct. work unit	3	0	0	0	0	0	0	0	0	0	0	3	0	0	6
Demobilizing	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Development Drilling	0	2	0	0	0	0	4	5	0	0	0	20	0	0	31
Drilling, unknown phase	0	0	1	3	0	0	0	2	0	0	0	17	0	0	23
Exploration drilling	0	0	0	0	0	0	0	5	0	0	0	31	1	0	37
Idle	0	0	0	0	0	0	0	3	0	0	0	2	0	0	5
Loading of liquids	0	0	0	0	0	0	0	0	9	0	0	0	0	0	9
Mobilizing	1	0	0	0	0	0	0	3	0	0	0	3	0	0	7
Other	2	0	0	0	0	20	0	1	1	0	0	0	0	0	24
Production	0	20	0	0	5	0	37	0	1	0	0	12	0	3	78
Repair work/under repair	0	1	0	0	0	0	0	1	0	0	0	2	0	0	3
Service	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
Stacked	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Standby	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Testing	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Transfer (unknown dry/wet)	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Transfer, dry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Transfer, wet	1	0	1	2	0	0	0	20	0	2	0	27	0	0	52
Under construction	0	0	0	0	0	0	4	0	2	0	2	4	0	0	12
Well workover	0	2	0	0	0	0	0	0	0	0	0	1	0	1	4
Grand Total	**7**	**25**	**2**	**6**	**6**	**20**	**47**	**42**	**13**	**2**	**2**	**137**	**1**	**4**	**314**

Table A 4
Number of incidents by type of incident (rows) and type of structure (columns)

	Barge (not drilling)	Concrete structure	Drill barge	Drill ship	FPSO/FSU	Helicopter-Offshore duty	Jacket	Jackup	Loading buoy	Mobile unit (not drill.)	Pipeline	Semi-submersible	Submersible	Tension leg platform	Grand Total
Anchor/mooring failure	0	0	1	2	1	0	0	0	0	0	0	45	0	0	49
Breakage or fatigue	1	5	0	1	1	1	5	4	3	0	2	14	0	1	38
Capsizing, overturning, toppling	0	0	0	0	0	0	1	7	0	0	0	3	0	0	11
Collision, not offshore	0	0	0	0	0	0	4	1	0	0	0	3	1	0	9
Collision, offshore	1	3	0	1	0	4	5	3	0	0	0	3	0	0	20
Crane accident	0	0	0	0	0	0	1	0	0	0	0	1	0	0	2
Falling load/Dropped Object	1	7	0	0	0	0	17	4	0	0	0	15	0	2	46
Fire	0	4	0	0	0	0	2	0	1	0	0	0	0	0	7
Grounding	0	0	1	1	0	0	0	4	1	1	0	7	0	0	15
Helicopter accident	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3
Leakage into hull	0	0	0	0	0	0	1	2	0	0	0	1	0	0	4
List, uncontrolled Inclination	0	0	0	0	0	0	0	4	0	0	0	1	0	0	5
Loss of buoyancy or sink	1	0	0	0	0	0	0	2	0	1	0	0	0	0	4
Other	1	3	0	0	2	15	7	1	3	0	0	7	0	0	39
Out of position, adrift	1	0	0	1	1	0	0	3	1	0	0	7	0	0	14
Release of fluid or gas	0	3	0	0	1	0	4	1	3	0	0	5	0	1	18
Towline failure/rupture	1	0	0	0	0	0	0	6	1	0	0	21	0	0	29
Well problem, no blowout	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Grand Total	**7**	**25**	**2**	**6**	**6**	**20**	**47**	**42**	**13**	**2**	**2**	**137**	**1**	**4**	**314**

References

Abaei, M.M., Arzaghi, E., Abbassi, R., Garaniya, V., Chai, S., 2018. A novel approach to safety analysis of floating structures experiencing storm. Ocean Eng. 150, 397–403. https://doi.org/10.1016/j.oceaneng.2017.12.011.

Abbassi, R., Khan, F., Khakzad, N., Veitch, B., Ehlers, S., 2017. Risk analysis of offshore transportation accident in arctic waters. Int. J. Marit. Eng. 159, A213–A224. https://doi.org/10.3940/rina.ijme.2017.a3.351.

Afenyo, M., Khan, F., Veitch, B., Yang, M., 2017. Arctic shipping accident scenario analysis using Bayesian Network approach. Ocean Eng. 133, 224–230. https://doi.org/10.1016/j.oceaneng.2017.02.002.

Arctic Council, 2009. Arctic Maritime Shipping Assessment 2009 Report. Available at. : https://www.pmel.noaa.gov/arctic-zone/detect/documents/AMSA_2009_Report_2nd_print.pdf. (Accessed 21 November 2018).

Arzaghi, E., Abbassi, R., Garaniya, V., Binns, J., Khan, F., 2018. An ecological risk assessment model for Arctic oil spills from a subsea pipeline. Mar. Pollut. Bull. 135, 1117–1127. https://doi.org/10.1016/j.marpolbul.2018.08.030.

Azvision, 2015. Criminal Case Launched on Azerbaijani Offshore Oil Platform Collapse. Retrieved from. https://en.azvision.az. (Accessed 21 November 2018).

Bagirova, N., 2015. One Worker Killed, 30 Missing after Azeri Oil Rig Fire: Government. Retrieved from. https://www.reuters.com. (Accessed 21 November 2018).

Bea, R.G., 2002. Human and organizational factors in reliability assessment and management of offshore structures. Risk Anal. 22, 29–45. https://doi.org/10.1111/0272-4332.t01-1-00003.

Bellino, P.W., Flynn, M.R., Rangwala, A.S., 2013. A study of spreading of crude oil in an ice channel. J. Loss Prev. Process. Ind. 26, 558–561. https://doi.org/10.1016/j.jlp.2012.07.001.

Bridges, R., Riska, K., Liangliang, L., du-Couedic-du-Kererant, M., Aubert, J.M., 2018. A study on the specification of minimum design air temperature for ships and offshore structures. Ocean Eng. 160, 478–489. https://doi.org/10.1016/j.oceaneng.2018.04.040.

Cruz, A.M., Krausmann, E., 2008. Damage to offshore oil and gas facilities following hurricanes Katrina and Rita: an overview. J. Loss Prev. Process. Ind. 21, 620–626. https://doi.org/10.1016/j.jlp.2008.04.008.

Christou, M., Konstantinidou, M., 2012. Safety of Offshore Oil and Gas Operations: Lessons from Past Accident Analysis. European Commission, Ispra, Italy.

Debernard, J., Saetra, Ø., Røed, L.P., 2002. Future wind, wave and storm surge climate in the northern North Athlantic. Clim. Res. 23, 39–49. https://doi.org/10.3354/cr023039.

Dehghani-Sanij, A.R., Dehghani, S.R., Naterer, G.F., Muzychka, Y.S., 2017. Sea spray icing phenomena on marine vessels and offshore structures: review and formulation. Ocean Eng. 132, 25–39. https://doi.org/10.1016/j.oceaneng.2017.01.016.

Dehghani-Sanij, A.R., Dehghani, S.R., Naterer, G.F., Muzychka, Y.S., 2017. Marine icing phenomena on vessels and offshore structures: prediction and analysis. Ocean Eng. 143, 1–23. https://doi.org/10.1016/j.oceaneng.2017.07.049.

Demirbiliek, Z., 2010. Hurricane Katrina and ocean engineering lessons learned. Ocean Eng. 37 (1), 1–3. https://doi.org/10.1016/j.oceaneng.2009.12.002.

Deyab, S.M., Taleb-berrouane, M., Khan, F., Yang, M., 2018. Failure analysis of the offshore process component considering causation dependence. Process Saf. Environ. Protect. 113, 220–232. https://doi.org/10.1016/j.psep.2017.10.010.

Directive 2013, 2013. 30/EU of the European Parliament and of the Council of 12 June 2013 on safety of offshore oil and gas operations and amending Directive 2004/35/EC. Off. J. Eur. Commun. L 178/66, 28.6.

DNV, G.L., 2016. DNVGL–OTG–13 Prediction of Air Gap for Column Stabilized Units. DNV GL, Norway.

Dong, Y., Frangopol, D.M., 2015. Risk-informed life-cycle optimum inspection and maintenance of ship structures considering corrosion and fatigue. Ocean Eng. 101, 161–171.

EMSA, 2009. Maritime Accident Review 2009. European Maritime Safety Agency, Lisbon. Available at: www.emsa.europa.eu/download/308/216/23.html. (Accessed 21 November 2018).

Gao, X., Barabady, J., Markeset, T., 2010. An approach for prediction of petroleum production facility performance considering Arctic influence factors. Reliab. Eng. Syst. Saf. 95, 837–846. https://doi.org/10.1016/j.ress.2010.03.011.

Gulev, S.K., Hasse, L., 1999. Changes of wind waves in the North Atlantic over the last 30 years. Int. J. Climatol. 19, 1091–1117. https://doi.org/10.1002/(SICI)1097-0088(199908)19:10%3e;1091::AID-JOC403%3c;3.0.CO;2-U.

Guozheng, S., Khan, F., Wang, H., Leighton, S., Yuan, Z., Liu, H., 2016. Dynamic occupational risk model for offshore operations in harsh environments. Reliab. Eng. Syst. Saf. 150, 58–64. https://doi.org/10.1016/j.ress.2016.01.021.

Hewson, T.D., Neu, U., 2015. Cyclones, windstorms and the IMILAST project. Tellus 67, 27128, 2015. https://doi.org/10.3402/tellusa.v67.27128.

Homlong, E., Kayrbekova, D., Panesar, S.S., Markeset, T., 2012. Assessing maintenance time, cost and uncertainty for offshore production facilities in Arctic environment. In: Frick, J., Laugen, B.T. (Eds.), Advances in Production Management Systems. Value Networks: Innovation, Technologies, and Management. APMS 2011. IFIP Advances in Information and Communication Technology, vol. 384. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-33980-6_26.

ISO 19900, 2013. Petroleum and Natural Gas Industries - General Requirements for Offshore Structures. British Standards Institution, London, United Kingdom.

ISO 19901-7, 2013. Petroleum and Natural Gas Industries - Specific Requirements for Offshore Structures - Part 7: Stationkeeping Systems for Floating Offshore Structures and Mobile Offshore Units. British Standards Institution, London, United Kingdom.

ISO 19906, 2010. Petroleum and Natural Gas Industries - Arctic Offshore Structures. British Standards Institution, London, United Kingdom.

Kaiser, M.J., 2007. World offshore energy loss statistics. Energy Policy 35, 3496–3525. https://doi.org/10.1016/j.enpol.2006.12.020.

Karadeniz, H., 2001. Uncertainty modeling in the fatigue reliability calculation of offshore structures. Reliab. Eng. Syst. Saf. 74 (3), 323–335. https://doi.org/10.1016/S0951-8320(01)00087-4.

KOLSKAYA, 2012. Kolskaya Offshore Oil-Drilling Platform Tragedy and Hope. Retrieved from. http://www.kolskaya.com. (Accessed 28 April 2017).

Kvitrud, A., 2014. Anchor Line Failure - Norwegian Continental Shelf - 2010-2014. PSA - Petroleum Safety Authority, Norway.

Kvitrud, A., Løland, A.H., 2018. Observed wave actions on Norwegian semi-submersible and TLP decks. In: Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering OMAE2018, June 17-22, 2018, Madrid. https://doi.org/10.1115/OMAE2018-77008. Spain, OMAE2018-77008.

Landucci, G., Bonvicini, S., Cozzani, V., 2017. A methodology for the analysis of domino and cascading events in Oil & Gas facilities operating in harsh environments. Saf. Sci. 95, 182–197. https://doi.org/10.1016/j.ssci.2016.12.019.

MarEx, 2018. Third Fatal Accident on SOCAR's Offshore Platforms. The Maritime Executive – Intellectual Capital for Executives. Retrieved from. http://www.maritime-executive.com. (Accessed 21 November 2018).

Necci, A., Krausmann, E., Girgin, S., 2018. Emergency planning and response for Natech accidents. In: NEA (2018) towards an All-Hazards Approach to Emergency Preparedness and Response: Lessons Learnt from Non-nuclear Events. OECD Publishing, Paris. https://doi.org/10.1787/9789264289031-en.

NTSB, 2015. Grounding of Mobile Offshore Drilling Unit Kulluk - Marine Accident Brief. NTSB/MAB-15/10. National Transportation Safety Board, USA.

OGP, 2013. Environmental Management in Arctic Oil and Gas Operations: Good Practice Guide – OGP Report No. 449. International Association of Oil and Gas Producers, London, United Kingdom. Available at: https://www.iogp.org/bookstore/product/environmental-management-in-arctic-oil-gas-operations-good-practice-guide/.

OGP, 2014. Reliability of Offshore Structures - Current Design and Potential Inconsistencies - OGP Report No. 486, OGP Workshop Proceedings, Standards Committee (Offshore Structures Sub-committee). International Association of Oil and Gas Producers, London, United Kingdom. Available at: https://www.iogp.org/bookstore/product/reliability-of-offshore-structures-current-design-and-potential-inconsistencies/.

Okoh, P., Haugen, S., 2014. A study of maintenance-related major accident cases in the 21st century. Process Saf. Environ. Protect. 92 (4), 346–356. https://doi.org/10.1016/j.psep.2014.03.001.

OWRPO PU, 2016. Evaluation on Fire at Stationary Deep Sea Platform No.10 in "Guneshli" Field of State Oil Company of Azerbaijan Republic on December 4, 2015. Oil-Workers' Rights Protection Organization Public Union (OWRPO PU), Azerbaigian. Available at. https://www.roughneckcity.com/file/download/file_file/30. (Accessed 3 December 2018).

PSA, 2016. Petroleum Safety Authority: Investigation of an Incident with Fatal Consequences on COSLInnovator, 30 December 2015, Stavanger, 6.7.2016. Available at: www.ptil.no. (Accessed 21 November 2018).

Samarakoon, S.M.K., Ratnayake, R.M.C., 2015. Strengthening, modification and repair techniques' prioritization for structural integrity control of ageing offshore structures. Reliab. Eng. Syst. Saf. 135, 15–26. https://doi.org/10.1016/j.ress.2014.10.023.

Singh, B., Jukes, P., Poblete, B., Wittkower, B., 2010. 20 Years on lessons learned from Piper Alpha. The evolution of concurrent and inherently safe design. J. Loss Prev. Process. Ind. 23 (6), 936–953. https://doi.org/10.1016/j.jlp.2010.07.011.

Sulistiyono, H., Khan, F., Lye, L., Yang, M., 2015. A risk-based approach to developing design temperatures for vessels operating in low temperature environments. Ocean Eng. 108, 813–819. https://doi.org/10.1016/j.oceaneng.2015.08.040.

WOAD, 2013. World Offshore Accident Database – Woad. Available at: https://www.dnvgl.com/services/world-offshore-accident-database-woad-1747. (Accessed 21 November 2018).

Yang, M., Khan, F., Lye, L., Sulistiyono, H., Dolny, J., Oldford, D., 2013. Journal of Ship Production and Design 29 (4), 199–210. https://doi.org/10.5957/JSPD.29.4.120059.

Yulmetov, R., Marchenko, A., Løset, S., 2016. Iceberg and sea ice drift tracking and analysis off north-east Greenland. Ocean Eng. 123, 223–237. https://doi.org/10.1016/j.oceaneng.2016.07.012.