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AN APPROACH TO THE QUANTITATIVE ASSESSMENT OF RISK DUE TO NATECH EVENTS

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Research article

Abstract: External hazard factors as natural events and intentional acts of interference are perceived as important threats affecting the safety of chemical and process plants. The increasing frequency of some natural events having a particularly high severity also raised a growing concern for industrial asset integrity and for the consequences of major accident scenarios that may be triggered by natural events. The specific features of technological accidents triggered by natural events were recently recognized, and these scenarios are now indicated as NaTech (Natural-Technological) accidents. The analysis of past accident databases points out that NaTech accidents frequently impacted industrial facilities. Methodologies and tools for the specific assessment of the potential consequences of NaTech accidents were only recently developed, and are still missing for a number of specific NaTech scenarios. In the present contribution, a framework for the analysis of NaTech accidents is proposed and recent advances in the tools available for the assessment of NaTech events are revised.

Key words: Major Accident Hazard, NaTech, Natural events, Quantitative Risk Assessment Technological accidents.

Introduction

In recent years, a number of intense natural events impacting on industrial infrastructures triggered severe technological accidents. The possibility of damage of process equipment due to the impact of natural events is well known in industrial practice. The term “NaTech” (Natural-Technological) events was introduced to identify this category of accidents.

The traditional approach to the prevention of NaTech scenarios is usually based on design. Conventional design approaches include protection from lightning and account the additional stresses due to wind, snow, and seismic events. Actually, the conventional approach to the prevention of such accidents is a deterministic method encompassed in design standards. Almost all national and international design standards address the issue of additional loads induced by natural events (earthquakes, wind, waves, lightning, etc.). However, conventional approaches are usually deterministic: on the basis of natural hazard assessment, a reference event is assumed (a reference earthquake, maximum snow coverage, a maximum wave height, a maximum wind speed, etc.) and an equivalent load is calculated. The design is then carried out including the additional stresses deriving from such events. This approach is widely used with effective results in civil engineering, from which its application to industrial equipment design is derived. Thus, procedures for the identification of the reference event to take into account in design are mostly derived from those developed for structural integrity of buildings or civil structures. However, when addressing the issue of residential buildings, usually the main point is to avoid the collapse of the building. On the contrary, in the context of a chemical or industrial plant, the issue is that the residual functionality should assure the containment of the dangerous substances present inside process equipment, avoiding loss of containment. Clearly enough, this leads to specific requirements seldom recognized at design level.

A further issue is that usually protection by design is assumed to be “perfect”. That is, no measure is taken to manage the exceedence risk. Thus, if the severity of the natural event exceeds that taken as a reference in design, unforeseen accident scenarios may take place for which no preparedness and no mitigation or emergency procedure is present. This is actually what happened in the recent accident involving the Fukushima nuclear power plant, although stress tests carried out in the nuclear industry evidenced a generally limited preparedness to natural events having a severity exceeding that assumed in the design case. In the chemical and process industry, an even lower preparedness was experienced e.g. during the severe hurricanes that involved the Gulf of Mexico in recent years (Cruz and Krausmann, 2008; Cruz and Krausmann, 2009).

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Even leaving apart the Fukushima event and the other events related to the 2011 earthquake and tsunami in Japan, past accident analysis clearly points out that natural events have triggered a number of severe accidents in the chemical and process industry due to the loss of containment (LOC) of hazardous substances (Lindell and Perry, 1996; Young et al., 2004; Krasumann et al., 2011a; Krausmann et al., 2011b). Industrial accidents triggered by natural events were an important cause of direct damages to the population present in nearby residential areas, due to the accidental scenarios triggered by equipment damage (blast waves, toxic releases, fire radiation). Moreover, these events were responsible also of indirect damages due to the delay of emergency rescue operations, caused by the effects of the accidental scenarios involving hazardous substances (e.g. in the case of toxic clouds or of the spread of flammable substances on water). Thus, the assessment of the contribution of natural events to the hazard associated to the activities of the process industry is of utmost importance for the protection of the population and for a robust and effective emergency planning (Cozzani et al., 2010; Renni et al., 2010; Krausmann et al., 2011b). The pioneering work of Lindell, Steinberg, Cruz and Krausmann lead to recognize the specificity of such accidents, due to several factors, among which the main are the following: i) the cause of the event is external to the industrial site, thus the prevention and mitigation of such events may not be managed only at a site level; ii) the extension of the natural event triggering the technological accident is wide, thus several equipment items may be simultaneously affected and loss of utilities may take place, leading to common cause failures; and iii) emergency response may be hampered or delayed by the natural event.

Several studies pointed out the features of NaTech scenarios and the need of a specific approach to the identification and management of hazard and risk due to this category of events (Lindell and Perry, 1997; Cruz, 2005; Cozzani et al., 2007; Cozzani et al., 2010). The increasing frequency of severe natural events caused by climate changes contributed to raise a concern about the consequences of NaTech scenarios, both on the population and on strategic industrial assets (Salzano et al., 2003; Antonioni et al., 2007; Cruz and Krausmann, 2008; Krausmann et al., 2011a).

However, even if presently a growing attention is devoted to NaTech scenarios, a limited number of methods and tools is available for the specific assessment of NaTech hazard and risk. The assessment of the risk related to accidents triggered by natural events, as well as to the prevention and to the consequence assessment of the specific accidental scenarios that may take place in NaTech events is seldom included in safety studies. In the following, some methods for NaTech hazard assessment were revised and an approach to NaTech quantitative assessment was described.

Materials and methods

Methodologies for NaTech hazard assessment

Analysis of past accident databases and lesson learnt from case-histories

The analysis of the more important accident databases recently carried out in several studies by Cozzani, Cruz, Krausmann and coworkers (Campedel et al., 2008; Cozzani et al., 2010; Krausmann et al., 2011) pointed out that at least 3 % of reported major industrial accidents should be considered as NaTech events. The analysis of past events also pointed out the specific features of NaTech scenarios deriving from the different impact that different natural events may have on industrial sites. As a matter of fact, while lightning clearly emerges as the more frequent cause of NaTech events (Renni et al., 2009), earthquakes resulted the events leading to the more severe scenarios, due to the contemporary damage of a high number of equipment items, as evidenced by Tab. 1. This is confirmed also by the analysis of specific and detailed case-studies (Steinberg and Cruz, 2004, Krausmann et al., 2010). Other studies pointed out that floods as well as hurricanes (wind, waves) are capable of triggering NaTech scenarios having specific features (Cruz and Krausmann, 2009; Cozzani et al., 2010).

In particular, the analysis of past accidents also evidenced that final outcomes of release scenarios induced by natural events may have specific elements, not possible or unlikely in the case of conventional release scenarios. As an example, in the case of floods reaction of released chemicals with water was experienced and the flooding of catch basins caused extended water and land contamination scenarios (Cozzani et al., 2010). Fig. 1 shows an example of specific event trees that should be considered in the analysis of NaTech events triggered by flooding.

A more detailed analysis of past accident data also allowed the identification of specific damage modes of process equipment due to the impact of natural events. The extrapolation of NaTech specific observational equipment fragility or vulnerability models was thus possible. Some of these tools, having a particular value in the framework of probabilistic risk assessment, were obtained by the analysis of Natech accidents induced by earthquakes (Salzano et al., 2003; Salzano et al., 2009; Antonioni et al., 2009).

Thus, the analysis of past accidents points out on one hand that natural events are a relevant cause of major accidents in industrial sites. On the other hand, the outcomes of past accident analysis clearly evidence the need of specific tools to address the analysis and the assessment of NaTech scenarios.

Screening methods

A first level in the assessment of NaTech hazard is the identification of the sites where such hazard is relevant. The problem is usually of concern at district, regional or national level, thus requiring the analysis of extended areas. Therefore the assessment may be reasonably based on simplified screening methods. Cruz and Okada (2008) proposed a detailed screening methodology mostly useful at a district level. Within the activities of the FP7 iNTeg-Risk project, a specific task was dedicated to the issue of NaTech hazard. A methodology was developed to obtain a ranking of the NaTech hazard, based on four hazard classes (iNTeg-Risk, 2011). Tab. 1 shows and example of the criteria used for the hazard ranking on the basis of the expected severity of the natural event. More recently, Rota and coworkers proposed the application of the Analytical Hierarchy Process to screening procedures for the ranking of NaTech hazard (Busini et al., 2011). Cozzani and coworkers proposed an index method mainly aimed at ranking NaTech hazard at a regional or national level (Sabatini et al., 2008), as shown in Fig. 2. The application of all these methods to case-studies proved to yield effective results in the identification of "hot-spots" and critical sites where the application of more detailed assessment techniques is recommended.

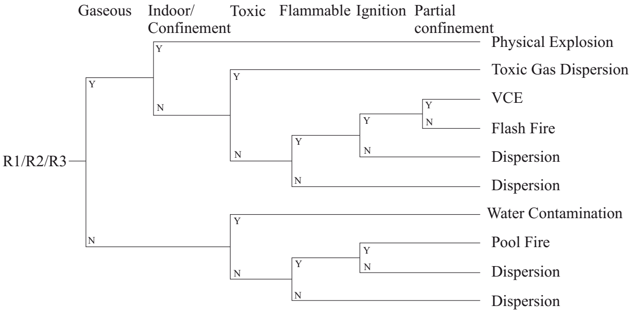

Fig. 1 Post-release event trees for substances reacting with water in NaTech accidents triggered by floods (Cozzani et al., 2010)

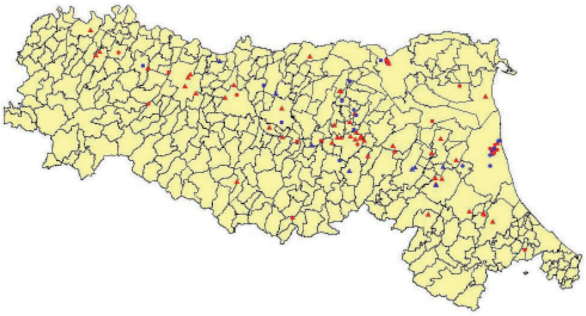

Fig. 2 Preliminary ranking of NaTech hazards for "Seveso" sites in an Italian region. Red: medium hazard; Blue: low hazard

Tab. 1 NaTech hazard ranking with respect to earthquake and flood expected intensities (iNTeg-Risk, 2011)

Hazard index	Hazard classification	PGA range in 50 years	Water depth $[m.s^{-1}]$	Water velocity $[m.s^{-1}]$
1	Very low	< 0.05 g	≤ 0.5	≤ 0.2
2	Low	0.05 - 0.15 g	0.5 - 1	0.2 - 0.5
3	Moderate	0.15 - 0.25 g	1 - 1.5	0.5 - 1.0
4	High	> 0.25 g	> 1.5	> 1.0

Methodologies for quantitative risk assessment of NaTech scenarios

Quantitative Risk Assessment

The issue of extending the bow-tie approach to NaTech hazards, schematized in Fig. 3, was proposed since the development of the MIMAH technique within the ARAMIS project (Delvosalle et al., 2006). Bow-ties including natural events as failure causes were developed in the approach. In parallel, Hazard Identification (HazId) Analysis technique spread out as a structured review technique able to account also threats caused by natural hazards to industrial facilities and assets.

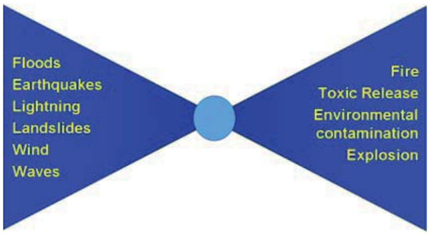

Fig. 3 The bow-tie approach extension to NaTech scenarios

More recently, the bow-tie approach was extended to allow a comprehensive quantitative assessment of the contribution of NaTech scenarios to industrial risk. A detailed procedure for the calculation of individual and societal risk due to NaTech scenarios was developed. Figure 4 shows the conceptual flow-chart of the procedure. As shown in the figure, several steps are very similar to those of conventional quantitative risk analysis and/or of quantitative analysis of domino scenarios (Cozzani et al., 2005). Specific steps include the identification of damage and release states and, mostly, of equipment damage probability as a consequence of the impact of the natural event. Cascade effects can be as well included in the assessment, by a specific modification of steps 5 and 6.

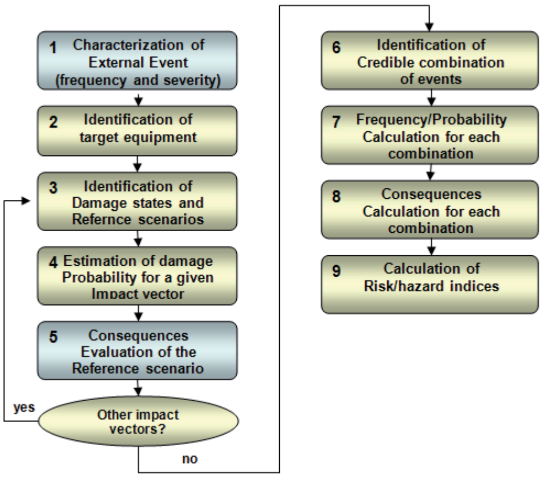

Fig. 4 Conceptual flow-chart for the quantitative assessment of NaTech scenarios (Antonioni et al., 2009)

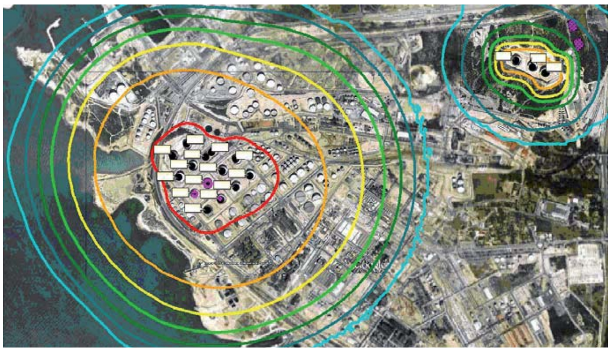

Fig. 5 Example of individual risk calculation for NaTech scenarios: iso-risk curves for atmospheric storage tanks (iNTeg-Risk, 2011)

Pilot applications of the methodology lead to the calculation of iso-risk curves for chemical plants and refineries. An example of results obtained for NaTech scenarios triggered by earthquakes is shown in Fig. 5. The approach also allows the calculation of societal risk if data is available on the distribution of population. An example is reported in Fig. 6.

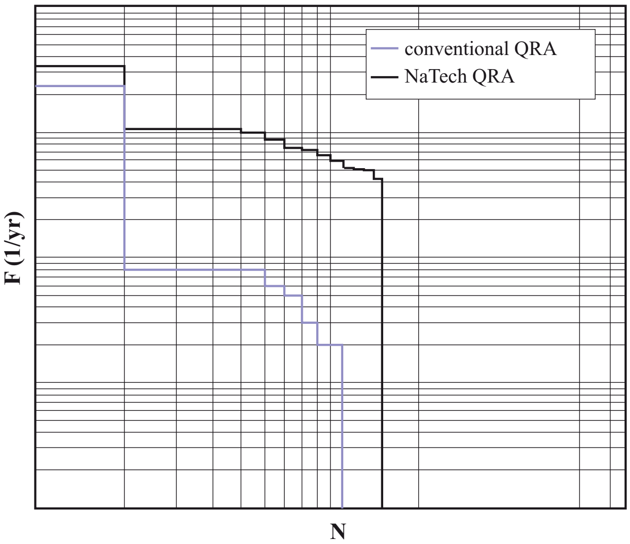

Fig. 6 Example of societal risk calculations for NaTech scenarios: overall expected frequency (F) of an accident with an expected number of fatalities equal or higher than N

The current work is aiming to consolidate and further extend the approach to make possible from a computational point of view the assessment of cascading events (first level domino effects caused by the accident scenarios triggered by the natural event) and to include the possible consequences of the failure of mitigation systems induced by the natural event (e.g. catch basins, fire deluges, etc.).

Equipment vulnerability models

The detailed quantitative approach presented in the previous section is based on the availability of models for equipment vulnerability. Several types of models may be applied to assess the failure probability of an equipment item due to the impact of a natural event. Detailed vulnerability models based on structural analysis may be developed. Observational fragility curves are also available in the literature (Salzano et al., 2003; Campedel et al., 2008; Antonioni et al., 2009; Salzano et al., 2009).

In the framework of quantitative risk analysis, simple models are needed to allow the swift assessment of a high number of scenarios. Thus, fragility curves or simplified probabilistic models are the preferred approach to support a quantitative assessment of NaTech risk. Tab. 2 shows an example of fragility curves for the calculation of equipment failure probability as a consequence of a seismic event. Several of these observational probabilistic models for categories of equipment are present in the literature.

Tab. 2 Values of the probit constants for different equipment categories, damage states and filling levels (Campedel et al., 2008). The constants should be used in the following equation: $Y = k_1 + k_2.\ln(\mathrm{PGA})$. PGA is the horizontal component of peak ground acceleration

Type of equipment	Damage state	Filling level	$k_{1,i,j}$	$k_{2,i,j}$
Anchored atmospheric tanks (AT)	≥ 2	Near full	7.01	1.67
	≥ 2	≥ 50 %	5.43	1.25
	3	Near full	4.66	1.54
	3	≥ 50 %	3.36	1.25
Unanchored atmospheric tanks (AT)	≥ 2	Near full	7.71	1.43
	3	Near full	5.51	1.34
	3	≥ 50 %	4.93	1.25
Horizontal pressurized storage tanks (PV)	≥ 1	any	5.36	1.01
	≥ 2	any	4.50	1.12
	3	any	3.39	1.12
Pressurized reactors	≥ 1	any	5.46	1.10
	≥ 2	any	4.36	1.22
	3	any	3.30	0.99
Pumps (G)	≥2	-	5.31	0.77
	3	-	4.30	1.00

Data on equipment failure as a consequence of floods are scarce in the literature. Antonioni et al. (2009) report a general correlation that allows a rough estimate of the failure probability. More recently, Landucci et al. (2012) have developed a simplified approach to verify the structural integrity of atmospheric tanks in flood events. Fig. 7 shows an example of the "failure charts" obtained from the approach. Filling level and density of internal fluid resulted to play a key role in determining failure conditions. A simplified correlation based on the calculation of a critical pressure based on tank geometrical features was also proposed (Landucci et al., 2012).

Lightning are as well a relevant cause of NaTech accidents (Renni et al., 2010). Also in this case, the approach discussed above may be applied to quantify the risk due to accidents induced by lightning. However, observational data do not allow the development of vulnerability models for failure probability. Renni et al. (2009) and Necci et al. (2012) presented an approach to the assessment of capture and damage probability, based on an electro-geometric model for capture probability and on a physical model for damage probability. The approach, which is based on consolidated statistical data concerning lightning probability and severity, provides the lightning damage probability both for single, isolated equipment item and for equipment items in complex lay-outs, where the mutual interference of equipment geometry on capture probability can not be neglected. Fig. 8 shows an example of capture probabilities calculated by this approach for a complex lay-out geometry corresponding to a tank farm of an oil refinery.

Several research groups are working on the further development of models to assess the damage due to wind, waves and other natural phenomena. It is worth to mention the relevant work of Milazzo et al. (Milazzo et al., 2012) concerning the expected damage due to volcano ash fallout on process equipment.

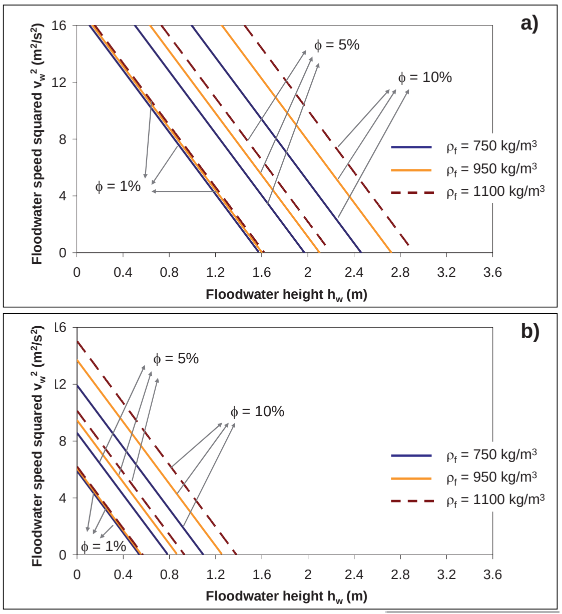

Fig. 7 Example of tank failure charts due to flood severity obtained from the simplified model developed by Landucci et al. (2012). Flood severity is expressed as a combination of maximum water height and velocity

Results and discussion

The comparison of the results obtained for individual and societal risk in the case of NaTech events always point out that NaTech scenarios are relevant. This is evident e.g. from the analysis of Fig. 6, that clearly evidences the importance of the accident scenarios induced by earthquakes when the overall societal risk is calculated including NaTech events.

Actually, the expected frequencies or return times of even every severe natural event are high if compared to expected frequencies of severe technological accidents due to internal failure causes. Moreover, the availability of mitigation and emergency systems is seldom compromised by an "internal" accident, while natural events are likely to impact on active and passive protection systems, reducing their effectiveness.

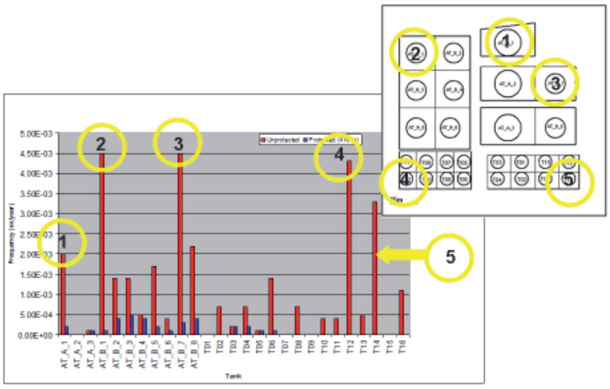

Fig. 8 Lightning capture probabilities for a complex tank lay-out calculated using the model proposed by Renni et al. (2009). The effect of protection rods at the edges of the tank farm on capture probabilities is also evidenced in blue

The results obtained from the assessment of industrial risk due to NaTech scenarios raise the issue of tolerability criteria. As a matter of fact, no clear correspondence exists among tolerability criteria for natural and technological risks. The individual and societal risk due to NaTech scenarios, calculated on the basis of the expected frequencies of reference natural events, may somehow be affected by differences in the procedures used for the assessment of return times or expected frequencies among natural hazards and technological events. Moreover, the real issue for some NaTech scenarios should be the analysis of the additional contribution to societal risk due to the natural event, not to that coming from the industrial facility. The analysis of the relevance of risk due to NaTech scenarios thus should be carefully analyzed, also considering the introduction of specific equipment-based or site-based criteria (Salzano et al, 2010).

Conclusion

The specific features of NaTech scenarios were only recently recognized. Since then, a relevant research work was carried out to explore the issues posed by the identification and assessment of NaTech scenarios. Several tools were developed, allowing the screening of NaTech hazard and the quantitative assessment of risk due to NaTech scenarios. However, many gaps still need to be filled, concerning the assessment of specific scenarios, the safe design of equipment and the development of mitigation and prevention barriers effective for NaTech events. Recent events, as the Fukushima accident, clearly evidence the importance of proceed forward on this route, and in particular to set up criteria for the management of the residual risk due to the impact of natural events exceeding the intensity taken into account in the design case.

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