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Awareness and mitigation of NaTech accidents: Toward a methodology for risk assessment

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Natural hazards affecting chemical and process facilities deserve particular attention since they can cause the release of hazardous substances possibly resulting in severe environmental pollution, explosions and/or fires (so-called NaTech accidents). Awareness of the hazard posed by Natech events is growing, and a need for explicitly including NaTech accidents into chemical-accident prevention and mitigation is nowadays widely recognized. Nevertheless, several elements that characterize Natech events still need to be investigated. In particular, only scarce data exists on equipment damage modes, release intensities and the final consequences for these accidents. The present contribution focuses on the development of a general framework for the assessment of NaTech risk. The analysis of past accident data allowed the gathering of data on the expected damage of process equipment caused by the impact of flood, lightning and earthquake events. Failure modes and damage states caused by these different natural events were identified. The expected intensity value of loss of containment (LOC) was obtained by statistical analysis.

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1. Introduction

When natural events, such as floods, earthquakes, lightning, landslides etc., affect an industrial facility it could result in an accident with major consequences on the population and/or the natural and built environment (a so-called NaTech accident (Showalter and Myers, 1992; Krausmann and Cruz, 2008)). Recently, the environmental consequences due to the impact of floods in central Europe and of hurricanes Katrina and Rita on the oil production facilities in the Gulf of Mexico contributed to arise a public awareness on NaTech events (Salzano et al., 2009; Cruz and Krausmann, 2009). NaTech risk is considered an *emerging* risk both due to climate change that could lead to an increase in severe hydro-meteorological events impacting industrialized areas and to its enhanced perception by the public and the competent authorities. It is also a *new* risk since there are no detailed methodologies for the assessment and the management of this kind of risk (Salzano et el., 2009).

In this study a general methodology is presented to analyze the contribution of natural events to the overall risk in the context of QRA (quantified risk assessment) in chemical facilities and plants. The methodology is based on the data collected on past accident NaTech accidents triggered by floods, earthquakes and lightning. The observed equipment damage modes from the impact of natural events and the expected intensity value of loss of LOC was obtained by statistical analysis and was related to the final consequences of accidents.

2. Methodology for NaTech risk assessment

The general approach to the risk assessment of NaTech events is similar for all such types of events and consists of a sequence of general steps:

1. Quantification of the expected frequency (e.g. events per year) that the facilities might experience the particular natural event (this information is usually provided by historical data);
2. Determination of the effects that various natural events will have on specific equipment and sections (components, systems, operator command and control functions, etc.). This point should take into account the likelihood of “common cause” failures, very likely in this kind of accidents, in which several systems or functions experience failure or degradation together in a correlated way;
3. Development of event-tree/fault tree methods to determine the effect of inoperative systems, components or functions on the ability of the entire plant to reach a safe, stable shut-down state;
4. Planning of mitigation measures by implementing all the prevention and protection measures required to reduce the risk level due to the natural event considered below a predetermined threshold.

Since carrying out a detailed analysis fulfilling the above issues is time consuming and may be affected by several uncertainties, the development of a preliminary qualitative screening procedure may be extremely important to identify when a detailed and a much more resource demanding analysis is required (Salzano et al., 2009). In order to identify the most vulnerable plant or equipment the simultaneous comparison of a large number of different parameters (location, presence of hazardous substances, intensity of external natural event, life line systems, etc) is required. This kind of comparison is based on a multi-criteria decision method such as the so-called Analytical Hierarchy Process (AHP) (Saathy, 2000), which provides a structured technique for dealing with complex decisions. More details regarding the applications of AHP to NaTech risk assessment is reported in Salzano et al., 2009.

The developed approach for NaTech quantitative risk assessment, as discussed by Antonioni et al. (2009), was obtained from the modification and the extension of the well known procedure used for conventional risk assessment (Lees, 1996; CCPS, 2000). Table 1 shows the steps composing the developed procedure. The starting point of the procedure is the analysis of each external hazard factor to identify the "impact vectors" by assessing the value of the severity parameter and the frequency parameter. The severity parameter of the external event is expressed by using the magnitude in case of earthquake, the water height and velocity in the case of floods, the current intensity in case of lightning events, etc. Once the severity parameters are defined, it is necessary to estimate the occurrence by using existing risk or hazard maps (e.g. seismic maps, flood hazard maps, lightning strikes maps, etc.) usually available for the region where the site of concern is located. This preliminary assessment step is the one requiring a specific approach for each different external event considered in the analysis. Moreover, the level of available information at this stage may be different, depending on the specific features of the external hazard and on the information available on the region where the site is located.

In the following step of the procedure, possible target equipment should be identified. This step is crucial to limit the analysis to relevant scenarios. The historical analysis provided the information on the most vulnerable equipment items that result to be those containing a large amount of hazardous materials as storage and process equipment items. Thus, thresholds based on substance quantities and on the physical state of the substance may be introduced (Cozzani et al., 2005). For each of the equipment items considered in the analysis, damage states may be defined on the basis of previous approaches proposed for the assessment of damage (HAZUS, 1997, Antonioni et al., 2007). A discretization of damage states was introduced, defining a limited number of damage states associated to a limited number of release states. Simplified vulnerability models based on Probit functions are available for the more important equipment categories in the case of earthquakes (Fabbrocino et al., 2005) and floods (Campedel, 2007) and on the basis of correlations between current intensity and equipment design for the case of lightning (Renni et al., 2009).

Table 1 Steps of the general procedure developed for the quantitative risk assessment of the NaTech risk due to natural events impacting on process plants or storage facilities.

n.	Step	Needs
1	Characterization of the external event	Frequency and severity parameters
2	Identification of target equipment	List of target equipment considered
3	Identification of damage states and reference scenarios	Event trees
4	Estimation of the damage probability	Equipment damage models
5	Consequence evaluation of the reference scenario	Consequence analysis models
6	Identification of credible combinations of events	Set of event combinations
7	Frequency/probability calculation for each combination	Frequencies of event combinations
8	Consequence calculation for each combination	Overall vulnerability map
9	Calculation of risk indices	Overall risk indices

Consequence analysis of reference scenarios is the same as that performed for conventional industrial risk analysis and it may be based on several models available in the literature. Steps 6 to 9 in Table 1 can be carried out by the standard procedure for the assessment of multiple scenarios originally developed for the quantitative assessment of domino effects (Cozzani et al., 2005) and then extended also to the assessment of accidental scenarios triggered by seismic events (Antonioni et al., 2007).

3. NaTech scenarios triggered by earthquakes

The earthquake impact on industrial facilities such as the chemical, petrochemical and oil processing industries may result in releases of hazardous materials and possibly major accidents leading to injuries and fatalities to people in the nearby area. The peak ground acceleration of the seismic event (PGA) has been considered as the most appropriate parameter to describe the intensity of the scenario. Fragility curves were developed, starting from a consistent data set describing the behavior of equipment loaded by earthquakes (Salzano et al., 2003; Fabbrocino et al., 2005).

Another key step is the definition of loss intensity categories. The performed accident analysis allowed to identify three loss intensity categories: instantaneous release of the complete inventory (R1), continuous release of the complete inventory in ten minutes (R2), continuous release from a hole having an equivalent diameter of 10 mm (R3). Table 2 gives and example of the failure modes possibly leading to the different loss of containment modes for atmospheric storage tanks.

The three release categories identified depend on the different impact modes of the earthquake on the atmospheric storage tanks. The resulting final scenario is a consequence of substance hazard and of the expected intensity of LOC.

Table 2 Earthquake failure modes and release intensities for atmospheric storage tanks.

Failure mode	**Definition**	**Intensity of LOC**
Elephant Foot Buckling	Large axial compressive stresses due to beamlike bending of the tank wall	R1
Base uplifting	Overturning moment may be cause a partial uplift of base plate; this vertical displacement can cause the failure of tank wall and/or the failure of piping connection	R1
Sloshing	Roof or Top damage due to liquid movement	R3
Sliding	For un-anchored tank only: the horizontal relative displacement between tank and base can cause the failure of I/O piping	R2
Collapse (Liquefaction)	Rapid release of content due to total collapse of structure for the ground liquefaction due to earthquake	R1

4. NaTech scenarios triggered by floods

As in the case of earthquakes, also the flood impact on industrial facilities may result in releases of hazardous materials, by either direct or indirect flood effects. The characterization of reference flood events may be based on the return time and two severity parameters: the maximum water depth (D) expected and the maximum water speed expected (W). Also in this case, fragility curves were developed, starting from a consistent data set describing the behavior of equipment loaded by forces due to the flood (Campedel, 2007). Past accident analysis allowed to identify three categories of water impact modes: slow submersion (water velocity is negligible), low-speed wave (water velocity is lower than 1 m/s) and high-speed wave (water velocity is higher than 1 m/s). Obviously, different failure modes are associated to the different water impact modes and consequently, different release states. Table 3 shows the damage modes and release states for atmospheric storage vessels that result to be the most vulnerable equipment items. Release categories are equivalent to those previously discussed in the case of earthquakes. The final scenarios depend on the hazardous properties of the released substances and on the intensity of LOC. In this case, beside conventional scenarios, it is necessary to also take into account the scenarios due to the release of substances reacting with water that could create flammable or toxic gases due to the reaction with water. Further, in the case of NaTech events triggered by floods, risk management and control can be significantly improved by implementing early warning systems, especially in the case of river floods.

Table 3 Flooding failure modes and release intensities for atmospheric storage tanks.

Flood impact mode	Type of structural damage	Release state
Slow submersion	Collapse for instability (catastrophic failure)	R1
	Complete failure of connected piping	R2
	Failure of flanges and/or connections	R3
Moderate-speed wave	Failure of flanges and connections	R3
	Damage of connections due to floating objects	R3
High-speed wave	Impact with/of adjacent vessels	R1
	Roof failure and/or shell rupture	R2
	Complete failure of connected piping	R2
	Failure of flanges and connections	R3

5. NaTech scenarios triggered by lightning

Past accident analysis indicates that lightning can be a powerful mechanism for causing direct and indirect hazardous materials releases in chemical process plants. Fire or explosion risk is very high in flammable storage sites. Besides starting fires, lightning can also disrupt control systems and electrical circuitry more than 3 kilometers away (corrupted data, false signals, immediate or delayed destruction of sensitive electronic devices, etc.) (EPA, 1997). The accident analysis carried out by Renni et al. (2009) on the damage caused by lightning strikes on 604 atmospheric storage tanks containing flammable materials showed that 163 tanks suffered structural damage and release, 228 immediate ignition and 213 electrical and electronic devices failure.

The characterization of reference lightning events can be based on lightning strike density maps (e.g. events per years) and the probability distribution function of the peak current intensity. Both terms are often available from historical data, and for many geographical locations they cover a wide time range. Using this information it is possible to predict the frequency (e.g. on yearly basis) of a generic lightning of any kind of current intensity. The frequency is quantified by the lightning ground flash density (N_g) measured in number of flashes per year and square meters and is given by national lightning detecting networks. The methodology provided by the EN 62305 standard on the protection against lightning and the analysis of accidents triggered by lightning allowed to define three release states that represent the most frequent and significant release scenarios that may follow a lightning strike on an industrial equipment (Renni et al., 2009). The three release categories are the same defined for flood and earthquake. Table 4 shows the results obtained form the analysis of 172 records regarding storage tanks that are the most frequent equipment items involved, due to their design and the high hold-up.

Table 4 Damage modes and release state considered for storage tanks damaged by lightning based on historical analysis of 172 records (n.s.: not specified).

Type of damage	**Number of records**	**Release state**
Electrical device malfunctions	9	--
Explosion	36	n.s.
Pipeworks detachment	1	R3
Pool fire	116	R2 or R1
Roof fire	10	R1

6. Conclusions

A methodology was presented for the risk assessment of risk related to NaTech events. The methodology allows the identification of the possible modes of structural damage of equipment items and to associate credible consequence scenarios. The possibility to evaluate the release state due to the natural events and their occurrence using the developed framework is of fundamental importance in order to evaluate the vulnerability of chemical plants to NaTech accidents.

Moreover, accident analysis based on historical data demonstrated that natural causes of chemical accidents should be explicitly taken into account in the conventional quantified risk analysis to allow for adequate NaTech prevention and emergency response planning.

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