MULTI-RISK APPROACH TO THE EVALUATION OF NATECH EVENTS

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ABSTRACT

AMRA, Research Centre in the field of the Analysis and Monitoring of Environmental Risk, is a permanent structure for the development of innovative methodologies applied to environmental issues. In the last years, AMRA has devoted significant efforts to develop a quantitative framework for multi-risk assessment to support the identification of effective strategies, economically viable, for the mitigation of impacts due to a wide range of risk sources and their possible interactions, considering scenarios of cascading effects. AMRA has participated and led several initiatives to promote theoretical developments of multi-risk approach and to apply this approach to cases of industrial accidents triggered by natural events (Natech). In particular, various research activities have been carried out by AMRA under projects funded by the European Commission (FP6-Na.Ra.S, FP7-CRISMA, FP7-STREST). Among the recent experiences of AMRA there is also the collaboration with the Italian Ministry of Economic Development DGS-UNMIG through the ARGO project (Analysis of natural and anthropoGenic Risks of Offshore platforms).
The general objective of the project is twofold:

- to develop methodologies to analyse natural and human-induced risks of offshore platforms;
- to provide technical support for the development of recommendations arising from the foregoing analysis.

In particular, ARGO aims at developing and applying a multi-risk approach to the analysis of Natech events on offshore installations for hydrocarbon extraction.
This paper discusses the principles of the AMRA multi-risk methodology and its applications to industrial sites. After a brief overview of the major natural phenomena that can trigger Natech events, this work focuses on the conceptual framework underpinning the multi-risk analysis applied by AMRA to the probabilistic assessment of Natech events.

INTRODUCTION

Natech accidents (Natural Events Triggering Technological Disaster) are typical cascading events in which the natural phenomenon (e.g. the earthquake, the flooding) triggers a series of industrial accidents that amplifies the effects of the original natural event. In order to obtain a suitable model for the prevention of these catastrophic events, or to mitigate their effects, it is necessary to use specific algorithms which allow, once the probability distribution of the expected intensity of the natural event is determined, to evaluate the probability of sequences of possible scenarios that constitute the cascade. Sometimes it is possible that multiple natural events may occur with non-negligible intensity. In this case, it is necessary to consider all the events that can affect the structure, and multi-risk methods are needed. This occurrence is particularly relevant in the recent years, because the percentage of the Earth's surface occupied by human infrastructure is increased in such a way that each natural catastrophic event has a high probability of hitting industrial plants or part of it. Recent examples having great resonance are the following:

- The amplification of the effects of Hurricane Katrina that hit the South Eastern United States in 2005, which produced the collapse of the system of dams and levees of Lake Portchartrain and the resulting power failure;
- The amplification of the effects of the Tohoku earthquake, Japan, which occurred in March 2011, due to the exceptional height of the produced tsunami waves, by a power failure and the damage suffered by the Fukushima nuclear power plant;
- The effects of Hurricane Sandy that struck the United States in 2013, amplified by the subsequent blow-out of a large power plant.

The geo-political structure of Europe and cross-border access of many life-line make the entire continent very sensitive to cascading events triggered by major natural events. Typical examples are:

- The Smyrna earthquake in 1999 that produced more than 21 Natech accidents in the industrial area near to the epicentre with serious consequences [1];
- The long power failure occurred throughout Italy and part of Switzerland in 2003 triggered by a strong windstorm in Switzerland and a similar event in Austria;
- The unusually heavy rainfall in Central Europe that, in 2010, triggered a huge flood that caused interruptions of service lines and the transportation network in Poland, Germany and Czech Republic;
- The explosive eruption of moderate intensity of the Icelandic volcano Eyiafjallajokul which in 2010 caused major problem to air traffic crossing the North Atlantic and northern Europe.

The most important way to mitigate the effect of these complex events is an appropriate planning and a multi-sectoral collaboration, based on a multi-risk modeling, which allow identification and quantification of the occurrence probability of various natural events triggering the crisis and of the various steps through which the cascade of events develops.
The Natech events are extremely complex events and we must remember that "all the complex event models are wrong; you just have to wonder what must be wrong not to be useful". "This statement agrees with a contemporary line of thought of the philosophy of science according to which, rather than validate and verify the models, you should try to confirm whether the models are not adequate in general, but to respond to specific purposes.
Stress tests can be considered as a method to evaluate the inadequacy of a model to achieve the purposes for which it was programmed. This pragmatic approach is common to all the science of disasters, in accordance with the greatest economist Maynard Keynes, according to which is better an approximately correct result that one definitely wrong" [2].
In this paper, after a brief overview of the major natural phenomena that trigger Natech events, it is exposed on the conceptual framework that underpins the multi-risk analysis applied by AMRA to the probabilistic assessment of Natech events.

NATECH EVENTS

Natural phenomena that most frequently produce Natech events are earthquakes, tsunamis, flooding and weather phenomena (lightning, windstorms). Natech events follow different evolutionary paths, depending on the triggering phenomenon and affected human work characteristics, but generally result in one or more of the following three types of hazard: rapid floods, pollution of ground water and/or air, fire and/or explosion.

NaTech events triggered by earthquakes

In the specific case of Natech accidents triggered by earthquakes, incidental post analyses have shown that the damage to industrial plants are mainly caused by the soil oscillations due to the passage of seismic waves of different frequencies and by permanent deformation of the soil in which the liquefaction phenomena play an important role [1,3,4,5]. The damage mode of the storage tanks include events such as "elephant foot-buckling" (Fig 1), "buckling on the top" (with consequent release of hazardous materials from the roof due to sinking of the floating roof), lengthening or detachment of the anchoring systems. The latter can cause both a lateral displacement or a lifting of the tank itself, the deformation or the yielding of the support columns and other types of foundation structures [6,7,8]. The containment releases can be mild or severe, large ones are caused by tipping the tank or from the collapse of the same.

During a long seismic crisis (such as the one that hit the Emilia Romagna in May-June 2012) repeated actions of subsequent events can produce significant damage (up to failure) of industrial buildings that had apparently survived unscathed the first quake. It is always advisable an immediate monitoring of the condition of the buildings after an earthquake of medium to high intensity.

Fig 1: Left, elephant-foot-buckling of a tank due to the del 17 January 1994 earthquake in Northridge, California; right, pipelines failure during 7 August 1999 earthquake in Tupras, Turkey [source: http://www.enea.it/it/comunicare-la-ricerca/events/tohoku-1lug11/20110701ENEAServa.pdf]

NaTech events triggered by tsunami

Regarding Natech accidents generated by tsunami, few data are available in the literature especially if compared with the purely seismic data, given the low relative impact of the tsunami respect to earthquakes. In the current literature, the definition of the vulnerability functions for tsunami has been addressed considering the three main components of tsunami: wave speed, wave height and size of the transported debris. For the first two components, they may be considered as a first approximation databases and existing methodologies for the analysis of NaTech accidents caused by floods. Thus, for similarity, the atmospheric vertical tanks and pressurized horizontal tanks can be identified as the most vulnerable equipment in the event of tsunami similarly to the danger of flooding [9], not only because of their structural properties, but also for the serious consequences related to possible damage in terms of release of hazardous substances. On the other hand, in the case of the tsunami we must consider not only the hydrostatic and hydrodynamic forces as in the case of floods [10], but also other forces, like the forces of impact from debris carried by the wave, of the atmospheric shock wave induced by the waves, the fire spread by floating debris and liquid fuels. Structural damage to industrial equipment attributed to the impact of debris can be assessed through impact analyses [11], but the main problem is related to the large uncertainties that arise from the presence of objects (which may also include ships) carried by the tsunami wave.

Fig 2: Tank destroyed by 11 March 2011 tsunami/earthquake in Tōhoku, Japan [source: http://www.telegraph.co.uk/news/worldnews/asia/japan/8377742/Japan-earthquake-and-tsunami-as-it-happened-March-11.html]

NaTech events triggered by flooding

Flooding is also a phenomenon which can affect entire industrial areas. The flooding of catch basins of fuel storage tanks can cause flotation of the latter resulting in displacement and detachment of the connection systems (pipelines). This results in the release of dangerous substances [9]. This type of phenomenon is particularly critical for the empty or partially filled tanks if not adequately anchored since their movement may cause collision with other installations on the site. If the power of the water flow due to the flood is sufficiently high, the collapse of the tanks can occur with consequent spillage of dangerous substances contained in. Floods can cause damage to any type of industrial structure that contains sensitive parts below the topographical level (e.g. Nuclear power plants or in general) and undermine the stability of structural components vulnerable to this type of event, causing damage to electrical systems and loss of containment.

Fig 3: a) Damage to pipe due to flooding of Pennsylvania, USA, 2004 [source: https://dcbureau.org/tag/earthjustice]; b) hydrocarbon release in a oil refinery after the flooding of Coffeyville (USA). 2007 [source: http://ksview.org/info/news.shtml].

NaTech events triggered by lightening

Several studies indicate that lightning are among the most frequent initiators phenomena of Natech accidents in chemical process industry [12]. Analyses of Natech accidents caused by lightning have shown that there are different mechanisms of injury [13]. In particular, direct structural damage may occur due to heating of the areas affected by lightning that can result for example to ruptures or perforations of the tanks or of the connecting pipes. Another cause of an accident can be the trigger by the lightning discharge of the vapours that are normally found on the floating roofs of atmospheric liquid fuel tanks. This can give rise to a real fire of the tank.

Strong wind storms may cause short circuits and other types of damage on all components of a transport system of energy or fuels which develop above the ground level. This damage can in turn trigger blackouts or fires over wide areas.

Fig 4: tank fire due to lightening, 28 August 2006 Whifesville (USA) [14]

MULTI-RISK APPROACH

Without exception, the exploitation of any energy resource produces impacts and intrinsically bears risks. Therefore, to make sound decisions about future energy policies, it is important to clearly understand the potential environmental impacts and risks in the full life-cycle of a project, distinguishing between the specific impacts intrinsically related to exploiting a given energy resource and those shared with the exploitation of other energy resources.

As with any other energy resource exploitation, a wide range of possible environmental impacts can be associated with offshore oil and gas (O&G) development. Arbitrarily, we can divide these environmental impacts in two general groups: (1) impacts caused by ordinary routine operations, and (2) impacts caused by incidents due to system failures or extreme events. A close examination of these two impact groups can provide insights about the potential environmental impacts associated with offshore extraction of geo-resources. However, from the perspective of risk assessment, the impacts caused by incidents, being low probability/high consequence events, are usually those of paramount importance because such a kind of events have often the potentiality of causing the most disastrous and unexpected damages. Conversely, the impacts associated with routine operations are usually better constrained and managing such impacts is a relatively easier task.

The main purpose of the multi-risk assessment is to harmonize both the methodologies employed and the results obtained for different risk sources, taking into account possible risk interactions [15, 16, 17]. The types of events considered in a multi-risk analysis may include events threatening the same elements without chronological coincidence, or events occurring at the same time or shortly following each other, because they are dependent on one another or because they are caused by the same triggering event [18]. The first case represents what is generally denominated 'multi-hazard risk', whereas the second case represents the possible interactions or cascading effects that are one of the main characteristic elements of multi-risk assessment [15, 17, 19].
Considering the assessment of different, independent hazards, the main effort within this multi-hazard perspective is the harmonization of the hazard assessment for the different threats. This is generally considered a requirement in multi-risk analysis to make the risks posed by different threats comparable [15, 16, 20]. Conversely, a multi-hazard assessment considering interaction/triggering effects is, in general, a more demanding process and the most pertinent typology of problem to be approached regarding the application of multi-risk assessments to offshore oil and gas operations.

Conceptual model

The main objective of a multi-hazard/multi-risk assessment applied to offshore O&G operations is to identify and to assess the rate (or the likelihood) of occurrence of incidents, and their potential impacts on surrounding environment, considering different hazards and their interactions. Furthermore, such analyses have to be performed considering the different stages of development of a project. According to this general objective, the implementation of a multi-hazard/multi-risk assessment applied to offshore O&G platforms needs to take into account different issues as the following:

1. It has to take into account the possibility of multiple (natural and anthropogenic) hazards as possible triggering mechanisms;
2. It has to explore all the plausible scenarios of cascading events, identifying the logical relationships among the different events driving to an unwanted consequence;
3. It has to assess the possibility of impacting different typologies of environmental and anthropic exposed elements.

The multi-risk assessment applied to offshore O&G operations poses a number of challenges, making of this one a particularly complex problem. First, a number of external hazards might be considered as potential system perturbations (i.e., triggering mechanisms). Such hazards can be either of natural origin, occurring underground (as e.g., natural earthquakes), in the atmosphere (as e.g., extreme meteorological events) or at the water/seafloor interface (as e.g. slides), or anthropogenic events caused by the same industrial activities (as e.g., subsidence, induced seismicity). Second, failures might propagate through the industrial elements, leading to complex scenarios according to the setting of the industrial site. Third, there is a number of potential risk receptors, ranging from environmental elements (as the air or water) to communities and ecosystems.

Considering the typology of problems faced in risk assessments involving industrial activities, a quantitative risk analysis can be structured in the following main steps [21].

1. The identification and description of potential accidental events in the system: An accidental event is usually defined as a significant deviation from normal operating conditions that may lead to unwanted consequences. In the oil/gas industry, for example, a gas leak may be defined as an accidental event.
2. The potential causes of each incidental event are identified by causal analysis. The causes are usually identified in a hierarchical structure that may be described using a fault tree. If probability estimates are available (of the basic events), these may be input to the fault tree and the probability/frequency of the accidental event may be calculated.
3. Offshore facilities include various barriers and safety functions that have been installed to stop the development of accidental events or to reduce their consequences. These barriers are a fundamental element for structuring scenarios for incidental events development.
4. The top event of the fault tree, usually, is the starting point for the consequence analysis, which is usually carried out using an event tree structure.

These general steps for the quantitative risk assessment can be clearly represented using a so-called “bow-tie” (BT) structure. This approach have been proposed for assessing risks in a number of applications in the field of georesource development, as for example in offshore oil and gas development [22, 23] and for the mineral industry in general [24]. We consider that such an approach constitutes a straightforward tool for framing a multi-risk assessment approach for offshore O&G operations. The multi-hazard/multi-risk approach for this problem is set by considering multiple hazards (and their possible interactions) as possible sources of system's perturbation that might drive to the development of an incidental event.
The BT is a graphical tool that facilitates structuring accident scenarios, starting from the accident causes and ending with the consequences. It is targeted to assess the causes and effects of specific critical events (also called “top events”). It is composed of a fault tree (FT) on the left hand side of the graphic plot, identifying the possible events causing the critical (or top) event, and an event tree (ET) on the right-hand side showing the possible consequences of the critical event (Fig 5).

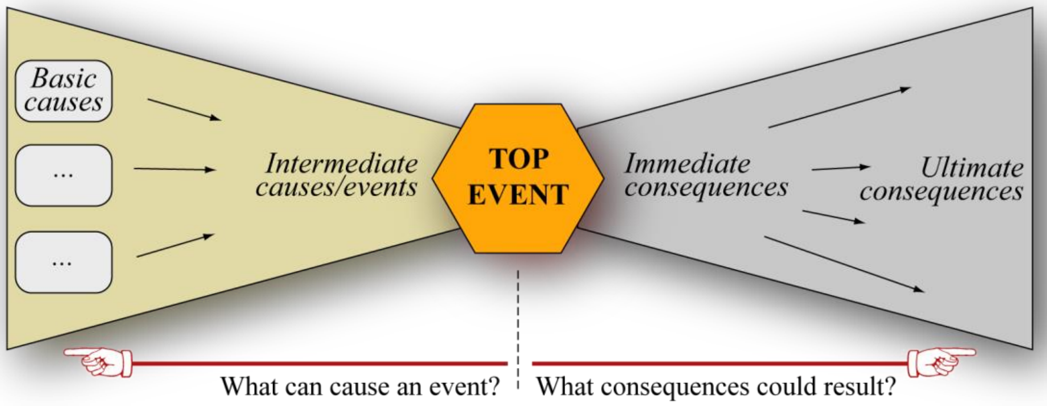

Fig 5: Generic representation of a Bow-tie structure

The Bow-tie (BT) structure and the multi-risk framework
Combining fault trees and event trees in a BT is a tool widely used in reliability analysis for risk assessment [21]. The definition of a BT structure requires a number of activities, starting from the definition of the critical or top event (TE). The critical TE should represent a well defined incident (e.g, what happens and where it happens) and is the endpoint of a number of possible paths represented in the FT. Furthermore, the TE represents the starting point of an ET, which in turn is

used to model the potential consequences that the occurrence of that specific incident may have on a number of exposed elements of interest.
Given the complexity of the problem, we adopt a multi-level approach [17] in which we first perform a qualitative analysis oriented to the identification of a wide range of possible scenarios. This process is based on a wide literature review of potential impacts in different risk receptors of interest. Second, the most important scenarios for quantitative multi-risk analyses are selected for further quantification. This selection is based on the identification of major risks, i.e., those related with the occurrence of low probability/high impact extreme events (therefore, the impacts associated with routine activities are not considered). Finally, the selected scenarios are structured for quantitative analysis following the model for quantitative assessments.

Identification and structuring of risk pathway scenarios

There are two key elements for developing scenarios for a multi-hazard/multi-risk analysis based on a bow-tie structure: first, the identification of the possible top events, and second the identification of the source events. The following criteria have been used for structuring scenarios:

1. Major risks are the target top events. A generic typology of top event can be characterized by a leak of fluids (i.e., gas or oil, according to the mineral produced). Top events have to be well specified events (e.g., what and where it happens?). An example of a top event is "leak of gas in a key producing system", or leak of gas in a given sea line".
2. Identification of the boundary conditions with respect to external stresses. In this way, we define the type of external hazards that are going to be included in the analysis.
3. For each top event identified, a deductive technique is used to identify the possible causes of such failure, considering the boundary conditions defined and the level of resolution of the analyses.
4. The identified top events are also the starting points of consequence analysis, which is evaluated for considering the impacts on final risk receptors of interest. Such analyses is structured using an event tree approach.

Keeping in mind such criteria for structuring scenarios, the first step for the multi-hazard/multi-risk analysis is the identification of the possible scenarios. There exist a number of approaches for identifying and structuring relevant risk pathway scenarios, most of which are based on either forward or backward logic approaches, or a combination of both [25]. The former approach follows a forward logic in the sense that for each initiating event, it identifies the possible outcomes (endpoints), following an event-tree-like structure. The backward logic strategy begins with and endpoint (effect) and works backwards to find the most likely causes of the effect, following a fault-tree-like structure. The combination of both approaches (adaptive approach) stems from the idea to iteratively use the forward logic and the backward logic approaches, and combines the results obtained in order to exhaustively identify all the relevant scenarios for the specific problem at hand.
Conceptually, to identify the risk pathways in a multi-risk approach we take into account possible Source-Mechanism-Receptor (SMR) linkages. In this context, a risk pathway starts from an initial, triggering event (Source) that subsequently develops in a chain of events upon causing an impact in a given risk receptor. The Mechanism defines the means of risk transfer from the source to the receptor, where the risk receptor is the element exposed to risk that can be impacted by the activity. The advantage of this approach is to define a logical subdivision of interrelated events leading to a given impact on the environment.
Once the scenarios have been indentified, a causal diagram as that shown in Fig 6 can be drawn. As shown in this example, the scenarios are structured in order to identify possible pathways driving to the final outcome of interest for the assessment. The causal diagrams are then used as the reference point for constructing the fault-tree (e.g., considering the causes) and subsequent event tree (e.g., considering the consequences) of the BT structure.

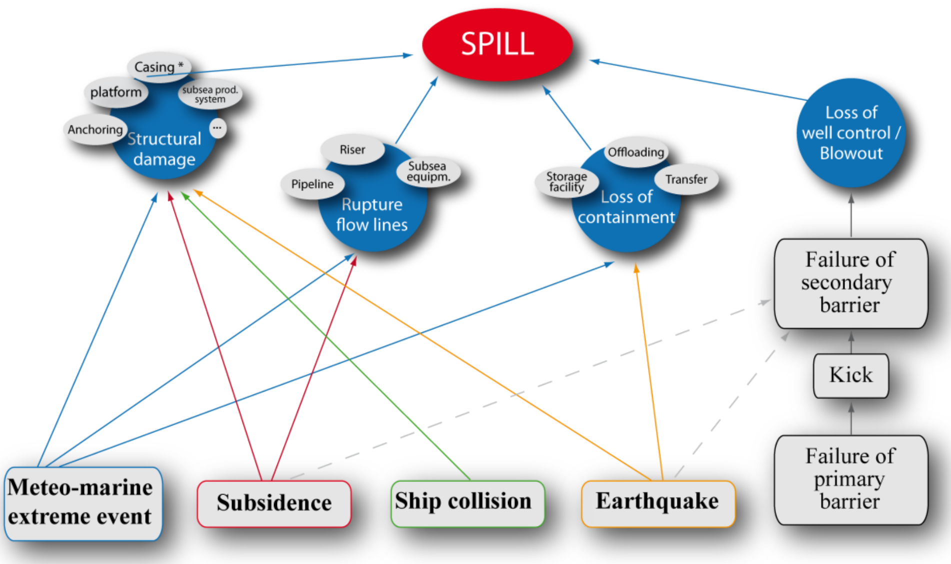

Fig 6: Examples of pathway scenarios that may lead to a spill of fluids

Probabilistic framework

The quantitative assessment of the BT structure is based on both the probabilities assigned to basic events of the fault tree and the probabilities at the nodes of the event tree. Since major risks are rare events for which scarce or none data is usually available, it is therefore useful to adopt a probabilistic framework that allows us to integrate as much as possible all the available data. On the one hand, generic data coming from a number of similar cases can be available as can be used as a reference for our analyses in a specific place. On the other hand, local, site-specific data can be also available or will be available in the future. A dynamic risk assessment method should be able to take any new information into account and to tailor itself to the dynamic environment which is dominant in the industrial operations. In our approach, the multi risk assessment framework take advantage of Bayesian data analysis techniques to provide a way for integrating different typologies of data and also to be able to update calculations as new infomaiton is available. In practice, generic data is used to set a “Prior” state of knowledge, while new (site specific) data, in the form of likelihood functions, is used to update the prior information (using Bayes’ theorem, [26]).

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